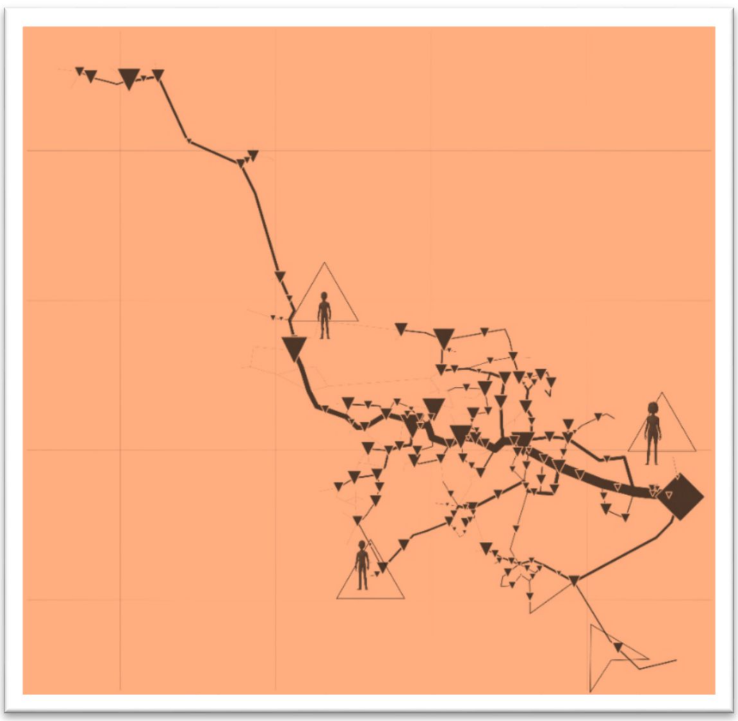
Strategic design of multi-actor nascent energy and industrial infrastructure networks under uncertainty

Yeshambel Girma Melese



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Strategic design of multi-actor nascent energy and industrial infrastructure networks under uncertainty

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Keywords: Energy and industrial infrastructure networks; design under uncertainty; design flexibility; risk sharing; cooperative game theory; real options.

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SETS Joint Doctorate

The Erasmus Mundus Joint Doctorate in ***Sustainable Energy Technologies and Strategies***, SETS Joint Doctorate, is an international programme run by six institutions in cooperation:

- Comillas Pontifical University, Madrid, Spain
- Delft University of Technology, Delft, the Netherlands
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This thesis is a part of the examination for the doctoral degree. The invested degrees are official in Spain, the Netherlands and Sweden respectively.

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The EACEA is not to be held responsible for contents of the thesis.

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Summary

Strategic design of multi-actor nascent energy and industrial infrastructure networks under uncertainty

Yeshambel Girma Melese,
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Key words: Energy and industrial infrastructure networks; design under uncertainty; design flexibility; risk sharing; cooperative game theory; real options.

Infrastructure networks, such as gas transmission and distribution pipelines, electricity transmission and distribution cables, district heating networks and carbon capture and storage pipeline networks are vital infrastructures that form the backbone of our energy system. They transport commodities (i.e. gas, hot water, electricity) from one or several sources to one or several consumption/conversion sites through dedicated pipelines and cables. These infrastructure networks are undergoing major changes due to an increasing integration of renewable sources in the energy sector and increasing adoption of CO_2 emission reduction measures by carbon intensive industries. For instance, the topology of the electricity network is undergoing changes to accommodate distributed power generation and the flexibility of consumers. Likewise, new pipeline infrastructures are being deployed for transporting CO_2 from industrial sources to storage sites and greenhouses.

This thesis focuses on design of nascent energy and industrial infrastructure networks: networks that still needed to be built and for which neither scope, size, nor participants were certain. The design of these networks is challenging for a number of reasons. Firstly, they are very capital-intensive and long-lived, meaning that the return on investment comes long after the up-front cost is made. Secondly, they involve several independent actors (i.e. private and public organizations) with different interests and requirements creating uncertainty regarding what good design is and how revenues and risks are allocated. Finally, if several independent organizations are to be connected to these networks, the actual commitment of these parties and the capacities they require from the network can remain uncertain for a long time. The above issues present engineering and institutional design challenges which may lead to inferior network layouts or even valuable infrastructures not being built at all.

Traditionally, strategic infrastructure design decisions are based on deterministic assumptions of main design requirements and macroeconomic variables (e.g. capital costs, inflation) leading to base-case demand forecasts and cost estimates. However, deterministic assumptions are no longer valid because actual design requirements and the future environment will always vary from what has been anticipated. Hence, a different way of dealing with uncertainty is required, one that recognizes and embraces uncertainties in design requirements and enables actors to properly assess associated risks and develop networks that can adapt to changing circumstances in a cost-effective manner.

This thesis develops systematic design analysis approaches that can provide value-enhancing design decision insights under uncertainty. The thesis contributions lie in four parts. The first part of the thesis focuses on understanding the concept of flexible design and its application to the design of engineering systems in general and the design of energy and industrial infrastructure networks in particular. This thesis concludes that flexibility is conceptualized and applied purely from an engineering design perspective, and the actor perspective is missing. In this regard, a new flexibility conceptualization framework which guides flexibility consideration both in the technical and contractual designs of energy and industrial infrastructure networks is presented.

The second part of the thesis focuses on flexibility in engineering design of energy and industrial infrastructure networks with the objective of improving their lifetime performance in the face of uncertain design requirements. The study develops a systematic engineering design approach that combines graph theory network modeling, the concept of exploratory modeling and the concept of real options to explore candidate designs, identify valuable flexibility enablers and appreciate the value of flexible design strategies. Illustrations in stylized case examples indicate that the proposed flexible design strategy can significantly improve the economic performance of irreversible and capital-intensive utility network projects. This thesis shows that improved economic performance comes from increases in the expected value, reduction in the maximum possible loss and increases in the maximum possible gain of the flexible design strategy when compared to deterministic designs.

The third part of the thesis looks at the role of risk sharing when actors co-invest in infrastructure networks under uncertain environment. A model is developed that conceptualizes contractual arrangements between actors as a cooperative game and analyses the effects of uncertainty. Model analysis leads to two main conclusions. The first finding is that cooperating actors with different risk attitudes can gain more synergies from risk sharing. The second finding is that the optimal revenue and risk share depends on the relation between the actors' pre-existing businesses and the new joint project. The findings may reduce uncertainty among actors and may encourage cooperation in vital infrastructure investments.

The fourth part of the thesis explores the question of how private and public actors, with different and conflicting objectives, can enhance desired performances (e.g. reduction in risk exposure and an increase in reliability) when they develop new energy and industrial infrastructure networks under uncertainty. The study develops an integrated approach that encourages flexible strategies both in the engineering and contractual designs to get a better appreciation of the value of flexibility in a multi-actor setting. The approach employs probabilistic and simulation methods to anticipate a range of future circumstances and then enables contracting parties to identify technical and contractual design strategies that provide enhanced desired performance. Application of the approach has shown that combination of flexible network designs and risk sharing revenue guarantee mechanisms emerged as a frontier design choice for both actors. The conflicting objectives between the private and public actors mean that trade-offs are necessary and the design that enhances value for both partners could be different from the design strategy favoured from an engineering perspective.

In conclusion, the conceptual frameworks and design analysis approach developed in this thesis have shown to provide a better appreciation of flexibility in the face of uncertainty during the conceptual design stage of infrastructure networks. Actors can gain valuable insights on how to strategically deploy networks by carrying out exploratory analysis on the value effects of different flexible design strategies. They can also get valuable insights regarding the values of cooperation, the optimal sharing of risk and the selection of suitable contractual partners in an uncertain investment environment.

Sammanfattning

Energi och industriella infrastrukturnät utgör ryggraden i vårt energisystem, eftersom de tillhandahåller väsentliga verktyg och tjänster. Under nätverkets konceptuella designfas, är inte alla deltagare eller den kapacitet som de behöver, fullt kända, vilket skapar osäkerhet för projektutvecklare eftersom beslut som nätverkslayout måste genomföras när osäkerhet existerar. Dessutom har projektutvecklare olika intressen som skapar osäkerhet kring vilken design som är bra och hur kostnader och intäkter ska fördelas. Därför leder osäkerheten ofta till sämre nätverkslayouter, eller till och med till att viktiga infrastrukturnätverk inte byggs över huvud taget eftersom parter blir riskavvikande och inte vill "satsa på fel häst". Därför krävs ett sätt att hantera osäkerhet, ett sådant som känner igen osäkerhet i designkraven och gör det möjligt för aktörer att bedöma risker korrekt, och utveckla strategier för att anpassa sig till framtida förändringar på ett kostnadseffektivt vis.

Uppsatsens bidrag återfinns i fyra delar. Den första delen av uppsatsen fokuserar på begreppet flexibel design och dess tillämpning på utformningen av infrastrukturnätverk. Begreppet flexibilitet tillämpas utifrån ett konstruktionsdesigns- och skådespelarperspektiv (t.ex. kontrakt) saknas för det mesta. I detta avseende föreslås en ny ram som styr flexibel övervägelse både i tekniska och kontraktsmässiga konstruktioner av nätverk.

Den andra delen av uppsatsen fokuserar på flexibilitet i konstruktionsdesign av nätverk med målet att förbättra dess livstidsprestanda inför osäkra designkrav. En systematisk konstruktionsmetod som kombinerar koncept från grafteori, utforskande modellering och analys och verkliga alternativ föreslås för att utforska värdiga kandidatdesigner, identifiera flexibilitetsmätare och uppskatta värdet av flexibla designstrategier. Illustrationer av de föreslagna tillvägagångssätten visade att en flexibel designstrategi skulle kunna förbättra nätverkets livslängd.

Uppsatsens tredje del tittar på riskdelningen när aktörer samfinansierar i infrastrukturs nätverksprojekt i osäkra miljöer. En modell som kombinerar begreppen kooperativ spelteori och är utvecklad för att analysera effekterna av osäkerhet. Modellanalys visade att aktörer kunde få mer synergier från riskdelning och optimala intäkter och riskallokering beroende på aktörernas redan befintliga verksamhetsprofiler. Dessa resultat kan minska osäkerheten bland aktörer och uppmuntra samarbete i viktiga nätverksinvesteringar.

Den fjärde delen av uppsatsen kombinerar flexibilitet inom konstruktionsflexibilitet och kontraktsmässiga riskdelningskoncept för att förbättra önskad prestanda när aktörer utvecklar nya nätverk under osäkerhet. Genom att använda riskdelning för att möjliggöra värdeavvägningar kan projektaktörer anpassa sina intressen och utforma nätverk som ömsesidigt kan förbättra dess värde.

Samenvatting

Strategisch ontwerp van opkomende infrastructuren van de energie en industrie sector onder onzekerheid vanuit een Multi-actor perspectief

Infrastructurele netwerken transporteren essentiële producten, zoals aardgas, warmte en elektriciteit, van één of meerdere bronnen naar één of meerder locaties waar ze omgezet of verbruikt worden. Deze netwerken van pijpleidingen of kabels voor transport- en distributie van gas, elektriciteit, warmte en kooldioxide vormen de ruggengraat van ons energie systeem. Het ontwikkelen en realiseren van nieuwe infrastructuren is om meerdere redenen een grote uitdaging. Ten eerste vergen deze infrastructuren met een lange levensduur, grote kapitaal investeringen. Hierdoor zal het lang duren voordat de investeringen renderen. Ten tweede, zullen meerdere onafhankelijke private en publieke partijen, elk met hun eigen interesses en randvoorwaarden, betrokken moeten zijn. Dit veroorzaakt onzekerheden over de beoordeling van het ontwerp en over de verdeling van inkomsten en risico's. Ten derde, is het op de lang termijn onzeker welke onafhankelijke partijen, wanneer en met welke gewenste capaciteit gebruik zullen gaan maken van de infrastructuur. De bovenstaande technische en institutionele factoren kunnen leiden tot risico-ontwijkend gedrag bij de betrokken partijen. Zij willen niet op het verkeerde paard wedden. Dit kan leiden tot een inferieur ontwerp van de infrastructuur of zelfs het afgezien van realisatie van een waardevolle infrastructuur.

Traditioneel zijn strategische ontwerpbeslissingen gebaseerd op deterministische aannames over de belangrijkste randvoorwaarden van het ontwerp en de macro-economische variabelen, zoals kapitaalkosten en inflatie, die leiden tot een basisverwachting van de marktvraag en een schatting van de kosten. Echter, deze aannames zijn niet nauwkeurig, omdat de actuele ontwerprandvoorwaarden en de toekomstige situatie zullen altijd afwijken van wat oorspronkelijke verwacht wordt. Daarom is een andere aanpak van omgaan met onzekerheid nodig. Deze aanpak moet de onzekerheden in de ontwerprandvoorwaarden erkennen en meenemen en moet de partijen in staat stellen om bijbehorende risico's goed te kunnen beoordelen en netwerken te kunnen ontwikkelen die zich op kosteneffectieve wijze aan veranderende omstandigheden kunnen aanpassen. Dit proefschrift geeft, in vier delen, methoden voor systematische analyses, die voor ontwerpen onder onzekerheid, waarde-vermeerderende beslissingsinzichten kunnen bieden.

Het eerste deel van het proefschrift richt zich op het begrijpen van het concept van flexibel ontwerpen en de toepassing daarvan op het ontwerpen van engineering systems in het algemeen

en het ontwerpen van energie- en industriële infrastructuurnetwerken in het bijzonder. Dit proefschrift stelt vast dat dat het concept flexibiliteit uitsluitend wordt toegepast vanuit een technisch ontwerpperspectief; Het actorperspectief ontbreekt. Daarom wordt een nieuw raamwerk voorgesteld dat het concept flexibiliteit meeneemt in het technische en contractuele ontwerp van energie- en industriële infrastructuurnetwerken.

Het tweede deel van het proefschrift richt zich op flexibiliteit in het technische ontwerp van energie- en industriële infrastructuurnetwerken met het doel hun levensduur prestatie te verbeteren in het licht van onzekere ontwerpvereisten. De studie heeft een systematische technologische ontwerpbenadering ontwikkeld die netwerkenmodellering op basis van Grafen theorie combineert met het concept Exploratory modellen en het concept Real Options. De ontwerpbenadering heeft als doel nieuwe ontwerpen te exploreren, waardevolle veroorzakers van flexibiliteit te identificeren en de waarde van flexibele ontwerpstrategieën te bepalen. Gestileerde case studies illustreren dat de voorgestelde flexibele ontwerpstrategie de economische prestaties van onomkeerbare en kapitaalintensieve netwerk projecten aanzienlijk kan verbeteren. Dit proefschrift laat zien dat verbeterde economische prestaties voortvloeien uit een toename in de verwachte waarde, een vermindering van het maximaal mogelijke verlies en toename in de maximale winst van de flexibele ontwerpstrategie in vergelijking met een deterministisch ontwerp.

In het derde deel van het proefschrift wordt gekeken naar de rol van risicodeling wanneer actoren samen investeren in infrastructuurnetwerken onder onzekerheid. Er is een conceptueel coöperatief spelmodel ontwikkeld voor de contractuele afspraken tussen actoren en. Het model, dat de effecten van onzekerheid analyseert, leidt tot twee hoofdconclusies. De eerste bevinding is dat samenwerkende actoren met een verschillende risicoperceptie meer synergiën kunnen krijgen uit risicodeling. De tweede bevinding is dat het optimale delen van inkomsten en risico afhankelijk is van de relatie tussen de bestaande bedrijvigheid en het nieuwe gemeenschappelijke project. De bevindingen kunnen onzekerheden bij de actoren verminderen en kunnen hun medewerking aan vitale infrastructuurinvesteringen aanmoedigen.

In het vierde deel van het proefschrift is onderzocht hoe private en publieke actoren, met verschillende en tegenstrijdige doelstellingen, de gewenste prestaties, zoals risicovermindering en betrouwbaarheidstoename, kunnen verbeteren bij het ontwikkelen van nieuwe energie- en industriële infrastructuurnetwerken onder onzekerheid. De studie heeft geresulteerd in een geïntegreerde aanpak die flexibele strategieën aanmoedigt zowel in de engineering- als contractuele ontwerpen om de waarde van flexibiliteit beter te waarderen in een multi-actor omgeving. De aanpak maakt gebruik van probabilistische en simulatiemethoden om een reeks toekomstige situaties te anticiperen en stelt de contractpartijen in staat technische en contractuele ontwerpstrategieën te identificeren die een betere gewenste prestatie bieden. De toepassing van de aanpak heeft aangetoond dat de combinatie van flexibele netwerkontwerpen en mechanismen voor risicodeling en inkomensgarantie ontstond als een elementaire ontwerpkeuze voor beide actoren. De tegenstrijdige doelstellingen tussen de particuliere en de publieke actoren betekenen dat afwegingen noodzakelijk zijn en dat het ontwerp dat waarde voor beide partners vergroot, kan verschillen van de optimale ontwerpstrategie vanuit alleen een technisch perspectief.

Ten slotte kunnen partijen, met de in deze studie ontwikkelde raamwerken en analyseaanpak, de waarde van flexibiliteit onder onzekere omstandigheden tijdens de conceptuele ontwerpfase van infrastructurele netwerken beter bepalen. Partijen kunnen waardevol inzichten verkrijgen over het strategisch inzetten van netwerken door verkennende analyse uit te voeren naar de waarde van verschillende ontwerpstrategieën. Ze kunnen ook waardevolle inzichten verkrijgen over de waarde van samenwerking, de optimale risicoverdeling en de selectie van geschikte contractuele partners in een onzekere investeringsomgeving.

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Slightly over four and half years have passed since I started my PhD at the Energy and Industry Section in the Faculty of Technology Policy and Management of the Technische Universiteit Delft as part of the Erasmus Mundus Joint Doctorate in Sustainable Energy Technologies and Strategies (SETS), a project which culminated with this Dissertation. This period in my life has been filled with excitement and growth not only personally but also academically and professionally. I would like to take this opportunity to express my gratitude towards all partners universities of the SETS programme, the European Commission and most importantly the incredible individuals that made this experience a life changing journey.

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Chapter 1 Introduction

1.1. Background

One of the biggest challenges facing human societies in the next decades is how to cope sustainably with our energy use. It is recognized that rising to the energy challenge requires finding the balance between satisfying a growing energy demand and addressing the effects of climate change. In this regard, we see several initiatives undertaken at a global as well as national scale to find sustainable solutions to our energy needs. Policies employed to adopt more renewable energy technologies and increase energy efficiency have made measurable progress over the last decade. At the same time, governments, industries, and citizens are making progress in their commitment to reduce CO_2 emissions. Most notably, in December 2015, 195 countries adopted the first-ever universal, legally binding global climate deal in Paris.

In addition to the sustainability challenge, we observe that over the last 25 years, the energy system has gone through a major institutional transformation as a result of liberalization and privatization. These institutional changes lead to increased participation of private actors and decentralized generation of energy which reduce dependency on centralized energy grids. In this situation , coordination among actors along the energy value chain is seen as necessary means to ensure proper functioning of the energy system. For instance, regional transmission operators in USA are coordinating to develop inter-regional electricity transmission lines that will facilitate the integration of renewable energy sources (MIT, 2011). Similarly, in Europe, bordering transmission operators invest in cross-border transmissions to facilitate electricity market integration (Brancucci Martínez-Anido, 2013).

There is greater recognition that rising to the sustainability and institutional challenges requires structural changes in our energy system. A critical component of the energy system is a reliable energy infrastructure network: pipes and cables which transport energy carriers, whether it is electricity, fuel or heat, to customers and therefore form a key link in the energy chain. We are already seeing that energy infrastructure networks are undergoing a transformation - existing infrastructures are being adapted and new infrastructures being built. For instance, the topology of the electricity network is undergoing changes to accommodate distributed power generation and the flexibility of consumers. Also, new pipeline infrastructures are being deployed for transporting CO_2 from industrial sources to storage sites and greenhouses; for collecting and distributing waste heat from industrial heat sources; and for pooling biogas from individual farmers and use it as a substitute for natural gas.

This thesis focusses on the design of nascent energy and industrial infrastructure networks: networks that still needed to be built and for which neither scope, size, nor participants were certain. More specifically, the emphasis is on the conceptual design stage of the design process. Energy and industrial infrastructure networks have characteristics that make the conceptual design stage of critical importance. These characteristics are:

- Capital intensive and long lifespan: The design and development new energy and industrial infrastructure networks require a substantial amount of irreversible investment. Additionally, these infrastructure networks have a long lifespan and the return on investment comes long after the upfront costs are made. As a result, the stakes are high for those who decide to invest in new infrastructure assets.
- Multiple actors: The development of new energy and industrial infrastructure networks involve multiple actors (Ligtvoet, 2013) of both commercial and public nature. Individual organizations often lack sufficient expertise and capability to deliver energy services demanded of them. The necessary resources, such as expertise, money, information, personnel and management, are divided among different organizations. As a result, cooperation has become necessary in order to make investments. In the private sector, we see commercial actors increasingly seeking refuge in strategic alliances and the formation of industrial networks (Ligtvoet, 2013). When markets fail to provide sufficient provision of energy and industrial infrastructure networks, public actors collaborate with commercial actors in the form of, for example, public-private partnerships (Samuelson, 1954). Regardless of the nature of actors involved, cooperation is challenging for two major reasons. Firstly, actors have different interests and requirements, and they display strategic and opportunistic behaviour to achieve their goal (Herder et al., 2008). Commercial actors generally seem to behave in their own interest within a cooperation which may not coincide with the general public's interest (Gao, 2005). Secondly, actors are reflexive; they interact and learn, but in the process take decisions while their information is incomplete thus leading to indecision or decisions that are not satisfactory(de Bruijn et al., 2008).
- Uncertainty: - Energy and industrial infrastructure networks are designed in an environment that is uncertain regarding stakeholder requirements, technological changes, market demand, cost and revenue, regulations and other aspects. Among these uncertainties, two are most relevant to the design of energy and industrial infrastructure networks, especially at the exploratory stage of the design process. The first uncertainty

comes from the lack of proper information regarding the capacity requirements of current and future participants. The second uncertainty is due to lack of information regarding the timing of entrance of future participants. These two sources of uncertainty introduce design challenges for two primary reasons. Firstly, uncertainty perceived as an amorphous and fuzzy concept reduces the confidence of infrastructure developers, and that may result in vital infrastructure not being built. Secondly, lack of a proper account of uncertainty during design could lead to an infrastructure that provides sub-optimal performance.

The above three major characteristics, among others, create uncertainty and consequently render decision making very difficult as actors become risk averse and are afraid to 'bet on the wrong horse'(Gong et al., 2009, McCarter et al., 2010). The uncertainty and indecision are especially visible during the conceptual design stage of the design process. However, at the same time, at the conceptual design stage, designers and decision makers have a greater degree of freedom to choose from design alternatives, to choose with whom to cooperate and the type of relationship. Moreover, the conceptual design stage determines the direction, the flexibility and bounds of the subsequent and more detailed designs, and ultimately the lifetime performance of the infrastructure (de Neufville et al., 2010). As one moves along the later stages of the design process the degrees of freedom substantially decrease thus placing a limit, either technically or financially, on the ability to influence desired attributes.

1.2. Design Perspectives

The roll-out of a new energy and industrial infrastructure network entails not only designing the technical/physical components (e.g., cables, pipelines) but also structuring institutional arrangements (e.g., contracts, markets) that coordinate the relationship between actors that develop, own and operate them (Koppenjan and Groenewegen, 2005). The institutional design aspect of new energy and industrial infrastructure networks can also be viewed as the choice of governance structure (Pateli, 2009). Governance structure refers to the kind of cooperative relationships such as joint ventures (Kogut, 1988), partnerships (Miranda Sarmento and Renneboog, 2014) and networks (Child and Faulkner, 1998) used by actors. Regardless of the governance structure, the value an actor gets by investing in a new infrastructure network depends not only on how the physical infrastructure is engineered but also how relational contracts that define the allocation of risk and benefit are structured (Sakhrani, 2015). Thus, design challenges actors face at the conceptual design stage, have both engineering and institutional characteristics.

From an engineering design perspective, designers face challenges in determining the most cost-effective strategy for deploying infrastructure networks in the face of dynamic requirements and operational environment. From an institutional perspective, actors face uncertainty regarding the allocation of benefits and risks under uncertain investment environment. How should the contract be structured to generate significant total value at an acceptable level of risk? How should this total value and the associated risks be shared amongst the partners? The search for a solution to these design challenges requires dealing with uncertainty in infrastructure design (Cardin et al., 2015b, de Neufville et al., 2010) and in risk allocation and management (Blenman and Xu, 2009, Child and Faulkner, 1998, Cruz and Marques, 2013a).

Conventional practices regarding uncertainty and infrastructure systems design tend to focus on either controlling the uncertainty by directly intervening at the source and minimizing the adverse effects or to design systems with the capability to handle uncertainty with a certain range- commonly referred as robust design (Mudchanatongsuk et al., 2008). The controlling uncertainty approach does not require modifying the design configuration and is important during systems operation but of less of an issue during systems design (de Neufville, 2004). The robust design performs well under a changing environment without the need for physical changes in the system. However, there are several drawbacks associated with robust designs (Saleh et al., 2001). For example, robust designs tend to be oversized and costly. As these designs are fixed, they lack the ability to downsize in response to reduced expectations (i.e., not possible to exploit upside opportunities) (Neufville, 2003, de Neufville and Scholtes, 2011). Moreover, robust design approaches only capture incremental uncertainties (such as modelling anomalies) and do not consider more substantial uncertainties associated with future changes. Hence the robust design approach is not appropriate for designing systems that need to be built in stages in order to respond to uncertainties over time.

Similarly, conventionally infrastructure contract design approaches are based on pre-defined forecasts and assumptions on the main macroeconomic variables (capital costs, inflation, etc.) leading to base-case demand forecasts and cost estimates (Cruz and Marques, 2013a). Particularly regarding demand, forecasts have proven to be less than accurate and several studies, in different sectors, illustrating a global trend to overestimate demand in large infrastructure projects (de Neufville, 2004, Flyvjberg et al., 2005). Moreover, at the conceptual design stage, contracting parties do not have full information to write a complete contract that fully addresses every state of the future (Robert and Triantis, 2005). As a solution, contracting parties 'overwrite' contracts in order to reduce the degree of exposure to situations out of the forecast (Marques and Berg, 2010). However, such kind of design approaches lock-in contracting parties and undermines the ability to adapt to changing circumstances (Grimsey and Lewis, 2005). Studies show that contract over-specification and rigidity are the primary cause of low effectiveness, frequent renegotiation and in many cases, contractual relationships fail (Hart and Moore, 1988, Grimsey and Lewis, 2005).

An emerging design paradigm for the design of engineering systems and contracts under uncertainty is the concept of flexible design approach. Theoretically, the essence of the flexible design approach is that intentional design should enable "design solutions' (i.e. contract or physical infrastructure) to pro-actively deal with uncertainty and change themselves accordingly over a range of uncertainty scenarios (de Neufville and Scholtes, 2011). In a flexible design approach, the decision-making process is not focused on a one-time step, but rather on several successive points in time. In engineering systems design, unlike robustness, flexibility entails changes in structure, scale, functionality and operating objectives after the system has been implemented (Saleh et al., 2003, Fricke and Schulz, 2005). In other words, the contract or infrastructure is designed to keep the options open to cope with new operational requirements as they occur. As postulated by Silver and de Weck (2007) and Zhao and Tseng (2003), flexibility enables design solutions to proactively deal with uncertainties. Designing for flexibility can transform risks associated with uncertainty into an opportunity (de Neufville and Scholtes, 2011). In this sense, the concept of flexibility is often related to the concept of real options which is defined technically as "the right, but not an obligation," to adjust the designed system favourably in the face of uncertainty (Cardin et al., 2015b). A flexible design approach claims to consider future uncertainty in design requirements and operational environment in the design and management of engineering systems to achieve enhanced performance (Domingues et al., 2014, Deng et al., 2013). Thus, the flexible design approach seems to be a promising design approach to effectively address uncertainty during the conceptual design of energy and industrial infrastructure networks.

1.3. Research Problem

Recently, research efforts on flexible design focus on where and how to generate and evaluate flexibility during conceptual design of an infrastructure system, with the goal of achieving design methodologies that could enhance value in the face of uncertainty. In this regard, de Neufville and Scholtes (2011) proposed a practical four-step process for developing flexibility in engineering systems design: (1) recognize major uncertainty; (2) Identify flexibility strategies that are appropriate to deal with the uncertainties identified in step 1, (3) evaluate flexible alternatives and choose the best for the system, and (4) implement the identified flexibility. More recently, the same authors proposed a slightly different four-step design catalog as a systematic approach to improving the design and evaluation of engineering systems based on the concept of flexibility (Cardin et al., 2015a). Typical questions of interest in both works are: How can flexibility be integrated into engineering systems? How can flexibility be valued? What trade-offs are associated with designing for flexibility (e.g., cost, preference, risk)?

Designing for flexibility involves defining a strategy and an enabler in design and management (Cardin, 2014). A strategy represents aspects of the design concept that captures flexibility, or how the network is designed to adapt to changing circumstances. An enabler represents what is done to the physical infrastructure design and management to provide and use the flexibility in operations. There are two major types of enablers also called real options (Wang, 2005). Options that involve technical design features are referred to as real options 'in' engineering systems and options that involve managerial decisions on engineering projects are referred to as real options 'on' engineering systems (Wang, 2005).

Similarly, the idea of flexibility is attracting attention in the design of contracts involving multi-actor infrastructure projects. In a multi-actor infrastructure investment environment, uncertainty is not limited to the engineering design but includes the design of contracts between actors (Walker et al., 2017). Domingues et al. (2014) studied the potential benefits of contractual flexibility with respect to infrastructure contracts and concluded that flexibility may contribute to enhancing the project's economic efficiency. Chiara and Kokkaew (2009) introduced the concept of "contractual flexibility analysis" to improve the economic efficiency of infrastructure development concession contracts. The concept argues that embedding flexibility mechanisms such as strategies that allow for shifting risks from one partner to the other, in order to improve the contract behaviour depending on the evolution of uncertainty. Cruz and Marques (2013a) use the concept of contractual flexibility and real options evaluation framework to enhance the value of public-private partnership contracts. The authors demonstrated that managerial flexibility options embedded in the infrastructure create economic value and allow public agencies to capture some of the resulting improvement.

This thesis is part of the ongoing research effort to develop and apply systematic flexible design methodologies that could provide valuable decision insights in the face of uncertainty. It primarily focuses on the conceptual design of energy and industrial infrastructure networks and addresses the following four major challenges.

First, the conceptualization of flexibility in the engineering systems design literature focuses uniquely on the physical design of the infrastructure as "the object of design," whereas hardly any attention is paid to the institutional structures required to enable the realization of such systems. The institutional aspects of the design are often treated as design contexts to the formulation of the engineering design. However, as pointed out previously, deploying an energy and industrial infrastructure requires collaboration between several actors. The institutional design aspects of energy and industrial infrastructure networks require bringing actor perspectives into the centre of the design formulation (Koppenjan and Groenewegen, 2005). The value a given actor gets by engaging into the development of an energy and industrial infrastructure networks depend not only on how the physical network is designed but also on how risk and benefit allocation contracts that define the relationship between actors are structured (Sakhrani, 2015). Hence, a new conceptual framework that considers the technical/engineering perspective, as well as the actor perspective in the design of flexibility is required.

Second, the concept of flexible design has not been applied to the engineering design of energy and industrial infrastructure networks. Networks have spatial and temporal characteristics that exhibit an evolutionary growth; they start small in scale and grow spatially to complex networks over their lifetime. Such characteristics of networks present unique design challenges compared to "batch" projects executed within a fixed time period such as multiple story buildings (de Neufville et al., 2006) or manufacturing plants (Benjaafar and Sheikhzadeh, 2000). For example, the current gas transmission and distribution grid started with few point-to-point connections linking a gas source to few consumption sites. Over time, it has grown into a complex pipeline network (what is now called the grid) by adding more production and consumption sites. The dynamic spatial and temporal characteristics of networks like the gas and electric grids make their design more complicated due to the much larger routing solutions space. The initial layout potentially locks-in the future pathways of the network and as a result, identifying where to embed flexibility capability from large numbers of layout possibilities is a very challenging task.

Third, normative approaches to the design of contracts under uncertainty are simplistic. The key to flexibility in contract design under uncertainty is how risk and future benefits are allocated among partners. In this regard, the literature has come a long way from deterministic cooperative game theory models of Nash (1950), (1953) and Shapley (1953) to models that consider uncertainty (Suijs et al., 1999, Savva and Scholtes, 2005). Similarly, the literature on risk allocation in infrastructure contracts has made advances to consider uncertainty in their quantitative analysis and modelling. Medda (2007) used a game theoretical approach to the allocation of risks in transport public-private partnerships. Other techniques applied to this problem include Artificial Neural Networks (Jin and Zhang, 2011) or fuzzy system dynamics (Nasirzadeha et al., 2014). However, all these previous works largely focus on closed contracts where the only payoff comes from the joint investment, and the effects of the agents' pre-existing businesses are ignored. Moreover, the methods used to model the uncertainty in the future performance of the common project are either deterministic or relatively simplistic, while the future revenues from most infrastructure investments are stochastic.

Last, energy and industrial infrastructure network design decision-making problems are often formulated from the perspective of a single actor (e.g. manager). For example, power transmission expansion planning and design problems are defined from the perspective of when to invest, how much capacity to add, what type of generation is needed, and where to locate new transmission lines and generating units (Lumbreras et al., 2016). Network planning and design problems and solution approaches are abstracted from a single decision maker perspective. However, as pointed out previously, the development of energy and industrial infrastructure networks requires the cooperation of several actors. Hence, a multi-actor perspective to co-design decision under uncertainty is missing.

1.4. Research Objective and Questions

Motivated by the design issues raised in section 1.2. and the research gaps discussed in section 1.3, in this thesis we investigate the promises of the flexible design concept to proactively manage uncertainty during conceptual design of energy and industrial networks. This requires an understanding of current engineering and contract design practices and will lead to developing new methods to analyse and appreciate flexibility using some selected case examples. Therefore, we aim to address the following research question:

How can we systematically analyse and appreciate flexibility opportunities during conceptual design of multi-actor energy and industrial infrastructure networks?

The proposed research aims to contribute to the design and investment decision making approaches of large-scale infrastructure projects in the face of uncertainty. Decision-making problems that actors face under uncertainty are conceptualized from the technical/engineering design and contractual design perspectives. Thus, the thesis looks at ways of improving expected value both from the engineering and actor perspectives. This leads to the following list of research sub-questions:

1. *How is the concept of flexible design described in the literature, and how can the concept be best applied to the design of energy and industrial infrastructure networks?*

2. *How to systematically analyse and appreciate technical flexibility options during conceptual design of energy and industrial infrastructure networks?*
3. *How to analyse and appreciate the value effects of cooperation under uncertainty?*
4. *How to systematically analyse and appreciate value-enhancing technical and managerial flexibility options in partnership network projects?*

1.5. Research Approach

To answer the first research sub-question, a literature study was carried out on the different conceptualization perspectives and design approaches of energy and industrial infrastructure networks. The literature study forms the basis to construct a new conceptual framework that integrates the technical/engineering perspective, as well as the actor perspective in the design of flexibility.

For answering the second research sub-questions, concepts and methods from the flexible systems design and real options approach were used. A simulation based design analysis procedure that combines a graph theoretical network model, the concept of exploratory analysis and the concept of real options is used to explore candidate designs and identify valuable flexibility enablers. Monte Carlo simulation is used to check the performance of design strategies. Several indicators of economic lifecycle performance (Net Present Value, Initial Capex, etc.) are used to compare the performance of the flexible design strategy to non-flexible design strategies. The economic value (cost saving and NPV gain) of flexibility is priced by comparing the flexible design strategy against the non-flexible design strategies.

To answer the third research sub-question, we took a contractual design perspective to the network design problem. The research question was framed in the context of contractual design focusing on the allocation of prospective risk and benefit when risk-averse commercial actors co-develop an infrastructure network with uncertain long-term revenue. Cooperative game theory was used to model prospective risk and benefit allocation between cooperating actors. A stochastic approach is used to represent uncertainty. Then, a real options concept is used to define and model the different flexibility options available for the actors both individually and jointly. A stylized cross-border merchant electricity interconnector partnership between two transmission systems operators is used to show the effectiveness of the modelling approach.

To answer the last research question, a combination of engineering design and contractual design perspectives is employed. The research question is formulated in the context of an infrastructure public-private partnership for developing a multi-user CO_2 pipeline network. A design procedure that allows partners (private and public actors) to look for value-enhancing flexibility options within the physical and contractual designs is proposed. The procedure involves the use of probabilistic and simulation methods to model uncertainty, use of graph theory to model the physical design of the infrastructure and a concession contract model. The flexible design concept is used to generate flexible design strategies both within the physical design and the concession contract. Then, Monte Carlo simulation is used to compare the effects of different technical and contract design strategies on the value of the private and public actors.

1.6. Scientific Contributions

As will be argued in detail in the literature discussions of the thesis chapters, this thesis identifies gaps in research regarding flexible design strategies during conceptual design of energy and infrastructure networks and addresses these gaps. Based on design concepts from the engineering design, real options, decision theory, and strategic management literature, the thesis presents new and improved systematic design analysis methods that can provide value-enhancing design decision insights under uncertainty. The hypothesis under analysis is that flexibility may increase desired value. Overall, this thesis contributes to the scientific literature in four major areas, pertaining to the four research problems identified in section 1.3.

Firstly, it contributes to the emerging research on the flexible design of infrastructure systems by extending the conceptualization of the flexible design concept from merely an engineering perspective to one that considers the actor perspective. In this regard, a new flexibility conceptualization framework which guides flexibility consideration both in the technical and contractual designs of energy and industrial infrastructure networks is introduced.

Secondly, it contributes to energy and industrial infrastructure networks engineering design methodologies by providing a systematic flexible network design approach. In this regard, systematic procedures that combine graph theory, the concept of exploratory modelling and the concept of real options are proposed to explore candidate designs, identify valuable flexibility enablers and appreciate the value of flexible design strategies.

Third, this thesis contributes to contractual risk allocation by providing a systematic modelling and analysis procedure. Existing literature on the allocation of benefits and risks when actors jointly invest in infrastructure assets did not consider the effect of the actors' pre-existing businesses. To address this gap, this thesis proposes a new modelling and analysis framework that employs concepts from cooperative game theory and real options. Finally, the thesis develops a flexible design concept for the deployment of infrastructure networks via public-private arrangements. Very little work has been done to develop an integrated approach that considers both engineering and contractual design. A notable exception is a work by Sakhrani (2014) which proposes a co-design procedure for the flexible design of infrastructure projects via risk sharing contracts. This thesis adds to the work of Sakhrani (2014) by incorporating a real options approach to the contract design.

1.7. Implications for Practice

This thesis shows, through systematic analysis methods and case examples, that proper accounting of uncertainty and integrating flexibility capabilities enhances desired value for those actors involved in the deployment of energy and industrial infrastructure networks. The goal of the methods and case examples discussed in this thesis is to inform decision makers and to help them make up their mind by reasoning through different options before committing to a design or a contractual relationship.

The primary benefits of the insights derived from the research work would be to network owners/operators, i.e. those who design and own energy and industrial infrastructure networks assets. For network operators, the thesis provides valuable insights on how to strategically deploy infrastructure networks by carrying out exploratory analysis on the value effects of different flexible design strategies. In many cases, network operators cooperate with each other or with other actors. The thesis can provide insights for cooperating partners on the effects of cooperation and the optimal allocation of benefits and risks. These insights are particularly appreciated during the conceptual design stage of the design process. Besides the network operators, public actors (at local, national and regional level) could benefit from the insights regarding the structuring of appropriate risk sharing mechanisms and ways of benefits from flexible design strategies during deployment of vital infrastructure in the form of public-private partnerships.

1.8. List of Publications

- Publication I

  Yeshambel Melese, Rob Stikkelman, Paulien Herder, "A Socio-technical perspective to flexible design of energy infrastructure systems," *Proc. IEEE International Conference on Systems, Man, and Cybernetics (SMC)*, Budapest, Hungary, pp. 004669- 004674, 2016.

- Publication II

  Y.G.Melese, P.W.Heijnen, R.M.Stikkelman, "Designing Networked Energy Infrastructures with Architectural Flexibility," *Procedia Computer Science,* vol 28, 179-186, 2014.

- Publication III

  Y.G.Melese, P.W.Heijnen, R.M.Stikkelman, P.M.Herder, "Exploring for real options during CCS networks conceptual design to mitigate effects of path-dependency and lock-in," *International Journal of Greenhouse Gas Control,* vol 42, pp. 16-25, 2015.

- Publication IV

  Y.G.Melese, P.W.Heijnen, R.M.Stikkelman, P.M.Herder, "An Approach for Integrating Valuable Flexibility during Networks Conceptual Design," *Networks and Spatial economics*, 2016.

- Publication V

  Y.Melese, S.Lumbreras, A.Ramos, R.Stikkelman, P.Herder, "Cooperation under uncertainty: Assessing the value of risk sharing and determining the optimal risk-sharing rule for agents with pre-existing business and diverging risk attitudes," *International Journal of Project Management*, vol 35, pp. 530–540, 2017.

- Publication VI

  Y.G.Melese, P.W.Heijnen, R.M.Stikkelman, P.M.Herder, "An Approach for Flexible Design of Energy Networks via a Risk Sharing Contract: The Case of CO_2 Transport Infrastructure," *International Journal of Greenhouse Gas Control,* vol 63, pp.401-411, 2017.

1.9. Thesis Structure

The rest of the thesis consists of four chapters (chapters 2-5) that deal with the research sub-questions, a conclusion chapter and an annex consisting of the journal and conference papers listed in section 1.8. A short summary of each chapter is given next.

Chapter 2 presents a brief discussion on the different conceptualization and design approaches used for infrastructure networks. It identifies some limitations of the flexible systems design approach and introduces a new conceptual framework that encourages flexibility consideration both in the technical and contractual designs. The chapter is based on publication I (Melese et al., 2017c).

Chapter 3 presents a brief background of the concepts of real options and flexible design approach. Then, it introduces a new design analysis method to enhance the value of networks under uncertainty. The proposed procedure is illustrated on a stylized gas pipeline network. The chapter is based on publications II (Melese et al., 2014), III (Melese et al., 2015) and IV (Melese et al., 2017d).

Chapter 4 discusses the role of risk sharing when actors co-invest in energy infrastructure networks under uncertainty. It presents a derivation of the optimal sharing rule and its implication for partners. The chapter is based on publication V (Melese et al., 2017b).

Chapter 5 discusses how actors, with different and conflicting objectives, can enhance desired performances when they co-develop new infrastructure networks under uncertainty. It introduces an integrated design analysis approach to simultaneously explore value-enhancing flexibility options within the technical and contractual designs. A multi-user CO_2 pipeline network is used to illustrate the approach. The chapter is based on publication VI (Melese et al., 2017a).

Chapter 6 highlights the key conclusions of the thesis, reflections on the limitations of the thesis and recommends for future research areas.

Chapter 2 Designing Multi-Actor Nascent Networks:-Engineering and Actor perspectives

This chapter presents a brief discussion on the different conceptualization and design approaches used for infrastructure networks. It identifies some limitations of the flexible systems design approach and introduces a new conceptual framework that encourages flexibility consideration both in the technical and contractual designs. The chapter summarizes publication I (Melese et al., 2017c)

2.1. Introduction

Energy and industrial infrastructure networks form the backbone of our society as they provide essential utilities and services. Examples include gas pipelines, electricity transmission and distribution grids, and pipelines for transportation of waste heat and carbon dioxide. These infrastructure networks share some typical characteristics. Spatially, since they are normally static, and occupy large space, they greatly influence the spatial organization of the society and the built environment at both macro and micro scales. Economically and temporally, their common characteristics are capital-intensive and long-lived, e.g. 40 - 50 years for gas pipeline networks (Ajah and Herder, 2005). Once these networks have been deployed, the physical assets are irreversible. Moreover, along with their value chain, they involve multiple actors in their design, ownership, and operation. Because of these characteristics, the designs are of paramount importance to the success of these infrastructure networks.

The roll-out of new infrastructure networks is challenging because they involve several independent actors (i.e. private and public organizations) with different interests and requirements creating uncertainty regarding what good design is and how revenues and risks are allocated. Moreover, at the exploratory stage of the design process, the actual commitment of participants and the capacities they require from the network can remain uncertain for a long time. The above issues present both engineering and institutional design challenges that could lead to inferior network deployment or in many cases for vital infrastructure not developed at all.

The rest of the chapter is structured as follows. Section 2.2 describes the socio-technical perspective used to conceptualise infrastructure systems. A network perspective is used to formalize the domains common to infrastructure networks. Section 2.3 discusses the different approaches used for guiding the design of infrastructure systems. Section 2.4 briefly reviews the key literature for dealing with uncertainty during the design of infrastructure networks and identifies some conceptual gaps. In section 2.5 a new conceptual framework for the flexible design of infrastructure networks is presented. Section 2. 6 summarises the chapter.

2.2. Conceptualizing Infrastructure Networks – A Socio-Technical Perspective

Infrastructure systems are socio-technical systems, systems that involve both technical and social components. Hughes (1989) was the first to coin the term large-scale technological systems (LTS) to describe systems comprising of physical artefacts, organizations, scientific components, and legislative artefacts. The term artefact applies to both the physical and nonphysical (e.g., legislative) parts of the systems that are constructed or adapted by social organizations. Kroes et al. (2006) treated infrastructure systems as a class of socio-technical systems in which technology is central to their operations, and organizational form of social control is established to ascertain a range of public values associated with their operation. A socio-technical view of infrastructure systems also means that their design, deployment and operation are governed by the interplay between social and technical elements The technical elements comprise of artefacts such as machines, factories, pipelines, and wires. The social elements comprise of social components such as humans, institutions, organizations, rules, laws and cultures.

The technical and social elements are governed by different principles. The social elements are governed by social rules (e.g., legislation, unwritten codes of behaviour, or economic contracts). The physical elements are governed by physical rules (e.g., Newton's laws, Einstein's theory of relativity, or the laws of thermodynamics). Infrastructure systems are, therefore, under the continuous influence of both social and physical rules. The technical component works in turning out the desired technical functionality of the system, while the social component strives at intentionally influencing the technical subsystem.

At the abstract level, both the physical and social elements of infrastructure systems can be conceptualized as a network. The physical elements can be described as a network of links and nodes allowing a certain amount of flow through the links which are processed at the nodes. It includes the facilities for energy production, transmission, distribution, and consumption, and for waste heat treatment, production, distribution, and supply in a district heating system, or for CO_2 capture, transportation, and storage. The links facilitate the flow of commodities (e.g., electricity, gas, heat and cold) and include pipelines and power cables.

In addition to the physical network, the infrastructure systems include networks of the interdependent actors (individuals, firms, organizations, and institutions) that design and operate them (Gao, 2005). Actors design institutions (e.g., contracts) to safeguard their value and achieve their objectives (Gao, 2005). Institutions serve as links that define the relationships between actors. They coordinate the behaviour of interdependent actors (which are abstracted as nodes) who may have diverging objectives (Williamson, 1979). For example, concession contracts, are the most common form of institutional arrangements providing the framework for the development and operation of infrastructure services (Cruz and Marques, 2013b). Concessions contracts serve as a link to align the interests of public and private actors by defining the allocation of risk and benefit (Jin and Zhang, 2011).

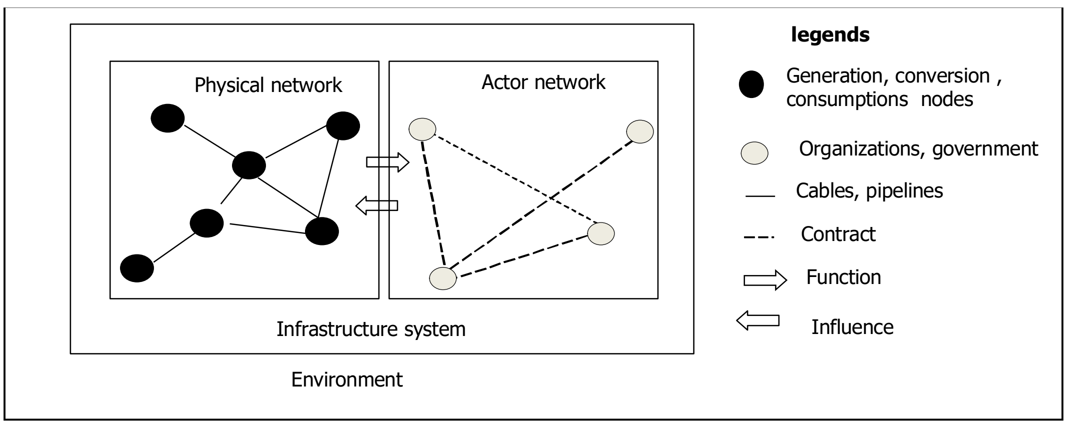

Figure 2.1 Abstraction of energy and industrial infrastructures as networks of physical artefacts and networks of actors.

Fig. 2.1 formalizes the domains common to the energy and industrial infrastructure and most other infrastructures from a network perspective. They include the following:

- *Technical/ physical networks*: the nonhuman components of the system which include hardware (physical infrastructure) and software (information).
- *Social/actor network*s: the human components and the relationships that hold between them.
- *Environment*: the exogenous components that affect or are affected by the system.
- *Function*s: the goals and purpose of the physical system.
- *Influence*: the actions, both intentional and unintentional, that shape the state of the system.

The technical and social elements are similar in that their structure comprises of components connected by incidental and permanent links of varying types (physical, information, knowledge, etc.), where the behaviour of each component is governed by a set of rules. The main difference is that the components of the physical elements are technical or physical artefacts governed by rules of nature and created by man, whereas the components of the social elements are reflective actors who interact, learn, and display strategic behaviour (de Bruijn et al., 2008). The two elements interact with each other and with the environment in complex ways, and this interaction determines the overall behaviour of the system.

2.3. Design Perspectives

Having socio-technical characteristics means that the design of energy and industrial infrastructure networks involves joint consideration of technical/physical and institutional variables (Koppenjan and Groenewegen, 2005, Bauer and Herder, 2009). The technical and actor elements are guided by different governing principles, and this has implications for their design. The technical design is dominated by "what and how" questions concerning technical decisions, whereas the institutional design largely focuses on "who and why" concerns about the acceptability of the system (Nikolic, 2009). For example, the design of a district heating network entails both engineering decisions (e.g., the dimensions of the pipes, the number of pipelines, the number and size of pumping stations, the form of the heat carrier) and institutional arrangements between the parties involved (e.g., contracts between waste heat suppliers and network operators or between the public sector and private network operators) (Ajah et al., 2007).

2.3.1. Systems engineering perspective

Systems engineering is the dominant guiding principle in the design of engineering systems. Blanchard and Fabrycky (2006) define systems engineering as:

"A technologically based interdisciplinary process for bringing systems, products, and structures (technical entities) into being."

The International Council on Systems Engineering (INCOSE) defines systems engineering like this:

"Systems Engineering is an interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, and then proceeding with design synthesis and system validation while considering the complete problem." (INCOSE, 2015).

From the above definitions, two major observations emerge. The first observation is that systems engineering identifies the technical elements of the system as "the object of design" while referring to the social elements (e.g. actors and institutions) as design contexts. The social dimensions of the infrastructure system take the form of regulations, laws, contracts, procedures, standards, organizations, and people and are often treated as the requirements and constraints of the engineering design. The second observation is that systems engineering asserts a systematic process and provides guidance on key process activities performed by systems engineers. However, as described in section 2.2, energy and industrial networks have institutional components that are considered as "objects of design". Moreover, the systematic and rational engineering approach may not be able to provide appropriate design principles when it comes to social institutions. Therefore, system engineering has some conceptual limitations when it comes to infrastructure systems design.

2.3.2. Engineering and actor perspectives

Addressing the analysis and design of infrastructure systems, de Bruijn and Herder (2009) suggested using technical/engineering perspective and actor/social perspective alongside each other. The engineering perspective focuses on the technical subsystem as the object of design and employs largely technical–rational design approaches. The underlying disciplines are mainly the engineering disciplines of systems engineering and operations research which apply a phased and structured approach to problem-solving. This involves problem analysis, conceptual design, basic design, detailed design, and implementation. Such an approach assumes that all problems can be identified and that the information required for modelling and understanding the system is available.

The actor perspective focuses on the design of a process within which actors with a stake in the system can address the problems between them. An important characteristic of these actors is that they are reflective and display strategic behavior. The existence of many dependencies between the actors (each with her/his objective) means that they are obliged to interact and negotiate. Process design offers a set of design principles (so-called rules of the game) which guide the interaction of the actors (de Bruijn et al., 2008). A good process offers parties security through protection of their core values, offers sufficient incentives for progress and momentum, and offers adequate safeguards for the substantive quality of the results (de Bruijn et al., 2008).

The socio-technical perspective, unlike the systems engineering perspective, promotes applying, in parallel, engineering principles to guide the design of the technical subsystems and process design principles to guide the design of institutions. Moreover, under the socio-technical perspective the "objects of design" are both physical and institutional components

(Koppenjan and Groenewegen, 2005). Therefore, the socio-technical perspective could provide a better design conceptualization for energy and industrial infrastructure networks.

2.4. Uncertainty and Multi-Actor Infrastructure Network Design

Uncertainty in multi-actor network design has multiple dimensions - technical such as flow rate, economical such as price, regulatory such as tariff and support schemes, and strategic behaviour (de Weck et al., 2007). It varies depending on the specific nature of the infrastructure project. Nevertheless, at the conceptual design stage, uncertainty affects design decisions in two major ways. On the one hand, uncertainty makes decisions very difficult when actors become risk averse and are afraid to 'bet on the wrong horse' (Gong et al., 2009, McCarter et al., 2010). Actors have little or no information regarding the future evolution of key value drivers such as price, regulations and motivation of partnering. One the other hand, improper accounting of uncertainty may result in a sub-optimal design decision (de Neufville, 2004). Failure to properly deal with uncertainty may lead to serious consequences including project delays, poor-quality, budget over-runs and contractual disputes. The question then becomes: how to deal with uncertainty during the conceptual design stage of multi-actor energy and industrial networks? Given the socio-technical nature of infrastructure systems, a solution to the above question should involve both engineering and actor perspectives.

2.4.1. An engineering perspective to managing uncertainty

The design of nascent networks presents a major challenge for network developers. In many cases, network layout decisions have to be made while uncertainty exists regarding capacity demand and supply and number of participants. Flexibility in design is a concept that can improve the economic value of projects under uncertainty. The core of the concept is that projects have to be designed with a capability to adjust to the evolution of uncertainties over time. The importance of the concept has been demonstrated in many applications, including manufacturing (Bengtsson, 2001) and infrastructure (Cardin et al., 2015b, de Neufville and Scholtes, 2011).

A good example to show the concept of flexible design and its value is the 25th of April bridge (Ponte 25 de Abril) connecting Lisbon to the municipality of Almada in Portugal. The bridge was originally designed to carry four car lanes, but engineers built extra strength into the columns to allow more lanes to be added if needed in the future, as well as a railway on the lower platform, should travel and demographic patterns warrant it. This design flexibility allowed expansion to the current six car lane and twin railroad track that exists today.

The above example shows the potential of flexibility in design to manage uncertainty during the conceptual design of energy and industrial infrastructure networks. However, examining the concept and its application to networks shows limitation. To show this limitation, we analyse the definition of flexibility and two examples of where the concept has been applied.

Developing a comprehensive treatment of flexibility in engineering systems design Saleh et al. (2003) gave the following definition of flexibility:

"Flexibility of a design solution is the property of a system that allows it to respond to changes in its initial objectives and requirements—both in terms of capabilities and attributes—occurring after the system has been fielded, i.e., is in operation, in a timely and cost-effective way."

In this definition, flexibility is conceptualized as an important property of the design solution, endowed on it by design (i.e., by intentional action) to enable it to respond to changes in a timely and cost-effective way. Flexibility, in this definition, means the various strategies that could be put in place early in the design process to allow effective handling of the various uncertainties that could affect the performance of the system over its entire life span.

Moreover, from the above definitions, two major features become apparent. The first is that a design solution (i.e., "object of design") of some sort exists into which flexibility needs to be integrated. The second addresses the level (e.g., strategic, operational, tactical) at which flexibility can be incorporated into the design solution. These features are particularly significant in the context of infrastructure systems, where the design solution requires both technical and institutional elements to be considered, and in which there is a considerable degree of freedom to build-in flexibility at the strategic, operational, and tactical levels.

and Cardin et al. (2015b) proposed a systems engineering approach to the flexible design of infrastructure systems. Both papers presented a process for designing and valuing the flexibility of systems and applied it to a multilevel parking garage built beside the Bluewater commercial centre near London in the United Kingdom. Two different types of flexibility were identified. The first type treats the system as a "black box" in which some exogenous flexibility options might be exercised, including abandon, switch, defer, and time to build (Wang, 2005). This is essentially managerial flexibility (Trigeorgis, 1996, Lumbreras et al., 2016). The second type covers flexibilities embedded in the engineering design. These generally involve physical designs which allow the system to adapt to cope with changes in requirements and the environment, for example, building in structural columns with extra strength (Wang, 2005).

In both papers, the object of design is clearly the technical/physical system. Managerial flexibilities are centralized so that all decisions are taken from the perspective of a single decision maker (the system designer or manager). In other words, the management dimension in addressing flexibility takes a single-actor perspective. Even if multiple actors are involved, it is assumed that their interests are aggregated into a single view, and that is reflected by the manager (decision maker).

2.4.2. Actor perspective to managing uncertainty

The previous discusses that the concept of flexible systems design can be helpful in improving the economic value of network projects under uncertainty. However, during the conceptual design stage of networks, actors also face challenges regarding the design of institutions that formalize their relationship. In many cases, uncertainty regarding the value of network investments and regarding the commitment of partners lead actors to be indecisive. What is the effect of co-investment in networks? How can one select a suitable partner? These are the kind of questions actors face at the exploratory or conceptual design stage of the design process.

To address the above concerns, actors engage into formal contractual agreements. Nevertheless, infrastructure contracts are exposed to different kinds of uncertainty (Algarvio and Lopes, 2014, Marques and Berg, 2011). Uncertainty arises from future changes in macroeconomic scenarios, technological changes, regulatory changes, and strategic behaviour of parties (Guasch and Straub, 2009, Shen et al., 2006).

In the literature, there are two kinds of uncertainty management strategies – those who view uncertainty as risk and equate it to the down-side of events (Freund and Jones, 2015, Hastings and McManus, 2004), and those who consider both the down-side (loss) and up-side (gain) of risk (Chapman and Ward, 2003, Chapman and Ward, 2011). In recent years there has been a growing recognition that a threat-focused risk management approach on projects is not appropriate to enhance the value of contracts (Chapman and Ward, 2002, Hillson, 2002, Stoelsness and Bea, 2005). Chapman and Ward (2002) concluded that having an approach that merely aims to reduce the possibility of underperformance results in a very limited appreciation of project uncertainty and undermines the potential benefits of project risk management. Similarly, other studies suggested that focusing on uncertainty management instead of risk management can improve the value of projects (Chapman and Ward, 2011, de Weck et al., 2007, de Neufville, 2004). These studies concluded that designing for uncertainty can lead contract designing parties to choose and create contract structures that are markedly different from contracts that are created to meet fixed specifications.

A. Risk sharing to manage contractual uncertainty

Risk sharing as an uncertainty management strategy originated from the unrealistic assumption of traditional contract theory (Williamson, 1979). The theory assumes that a contract should contain the agreements on how to deal specifically with all expected incidents which may, or may not, occur in the future (Mirrlees, 1999). However, if the parties to a contract intend to contain all agreements for uncertain situations, a contract document may become extremely complex. Moreover, the presence of uncertainty makes it impossible to draft a complete contract. In such cases, provisions for risk sharing are embedded in contracts to avoid losses.

In the literature, risk sharing is commonly used to manage uncertainty in different types of contracts: supply-chain (Xiao and Yan, 2009), insurance (Townsend, 1994), and construction (Marques and Berg, 2011). Marques and Berg (2011) used risk sharing to allocate risk between the public and the private parties in infrastructure concession contracts.

B. Flexibility to manage contractual uncertainty

In addition to flexibility options from an engineering perspective, opportunities also exist to design flexibility with the contract structure. Recently, the concept of contractual flexibility is becoming increasingly important as a tool to address uncertainty affecting Public Private Partnership (PPP) projects. Chiara and Kokkaew (2009) introduced the concept of "contractual flexibility analysis" to improve the economic efficiency of public-private partnerships for infrastructure development. The concept basically argues for embedding flexibility mechanisms (e.g. contingency clauses) that allow for shifting risks from one partner to the other, in order to improve the contract behaviour over time. Tan and Yang (2012) examine flexible PPP contracts for a new highway project in the face of demand uncertainty. Cruz and Marques (2013a) use the concept of contractual flexibility and real options evaluation framework to enhance the value of hospital PPP contracts. Domingues et al. (2014) explore the potential benefits of contractual flexibility in the road PPP contracts. The underlying theme of the above mentioned studies is that the infrastructure investments are exposed to a multitude of uncertainty and as a result partnering actors need to look past reactive risk minimization efforts and introduce pro-active flexibility measures into the contract.

However, the literature on both risk sharing and flexibility mainly focus on contracts as "objects of design" and disregard the value enhancing flexibility opportunities that exist from the technical perspective. For example, risk sharing approaches focus on risk adjustments i.e. adjusting the impact of uncertainty for each partner by transferring risk from one to the other. Similarly, the literature on contractual flexibility largely focuses on including flexibility clauses such as contract re-negotiation within the contract and miss on technical flexibility opportunities.

2.4.3. Integrating engineering and actor perspectives

To address the gaps discussed in the previous sections, an integrated approach which combines engineering and actor perspectives in parallel may enable actors to improve the economic performance of network projects under uncertainty. The concept of flexibility has shown promising results both in engineering and contractual designs. Risk sharing can help align the interests of actors involved in developing the infrastructure. Using the integrated approach, actors can explore the technical and contractual design space and identify value-enhancing design strategies. One hypothesis is that integrating flexibility in the physical designs as well as in contracts may improve value for all actors involved.

The 25th of April bridge (Ponte 25 de Abril) is a good example to make a case for an integrated flexible design approach. In 1997, a 30 year concession contract was signed between the private party (Fertagus) and the government to construct a railway line over the bridge (de Lemos et al., 2004, Sarmento and Renneboog, 2014). The contract included a clause that allows the private party to renegotiate revenue in response to traffic density. This clause enabled the private party to adjust the initial contract depending on the realization of future toll revenues. The example shows that embedding flexibility in the physical and contractual design allows project actors to manage traffic density uncertainty. The extra length built into the columns allowed physical flexibility to add the rail line while the revenue renegotiation clause in the concession contract allowed contractual flexibility between the private and public party.

2.5. Summary

This chapter discusses the different perspectives that can be used to describe and design energy and industrial infrastructure networks. Energy and industrial infrastructure networks are formalized as systems comprising both networks of technical/physical elements (e.g., cables, pipelines) and networks of interdependent actors (e.g., contracts). Designing these networks, therefore, requires applying both engineering and actors perspectives. In this regard, the systems engineering perspective has been shown to have some conceptual limitations because i) it mainly focuses on the physical elements of the system as “the object of design”, and ii) prescribes systematic and rational approach to design. The social or institutional elements such as contractual relationships and policies are mostly treated as design contexts. On the other hand, the academic literature that discusses the design of contractual arrangements mainly focus on contracts as “the objects of design” and ignore the value enhancing opportunities that exist within the technical perspective.

To address these conceptual gaps a new flexibility conceptualization framework which guides flexibility consideration both in the technical and contractual designs of energy and industrial infrastructure networks is introduced, see publication I (Melese et al., 2017c) for more detail. In general, the proposed conceptual framework encourages exploring both the technical and contractual design space to find opportunities that can improve value for all actors co-investing in the network.

Chapter 3 Designing Flexibility to Manage Uncertainty during Conceptual Design of Networks

This chapter focuses on the flexible design of infrastructure networks under uncertain design requirements. First, it presents a brief background of the concepts of real options and flexible design approach. Then, it introduces a new method to improve the expected value of networks when there is capacity uncertainty. The proposed method is illustrated on a stylized gas pipeline network. The chapter summarizes publications II (Melese et al., 2014), III (Melese et al., 2015) and IV(Melese et al., 2017d)

3.1. Introduction

Networks transport a commodity (such as gas and electricity) from one or several sources to one or several sinks. In the exploratory or design phase of the project, not all participants (i.e. sources and sinks) nor the capacities they require are fully known. This creates uncertainty for project developers because of decisions, such as network layout, have to be made while uncertainty exists. Among some of the key strategic-level design questions facing network project developers are:

- What is the most cost-effective strategy for phasing a network to meet increasing flow from existing and future sources?
- How to strategically design a network to be able to coordinate the capacities of source facilities, pipelines, and the sink as the network expands over time with new sources joining the network?
- Is overbuilding capacities with large-diameter pipeline early in the design to accommodate future flow increase from sources making economic sense?
- Is it worthy to wait for a new source to join the network and for how long?

The common engineering practice of designing networks is to find an optimal network that satisfies a fixed set of parameters such as shortest path and minimum cost(Koy, 1990). While these are required objectives, an optimized solution based on deterministic assumptions often found to be rigid and do not perform well when uncertainty is high (Goel et al., 2006). If the future uncertainty turns out to be favourable, the point-optimized solution is unable to be expanded and modified easily, which causes a loss of opportunity. On the other hand, if the future turns out to be unfavourable, point-optimized solutions cannot easily be reduced in scale, which wastes capital. This means there is a need for a method that can help to design of infrastructure networks with the capability to pro-actively deal with these uncertainties.

3.2. The Real Options Framework

The Real Options (ROs) concept is a method that recognizes and embraces the effect of uncertainty in engineering design (Neufville, 2003, Trigeorgis, 1996). The technical definition of an option is "a right, but not an obligation, to do something at a certain cost within or at a specific period of time (Myers, 1984)". Myers (1977) was the first to introduce the term Real Options. The concept first appeared in a field of finance called financial options and has entered the field of engineering systems. The ROs approach facilitates adaptive design strategy as it enables the value of flexibility to be included in the decision-making process. Opportunities are provided for decision makers to modify and update investments when knowledge of future states is gained that enables them to identify the most appropriate long term intervention strategies. This concept gives a totally different perspective to a decision strategy because there is no need for decisions to be inflexible and there is no specific date on which to take them.

Multiple sources of flexibilities (real options) exist in the design and management of infrastructure networks. Nevertheless, a key factor is that real options should be integrated into the network at the early stage of the design process to enhance the value of the network. At the early design stage, commonly called conceptual design stage, designers and decision makers have a greater degree of freedom to choose from design alternatives, to choose with whom to cooperate and the type of relationship. Moreover, decisions at the conceptual design stage determine the direction, the flexibility and bounds of the subsequent and more detailed designs, and ultimately the lifetime performance of the infrastructure (de Neufville et al., 2010).

To think in terms of options alters the way one deals with uncertainty. Conventionally, a good design minimizes risk. It focuses on increasing reliability and making the best decisions in risky situations. However, a design focusing on reliability is passive regarding risk. That is to say that a design approach focuses on ensuring good performance give the wide range of possible uncertainty. In contrast, options thinking to design recognizes uncertainty and adopt a proactive approach to deal with it. In other words, under the real options approach uncertainty is a driver of value and is viewed as a positive element. Correspondingly, systems design from this perspective is proactive towards risk. It seeks out opportunities to add value and commits to ongoing processes of information gathering to ensure that options can be exploited at the correct time.

In engineering systems, the term flexibility is widely used, and real options are a way to define the basic elements of flexibility (de Neufville et al., 2010, Wang, 2005). Wang and de Neufville (2004) divided real options involving engineering systems into two categories: ROs "on' systems and ROs "in' systems. Options that involve technical design features are referred to as real options 'in' engineering systems. On the other hand, options that involve financial decisions on engineering projects are referred to as real options 'on' engineering systems (Wang, 2005). Real options 'on' engineering systems refer to another name as managerial flexibility. Both real options 'in' and 'on' engineering systems provide embedded flexibility and enable network developers to minimise downside risks and gain from upside opportunities (de Neufville et al., 2006, de Neufville and Scholtes, 2011, de Weck et al., 2004).

A number of studies have developed ROs approaches to solving a variety of engineering systems design problems. de Neufville et al. (2006) applied ROs analysis for the design of car parking; Wang (2005) applied ROs analysis to the design of hydropower plants, and Nembhard and Aktan (2010) developed a systematic design analysis approach using the ROs concept to design and develop engineering design. Zhang and Babovic (2012) and Huang et al. (2010) also use ROs approach to evaluating different water network design strategies under uncertainty.

The core question that has been at the centre of the ROs application in engineering systems is: *How to identify real options that could enable cost-effective expansion of pipeline networks as future capacity requirement increases*? There are two key difficulties involved in answering the question. Firstly, there are numerous design variables and parameters that make real options identification and valuation difficult in networks. Secondly, real options in engineering systems often exhibit complex path-dependencies and interdependencies that standard options theory does not deal with (Wang and de Neufville, 2004). Addressing these difficulties requires using a systematic design analysis framework. For this purpose, this thesis uses the two phase framework proposed by Wang and de Neufville (2004) for the analysis of real options "in" engineering systems design. The framework is shown in Fig. 3.1 below.

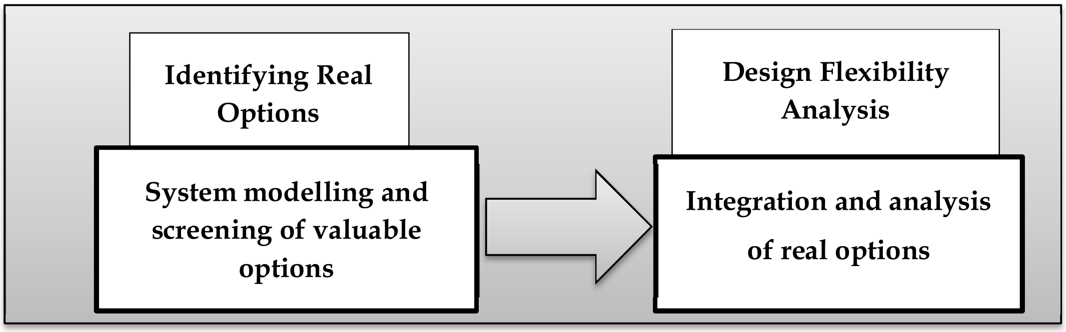

Figure 3.1 Framework for Analysis of Real Options "in" engineering systems, adapted from Wang and de Neufville (2004)

3.2.1 Identifying valuable real options

There can be several real options that might lead to flexibility. We listed some of the real options relevant in the context of networks.

- **Option to expand/contract**: the option to expand/contract seems useful vis-à-vis the flexibility needs of infrastructure networks as they are often developed in phases. For example, overbuilding the capacity of a large-diameter pipeline in an earlier period to have the flexibility to accommodate increasing capacity requirements in the later period.
- **Option to defer**: in the presence of irresolvable uncertainty (at least within the decision time frame) it could be interesting to wait and invest later. This is typical (wait and see) real option which projects managers exercise often when information about important uncertain variable(s) is not well known.
- **Options to abandon**: is it at any point in time possible to abandon the investment? This includes options not to commit further assets.
- **Options to switch**: What are the main inputs and outputs of this project? Is it possible to accommodate multiple inputs or outputs so that it is possible to switch later? For example, is the pipeline material able to handle liquid and gas phase substances as required?

The task of identification valuable real options requires exploring and evaluating large sets of potential design configurations. It involves exploring multiple future scenarios of the future evolution of the network. Depending on the scenarios, a huge number of design alternatives can be generated. The temporal and spatial dimensions of future scenarios produce many possibilities of designing the network and implementing flexibility decisions. Therefore, a method that enables designers to generate several initial design architectures before the final detailed design is required.

In literature, different types of approaches have been proposed in relation to designing and evaluating flexibility from the real options perspective. Ajah and Herder (2005)presented the adoption of the real options approach in the conceptual design stage of energy and industrial infrastructures and provided a systematic procedure for real options integration. Hassan and de Neufville (2006) presented a practical procedure for using real options valuation in the design optimization of multi-field offshore oil development under oil price uncertainty. Lin (2008) proposed a two-step procedure for identifying real options for offshore multi-oilfield development. The procedure involves developing a screening model and a simulation model. The screening model is a non-linear programming, low fidelity model for identifying the elements of the system that seem most promising for options. The simulation model tests the candidate designs from runs of the screening model. It is a high fidelity model whose main purpose is to examine candidate designs under technical and economic uncertainties, the robustness and reliability of the designs, and their expected benefits. Both ways of identifying real options are meant to simplify the task of an early search for the most promising flexible design.

More related to the study in this thesis is a method developed by (Heijnen et al., 2014) which addresses the design of networks under uncertainty. The method is a novel combination of graph theory and concepts of exploratory modelling for the analysis of most likely paths that maximizes the value of network designs. The physical infrastructure is abstracted as consisting of nodes (e.g. producers and/or consumers) and links (e.g. pipelines). The network design problem considers uncertainty about the timing and number of future participants and the capacity they require. The method is powerful because it allows easy and fast assessment of low-regret options and quick re-assessment of these options should new information arrive that narrows down or expands these options.

3.2.2 Design flexibility analysis

After identifying the most promising real options, designers need a model that enables them to analyse design strategies. The task involves defining flexible strategies and evaluating those strategies. Flexible strategies are the actions decision makers can take when a particular path of uncertainties is realized (e.g. expand the capacity of a network if a new participant joins the network in future) (Jablonowski et al., 2011). The actions of decision makers are defined as decisions rules in the network model. The decision rules are triggering mechanisms or "if" statements that specify clearly when flexible strategies will be exercised depending uncertainty realizations (Cardin et al., 2013).

3.3. Proposed Methodology

This chapter proposes a new design analysis method to enhance the value of networks under uncertainty. It builds on the work of Heijnen et al. (2014) by adding 1) an uncertainty analysis procedure, and 2) a design flexibility analysis procedure. The objective is to provide a systematic procedure for fast and easy assessment of network design options under uncertainty and screen promising designs that could provide cost-effective expansions. Fig.3.2. shows the proposed method.

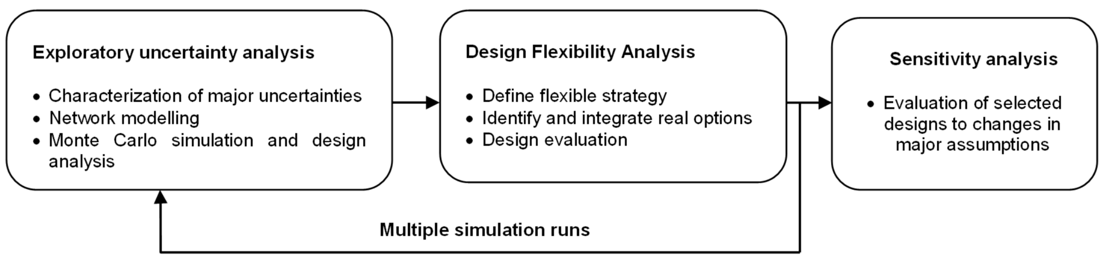

Figure 3.2 Proposed method for flexible design of networks

3.3.1. Step 1: - Exploratory uncertainty analysis

This step consists of characterization of major uncertainties, modelling and simulation the network, and design analysis.

A. Characterization of major uncertain variables

The objective of uncertainty characterization is to model initial distributions and future trajectories of selected uncertain variables. To define initial distributions of selected uncertain variables, two approaches are often employed: data-driven and an analytical. The data-driven approach requires a large quantity of historical data and applies statistical methods (e.g. regression) to fit the empirical model. The analytical approach is more useful in the absence or limitation of full historical data the analytical. It requires making initial estimations on the behaviour of uncertain variables (i.e. types of distribution and speed of convergence). The initial estimates are then transformed to a probability distribution, such as a normal distribution, characterized by a vector containing the moments of the distribution (means and variances).

Modelling the future trajectories of uncertain variables requires defining their states over a planning period of the network. The future states can take continuous or discrete behaviour.

To model continuous behaviour, stochastic processes such as Geometric Brownian Motion (GBM) and Wiener processes are often used (Ibe, 2013). To model discrete behaviour, lattice models can be used (Albanese and Campolieti, 2006).

B. Network modelling, simulation and design analysis

To generate network design concepts, a network model is developed, and exploratory simulations of uncertain variables are carried out. In this study, a graph theoretical network model (Heijnen et al., 2014) is employed. The model is effective in conceptualizing energy and industrial infrastructures as networks consisting of nodes (e.g. production and/or consumption sites) and links (e.g. pipelines). Monte Carlo simulation of uncertain variables over the network model is carried out to generate multiple network design concepts. The main inputs of the model are the spatial positions of the source and sink nodes and flow rate from sources. The outputs of the simulation are minimum-cost tree-shaped network configurations. The resulting network configurations are edge-weighted Steiner minimal tree-shaped networks. An edge-weighted Steiner minimal tree network is a minimum cost network that considers the effect of capacity and length of edges on the total cost. The details of the graph theoretical network model employed are explained in section 3.3.2.

3.3.2. Step 2: Design flexibility analysis

In this step, the concept of flexibility is employed to improve the life cycle performance of network designs selected in step 1. It involves defining flexible strategies, identifying real options to enable these flexible strategies and evaluating designs. Design evaluation helps to determine the cost of implementing real options for the desired flexibility and to decide the appropriate time to exercise the real options. In literature, different kinds of methods are proposed to evaluate real options. de Weck et al. (2004) applied binomial tree approach to obtain the value of real options in stage deployment of communication satellites. Babajide et al. (2009) used decision tree method to evaluate the value of flexibility in oil deployment projects. The binomial approach has limitations in that it assumes path-independency which does not hold in engineering systems and decision tree analysis suffers from intractable computations as the number of decision-making periods and states increases. Recently, simulation based methods are being adopted for valuing flexibility in oil field developments (Jablonowski et al., 2011, Lin, 2008), and water management systems (Deng et al., 2013). In this work, a simulation approach is adopted as it can be more generally applied since it has fewer restrictions on the number of time periods and the distribution of uncertainties. Besides, the simulation approach considers decision rules as explicit variables in the modelling framework, so that the model itself can be more easily modified to capture more diverse design configurations.

3.3.3. Step 3: Sensitivity analysis

In this step, sensitivity analysis is performed to examine how the results obtained following the above steps respond to changes in underlying assumptions. This step can be seen as a way to test the robustness of the design alternatives in response to the variation that may happen to the assumptions. There are standard mathematical (Czitrom, 1999), statistical (Saltelli et al., 2000) and graphical (Canon and McKendry, 2002) methods to perform sensitivity analysis. These sensitivity analysis methods can be carried out on global or local variables. One-factor-at-a-time method (Czitrom, 1999), which addresses the parameter sensitivity relative to the point estimates chosen for the parameters held constant, is used in this work. The one-factor-at-a-time method is more convenient than the other methods because it enables to analyse the effect of one parameter on the dependent variable at a time by keeping other parameters constant.

3.4. Application

This section illustrates the proposed method on a hypothetical pipeline based network. The situation described in this illustration is stylized and has the aim of allowing to create a numerical case where conclusions can be obtained in a transparent way. The parameters are purely hypothetical although they were inspired by an initiative to transport biogas from distributed bio-gas producers using a pipeline network in the province of Overijssel, The Netherlands. The illustration example could represent any network consisting multiple sources and a single sink (sink refers to consumption, conversion or storage sites) including district heating networks and CO_2 pipeline networks. It, therefore, serves our purpose of demonstrating the value of our approach.

3.4.1 Description of the design problem

The hypothetical field has three sources S1, S2 and S3 and one sink S0. Fig.3.3 shows the position of the three sources and the sink on a 60 km by 60 km field. The objective is to build a pipeline network which transports material X[1] from supply points (sources) to a single

[1] By material we mean flowing matter in gas (e.g. CO_2, (bio)gas) or liquid (e.g. hot water) state.

demand point (physical sink). The design problem takes the perspective of a network owner whose objective is to make a profit by connecting the spatially distributed sources to a sink. During the design exploration phase, the future flow rates of existing sources and the capacities they require are uncertain. Moreover, the timing and flow rate of future sources is also uncertain. For example, biogas plants could increase their production capacity with time. Moreover, biogas pipeline networks are expected to expand by adding more biogas producers in the future. The objective of this study is then to design networks that enhance value for the project investor (i.e. network owner) given the uncertainty in flow rate from existing sources and future new sources.

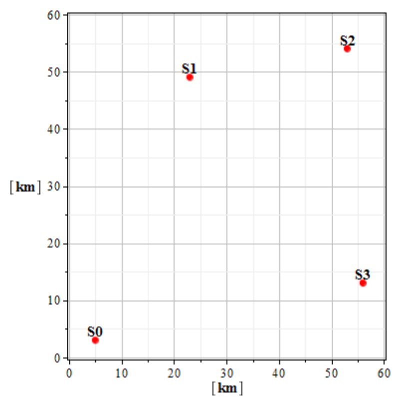

Figure 3.3 Layout of the hypothetical field

We specify the design problem scenario such that S2 and S3 are existing sources and S1 will join at some unspecified future time. The economic lifetime of the network is limited to 10 years. The rest of this demonstration is to apply the methodology proposed in the previous section with the aim to design a network that provides enhanced value for the investor given the uncertainty (1) in flow rate from existing sources (S2 and S3); and (2) timing and flow rate of the future new source (i.e. S1).

3.4.2 Step 1: Exploratory uncertainty analysis

The objective of this step is to model the major uncertainties and explore their effect on the performance of design alternatives. In this study, we focus on two major uncertainties: (1) stochastic behaviour of flow rate from existing sources, hereafter called flow uncertainty, and (2) the uncertainty in the new source(s) that may join the network in the future called participant uncertainty. Flow uncertainty represents flow rate changes from existing sources over the economic lifetime of the network Participant uncertainty represents the uncertainty in the timing of new sources and their flow rates.

A. Characterization of major uncertainties

I. <u>Flow uncertainty</u>

Flow uncertainty is due to the stochastic nature of volume flow rates from sources over the life time of the network. Volume flow rate is important because it directly determines the capacity of the pipeline. It varies in short-term as well as long-term time due to operational changes and is unknown (increase or decraese) over time. For example, over a longer time period (i.e. years), the supply of CO_2 from a power plant equipped with post-combustion carbon capture may increase due to an increase in its emission reduction target. CO_2 flow rate from power producing plant could vary in short time span (i.e. hourly and daily) due to operational changes in power production.

In this study, analytical approach is used to model flow uncertainty mainly because of the lack of empirical data. The framework used for the analytical approach is shown in Fig. 3.4. below. First, assumptions are made on the initial flow rate from source nodes. The initial flow estimates (at time t=0) are transformed into normal distribution creating a vector I(t0) which consists of the moments of the distribution (mean and standard deviation). The second step is to generate flow estimate trajectories F(t) given the model, shown in Fig. 3.4.

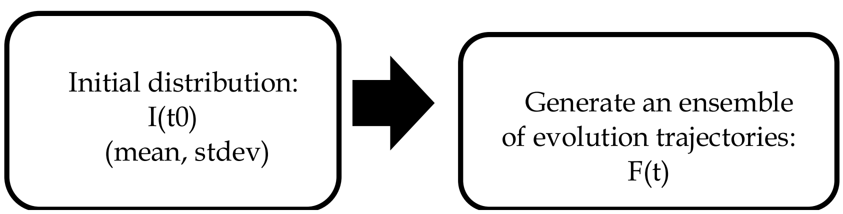

Figure 3.4 Modelling framework for flow uncertainty

For this illustration, the initial flow estimates of the three sources are as follows. The values used for initial flow estimate are not real. They are, however, inspired by a project to develop a bio-gas network. Bio-gas fields do not yield a stable continuous gas production mostly due to lack of sufficient substrate (Hamawand and Baillie, 2015). Normal distribution is used to model the uncertainty in supply of gas from source nodes. The situation is hypothetical and the numbers used are stand-ins to permit calculation.

- S1: mean 100 m^3 tonne/year and standard deviation 20 m^3 tonne/year.
- S2: mean 400 m^3 tonne/year and standard deviation 100 m^3 tonne/year.
- S3: mean 350 m^3 tonne/year and standard deviation 70 m^3 tonne/year.

Then the next task is modelling the future trajectories of volume flow rates. For the purpose of this demonstration, the life time of the network is assumed to be 10 years. In reality gas networks last longer than 10 years. However, 10 years is a reasonable time frame to analyse the economic feasibility of such kind of infrastructure networks. The future flow rate of gas from the three sources is stochastic and assumed to follow a Geometric Brownian Motion (GBM) process. For the GBM process, the expected drift rate of 1% and volatility of 30% are assumed for all the three sources. These assumptions take into consideration the current reality of biogas plants. A study by (Gebrezgabher et al., 2010) shows that most biogas plants operate close to their design capacity. That means the potential for growth is limited hence the low drift rate. Moreover, biogas production rate of most of the biogas plants heavily depend on substrate availability and it is common to see a huge fluctuation on production rate (Weidenaar, 2011), hence the high volatility assumed in this demonstration.

The Monte Carlo simulation technique is used to generate multiple evolutionary paths. In each simulation, the GBM model produces yearly volume flow rate values. Fig.3.5 shows initial flow estimate model of the three sources and one instance of the future flow rates of the three sources over a 10-year time period. The sink is assumed to have enough capacity to absorb all flows from the existing as well as future new sources.

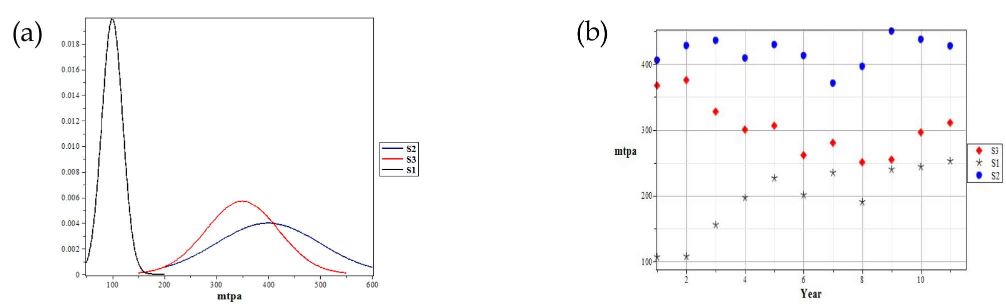

Figure 3.5 Initial flow estimate model of sources (a) and one instance of the evolution of flow of the three sources over a 10-year period (b)

II. Participant uncertainty

Participant uncertainty represents the uncertainty arising from new source(s) that may join the network in the future. The uncertainty originates from two dimensions: spatial and temporal. Spatially, the new participant could assume any geographical position relative to the existing network. Temporally, the new source could join the network at any time within the technical life time of the network. For designers, both dimensions of participant uncertainty could result in infinite possibilities of network configuration alternatives. Thus, the identification and evaluation of design options is extremely difficult, if not computationally intractable. For simplification, we assume that the new participant will be S1 and this will avoid the spatial uncertainty. With this simplification, the uncertainty will be regarding the future time S1 will join the network. S1 does not exist at the beginning but will join the network sometime within the 10-year period. For this analysis we consider only three scenarios, as shown in Fig.3.6. below.

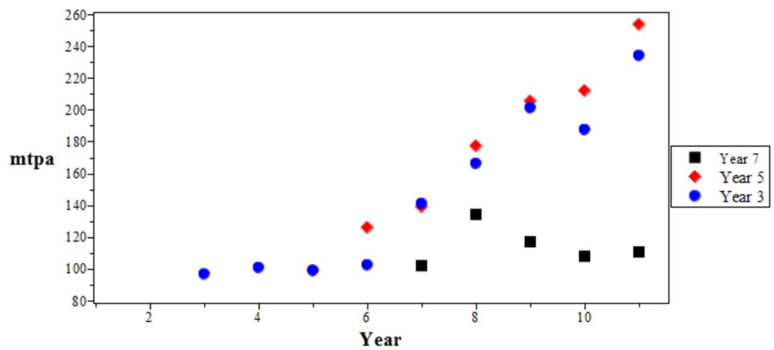

Figure 3.6 One instance of S1 joining a network at year 3, 5 and 7 and its flow evolutionary path

Fig.3.6 shows 3 instances (years 3, 5 and 7) of future flow evolutionary path of S1. It represents the model of the uncertainty regarding the year S1 will be connected to the network. The main reason for modelling timing uncertainty of S1 is to explore for value maximizing configuration of the network if

B. Network modelling

For this study, we employ a network model based on the concept of graph theory, see (Heijnen et al., 2014) for more detail. In a graph theory representation of networks, sources and sinks are nodes (e.g. bio-gas fields and gas consumption sites) and their connections are edges (e.g. pipelines). The main inputs of the model are flow rates and the spatial positions of sources and sink nodes. The model generates minimum-cost tree-shaped network configurations connecting the source nodes to the sink node. The resulting networks are edge-weighted Steiner trees. An edge-weighted Steiner tree network is a minimum cost network that takes into account the capacity and length of the pipeline in the cost function. The network model uses the following cost function.

$$C_e = l_e q_e^{\beta} \tag{3.1}$$

In (3.1), l_e is the length and q_e is the capacity of an edge e. β is the cost exponent for the capacity with $0 \leq \beta \leq 1$. If $\beta = 0$, the capacity of the pipelines has no influence on the cost. If $\beta = 1$, building two pipelines of capacity 1 is just as expensive as building one pipeline of capacity 2. A value of $\beta = 0.6$ is commonly used indicating that there are economies of scale to building high-capacity pipelines (Desai and Sen, 2010, Heijnen et al., 2014). Then, the total investment cost $C(T)$ of a network T is sum of all connection costs as given in (3.2).

$$C(T) = \sum_{\forall e \in E(T)} l_e q_e^{\beta} \tag{3.2}$$

where $E(T)$ is the set of all edges in a network tree T.

In addition to cost, it is also necessary to calculate the expected income of the network. A revenue model that calculates the expected income as a linear function of capacity required by the source is used. The assumption is that the network developer generates income by charging a certain fee per unit capacity. The expected income (EI) from a network T is then given as:

$$EI(T) = \alpha \sum_{i \in V(T) \setminus \{s\}} q_i \tag{3.3}$$

In (3.3), q_i is the used capacity by a source i in a network T, V(T) is the set of all nodes in the network T, s is the sink and α is the constant coefficient representing, for instance, a constant fee per a unit volume of liquid/gas charged by the network developer. In this demonstration, we assumed $\alpha = 1$.

The total income from a given network in its life time is calculated as a summation of discounted yearly income flows over the 10-year period. The interest rate of r = 8% is used for this demonstration. The sum of the discounted cash flows is the present value of income (PVI).

$$PVI(T) = \alpha \sum_{t=0}^{n} \frac{\sum q_i}{(1+r)^t} \tag{3.4}$$

The life time performance of a network under a given scenario of an uncertain parameter is evaluated using the Net Present Value (NPV) metric.

$$NPV(T) = PVI(T) - C(T) \tag{3.5}$$

C. Monte Carlo simulation and design analysis

In this section, Monte Carlo simulation of the network model is carried out by varying flow scenarios. Given the low flow rate from S1 at the beginning and the uncertainty in the time it may join the network, the following two design strategies are proposed: committing design strategy (CDS) and abandoning design strategy (ADS). Under the CDS the network will be designed by connecting all the three sources, and in the case of ADS the decision is to connect S2 and S3 only by abandoning S1. The inputs of the model are yearly flow rate values from each source over 10-year period and the spatial position of the sources and the sink. The simulation results in minimum-cost tree-shaped network configurations connecting source nodes to the sink.

Fig. 3.7 (a) and Fig.3.8 (a) show density diagrams of 10 network configurations based on a single flow evolutionary path (scenario) under CDS and ADS respectively. Each network configuration is an edge-weighted Steiner tree generated by taking flow rate values at each year of a single flow evolutionary path. The simulation outputs provide designers a better insight into what would be the optimal configuration of the network, not only based on the values of design variables at the time of design but also in multiple future stages.

However, in practice networks are path-dependent, i.e. the state of a given network at a later stage is dependent on the decisions made at an earlier stage. Network developers will not build one network in year 1 and another network in years after that. Then, the question becomes, how to select the network that provides maximum value for a given scenario?

One way to select the network that maximizes value among several design alternatives is to use a preliminary economic evaluation technique the Present Worth Ratio (PWR), as in (Heijnen et al., 2014). The PWR illustrates the efficiency of the invested capital by considering the investment cost and the expected revenue of a network over a fixed period.

$$PWR = \frac{Expected\ revenue - Investment\ cost}{Investment\ cost} \tag{3.6}$$

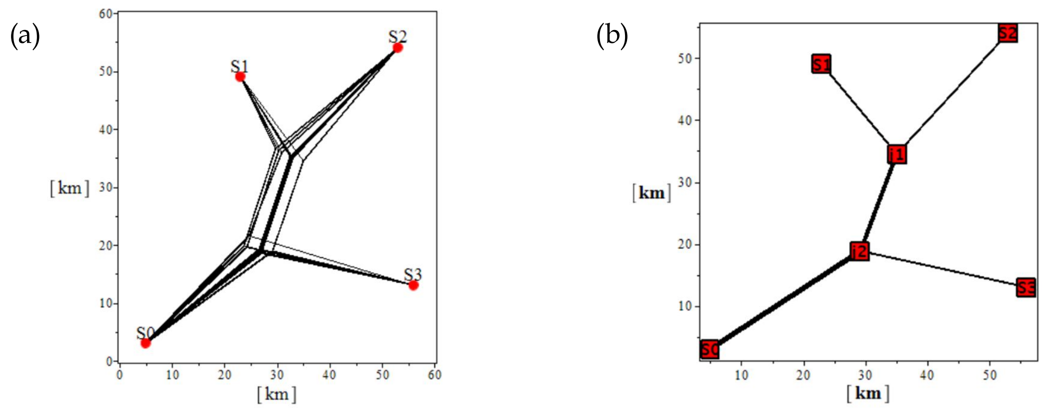

Figure 3.7 Network configurations under the committing design strategy: density diagram of multiple network configurations (a) and the value maximizing network (b).

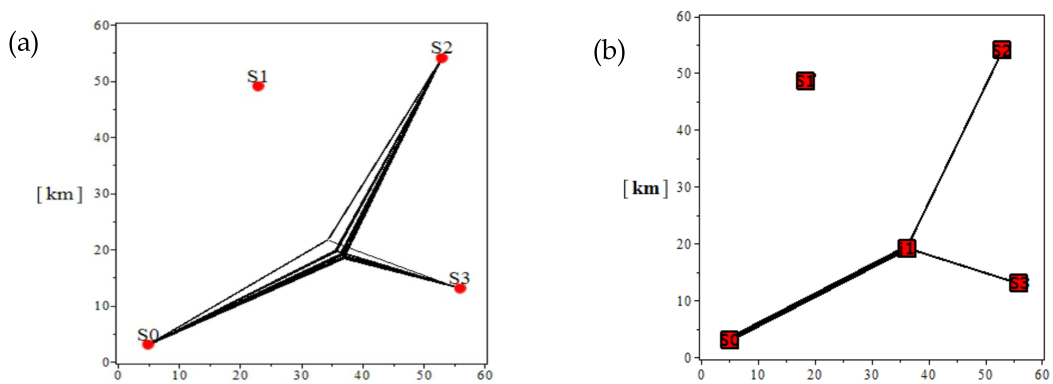

Figure 3.8 Network configurations under the abandoning design strategy: density diagram of multiple network configurations (a) and value maximizing network (b)

Fig. 3.7 (b) and Fig.3.8 (b) show the network that maximizes value out of the 10 configurations under CDS and ADS respectively. The thickness of edges indicates their capacity. Monte Carlo simulations of the network model result in multiple value maximizing networks and their respective economic performances (i.e. cost and PWR values). 200 different flow path scenarios are simulated resulting 200 optimal networks for each design strategy. Then, the value maximizing network with the highest PWR is selected. This step is used to screen network design alternatives that make economic sense given the future evolution of flow. It serves a preliminary design exploration step by simulating different uncertain scenarios. Exploring multiple design concepts using multiple scenarios provides decision makers with a better insight into the effects of uncertainty compared to a deterministic design based on a single scenario or a few pre-defined scenarios.

Once the networks with the highest PWRs are selected for both design strategies, their life-time economic performances are evaluated over multiple uncertain scenarios. Net Present Value (NPV) metric is used to evaluate the economic performance in this study. 200 Monte Carlo simulation runs were carried out to compare the economic performance of both design strategies. The 200 NPVs of both design strategies are plotted as cumulative distributions, or also known as target curves, see Fig.3.9. Moreover, from NPVs of each design strategy, the corresponding expected net present values (ENPVs) are calculated. The ENPV is the most likely NPV (i.e. NPV at 50% probability in the cumulative distribution curve) calculated by probability-weighting NPVs. The two design strategies are also compared using other economic metrics as shown in Table 1. For the purpose of comparison, the NPVs of the two designs are normalized against the expected net present value (ENPV) of the abandoning design strategy.

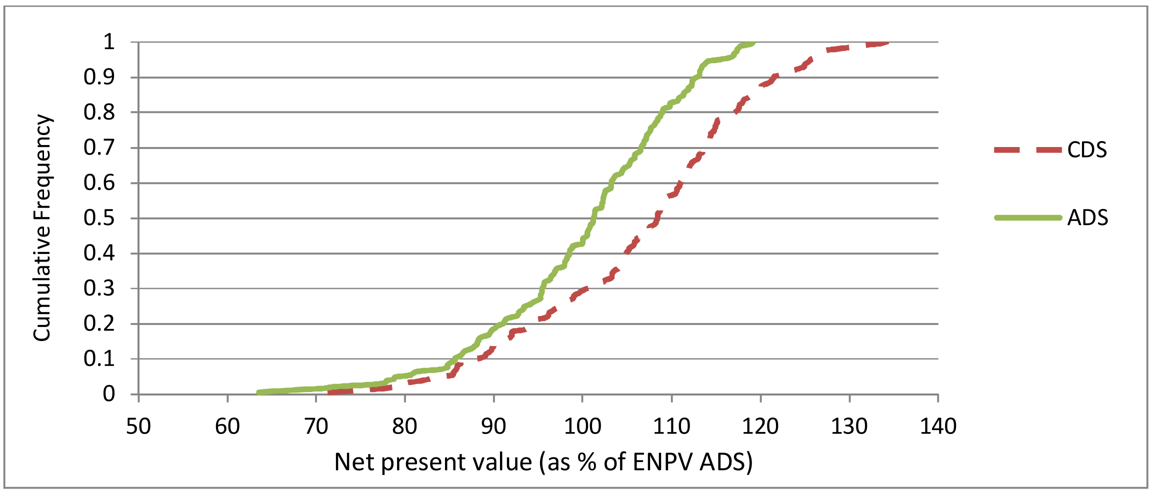

Figure 3.9 Target curves for the two design strategies (connection fee a=1).

Table 3.1 summary of statistics for the two designs strategies (% of ENPV or as % of initial CAPEX of ADS)

Parameters	ENPV	Min NPV	Max NPV	Initial CAPEX	Min CAPEX	Max CAPEX
Committing design strategy	106±6	72±6	134±6	116±8	110±8	128±8
Abandoning design strategy	100±4	64±4	119±4	100±5	95±5	108±5

From Fig.3.9 and Table 3.1 it is clear to see that the committing design strategy results in a better ENPV than the abandoning design strategy. The value enhancement suggests that the revenue obtained from S1under the committing design strategy outweighs the avoided cost of connecting S1 under the abandoning design strategy. Even though abandoning design strategy helps to avoid revenue risk due to the low flow rate of S1 in the early years, it loses the opportunity that may be obtained due to future flow rate increases. However, this conclusion is only valid under flow uncertainty. Under participant uncertainty abandoning design strategy is the only realistic solution of the two strategies. If the network is developed based on abandoning design strategy and a new source wants to join after some years, then the design will not be able to accommodate it. The only possibility is to make a connection directly to the sink. In such a case, the cost will increase, and the overall performance of the network will even further decrease.

In addition to NPV (ENPV, minimum NPV and maximum NPV), Capital expenditure (CAPEX) can provide valuable insight during decision making. For example, the NPV of the network under CDS is higher than ADS. However, ADS requires a lower CAPEX than CDS and that can be a factor in decision making.

3.4.3 Step 2: Flexibility analysis

The objective of this step is to further enhance the life time performance of the network given the two uncertainties defined in step 1. It involves defining flexible strategies, identifying real options to enable these flexible strategies and evaluation of designs with real options. A stage-wise development of the network with expansion options is defined as a flexible design strategy (FDS).

A. Identification of real options

To enable the flexible design strategy, two real options are identified: expansion option to accommodate future flow increases from all sources and an option to delay the connection of S1. The two real options enable the network to pro-actively manage flow and participant uncertainties. If S1 exists, but its flow rate remains low in the future delaying its connection could be valuable. If S1 exists and its flow rate increases in the future or if S1 does not exist at the beginning but appear later in the future the expansion option could be valuable. The expansion option is made possible by embedding redundancy in the length and capacity of the network. Having the expansion option may require more initial capital but could give the network manager the right to accommodate future connection of S1 at lower overall cost.

Fig. 3.10 (a) shows 10 different layouts of the network connecting the three source points with the sink. It can be seen that S1 is not connected to the network all the time. The simulation showed that connecting S1 is not worthwhile before year 5 given its low flow rate. One strategy to design the network is to start by connecting S2 and S3 with an option to connect S1 in the future. We call this strategy as the flexible design strategy.

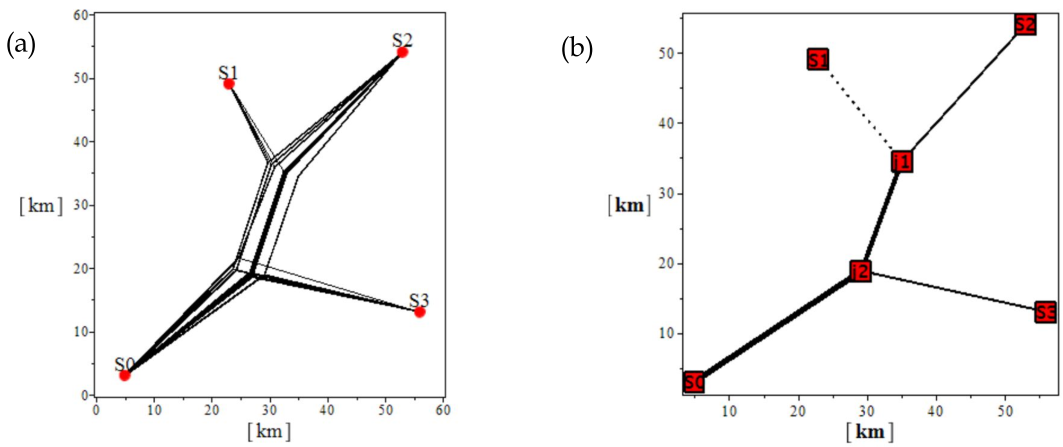

Figure 3.10 Density diagram of network layouts (a) and the layout of the network under the flexible design strategy (b)

Fig.3.10 (b) shows the layout of the network under the flexible design strategy. A dotted line is used between node S1 and node J1 to represent the future connection of S1. Real options are embedded in the network by committing large-size pipes between nodes S0 and J2, i.e. laying out line J1-J2-S2 instead of J2-S2. Both options require extra pipe capacity on line J2-J1 and extra length (i.e. the difference between J2-J1-S2 and J2-S2). Real options can also be considered in line S2-J1 and S3-J2 by having extra capacity to handle future flow rate increases. When the flow from S1 makes an economic benefit, the developer can build the pipeline J1- S1. The redundant pipeline capacities and lengths embedded in the network enable the network developer to exercise stage-wise expansion strategy.

B. Design evaluation

The performance of the three design strategies is evaluated using flow and participant uncertainty scenarios define in step 1. NPV is used to compare the performance of the three design strategies. 200 Monte Carlo simulations are carried out resulting in 200 NPVs for each design strategy. Then, target curves are plotted based on the 200 NPVs. Moreover, from NPVs of each design strategy, the corresponding expected net present values (ENPVs) are calculated. The ENPV is the most likely NPV (i.e. NPV at 50% probability in the cumulative distribution curve) calculated by probability-weighting NPVs. In addition to ENPV, decision makers also use capital expenditure (CAPEX) to evaluate design strategies. Explanation of how the decision rule operates within the simulation model is presented in the Appendix section of

Publication IV (Melese et al., 2017d). Table 3.2 shows ENPV and CAPEX of the three design strategies.

I. Under flow uncertainty

From Fig.3.11 and Table 3.2 it can be seen that the flexible design strategy performs much better than the two rigid design strategies. The sources of improvement in performance are from the flexibility that enabled by the real options built in the edges and lengths of the flexible design strategy. The real options help to reduce down-side risks such as commitment to big pipeline capacity when flow from S1 is low. They also help to capitalize on the upside opportunity when the flow from S1 increases. Therefore, the improvement in performance of the flexible design strategy when compared to the other two design strategies can be considered as the expected value of the real options ($VoRO$). The value of the real options can be calculated by subtracting the ENPV of the rigid design strategies from the flexible design strategy, see Eq.3.7.

$$VoRO = ENPV_{flexible\ design} - ENPV_{rigid\ designs} \tag{3.7}$$

From Table 3.2 the flexible design requires a lower initial CAPEX when compared to the committing design strategy but a higher initial CAPEX when compared to the abandoning design strategy. The committing design strategy is the most expensive of the three. Initial CAPEX could be an important factor when evaluating designs and the flexible design strategy reduces costly initial commitments when uncertainty about the future flow evolution of S1 is higher.

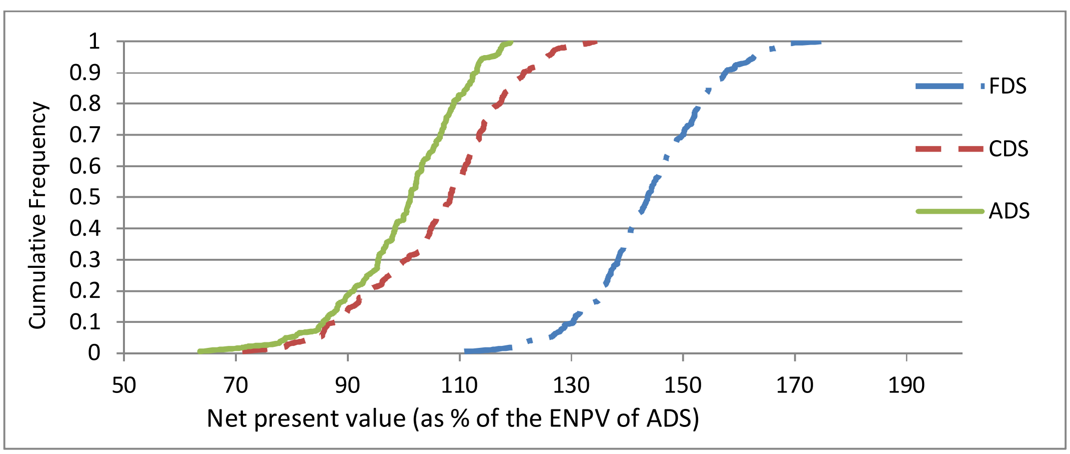

Figure 3.11 Cumulative probability distribution curves of NPVs of the three design strategies (connection fee α=1)

Table 3.2 Summary of statistics for the three designs strategies (expressed as % of ENPV ADS or as % of initial CAPEX of ADS)

Parameters	ENPV	Min NPV	Max NPV	Initial CAPEX	Min CAPEX	Max CAPEX
Flexible design strategy	144±10	111±10	174±10	105±6	98±6	112±6
Committing design strategy	106±6	72±6	134±6	116±8	110±8	128±8
Abandoning design strategy	100±4	64±4	119±4	100±5	95±5	108±5

The initial CAPEX of ADS is smaller than the other two design strategies largely because there is no connection to S1. Even though the strategy minimizes investment cost in the early years compared to the CDS and FDS; it loses significant revenue from future increases in the flow rate of S1. However, in ADS S1 may join the network when information about S1 is known. However, under such scenario connecting S1 requires building dedicated pipeline directly to sink. As a result of such practice, the network could provide much inferior value when compared to the FDS and the CDS.

II. Under participant uncertainty

The time a new participant could join the network influences the value of the overall network. A comparison is made between the FDS and ADS, as the CDS is not a realistic solution, in this case. The analysis is carried out for scenarios on which the new source (S1) joins the network in years 3, 5 and 7. The performance of the two design strategies is shown using cumulative probability distribution of NPV, see Fig. 3.12.

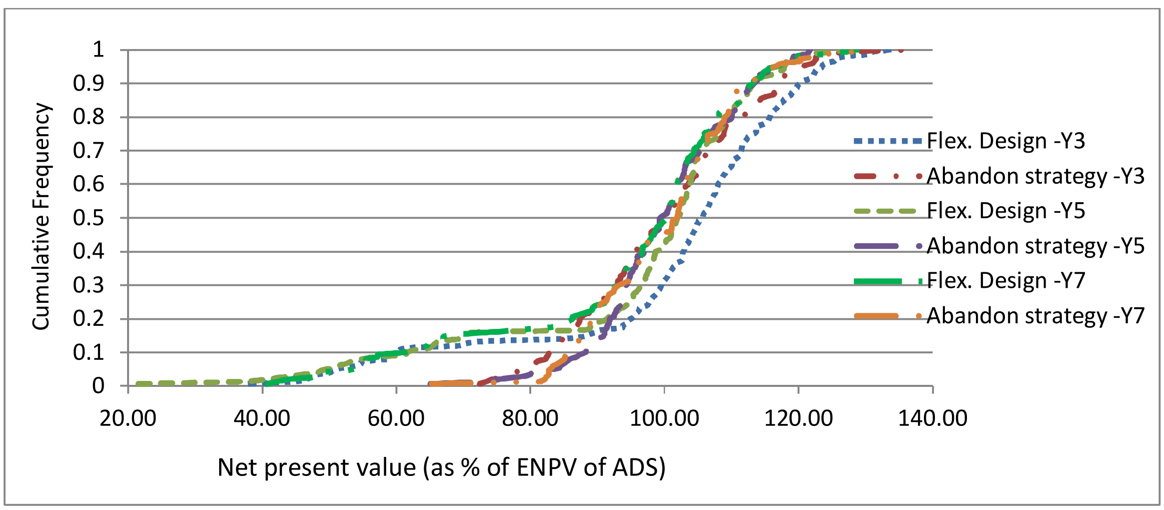

Figure 3.12 Target curves for the two design strategies for year 3, 5 and 7. (NB: Y3 –year 3, Y5-year 5, Y7-year 7).

It can be seen from Fig. 3.12 that the ENPV of the FDS is higher than the ADS in each of the three scenarios. However, the superiority of FDS over ADS diminishes as the time for connecting S1 is delayed. The curve below P50 (i.e. the lower half of the target curve) shows that the risk of FDS increases faster than the risk of ADS if the connection to S1 is further delayed from Y5 to Y7. In such cases, it does not make economic sense to build a real option that can be exercised only after a long period as the value of the option diminishes with time.

In real pipeline network design, the decision regarding the time to consider extra capacity to accommodate future new sources is called 'no-regrets-period.' The 'no-regrets-period' depends on the profitability of the fluid flowing through the network and varies from one case to another. In carbon capture networks, the 'no-regrets-period' for having redundant pipe capacity extends up to 10 years based on the current CO_2 price (Austell et al., 2011). In natural gas networks, the 'no-regrets-period' can extend beyond 15 years.

The analyses of the design strategies under flow uncertainty and participant uncertainty show that there are values to be gained from flexibility. Mainly, there are two flexibility enablers (real options) that can be built in the physical design. The first is the extra diameter in edges, required for accommodating future flow rate increases from existing sources and new connections. The second is the extra length that is built in the configuration. These real options anticipate increases in flow rate from existing sources that are not financially feasible to connect at the beginning due to their low flow rate and from new sources that could join in the future. Flexibility would not be possible if designers do not plan and embed those real options at the early stages of the design process.

3.4.4 Step 3: Sensitivity analysis

In this step, sensitivity analysis is carried out to examine how the three design strategies depend on the two key assumptions: the connection fee (α) and the initial flow estimates.

A. Sensitivity to the connection fee

The connection fee value is varied to check its effect on the performance of the flexible design compared to the rigid designs. The connection fee is the amount paid by sources per unit capacity. In other words, the connection fee is the price that is charged by the network developer. Fig. 3.13 shows the relative performance (in terms of NPV) of the three design strategies at various connection fee values. The network model is simulated 200 times for each connection fee values. For the purpose of comparison, the NPVs of the three designs are normalized against the ENPV of the abandoning design strategy at α=1.

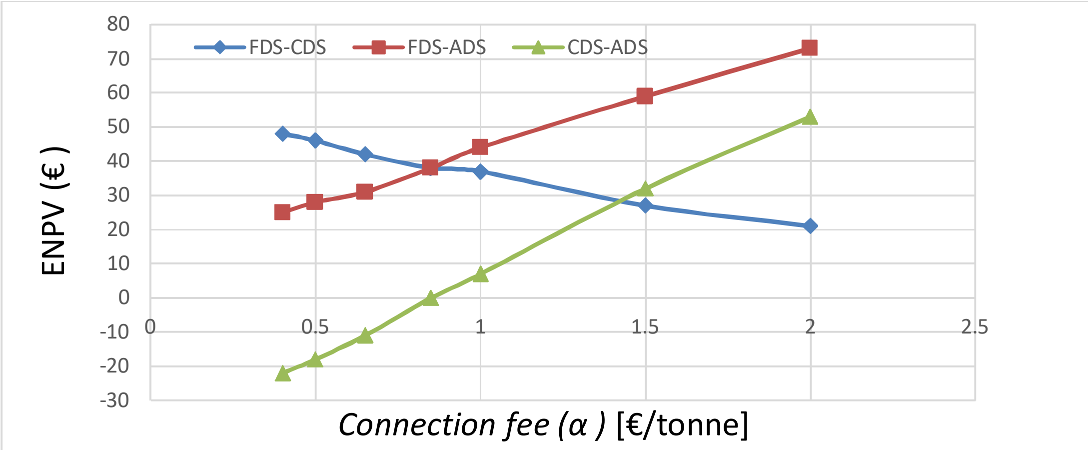

Figure 3.13 Effect of connection fee on the performance of design strategies shown in relative comparison

Fig.3.13 shows that the difference between the flexible design strategy and the abandoning design strategy increases when the connection fee increases. This is mainly due to the increase in revenue as α has a linear relationship with revenue. At low α the difference between the committing design strategy and the abandoning design strategy becomes negative. The negative value implies that, as the connection fee decreases, the abandoning design strategy becomes more valuable than the committing design strategy for the network developer. On the other hand, the flexible design strategy performs better than the abandoning design strategy on all α values. However, as α decreases the, difference between the flexible design strategy and the abandoning strategy decreases. Another observation from Fig.3.13 is that the difference between the flexible and the committing design strategies decreases when the connection fee increases. The decreasing trend is because as α increases its effect on the revenue increases. So the value of early commitment increases with increasing α.

B. Sensitivity to initial flow estimate

In this section, the effect of initial flow estimates is analysed. Specifically, the mean value of S1 is varied as S1 is used to make a case for uncertainty analysis in previous steps (low flow rate in case of flow uncertainty and new source in case of participant uncertainty). Since the abandoning design strategy does consider S1, the analysis is focused on the flexible and the committing design strategies. The analysis carried out for flow uncertainty and participant uncertainty.

Fig.3.14 shows the performance of the flexible and the committing design strategies versus the mean value of S1. It is clear to see that both design strategies increase with increasing mean value of S1. This is due to the linear relation between flow rate and revenue. Up to a mean value of 400 m^3 tonne/year, the flexible design strategy performs better than the committing design strategy. However, above 400 m^3 tonne/year, the committing design strategy appears to be better than the flexible design strategy. The above observations indicate that at a higher mean value of S1 early commitment is valuable than investing in real options.

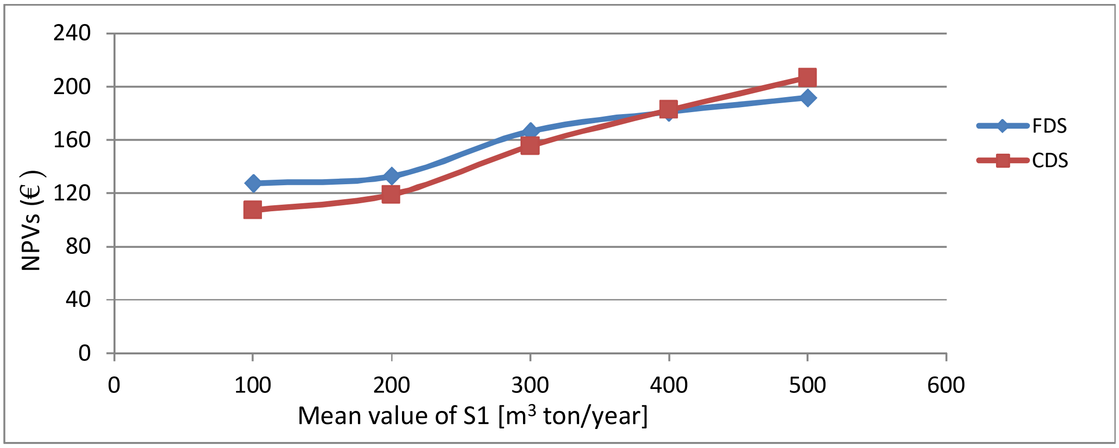

Figure 3.14 Sensitivity of flexible and committing design strategies to the mean value of S1

One the other hand, one can expect that the abandoning design strategy to have constant value since there is no connection to S1. However, the lost opportunity due to a potential increase in flow rate of S1 or avoided risk due to low flow rate from S1 by the abandoning design strategy can be implicitly inferred by comparing it against the other two design strategies. If the mean value of S1 increases, then the opportunity lost by the abandoning design strategy increases. Conversely, if the mean flow of S1 decreases the risk avoided by the abandoning design strategy increases and at much lower mean value, the abandoning strategy can become better than the committing strategy.

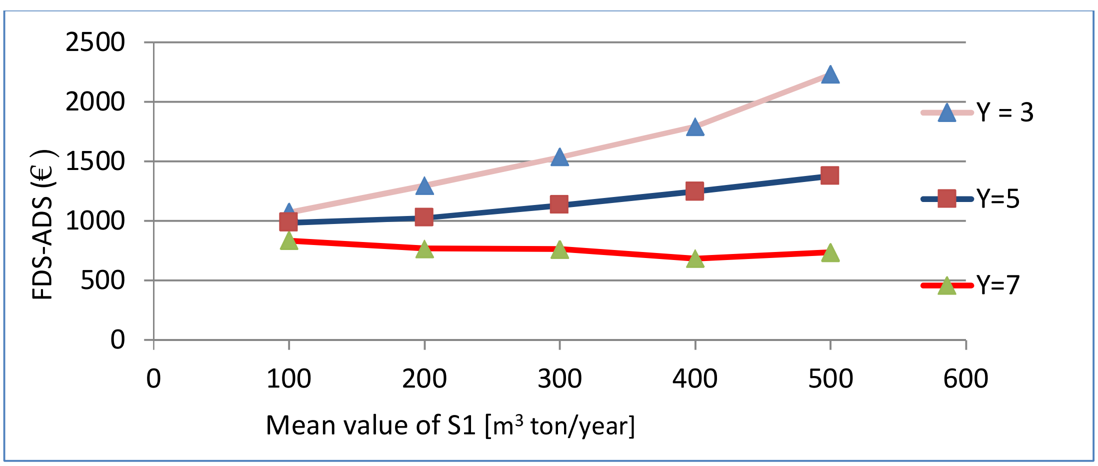

Figure 3.15 The effect of the initial estimate of S1 on the performance of the flexible and the abandon design strategies

The effect of the initial estimate is very strong for the case of participant uncertainty. Fig. 3.15 shows the effect of the initial mean value of S1 on the performance of the flexible and the abandoning design strategies. The performance of the flexible strategy compared to the abandoning strategy largely depends on the time S1 is connected. If S1joins the network early in the investment period, the value of the flexible strategy increases or decreases proportionally to the mean value of S1. Conversely, if S1 joins the network later in the investment period, the value of the flexible design strategy diminishes with increasing mean value of S1. For instance, if S1 joined the network in year 7, the flexible strategy provides inferior value compared to the abandoning strategy. The cost of having the real options for a flow rate of 500 m^3 tonne/year is higher than the cost for 100 m^3 tonne/year. At higher flow rate, the size of extra capacity to accommodate flow increases will be larger. Moreover, as shown in Fig.3.12, the value of having the real options would be higher if S1 joins the network at year 3 than at year 7. As a result, the value of the option with higher initial flow rate at year 7 becomes lower than with lower initial flow rate. On the other hand, the performance of the abandoning design strategy is the same as it does not depend on S1. Therefore, at year 7, the difference between the flexible design strategy and the abandoning design strategy decreases with increasing initial flow rate of S1.

3.5. Conclusions

This chapter introduced a method to enhance the value of networks by identifying and integrating flexibility enablers under uncertainty. In the chapter, we argued that one way to design flexible networks is to adopt a real options-based design approach. The proposed method combines a graph theoretical network model with Monte Carlo simulation to carry out exploratory uncertainty analysis of design alternatives. The aim of the exploratory analysis is to screen out promising design concepts from several alternatives. Once candidate designs are selected, design flexibility analysis is carried out to improve the life cycle performance of networks by considering uncertainties. The design flexibility analysis uses the concept of real options to enhance the value of the network. The proposed design approach contrasts with the typical design and planning approach which tends to focus on pre-defined requirements and could lead to inflexible and sub-optimal networks.

Using a hypothetical pipeline-based network for demonstration purposes, the method provides valuable insights to designers and decision makers on how to design flexible networks under capacity and participant uncertainty. Moreover, the proposed method provide valuable insight into which parts of the network should designers include real options. Results reveal that physically built-in capabilities, such as extra pipe capacities and lengths, provide easy and cost-effective expansion option of the network when compared with a deterministic design approach. More detail about real options identification in networks can be found in publication III.

The procedure introduced in this chapter generally can be applied to most pipeline-based network design problems including natural and bio gas pipeline networks, water distribution networks and district heating networks. However, different networks are subject to distinct costs and benefits and faced with their respective sources of uncertainties; thus, details of modelling and computation may need to be adjusted to suit the particular network at hand. Moreover, the approach in this chapter is related to the technical dimension of socio-technical system: pipes, and relay stations. The focus is on the physical network while the boundaries of a physical network are determined by institutional dimensions: social and legal requirements. Consideration of institutional elements may affect the design strategy and the resulting optimal design configuration.

Chapter 4 A Risk Sharing Approach to Deal with Actor Uncertainty during Conceptual Design of Networks

This chapter discusses the role of risk sharing when actors co-invest in energy infrastructure networks under uncertainty. It presents a derivation of the optimal sharing rule and its implication for partners. The chapter is based on publication V (Melese et al., 2017b) with minor differences.

4.1. Introduction

The development of new energy and industrial infrastructure networks increasinly involves multiple actors both from the private and public sectors (Ligtvoet, 2013). Individual organizations lack sufficient expertise and capability to deliver the energy services demanded by the customers. The necessary resources, such as expertise, money, information, personnel, and management, are divided among different organizations. As a result, cooperation has become necessary in order to make investments and solve social problems. In the private sector, we see commercial actors increasingly seeking refuge in strategic alliances (Smit and Trigeorgis, 2009) and the formation of industrial networks (Ligtvoet, 2013).

According to the strategic management literature, cooperation enables agents to reduce the effects of uncertainty by aligning the interests of the parties (Williamson, 1979, Bronder and Pritzl, 1992). Cooperation also provides other strategic advantages such as the ability to achieve objectives faster, getting access to know-how or to markets that would otherwise be closed to them, cost advantages, transfer or complementarily of technologies or economies of scale (Bronder and Pritzl, 1992). However, cooperation is not always straightforward, and various uncertain factors expose parties to different kinds of risks (CPI, 2012, Lee et al., 2015, Kulatilaka et al., 2014). By its nature, cooperation is a multi-motive game and because each party is performing rational rent-seeking behaviour, there are considerable costs and risks involved in the decision to join (Williamson, 1979, Nooteboom, 2000). Moreover, infrastructure network investments have intrinsic characteristics that make them particularly vulnerable to exogenous uncertainty related to the macroeconomic scenarios, technological changes, regulatory changes, competition or emergence of substitute services (Shen et al., 2006). These uncertainty sources often lead to a deadlock in which decision making becomes impossible as parties involved become risk averse and are afraid to 'bet on the wrong horse' (McCarter et al., 2010). Therefore, with incentives on one hand and costs and risks on the other, the challenge in most infrastructure network development cooperation is how the associated risk and value be shared amongst the partners.

In the strategic management literature, the discussion on the allocation of benefits and risks from cooperation under uncertainty is based on two perspectives: a value-creation perspective and a risk-sharing perspective. On one hand, the value-creation perspective takes the view that agents cooperate to gain value and hence focuses on the allocation of value from cooperation (Folta and Miller, 2002, Holta et al., 2000). In that respect, real-options valuation is receiving increasing attention as a tool to analyse the value of cooperation, see for example (Kogut, 1991, Liu et al., 2014, Park et al., 2013). On the other hand, the risk-sharing perspective uses the concept of risk sharing to explain the motive for cooperation and allocation of risk among cooperative agents, see for example(Allen and Lueck, 1999, Medda, 2007, Blenman and Xu, 2009). Regarding the allocation of value from cooperation, the literature has also come a long way from deterministic cooperative game theory models of (Nash, 1950, Nash, 1953) and (Shapley, 1953) to models for stochastic payoffs by Suijs et al. (1999). The literature on optimal risk sharing between two parties was first analysed by Borch for the specific case of insurance contracts (Borch, 1962). Later, Wilson led the research for efficient risk sharing in syndicates (Wilson, 1968) and more recently this was advanced by Pratt (Pratt, 2000). Various risk-sharing allocation techniques have been presented for infrastructure investments. Lam et al. (2007) used qualitative risk allocation for construction projects using a fuzzy inference mechanism. Medda (2007) used a game theoretical approach to the allocation of risks in transport public-private partnerships. However, all these previous works largely focus on closed contracts where the only payoff comes from the joint investment, and the effects of the agents' pre-existing businesses are ignored. Moreover, the methods used to model the uncertainty in the future performance of the common project are either deterministic or relatively simplistic, while the future revenues from most infrastructure investments are stochastic.

Another body of literature advocates combining the analytical capabilities of game theory with real options to deal with uncertainty in a multi-actor investment environment where the decision of an agent is affected by other agents. In this regard, Smit (2001) and Smit and Trigeorgis (2007) illustrated the use of option-game principles to analyse dynamic technology investment opportunities involving important competitive/strategic decisions under uncertainty. Suttinon et al. (2012) developed an option-game analytical framework to evaluate trade-offs between flexibility and strategic commitment in industrial water infrastructure projects. The case involves a government and private investor to develop water infrastructure.

Smit and Trigeorgis (2009) analyzed infrastructure investment as a real-option game in the case of European airport expansion. The above studies show that the combination of option games is a new valuation tool that combines real option and game theory so as to value flexibility and commitment in technology and infrastructure investemnt decisions. However, the above studies focus on the application of options-game theory to analyse uncertainty in a competitive investment environment and do not provide much insight into cooperative investment situations in which actors try to maximize their joint payoffs.

This chapter discusses the potential of risk sharing when commercial actors co-develop infrastructure networks under uncertainty. We use concepts from the risk sharing and game theory literature to model a risk sharing contract between two risk-averse agents who want to invest in a common infrastructure project.

The rest of the chapter is organized as follows. Section 4.2 provides the basic model set-up and assumptions. Section 4.3 presents analyses of optimal risk rule and values of risk sharing. Section 4.4 presents an illustrative example. Chapter 4.5 concludes the chapter.

4.2. Modelling Revenue and Profit

Let's take two agents (i) who intend to create a joint venture to share the development cost and future profit of an energy infrastructure project. Each agent has a pre-existing risky business before the possibility of investing in the common project is considered. Moreover, agents agree to share the profit risk associated with the common project. We assume that cooperating agents observe the evolution of the joint cooperative project´s value and they have symmetric information. All parties have access, ex-post, to the true realized returns of the common project. All profits of the new venture will be shared between the two agents. The applicability of the proposed model is general but throughout this chapter a joint project to develop a merchant transmission line is used as an illustrative case.

We assume that the future performance of the common project is uncertain and follows a stochastic process. For example, in merchant power interconnectors[1], the daily revenue is stochastic due to the random nature of congestion revenue, which depends on daily electricity demand and nodal prices (Salazar et al., 2007). There is an array of approaches (e.g., Brownian

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[1] Merchant electricity interconnector, also called non-regulated transmission investment, is an arrangement where a private party constructs and operates electric transmission lines between unrelated electricity markets, often across borders. Interconnectors are the physical links which allow the transfer of electricity across borders.

motion, mean reverting process) that can be used to model the revenue time series (Dixit and Pindyck, 1994). Geometric Brownian Motion (GBM) processes are frequently applied to model stochastic price and revenue behaviours. Salazar et al. (2007) and Fleten et al. (2011) employed a GBM process to model electricity prices for an economic analysis of merchant power interconnectors. Brandao and Saraiva (2008) and Carbonara et al. (2014) used GBM process to model revenue in infrastructure projects.

Although GBM is preferred for the purposes of price modelling, it fails to effectively model profit and cash flows as it does not allow for negative realizations. Arithmetic Brownian Motion (ABM) processes are frequently used to model economic performance measures that can become negative (e.g. profits) (Copeland and Antikarov, 2001). Since the revenue of merchant interconnector project depends on price differences between the connected markets, ABM can be used to model its dynamics over time. Moreover, if the price of each individual price region is modelled using a GBM process, the dynamics of the difference can be reasonably approximated using an ABM process (Carmona and Durrleman, 2003). Therefore, in this study, we assume that the investment-flow returns follow an ABM process.

An ABM process representation of profit $p(t)$ at any time is given by

$$p(t) = p_0 + \mu t + \sigma W(t), \tag{4.1}$$

where p_0 is the initial value, μ is the expected return (the drift), σ is the volatility of profit, and $W(t)$ is a standard Brownian motion.

To illustrate the risk-sharing rule, we consider the following cooperation scenario. The agents agree on creating the joint venture S at time $t = 0$. Then, at time $t = \tau < T$, the partners decide to sign a risk-and-profit-sharing agreement based on the discounted value[2] of the common project's profit for the period $[\tau, T]$. Therefore, we are interested in the distribution of the present value of the profit of the three entities: i.e. the common project and the two pre-existing businesses of the agents. Mathematically, the present value of an ABM process can be reasonably approximated using a normal distribution (Ross, 1999, Cartea and González-Pedraz, 2012). Therefore, a time $= \tau < T$, the profits of the common project and the agents' pre-existing businesses are denoted as follows:

[2] In a continuous-time game the payoffs are realized along the time of the cooperation. However, we assume that agents evaluate the worth of cooperation (i.e. their individual share) by discounting the sum of future payoffs at the time of entering into the cooperation.

- ${x_i}^0(\tau)$ = the discounted value of the profit from agent i's existing business.
- ${x_i}^1(\tau)$ = the discounted value of the profit if either of the agents invests on the joint venture alone.
- $x(\tau)$ = the discounted value of the profit from the common project.
- $x_i(\tau)$ = the discounted value of the profit from the joint venture received by agent i.

The expressions of the distributions of the pre-existing business and the common project are shown as follows.

$$ {x_i}^0(\tau) \sim N\left(\mu_i^0, \sigma_i^0\right) \tag{4.2} $$

$$ x(\tau) \sim N(\mu_s, \sigma_s) \tag{4.3} $$

Whether the agents decide to take up the new project as a single investor or together as a joint project, it is important to define the relationship between the joint venture and their existing projects. Since the two agents have some existing risky businesses, their decision whether to invest in the shared infrastructure project or not depends on their pre-existing business and the characteristics of the new shared project. For example, if two neighbouring countries jointly invest in an electricity interconnector, the electricity prices in both countries will be affected and that, in turn, will affect the revenue of transmission operators and generators in each country (Parail, 2010). As a result, neighbouring countries (at least the transmission operators and generators in the high electricity price market) have the interest to keep the two electricity markets separate (Kristiansen and Rosellón, 2010, Parail, 2009). To consider the influence of the new common project, we consider its correlation with the pre-existing businesses of the two agents.

The dependence between the pre-existing businesses and the common project is determined by a linear correlation coefficient ρ_i. The correlation coefficient takes a value between -1 and 1, i.e. $-1 \le \rho_i \le 1$. If $\rho_i = 0$, then the common project and the pre-existing business are independent. If $0 < \rho_i \le 1$, then the two are positively correlated and if $-1 \le \rho_i < 0$, then they are negatively correlated.

The sum of two dependent normal distributions (which can each describe the present value of an ABM-cash-flow) is a normal distribution (Pastore, 1988). By this principle, we can define the distribution parameters of ${x_i}^1$ and $x_i(\tau)$ based on (4.2) and (4.3).

If one of the agents carries out the investment alone[3], the total uncertain payoffs can be obtained by adding the payoff from the existing business and the payoff from the common project.

$$x_i^{\,1}(\tau) = x_i^{\,0}(\tau) + x(\tau) \tag{4.4}$$

Therefore, $x_i^{\,1}(\tau)$ is given as

$$x_i^{\,1}(\tau) \sim N\left(\mu_i^1, \sigma_i^1\right) \tag{4.5}$$

$$\text{where } \mu_i^1 = \mu_i^0 + \mu_s \text{ and } \sigma_i^1 = \sqrt{(\sigma_i^0)^2 + \sigma_s^2 + 2\rho_i \sigma_i^0 \sigma_s}$$

Similarly, if the agents cooperate the total value of each agent's payoff from engaging in the joint venture is the sum of the uncertain payoff from the existing business and a share $\varphi_i \in [0,1]$ of the uncertain payoff from the joint venture. Here we define the risk-sharing contract to be a rule to calculate the percentage share of the equity stake in the common project. Therefore, if the agents cooperate in developing the project the cash flow depends on the contractually agreed share rule φ_i.

$$x_i(\tau) = x_i^{\,0}(\tau) + \varphi_i x(\tau) \tag{4.6}$$

$$x_i(\tau) \sim N(\mu_i, \sigma_i) \tag{4.7}$$

where $\mu_i = \mu_i^0 + \varphi_i \mu_s$ and $\sigma_i = \sqrt{(\sigma_i^0)^2 + \varphi_i^2 \sigma_s^2 + 2\rho_i \varphi_i \sigma_i^0 \sigma_s}$

The probability density distribution of a normal distribution function x with mean μ and variance σ^2 is expressed as

$$f(x; \mu, \sigma) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \tag{4.8}$$

Inserting the mean and variances of (4.5) and (4.7) in (4.8) we get a probability density distribution of for $x_i^{\,1}(\tau)$ and $x_i(\tau)$.

[3] However, for reasons of investment risk and other regulatory barriers, they are not willing to do it alone or not allowed by law. This is mostly the case for cross-border power transmission investments.

$$f({x_i}^1(\tau)) = \frac{1}{\sqrt{2\pi(\sigma_i^2 + \sigma_s^2 + 2\rho_i\sigma_i\sigma_s)}} e^{-\frac{({x_i}^1 - (\mu_i + \mu_s))^2}{2(\sigma_i^2 + \sigma_s^2 + 2\rho_i\sigma_i\sigma_s)}} \tag{4.9}$$

$$f(x_i(\tau)) = \frac{1}{\sqrt{2\pi(\sigma_i^2 + \varphi_i^2\sigma_s^2 + 2\varphi_i\rho_{is}\sigma_i\sigma_s)}} e^{-\frac{({x_i}^1 - (\mu_i + \varphi_i\mu_s))^2}{2(\sigma_i^2 + \varphi_i^2\sigma_s^2 + 2\varphi_i\rho_{is}\sigma_i\sigma_s)}} \tag{4.10}$$

The expressions in (4.9) and (4.10) respectively show the probability distribution of profit for each agent if they invest in the common project alone and if they invest jointly. Determining the profit distributions in equation (4.9) requires only calculating the correlations (ρ_i) between the profit from the agents' pre-existing businesses and the profit from new common project, given their distribution is known. However, determining the profit distributions in equation (4.10) requires deriving the optimal risk sharing ratio (φ_i) in addition to correlation. In the next section, we use utility theory to derive the optimal risk share ratio.

4.3. Optimal Risk-Sharing Rule

In the previous section, we defined what the uncertain profit agents will receive when they engage into a shared investment. However, the value of the uncertain payoff depends on the risk preference of the agent. Without loss of generality, we assume both agents are risk averse. A risk-averse agent is reluctant to accept a bargain with an uncertain payoff compared to another bargain with a more certain, but possibly lower, expected payoff (Pratt, 2000). We model the payoff preference of agents using expected-utility functions, i.e. party i prefers an uncertain payoff X over an uncertain payoff Y if $E[U_i(X)] > E[U_i(Y)]$ where U_i is a suitable utility function (Pratt, 1964). The underlying assumption is that the agents' perception of risk can be fully captured by the expected utility function, which reflects the value of the payoff share from the common project (Schoemaker, 1982). The utility function translates each of the possible payoffs into a non-monetary measure known as utility. For tractability reasons, we consider a negative exponential utility function assuming the agents that the risk preference of each firm is governed by a constant absolute risk aversion (CARA)[4] utility function.

$$\mathrm{U(X)} = -\mathrm{e}^{-\gamma \mathrm{X}} \tag{4.11}$$

where $U(X)$ represents the utility function, X is the evaluation measure (such as profit or cost), γ is a constant that describes risk aversion. The degree of risk aversion that is appropriate depends, for instance, on the nature of the agent or on its asset position (Pratt, 1964). CARA means that, if we change uncertain payoff X by adding a fixed additional amount of money to the agent's payoff in all possible outcomes of the gamble, then the certainty equivalent of the gamble should increase by this same amount. Constant risk aversion is widely used for practical decision analysis due to its convenience (Myerson, 2004). Moreover, constant risk aversion allows us to evaluate independent uncertain payoffs (i.e. $\mathrm{P(t)}$ and $\mathrm{P_i}^0\mathrm{(t)}$) separately.

For a CARA utility function shown in (4.11), the expected utility of (4.8) is given by

$$EU(x) = -\mathrm{e}^{-\gamma(\mu - \gamma\frac{\sigma^2}{2})} \tag{4.12}$$

Using the same formulation $x_i(\tau)$ can be given by

$$E(U(x_i)) = -e^{-\gamma_i\left(\mu_i^0 + \varphi_i\mu_s - \gamma_i\frac{(\sigma_i^0)^2 + \varphi_i^2\sigma_s^2 + 2\rho_i\varphi_i\sigma_i^0\sigma_s}{2}\right)} \tag{4.13}$$

Equation (4.13) shows that the expected utility of the discounted value of the joint venture for agent i is a function of her share from the joint venture and the correlation of her existing business to the new joint venture.

For the CARA utility function, $\gamma_i > 0$ implies that agents are risk averse. Therefore, for each random x_i, an agent prefers receiving the expected payoff $\mathrm{E}[x_i]$ with certainty to receiving the random payoff x_i. Moreover, agent 1 is more risk averse than agent 2 if $\gamma_1 > \gamma_2$. If it is the reverse, the utility function becomes convex and, consequently, the player will be a risk-seeker, see Schoemaker (1982) for more. Therefore, we can define the certainty equivalent (CE) of a random payoff x_i by $\mathrm{CE_i}\,(x_i) = \mathrm{U_i^{-1}}\,(\mathrm{E}(\mathrm{U_i}\,(x_i)))$, provided that the expected utility exists. Then, for all these random payoffs x_i, $\mathrm{E}(\mathrm{U_i}(\mathrm{CE_i}(x_i)) \equiv \mathrm{U_i}(\mathrm{CE_i}(x_i)) = \mathrm{E}(\mathrm{U_i}(x_i))$ holds. Since the expected utilities equal one another, agent i is indifferent between the random payoff x_i and

[4] The assumption of CARA utility function may seem far from reality compared to constant relative risk aversion (CRRA). However, the kind of utility function that describes the average is still controversial.

the deterministic payoff $\mathrm{CE_i}(x_i)$. Therefore, the certainty equivalent expression of distributed x_i is given by

$$CE_i(x_i) = \mu_i^0 + \varphi_i\mu_s - \gamma_i \frac{(\sigma_i^0)^2 + \varphi_i^2\sigma_s^2 + 2\rho_i\varphi_i\sigma_i^0\sigma_s}{2} \tag{4.14}$$

Individual rationality dictates that each agent will try to maximize their expected utility. Then the question becomes: what is the optimal contract for two agents to efficiently share the risk involved in a cooperative project?

To derive the optimal risk-sharing rule, we assumed that parties act cooperatively and have symmetric information about the characteristics of the venture. The returns to the venture are also verifiable ex-post, and the management of the joint venture acts to maximize the joint venture profits. It is also rational to think that both firms prefer to take up as little risk as possible while trying to increase their own gain. However, for risk-averse firms with a concave utility function, marginal gains decrease as risk taking decreases. Furthermore, this rate of reduction of marginal gains will be different for both players in view of their differing risk aversion levels. Therefore, the task for a rational firm in such situation is to optimize the amount of risk-taking in relation to the amount of gain.

The maximum total value of the joint venture will be obtained at a risk-sharing rule where the marginal value of taking up some infinitesimal fraction of the risky venture is the same for both agents (Bolton and Dewatripont, 2005). If the marginal gains were different for the two agents, it would be possible to add to the total value by taking away an infinitesimal amount of risk from the firm with the smaller marginal gain and giving it to the firm with a larger marginal gain. Therefore, the first optimality condition equates the marginal gains of the uncertain payoff of the two agents (Borch, 1962).

$$\frac{d}{d\varphi_1}CE_1(x_1) + \frac{d}{d\varphi_2}CE_2(x_2) = 0 \tag{4.15}$$

$$\sum_{i=1,2} \varphi_i = 1$$

where, φ_1 is the share of agent 1 and the share of agent 2 is $1 - \varphi_1$. The expression in equation (4.15) means that the risk sharing problem is given as a maximum of the sum of the certainty equivalents of the two agents.

$$x(\tau)^* = \max_{\varphi_1}[CE_1(x_1) + CE_2(x_2)] \tag{4.16}$$

Inserting (4.14) in (4.15) and rearranging, we get the optimal share of the risk φ_1^* for agent 1.

$$\varphi_1^* = \frac{\gamma_2}{\gamma_1 + \gamma_2} + \rho_{2s}\frac{\gamma_2}{\gamma_1 + \gamma_2}\frac{\sigma_2^0}{\sigma_s} - \rho_{1s}\frac{\gamma_1}{\gamma_1 + \gamma_2}\frac{\sigma_1^0}{\sigma_s} \tag{4.17}$$

With $0 < \varphi_i^* < 1$ and $\sum_{i=1,2}\varphi_i^* = 1$

Note that the optimal risk-sharing rule does not depend on the mean rate of the returns of the pre-existing businesses (μ1 and μ2). Only the risk aversion of the two parties, the volatilities of the pre-existing businesses and the correlations of the pre-existing businesses with the joint venture affect the optimality conditions. There is no risk-sharing agreement when $\varphi_1^* = 0$, $\varphi_2^* = 1$, or equivalently $\frac{\gamma_1}{\gamma_2} = \frac{\sigma_s + \rho_{2s}\sigma_2}{\rho_{1s}\sigma_1}$; or $\varphi_2^* = 1$, $\varphi_2^* = 0$, or equivalently $\frac{\gamma_1}{\gamma_2} = \frac{\rho_{2s}\sigma_2}{\rho_{1s}\sigma_1 + \sigma_s}$. The condition that $0 < \varphi_i^* < 1$ can be equivalently expressed as $0 < \gamma_2(\sigma_s + \rho_{2s}\sigma_2) - \gamma_1\rho_{1s}\sigma_1 < (\gamma_1 + \gamma_2)\sigma_s$. This condition is expressed with the parameters that represent the distribution of profit from the agents' existing businesses and the common project, and the agents' risk aversions.

Let us define the following variables that depend on risk aversion, correlation, and volatility:

$$K_1 = \frac{\gamma_2}{\gamma_1},\ K_2 = \rho_{1s}\frac{\sigma_1}{\sigma_s},\ \text{and } K_3 = \rho_{2s}\frac{\sigma_2}{\sigma_s}\ \text{ for } \forall\gamma_1, \forall\sigma_s \neq 0$$

Then, the condition for the existence of a feasible risk sharing agreement is given as:

$$\begin{gathered} K_1 > 0 \\ K_2 < K_1(1 + K_3) \\ K_2 > K_1K_3 - 1 \end{gathered} \tag{4.18}$$

An important feature of expression (4.17) is that it is time-invariant. This implies that after the risk-sharing contract has been agreed neither party will have an incentive for dynamic re-negotiation of their respective risk share unless these correlations and volatilities change.

4.3.1. The Effect of correlation

In expression (4.17) we can see that the optimal amount of risk an agent is willing to take partly depends on the correlation of the agents' existing projects with the common project. If there is no correlation between the common project and the agents' existing businesses the optimal risk share is only a function of the agents´ risk aversions (for instance for agent 1, $\overline{\varphi}_1^* = \frac{\gamma_2}{\gamma_1+\gamma_2}$). In such case, the certainty equivalent of agent i is given by:

$$\overline{CE}_i = \mu_i^0 + \overline{\varphi}_i^* \mu_s - \gamma_i \frac{(\sigma_i^0)^2 + \left(\overline{\varphi}_i^*\right)^2 \sigma_s^2}{2} \tag{4.19}$$

If the pre-existing businesses and the new common project are correlated, the agents' certainty equivalents can be found by using (4.20).

$$CE_i = \mu_i^0 + \varphi_i^* \mu_s - \gamma_i \frac{(\sigma_i^0)^2 + (\varphi_i^*)^2 \sigma_s^2 + 2\rho_i \varphi_i^* \sigma_i^0 \sigma_s}{2} \tag{4.20}$$

Then, the effect of correlation can be obtained by subtracting (19) from (20) as shown in (4.21).

$$CE_i - \overline{CE}_i = \mu_s\left(\varphi_i^* - \overline{\varphi}_i^*\right) - \frac{\gamma_i \sigma_s^2}{2}\left((\varphi_i^*)^2 - \left(\overline{\varphi}_i^*\right)^2\right) - \gamma_i \rho_i \varphi_i^* \sigma_i^0 \sigma_s \tag{4.21}$$

The correlation coefficient (i.e. $\rho_i > 0$ or $\rho_i < 0$) affects the value of the right-hand side of equation (4.21). Using expression (4.21) agents can get valuable insight, at least at exploratory stage of cooperation, about the effect of the new project to their overall expected utility.

4.3.2. The value of risk sharing

In this section, we derive the value of risk sharing that can be obtained from cooperation. We treat cooperation in the joint venture as an investment option that can be exercised by committing some given capital. As with any investment, cooperation in the joint venture comes with its own risks.

At the conceptual stage of the cooperation agents have three options: exercise the investment in the project through cooperation, invest in the project alone or do nothing. We refer to the first one as *cooperation option*. The solo investment and the abandoning options are referred as *non-cooperation* options.

If agent i neither cooperates or invests alone (i.e. carry out only existing project), the certainty equivalent of the uncertain payoff from the existing project x_i^0 is given by

$$CE_i^0 = \mu_i^0 - \gamma_i \frac{(\sigma_i^0)^2}{2} \tag{4.22}$$

If either of the agents invests alone, then the certainty equivalent of the uncertain profit x_i^1 is given by

$$CE_i^1 = \mu_i^0 + \mu_s - \gamma_i \frac{(\sigma_i^0)^2 + \sigma_s^2 + 2\rho_i\sigma_i^0\sigma_s}{2} \tag{4.23}$$

In this case, the value of risk sharing for each agent, $\mathrm{VoRs_i}$, can be obtained by comparing the utility agent i gets from the cooperation option with that of the non-cooperation options. The value of cooperation via risk sharing can be obtained by subtracting the maximum of the certainty equivalent values of the two non-cooperation options from the cooperation.

$$\mathrm{VoRs_i} = CE_i - \max\left(CE_i^1, CE_i^0\right) \tag{4.24}$$

Expression (4.24) allows us to define the condition under which partners will choose cooperation to undertake a project when there is a background risk (from their existing business) and project risk (from the common project), provided that they can also consider investing on their own. It shows the minimum of the value that the agent gets because of cooperation. Theoretically, the minimum $VoRs_i$ should be greater than zero for the agent to engage into cooperation. Otherwise, the agent could compare the maximum of CE^1 and CE^0 to either invest in the project alone or not invest at all.

Expression (4.24) can also be used by individual agents to select a cooperating partner to set up a joint venture for a project. Different agents are most likely to have different background risks, resulting in an increase in the value of risk sharing. Using expression (4.24), agents can compare the amount of value they obtained by sharing the risk of the common project with the different kinds of prospective partners who have different background risk.

4.3.3. The risk-sharing zone

In expression (4.24), we presented a model to determine the value agents get if they take an optimal share of the risk. The direct takeaway from (4.24) is that depending on the VoRs agents can decide whether to engage in cooperation or not. However, cooperation could be possible if one agent has a positive VoRs and can transfer a portion of the surplus to the other agent with negative VoRs. In this section, we check whether cooperation is possible via a side payment. We assume that agents agree on the cooperation at time $t = 0$. Then, after uncertainty is resolved, they decide to exercise the cooperative option $t = \tau < T$ and receive an instant payoff. The core of a cooperative game is the set of payoff allocations that make both partners better off than if they were to go it alone. i.e.

$$CE_i \geq CE_i{}^1$$

$$\sum_{i=1,2} CE_i = CE$$

A payoff for either firm is in the core if

$$CE_i{}^1 \leq CE_i \leq CE \tag{4.25}$$

The focus now is to define the risk-sharing-value core in which cooperation is possible. In this core, partners can agree to maximize the sum of their certainty equivalents by sharing the risky returns in proportion to their respective risk tolerances. We will focus on linear contracts, i.e. agreements involving a deterministic cash payment D_i and a share φ_i of an uncertain payoff CE at $t = \tau$. The total payoff of agent i from the joint project will be

$$CE_i = D_i + \varphi_i CE \tag{4.26}$$

Linear contracts are very common in most joint-venture revenue-and-cost-sharing arrangements (Bolton and Dewatripont, 2005, Savva and Scholtes, 2005). In (4.17) we derived the optimal share of risk when two agents cooperate to maximize their joint certainty equivalents. However, the optimal risk-sharing rule only specifies how much risk each player will take and does not determine the optimal payoff for each agent from the cooperation. This is because the deterministic amount D_i that the two agents exchange is not constrained and is determined through negotiation.

To know the amount of D_i let us define the sharing rule in a situation where agent 1 owns the option to develop the project alone. For agent 2, there is always the alternative of not participating in the project with a zero payoff. The best sharing rule for agent 1 would be one that maximizes 1´s certainty equivalent subject to the constraint that 2´s certainty equivalent should not be less than zero. The best sharing rule can be achieved by sharing in the optimal proportions, to maximize the sum of each agent´s certainty equivalents, with an additional payment from agent 2 to agent 1 on the condition that 2´s certainty equivalent should be equal or greater than zero. The best possible sharing rule for agent 1 would be to sell agent 2 an optimal share of the project which is φ_2^*. The maximum price of the optimal share of the investment is equal to $\varphi_2^* * CE$. Agent 1´s overall certainty equivalent is equal to $(\varphi_1^* * CE) + (\varphi_2^* * CE)$. This value is the maximum sum of certainty equivalent that the two partners can get from the project and it is allocated to agent 1.

However, agent 2 would prefer to pay less than $\varphi_2^* * CE$ for an optimal share φ_2^*. Agent 2 may try to negotiate for lower price. The negotiated price that is given from agent 2 to agent 1 for an optimal share of the project is the cash D. Although D is determined through negotiation it has minimum value that agent 1 can accept. At the minimum, D should make agent 1´s certainty equivalent better than owning 100% of the project alone. Hence, the conditions for the core of the cooperation game, subject to optimal sharing, is given as

$$CE_1 + D \geq CE_1{}^1$$

$$CE_2 \geq D$$

$$\sum_{i=1,2} \varphi_i^* = 1$$

The first two conditions guarantee that the optimal share value, as estimated by each agent, is at least as good as going it alone and the third condition will ensure efficient risk sharing. Then, the core of the cooperation game captures the risk exchange zone. In this case, the risk exchange zone is determined by the amount of D that is exchanged between the two agents. It is given as follows:

$$CE_1{}^1 - CE_1 \leq D \leq CE_2 \tag{4.27}$$

It can be seen from (4.27) that the core of the cooperation game is non-empty as long as D is positive[1]. A non-empty core indicates that there are gains to be made by cooperating via risk sharing. In other words, the risk-sharing zone is the risk-sharing core of the contract. It can also be seen from expression (4.27) that the size of the risk sharing core depends on the risk aversion γ_i of the two agents in addition to the variances σ_1, σ_2 of the pre-existing businesses and the correlations ρ_1 and ρ_2 of the pre-existing businesses with the joint venture.

So far, we have seen the value that risk sharing provides for risk-averse agents seeking cooperation. We showed that for a stochastic cooperative joint venture between agents with a CARA utility function, linear contracts provide Pareto-efficient payoff allocation and allow an optimal risk-sharing rule. We assumed that agents maximize their joint welfare and under that assumption, linear contracts can provide optimal risk sharing mechanism. The optimal risk sharing contract is determined by the exchange of a negotiated cash payment from one party

[1] Individual rationality is the boundary condition for having non-empty core of the cooperative game.

to another. It is dependent not only the parameters that affect the optimal risk share (i.e. risk aversion γ_i, volatilities σ_1, σ_2 of the pre-existing businesses and the correlations ρ_1 and ρ_2 of the pre-existing businesses with the joint venture), but also the agents' relative bargaining power (Choi and Triantis, 2012, Murnighan et al., 1988).

4.4. Illustrative example

In this section, we provide an example of our results for illustration purposes. Specifically, we present analyses of the effect of correlation on the optimal risk share and the value risk sharing for cooperating partners. A stylized joint investment on merchant electricity interconnector is used for demonstration. We provide some background that presents the need for analysing the value of risk sharing in this specific situation. However, the example should be taken only as an illustration rather than a numerically accurate case study. Fitting model parameters would require access to confidential information and interactions with the agents in order to extract accurately their risk preferences, and it would not add to the illustration intended, which considers many different possible values for the parameters.

4.4.1 Problem Background

The current electricity infrastructure across the EU is outdated and inefficient and bottlenecks prevent efficient transmission of electricity from one part of Europe to the other and from one country to another(EC, 2015). The lack of much new public interconnection investment has induced the European legislator to opt for merchant transmission projects(Parail, 2009). Merchant projects could be carried out by new actors as in the case of *East-West cables* and by incumbent transmission system operators (TSOs) as in the case of *BritNed (Supponen, 2011)*. However, investment by new actors to connect different market regions is discouraged by the protection tendencies of incumbent TSOs on both sides of the market(Kristiansen and Rosellón, 2010). As a solution, regulators allow incumbent TSOs of both regions to invest in the interconnection as merchant project. A notable example is BritNed merchant interconnector between the UK and the Netherlands(BritNed, 2015).

There is a conflicting choice between national and company interests in cross-border transmission investments(Supponen, 2011). From the national perspective, the motivation for interconnector investment originates from a need to improve the security of supply, facilitate renewable energy integration or electricity price reduction(Kristiansen and Rosellón, 2010). For example, the major motivation for expanding the Germany- Nederland interconnector capacity is Germany's increasing share of electrcity from wind which can be exported to

Norway. The major motivation for constructing the NorNed cable is the security of supply, since Norway is almost entirely dependent (99%) on hydro generation, and the Nederland is predominantly thermal. BritNed has been undertaken because of security-of-supply issues and the European Commission's desire to link electricity markets. However, from a TSO perspective, the project is risky. For instance, historically the Netherlands has been a higher-priced country (especially during peak hours) relative to its neighbours. From an organizational perspective Tennet (the Dutch TSO) has an incentive to isolate the market, while the Dutch regulator's objective is to introduce renewable energies in an otherwise thermal-dominated system. On the one hand, there are national interests and associated incentives to cooperate. On the other hand, there are costs and associated risks. Therefore, TSOs need to understand the effect of cooperation: i.e. the share of risk during cooperation, the potential value of cooperation and the effect of the interconnector on their existing business. Next, a simplified Numerical analysis is presented to demonstrate these issues.

4.4.2 Main assumptions of the case study

The main parameter values defining the performance of the three entities and the risk aversion of the agents are shown below, in annual terms.

- Initial cost of the common project $C_s = 15$
- Distribution of revenue of the common project $\mu_s = 40$, $\sigma_s = 20$
- Distribution of revenue of the agent 1 $\mu_1 = 400$, $\sigma_1 = 100$
- Distribution of revenue of the agent 2 $\mu_2 = 250$, $\sigma_2 = 50$
- Risk aversion of agent 1 = 0.1
- Risk aversion of agent 2 = 0.3

As highlighted above, although this case study is inspired by BritNed, the situation is hypothetical, and the estimated parameter values are intended for illustration only.

4.4.3 Effect of correlation on the risk sharing ratio

Fig 4.1 shows agent 1's optimal share of risk as a function of correlation coefficients assuming constant risk aversion. In Fig 1a it can be seen that, for $\rho_{1s} > 0$, agent 1's share of risk decreases linearly as the correlation between its pre-existing business and the common project increases. On the other hand, for $\rho_{1s} < 0$, the optimal share of risk for agent 1 increases as its correlation increases. Fig1a also shows that the risk share of agent 1 depends on ρ_{2s} as well. It can be said that the risk share of agent 1 increases as the correlation of agent 2 shifts from negative to positive. However, it is important to notice that for a given correlation coefficient of agent 2, the correlation coefficient of agent 1 should be between certain value range for optimal risk sharing to exist. For example, if $\rho_{2s} = 0.5$, the optimal risk sharing between the two agents, is possible when $0.2 \leq \rho_{1s} \leq 1$ for the assumed risk aversion and volatility parameters. The optimal risk share of agent 1 steeply decreases from 90% at $\rho_{1s} = 0.2$ and $\rho_{2s} = 0.5$ to 10% at $\rho_{1s} = 1$ and $\rho_{2s} = 0.25$. In Fig 1b it can be seen that the risk share of agent 2 linearly varies with the correlation of its pre-existing business with the common project.

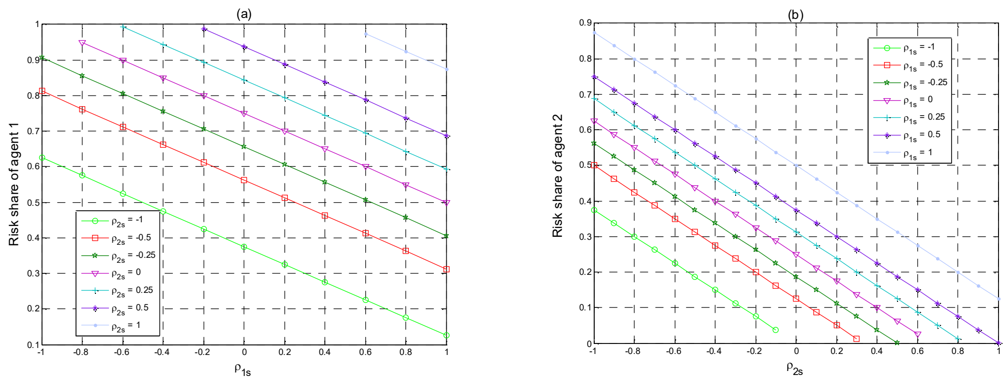

Figure 4.1 Optimal risk share as a function of correlation coefficients: (a) agent 1, and (b) agent 2.

In a particular case where the correlations coefficients of both agents are equal to zero agents 1 and 2 take 75% and 25% of the risk respectively. The more risk-averse agent takes a smaller share of the risk and vice versa. However, Fig 4.1 shows that the agents can take a higher or lower share of the risk when the correlations of their pre-existing businesses are considered. If agent 1's pre-existing business profit is positively correlated to the projected revenue of the common project and agent 1 knows that agent 2's pre-existing business is negatively correlated to the common project revenue, then it is optimal for agent 1 to take a lower share of the risk than the one obtained at zero correlation.

Therefore, considering correlation provides a deeper insight for agents regarding their optimal share of risk in cooperative ventures. Previous approaches only considered that the share of risk taken by a partner is higher for lower risk aversion. However, we show how the optimal risk share depends greatly on the correlation of the joint venture with the agent's pre-existing businesses.

4.4.4 The value of cooperation via risk sharing

In the previous section, we showed that the optimal stake of risk is influenced by the correlation of the pre-existing businesses with the common project. However, the optimal risk ratio only informs how much stake of the risk each player will take and does not provide information about the value of cooperation via risk sharing. Fig 4.2 shows the value of cooperation via risk sharing (VoRs) as a function of correlation coefficients. In Fig 4.2a it can be seen that the value of cooperation for agent 1 is positive when her pre-existing business is positively correlated to the common project. However, the value of risk sharing depends also on the correlation coefficient of agent 2. If agent 1 has a positive correlation, the value of risk sharing increases as agent 2's correlation increases. The effect of the correlation of agent 1's business on its value of risk share can be clearly observed when the correlation coefficient of agent 2 is fixed. For example, in Fig 4.2a it can be seen that for $\rho_{2s} = 0.5$ the VoRs1 increases from close to zero at $\rho_{1s} = -0.2$ to 15 million Euros at $\rho_{1s} = 1$.

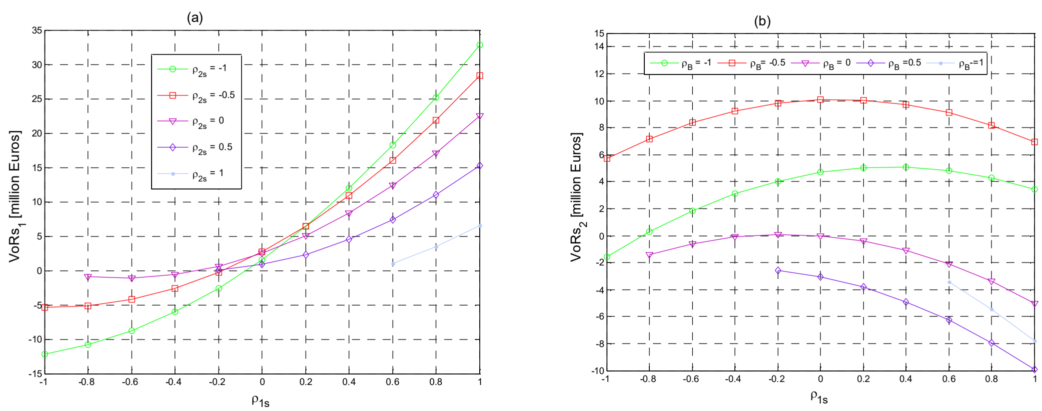

Figure 4.2 The value of risk sharing for (a) agent 1, (b) agent 2

Similarly, for agent 2, the value of risk sharing is influenced by the correlation of its pre-existing business with the common project, in addition to the correlation coefficient of agent 1. In Fig 4.2b it can be seen that for $\rho_{1s} < 0$ the value of risk sharing for agent 2 decreases as his pre-existing business is more negatively correlated to the common project. On the other hand, if $\rho_{1s} > 0$, the value of cooperation for agent 2 decreases as her/his existing business is more positively correlated to the common project. If the VoRs for both agents is positive, it indicates that partners with divergent risk attitudes and correlation coefficients can gain more synergies from risk sharing in uncertain environments.

It is likely that different agents have different background risk from their pre-existing businesses. If an agent knows about the performance of the co-partner's businesses profit, then it is possible to calculate the share of risk and the value of cooperation with another agent. However, symmetry information among partners is required regarding the performance of the common project and their pre-existing businesses. If an agent has information about the pre-existing businesses of potential candidate partners, she/he can use that information to determine worthy co-investors. This is particularly important at the exploratory stage of the co-investment and during contract negotiation stages. Having a better understanding of the economic implications of committing contractual agreements, especially when the new venture has implications on the performance of the pre-existing business, could help build resilient partnerships and avoid problems.

4.5. Conclusions

The exploratory phase of a joint infrastructure project entails uncertainties to cooperating agents with respect to the value of the project and the optimal share of risk. Uncertainty often leads to a deadlock situation in which decision-making stagnates. To address uncertainty in such situations, an approach is required that allows the assessment of the risk and gain of cooperation for each agent. In this chapter, we analyze the effect of risk sharing when two risk-averse agents co-develop an energy infrastructure project under uncertain environment. The two agents have background risks from their pre-existing businesses, and the joint project is represented by a risky cash flow. The cooperating partners are risk-averse but need not have the same risk aversion. We assume that the partners will act cooperatively to maximize their joint welfare and there is information symmetry on the common project performance. The models and numerical analyses provide valuable managerial insights.

First, agents with divergent risk attitude can gain more synergies from risk sharing in uncertain investment environments. This is in agreement with earlier work by Savva and Scholtes (2005) and implies that cooperating with a partner with a different risk attitude can be very beneficial. Risk-sharing opportunities increase the risk exchange zone (i.e. the synergy set) from traditional economies of scale and scope. This could encourage uncertain agents to engage in cooperation to develop vital energy infrastructures.

Secondly, agents can structure better risk-sharing contracts. Conventionally, the risk preference of cooperating agents described with their respective risk aversion is used to allocate risk optimally. In this study, we found that the optimal share depends also on the future projection (i.e. volatility) of the new common project and the agent's pre-existing businesses. Furthermore, the optimal risk share depends on the correlations between the agents' pre-existing businesses and the new common project. These additional insights can help agents understand better the economic implications of long lasting contractual agreements and build enduring partnerships.

Last, the model can help agents to select the most suitable partner for a project. Agents can carry out an exploratory assessment of the value risk sharing with the different prospective partners. Different agents have a different background (pre-existing business) and risk attitudes, and the developed model can support the selection of a partner.

Finally, the modelling framework and the numerical analysis presented in this paper invite opportunities for future work. One area of future work could involve extending the model for multiple agents and considering the relative negotiation power of agents. Moreover, a real case study would make the model more relevant for practical deal negotiations.

Chapter 5 Conceptual Design of Infrastructure Networks via a Risk Sharing Contract

This chapter discusses how actors, with different and conflicting objectives, can enhance desired performances when they co-develop new infrastructure networks under uncertainty. It introduces an integrated design analysis approach to simultaneously explore value-enhancing flexibility technical and contractual design options. A multi-user CO_2 pipeline network is used to illustrate the approach. The chapter summarizes publication VI (Melese et al., 2017a) which is under review in the International Journal of greenhouse Gas Control.

5.1. Introduction

Infrastructure network projects are subject to risk due to large initial costs, high irreversibility (sunk costs) and long-term durability of assets. As a result, in many cases, investment in such projects becomes financially unattractive for commercial actors. When investments are not attractive to commercial actors, it is common to see public actors partner with commercial actors by providing risk-sharing provisions to improve the financial viability of such projects (Samuelson, 1954). A common means of collaboration between private and public actors for the delivery of infrastructure services is public private partnership (PPP) by which the government provides guarantees in order to reduce the risk for the private investor) (Bryce, 2001).

Collaboration between public and private actors in the form of PPP, however, is not the norm because of the fundamental tension between the two types of actors. The tension is one of reconciling public interest and private motives in the delivery of public goods. Private actors are mostly concerned with the financial feasibility of the investment as they are especially sensitive to revenue risk. The public actor is concerned with cost, the associated revenue guarantee payment and at the same time maintain high reliability of the service provided by the infrastructure. In addition, there are intrinsic characteristics that make infrastructure PPPs particularly vulnerable to different uncertainty. Some of these uncertainties are large sunk investments, meaning large construction costs and large debts (public and/or private); high sensitivity to demand variations/estimations, particularly, new projects; great exposure to financial markets (due to the large debt); and vulnerability to regulatory changes (Marques and Berg, 2011).

This chapter looks at the opportunities that exist to improve value for partners when they develop infrastructure networks. It particularly focuses on the opportunities that exist from a design perspective. By combining technical and contractual design perspectives, the chapter presents a systematic design analysis framework that would allow actors to find design solutions that could provide enhanced value in the face of uncertainty. A PPP arrangement to develop a multi-user CO_2 pipeline transport infrastructure is used to illustrate the framework.

5.2. Flexibility to Deal with Uncertainty in Infrastructure PPPs

From a design perspective, infrastructure PPPs involve engineering and contractual dimensions that could provide an opportunity to incorporate flexibility to cope with uncertainty. From an engineering design perspective, the physical infrastructure can be designed with flexibility capabilities that will allow it to adapt to changes, e.g. demand (de Neufville and Scholtes, 2011, Zhao and Tseng, 2003). Staged design, the option to delay the investment, and anticipatory investments are some common forms of flexibility strategies(de Neufville and Scholtes, 2011)de Bruijn et al., 2008de Neufville et al. (2006). Opportunities also exist to design flexibility within the contract arrangements. Flexible duration contract, flexible revenue guarantee and step-in rights are some common forms of flexibility strategies (Cruz and Marques, 2013a).

The concept of contractual flexibility is becoming increasingly important as a tool to address uncertainty affecting Public Private Partnership (PPP) projects. Chiara and Kokkaew (2009) introduced the concept of "contractual flexibility analysis" to improve the economic efficiency of public-private partnerships for infrastructure development. The concept basically argues on embedding flexibility mechanisms (e.g. contingency clauses) that allow for shifting risks from one partner to the other, in order to improve the contract behaviour over time. Zhang and Babovic (2012) examine flexible PPP contracts for a new highway project in the face of demand uncertainty. Cruz and Marques (2013a) use the concept of contractual flexibility and real options evaluation framework to enhance the value of hospital PPP contracts. Domingues et al. (2014) explore the potential benefits of contractual flexibility in the road PPP contracts. Brandao and Saraiva (2008) use the real options model to structure concession contracts as a composition of a minimum revenue guarantee and a maximum revenue ceiling allowing the private actor to be protected from revenue risk and at the same time protecting the government from excessive guarantee payments.

However, a design approach that simultaneously considers flexibility both from an engineering and contractual design perspective is still missing. Therefore, in this chapter, an integrated approach that models both engineering and contractual design explore flexible design strategies network design options under uncertainty is introduced. Simultaneous modelling of technical and contractual design domains could enable effective design exploration and value analysis that could enhance value for partners. The question is how to explore for technical and contractual design solutions that could satisfy both the network operator and the public actors during conceptual design of infrastructure PPPs.

5.3. Proposed Design Analysis Framework

Combining the approach by Melese et al. (2015) on the engineering design of networks with that of the work by Brandao and Saraiva (2008) on contractual design, this chapter presents a systematic framework for an integrated analysis of infrastructure network PPPs. It involves three major steps: step 1- identifying and characterizing uncertain design variables; step 2- developing an integrated model of the physical and the contractual structures of the partnership, and step 3- Monte Carlo simulation and design analysis. A brief description of each step is given below.

5.3.1 Identify and characterize uncertain design variables

The objective of uncertainty characterization is to model initial distributions and future trajectories of selected uncertain variables. To define initial distributions of selected uncertain variables, two approaches are often employed: data-driven and analytical. The former approach requires a large quantity of historical data and applies statistical methods (e.g. regression) to fit empirical an model (Agarwal and Aluru, 2010). In the absence of or limitation of full historical data an analytical approach could be more useful because it allows making use of initial assumptions on the behaviour of uncertain variables (i.e. types of distribution and speed of convergence) (Sankararaman et al., 2014). The initial estimate is then transformed to a probability distribution, such as a normal distribution, characterized by a vector containing the moments of the distribution (means and variances). Then, it is important to quantify the future trajectories of the selected uncertain variable over several stages or design period in the futures. A stage or design period in this context would be a suitable planning period (i.e. months, years). The future stages can be generated using a continuous or a discrete model. Continuous stochastic processes such as Geometric Brownian Motion (GBM) and Wiener processes, and discrete models such as the lattice model, can be used to model the evolution of the selected uncertain variable.

5.3.2 Integrated model of the physical and the contractual structures of the PPP

This step develops an integrated model of the PPP. The model includes both the physical layout and the contractual relationship between the partners. The physical configuration of the network includes design variables such as capacity, length and flow rate. The contract design variables include tariff for the users of the infrastructure, concession period, and revenue sharing rule. The integrated model then defines the relationship between uncertain design variables of physical and the contractual designs, for example, tariff and revenue sharing.

5.3.3 Monte Carlo simulation and design analysis

The objective of this step is to evaluate, to analyse and to compare the performance of different combinations of physical and contractual design strategies by simulating them under different scenarios. The inputs are the evolution of the uncertain parameters and the flexible design strategies. The result is a distribution of the project value, for example, its net present value (NPV), and capacity availability. Then compare the resulting distributions, along with aggregate statistics of interest, to get an understanding of the value effect of the different design solutions for the partners.

5.4. Application

5.4.1 Background

The high risk of building large-scale multi-user CO_2 pipeline network raised an argument that government support is required. The support is justified on the basis that taking advantage of economies of scale can reduce the overall cost to society of reducing greenhouse gas emissions through Carbon capture and storage (CCS). In this regard, there are studies that encourage the use of public funds in the form of public-private partnerships, to realize large scale deployment of CCS technology (Chrysostomidis and Zakkour, 2008, Austell et al., 2011, Groenenberg and de Coninck, 2008).

However, as is the case in other infrastructure PPPs there exist conflicting objectives between the public and the private actors. Major conflicting issues are tariff/connection fee and capacity of the network. On the capacity aspect, private actor usually invests in smaller capacity to save the sunk cost. On the price aspect, the private are likely to charge a high connection fee which could eventually discourage emitters from participating (Massol and

Tchung-Ming, 2012). In general, the public actor's objective is to ensure sufficient capacity for an integrated CCS deployment.

5.4.2 Design problem and assumptions

For the purpose of illustration, we formalized a stylized design problem that resembles a real-world network design context but is more abstract and general. The problem involves the conceptual design of a CCS network. The field has two existing CO_2 sources, S2 and S3, and one potential source, S1, that could join in future. All existing and future new sources will be connected via a pipeline network to a single sink S0 (e.g. storage site). Fig.5.1 shows the spatial location of the three sources and the sink. The parameters are hypothetical though they were inspired by an initiative to develop a CCS pipeline network in the Rotterdam area, the Netherlands (Read et al., 2014).

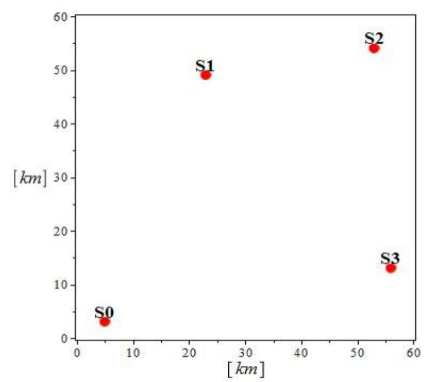

Figure 5.1 Layout of the hypothetical Field with three CO_2 sources and one storage site

It is assumed that there are two actors who create a partnership to develop a multi-user CO_2 pipeline infrastructure: a private firm who will own and operate the network, here-after called, network operator; and a public sector, here-after called, public actor. The public actor and the network operator enter a long-term concession contract in which the public actor will support the network operator via a risk sharing mechanism. It is assumed that the network operator would not invest in and operate the network without the assurance of a risk sharing contract with the public actor. The network operator will build and operate the network for the period of the concession.

Each of these actors has different objectives and perceives the value of designs in view of that. The public actor's objective is to ensure the public interest- reduction of CO_2 emission by facilitating the availability of sufficient pipeline capacity transporting CO_2 from existing and future CO_2 sources. To meet its objective, the public actor provides subsidy payments for the network operator as a form of minimum revenue guarantee. One the other hand, the network operator's objective is profit. It may be willing to provide reliable capacity for profit. As it is the case in many public infrastructure concession contracts, there are three dimensions of value in this design problem: contractual payments (public actor's view of the problem), profit (network operator's view of the problem), and availability of sufficient capacity which trades off the other two values and relates the outcomes to both actors.

The abovementioned values could be affected both by the technical configuration of the network and contract structure. Under CO_2 supply uncertainty, the reliability of the network is its ability to provide the required capacity as and when CO_2 supply increases over time. Therefore, the design strategy will influence the reliability as some design configurations may be more reliable than others. The concession contract creates a mechanism for the exchange of values for the actors. It serves as a structure to link the interests of the two actors. It also provides a legal framework that governs how risk affects the two actors. For example, the contractual connection tariff term and other risk sharing provisions determine the payments that the public actor makes to the network operator. In concession contracts risk sharing provisions include risk allocation mechanisms such as revenue guarantee and cap structures to manage the CO_2 supply (or capacity utilization) risk.

By integrating the technical and contractual design, this case study investigates the effects of architectural flexibility, i.e. extra capacity and length, in the technical domain and connection fee and revenue guarantee in the contractual domain. Each of these design dimensions presents difficult choices given the uncertainty in CO_2 supply and changing regulations.

5.4.3 Capacity demand uncertainty model of existing sources

In this chapter we focus on capacity demand uncertainty, a major design variable, that makes the deployment of an integrated CCS network very challenging (Austell et al., 2011). The uncertainty over capacity demand originates from two sources: (1) from existing participants whose demands may change over time; and (2) from participants who may be interested in joining the network in the future. The profitability of the CCS network investment highly depends on the capacity requirement as well as the tariff charged by per unit volume of CO_2. Therefore, the uncertainty of capacity demands of future and existing sources should be clearly quantified and considered in the investment decision.

Similar to chapter 3, the uncertainty over the capacity demand of existing sources is modelled using an analytical approach. The capacity demand of a CO_2 source is related to its CO_2 flow. Therefore, to model the initial capacity demand uncertainty of the two existing sources (S2 and S3) a normal distribution model is used.

- S2 (mean = 350 ktonne CO_2/year and standard deviation = 40 ktonne CO_2/year)
- S3 (mean = 400 ktonne CO_2/year and standard deviation = 50 ktonne CO_2/year)

Next, future states of CO_2 flow over several stages of the planning period is quantified. In this study, the planning period is set for 20 years, which is a reasonable time horizon for a progressive CCS deployment strategy (ADB, 2015). In reality there is a very high uncertainty regarding the future evolution of CO_2 supply because it depends not only on the operation of a capture unit but also on carbon emission policies. Since we are interested in average annual CO_2 production values, the amount of CO_2 produced in a given source can vary greatly from year to year. Nevertheless, one think is clear and that is supply of CO_2 from say capture unit of a coal power plant is stochastic due to changes in electricity production. It assumed that the source stations will add new capture capacity and therefore CO_2 supply will increase over the long term. In this study, we choose to use chose Geometric Brownian Motion (GBM) process to model the stochastic nature of average yearly CO_2 flow supply from each of the sources. Moreover, for sake of simplicity we assumed that the parameters that determine the GBM process (i.e. drift and volatility) are the same for both sources. The parameters are assumed to be as follows: drift = 5% and volatility= 7%. These assumptions are take into consideration the current reality and future prospect of CCS.

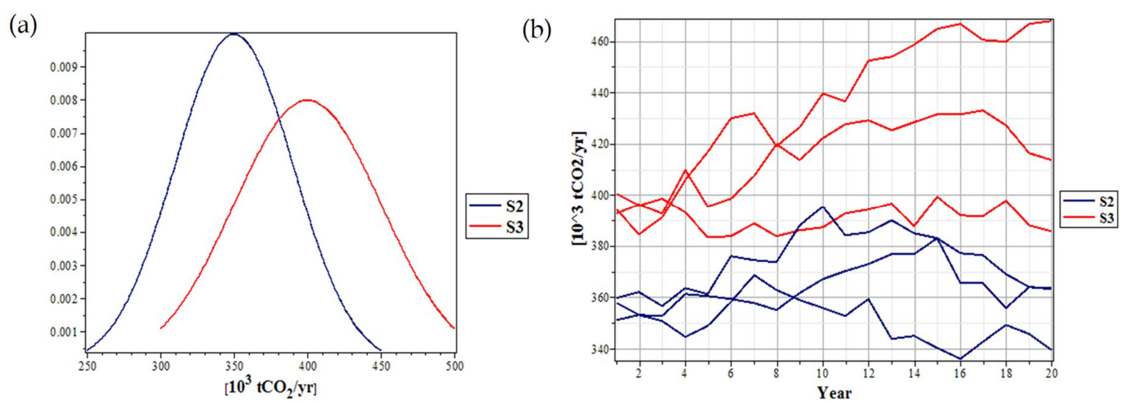

Figure 5.2 Sources capacity demand model. Initial flow estimate model (a) and three instances of future trajectories of flow (b)

Using the initial flows, drift rate and volatility, the GBM process generate yearly flow data over the planning period. Fig.5.2 shows initial flow estimate model and flow evolution pathways for sources S2 and S3.

5.4.4 Capacity demand uncertainty model of future sources

Timing and capacity demand of future sources present another challenge for an integrated CCS network deployment. In this study, we only consider one future source, S1. Theoretically, S1 could be CCS ready and join the network at any time over the planning period. However, in reality, it takes years to install a CO_2 capture unit and to be ready to join a CCS network. In this study, four timing scenarios are considered with a time step of four years: Year 4, Year 8, Year 12 and Year 16. A time period of four years is considered reasonable for an emitter to install a capture unit and connect to a network[1]. The capacity demand of S1 is modelled in a similar way to that of S2 and S3 with initial flow estimate modelled as shown in Fig. 5.3 with mean = 300 ktonne CO_2/year and standard deviation = 50 ktonne CO_2/year. Then, GBM process is used to model future yearly CO_2 flow rates. Parameters of the GBM process are, drift rate = 1% and volatility = 30%. In reality, the evolution future CO_2 flow depends on future policy incentives, technological developments.

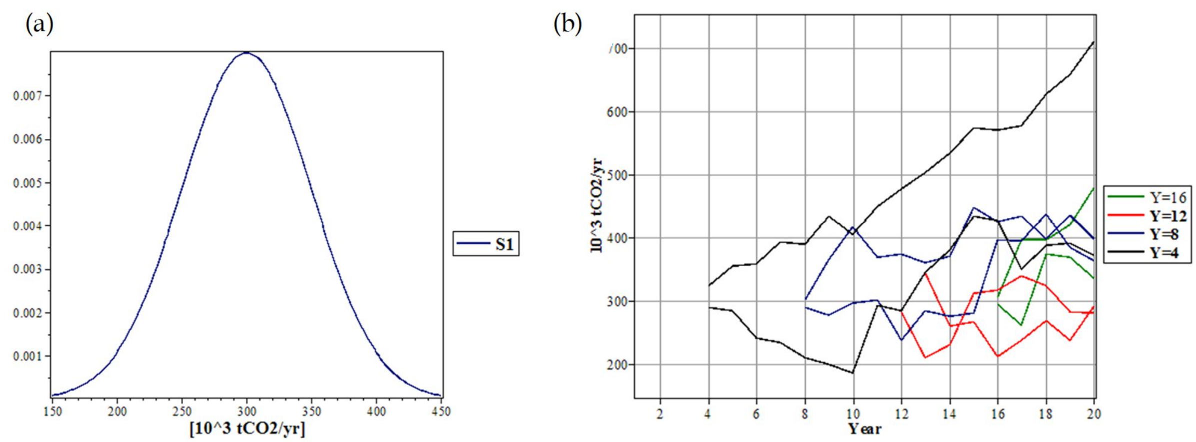

Figure 5.3 Capacity demand model of S1: (a) initial flow estimate, (b) instances of flow trajectories over time. Each trajectory represents one instance of S1 flow path. Y stand for Year

5.4.5 The integrated model

The integrated model defines the structural relationship between technical and contractual design variables. The technical configuration of the network includes design variables such capacity, length, and flow rate. The design of variables in the structure of the contract includes

1 The actual installation time of a capture ready plant could vary depending on the size of the capture unit, the type of capture technology, and other project specific factors.

service charge per unit capacity or tariff, and a risk sharing mechanism between the cooperating agents.

A. The physical network design model

Similar to the model in chapter 3, a graph theory-based modelling technique is used to model the physical layout of the infrastructure network. The technique is effective in modelling the layout of spatially distributed and connected infrastructures as networks consisting of nodes and links (Heijnen et al., 2014).

During pipeline network design, various goals may be pursued. Minimization of investment cost and availability of sufficient capacity are probably the most important and evident. The investment cost of the network depends on the length and capacity of the pipeline. The inputs of the model are flow rates of sources to determine capacity and the spatial positions of sources and sink nodes to determine length. The spatial positions of the three sources and the sink node are fixed. The total cost of a network N is the sum of all the costs of edges.

$$C(N) = \sum_{e \epsilon E} l_e f(q_e) \tag{5.1}$$

where E is the set of all edges in a network N, l_e is the length of an edge e and $f(q_e)$ is the cost per unit length of building an edge e with a flow capacity of q_e. The flow capacity is assumed to be given by

$$f(q_e) = q_e^{\beta} \text{ with } \quad 0 \leq \beta \leq 1. \tag{5.2}$$

where β is the exponent taking account capacity variation on the cost.

The cost exponent takes into account the capacity factor in the cost calculation. The lower the cost exponent, the more beneficial it is in terms of construction costs. An empirical cost exponent value of 0.6 is commonly used in pipeline networks models (Heijnen et al., 2014). The cost exponent indicates that building high-capacity pipelines have cost advantages. The network model then produces edge-weighted Steiner minimal trees[2] that consider both the capacity and the length of the pipeline.

[2] A Steiner minimal tree is a tree connecting points in a plane using lines of shortest possible total length.

In addition to cost, expected revenue over the planning period should also be modelled. For this purpose, the expected revenue is modelled as a linear function of flow rate. It is assumed that the network operator generates revenue by charging a connection tariff from sources. Hence, the revenue R_t of a network N in year t is given as,

$$R_t(N) = \alpha \sum_{i \epsilon V(N) \backslash \{s\}} q_i \tag{5.3}$$

where q_i is the used capacity by CO_2 supplier i in a network N, $V(N)$ is the set of all nodes in the network N, s is the sink and α is the constant coefficient representing the tariff.

Searching for the worth maximizing network involves simulation of the network model with different CO_2 supply scenarios. The simulation will result in multiple design possibilities. The advantage of the network model is that it is simple low-fidelity and therefore can be run much faster than detailed high-fidelity models. This characteristic of the model comes in handy when one tries to search and screen for a few promising design concepts out of thousands of possibilities.

B. The contractual structure design model

The objective of the contract model is to structure the allocation of risk between the two actors given the uncertainty in capacity demand from existing and future sources. As shown in (5.3) revenue depends on uncertain CO_2 supply/capacity utilization [in units of cubic meters/year] and the constant tariff level [in euros per cubic meter]. When the profitability of the network project is weak, the public actor provides a revenue guarantee to the network operator.

We assume there is a contractual guarantee where the government is obligated to make certain payments to the concessionaire whenever the actual revenue (R_t) level falls below a pre-established floor, and that the connection fee is constant throughout the concession period.

Let P_t be the minimum revenue guaranteed by the public actor in year t. If we assume a constant connection fee (tariff), the actual revenue resembles the stochastic process of CO2 supply, q_i. Considering the guarantee, the effective revenue I_t for the network operator in year t can be given as:

$$I_t = \max(R_t, P_t) \tag{5.4}$$

Adding discounted values future incomes over the planning period gives the present value of total revenue (PVR). The connection cost or tariff is assumed to be 1 €/t CO_2. It is also assumed that the real discount rate, r, to be 8%.

$$PVR(N) = \sum_{t=0}^{20} \frac{I_t(N)}{(1+r)^t} \tag{5.5}$$

The expression (5.5) is critical in defining the contractual relationship between the network operator and the public actor. From the perspective of the network operator, the performance of a given network design over its lifetime can also be analysed based on the Net Present Value (NPV) valuation, as shown in (5.6).

$$NPV(N) = PVR(N) - C(N) \tag{5.6}$$

At the conceptual design stage, the expression in (5.6) can be used by the network operator to explore the economic performance of different network design choices.

On the other hand, the public actor is concerned with the amount of subsidy to be paid to the network operator. The value of the guarantee, $V(t)$ in year t is given as:

$$V(t) = max\,(0, P_t - R_t) \tag{5.7}$$

The total present value of payments over the concession period can be calculated by discounting $V(t)$ over the concession period. The present value of (5.7) is the value of the option in each year. The total sum of the option gives total value of guarantee payment, VG_f.

$$\mathrm{VG}_f = \sum_{t=1}^{t=T} \frac{V(t)}{(1+r)^t} \tag{5.8}$$

The expressions in (5.6) and (5.8) model the objectives of the network operator and the public actors. The network operator's objective is to maximize the NPV or PWR and the public actor is interested in minimizing the amount of VG_f. The conflict arises because the public actor main objective is to provide sufficient capacity for existing and future sources. These design objectives are affected by the way the network designed, i.e. l_e and q_e, and the way the contract is designed, i.e. P_t and α. Therefore, both actors should analyse the value effects of different design concepts in the face of capacity demand uncertainty.

The value of guarantee payment not only depends on the level of P_t but also on the design configurations. Some design configurations could cost more than others. Moreover, the way the network is designed closes or opens options for cost-effective expansion of the network over its lifespan. Therefore, the public actor has to find the combination of both physical and contractual design inputs that will help to accomplish the stated objective, i.e. reduce capacity shortage and minimize subsidy payment.

In addition to the revenue floor that protects the network operator against low capacity utilization (i.e. low revenue), the government may appropriate revenues significantly in excess of the expected value by establishing a revenue ceiling in order to prevent excessive profits. Revenue floor in combination with revenue ceiling is a commonly used arrangement in road concession contracts(Brandao and Saraiva, 2008, Tan and Yang, 2012). The joint modeling of the revenue floor and the ceiling is a case of compound options, where distinct options can be exercised over the same underlying asset (Brandao and Saraiva, 2008). The two options are mutually exclusive and can be modelled by assuming that the actual revenue level will fall in any of three distinct and mutually exclusive regions: below the floor, between the floor and the ceiling or above the ceiling. Under revenue floor and ceiling arrangement, effective revenues received by the network operator (i.e. from observed from tariff and subsidy) in each period t are given by:

$$\mathrm{R(t)} = \min\{\max\,(\mathrm{R_t}, \mathrm{P_t}), \mathrm{Q_t}\} \tag{5.9}$$

Where $Q_{\ t}$ is the level revenue ceiling

Government exposure can be limited by the use of caps/ revenue ceilings, where the outlays cease once a pre-established ceiling is reached. This upper limit only affects the total aggregate value of the options and not the value of each option individually, except for the borderline option. With caps, the value of the option in each year is still determined as shown in Eq.5.9, but the cumulative sum of all government outlays is limited to the cap. Then, under the revenue floor and ceiling arrangement, the total value of guarantee payment, VG_{fc} such as shown in Eq. 5.10.

$$\mathrm{VG}_{fc} \ = \min\left\{\mathrm{VG}_{f}\ , Cap\right\} \tag{5.10}$$

$\mathrm{VG_{fc}}$ depends on the choice of the Cap. In practice, the Cap takes into account the type and size of the investment, the maximum exposure the government wishes to have on the project, and the impact on the effectiveness of MRG (Brandao and Saraiva, 2008). Because the Cap affects only the total outlays of highest value, which are the ones that have the lowest probability of occurring, its effect on the guarantee is limited. This way, it is possible that the cost of the Cap relative to the guarantees be reasonably small relative to the benefits derived from the elimination of the uncertainty over the maximum government exposure in the project (Brandao and Saraiva, 2008).

5.5. Results and Discussion

This section presents evaluation and analysis of the performance of different combinations of physical and contractual design strategies. In section 5.5.1 the performances of the two physical design strategies are compared in a situation where the network operator invests without a risk sharing arrangement. Profit (i.e. NPV) and capacity shortage are used to compare the two physical design strategies. The network operator is mainly concerned about profit but still considers reducing capacity shortage as a secondary objective. Then, in section 5.5.2, the outcomes of two physical design strategies are compared under a risk-sharing contract arrangement. Profit, capacity shortage, and subsidy payment are evaluated at different revenue guarantee level, and their implications for the network operator and the public actor are analysed and compared.

5.5.1 Design concepts

The choice of flexible design concepts should take into account the evolution of capacity demand uncertainty and the effect on the value of the contracting partners. At the conceptual design stage, the network operator and the public actor have two degrees of freedom to integrate flexibility: the layout of the physical network, i.e. capacity and length of the network and the structure of the risk-sharing contract, i.e. the level of the floor and ceiling levels. By playing with these two degrees of freedom, the two actors can find combinations of design strategies that enhance their value under capacity demand uncertainty.

From an engineering design perspective, two network design strategies are considered. The first design strategy is to develop the network by connecting the two existing sources S2 and S3 but without taking into account the future source S1. It is normally considered as the base case design strategy by which the network operator develops the network with the only information available during the conceptual design stage. We name this design strategy as the deterministic design strategy. The expected capacity demands of S2 and S3 are the basis for the deterministic design strategy.

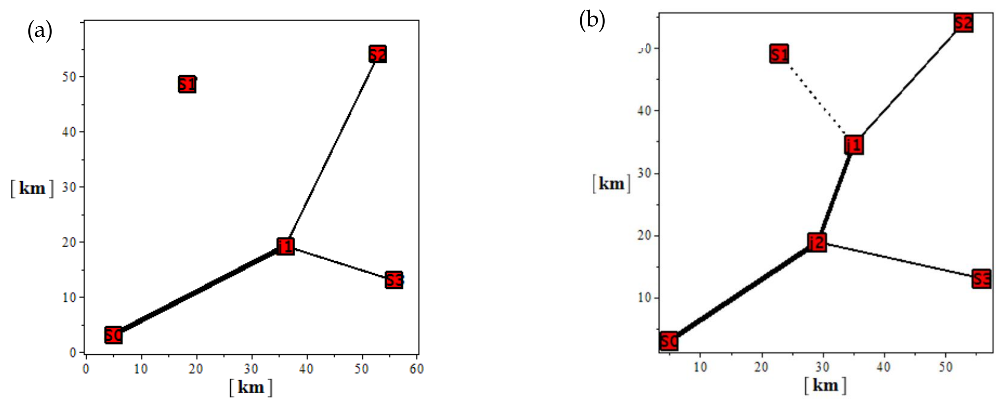

Figure 5.4 Network design concepts based on the deterministic design strategy (a), and the flexible design strategy (b)

The second design strategy is to develop the network by connecting the two existing sources S2 and S3 and taking into account the possibility that S1 will join the network sometime in the future. We call this design strategy as the flexible design strategy. Moreover, the flexible design strategy takes into account variations in the capacity demands of existing sources (i.e. S2 and S3). Fig. 5.4 shows the design concepts of the two design strategies.

In the face of capacity demand uncertainty, the network operator can satisfy her/his participation constraint (i.e. expected net present value, ENPV > 0) by carefully selecting the technical and contractual design variables. At the same time, the network operator may also be concerned that capacity shortage will not only reduce revenues but also damages reputation. Therefore, it is assumed that the network operator shares the value of public actor to minimize the capacity shortage for existing and future sources. The network operator can try to accomplish this by finding a suitable combination of the physical design inputs. To summarize, the network operator has to try to find a combination of both physical and contractual design inputs that best accomplishes the stated objectives.

One the other hand, the public actor's primary interest is ensuring the availability of sufficient capacity for current and future CO_2 emitters. The public actor can try to accomplish this objective by finding a suitable combination of the physical and contractual designs. However, the public actor faces a trade-off between providing sufficient capacity and contractual payments that must be made to the network operator. Since revenue to the network operator depends on the capacity utilization which is uncertain, if it falls below MRG, the public actor will have to pay a subsidy to the network operator to bring its revenue back to the MRG level.

5.5.2 Comparing physical design strategies without risk sharing arrangement

The performances of the two physical design strategies are evaluated for different uncertainty realizations defined in step 1. The analysis is carried out for the scenarios on which the new source (S1) joins the network in years 4, 8, and 12. The connection fee/ tariff level paid by the sources is set at 0.65 €/tonne of CO_2. Monte Carlo simulation is carried out resulting in distributions of NPVs and capacity shortage values for each design strategy. Then, NPVs are sorted and plotted as cumulative distribution function, otherwise known as value-at-risk-gain (VARG) curve (Austell et al., 2011). Fig 5.5 shows cumulative probability distribution curves of NPV and capacity shortage for both design strategies.

Fig. 5.5a shows that both physical design strategies present risk for the network operator to a varying degree. By comparison the flexible design strategy performs better than the rigid design strategy if S1 joins at year 4 or earlier. The flexible design strategy enables the network operator to capitalize from future CO_2 flow increases from existing sources S2 and S3, and the new source S1. The redundant pipe capacities in edge S0-J1 and edge J1-J2 and the proximity of the connection node J1 to source S1 enable cheaper expansion of the network. In contrary, the rigid design strategy cannot allow accommodation of S1 and potential flow increases from existing sources. Under the given problem definition, if the network developed based on rigid design strategy, S1 may have to build in individual connection directly to sink (i.e. a line from S1 to S0), which would be much more expensive than building a line from S1 to J1.

However, the performance of the flexible design strategy decreases when S1 joins later, as seen in year 8 and year 12 scenarios. Moreover, when S1 joins the network at year 8 and year 12, the flexible design strategy performs lower than the rigid design strategy. The decrease in the performance of the flexible design strategy suggests that the economic value of having oversized capacity diminishes with time. Therefore, the economic viability of designing the network with oversized capacity is contingent on the timing of the future sources joining the network. Unused capacity locks capital and imposes a great risk for the network operator. In commercial CO_2 pipeline investment, the term 'no-regret-period' is used to indicate anticipatory extra capacity investment decisions. At tariff level of 0.65 €/tonne, the 'no-regret-period' for the flexible design strategy is around 4 years. Currently, in commercial CO_2 pipeline investments a ´no-regrets-period´ is around 10 years (Austell et al., 2011).

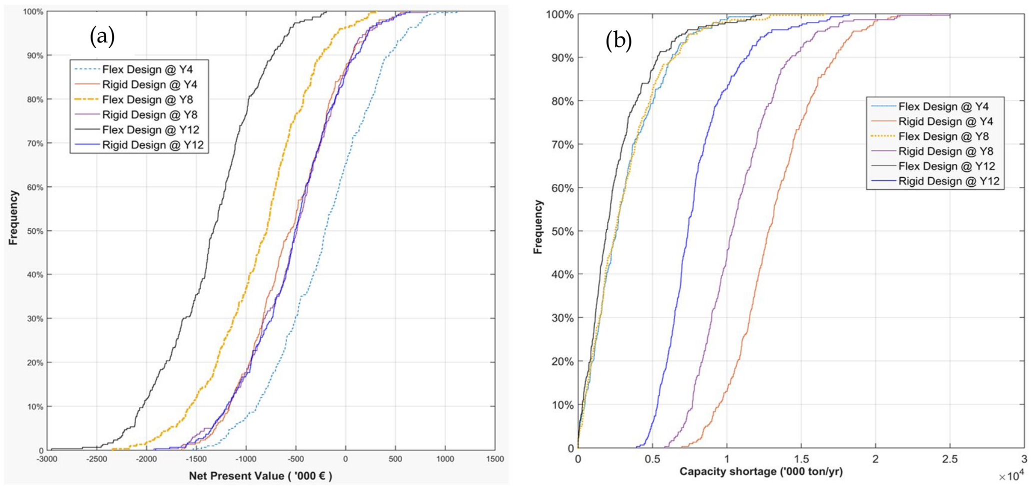

Figure 5.5 Cumulative probability distribution curve of NPVs (a) and capacity shortage (b).

Another, performance evaluation measure for the network operator is the capacity shortage. From Fig.5.5b it is clear to see that the flexible design strategy minimizes capacity shortage compared to the rigid design strategy. It shows that including oversized pipelines in critical links of the network enables cost effective accommodation of future CO_2 flow increases from existing sources and new sources. Moreover, since the flexible design strategy allows anticipatory capacity availability, it may encourage other emitters (i.e. CO_2 sources) to invest in CO_2 capture technologies. Therefore, the flexible design strategy could be interesting for potential future participants and the public actor as it allows realization of integrated CCS network. However, such a design strategy could have a negative economic incentive for the network operator as shown in Fig.5.5b.

However, from the network operator's perspective, the economic performance of the flexible design strategy can be improved by increasing tariff paid by CO_2 sources. Fig.5.6 shows the expected net present value (ENPV) of the two design strategies at different tariff level. It can be seen that when the tariff level is increased from 0.65€/tonne to 1.5€/tonne, the flexible design strategy provides better economic performance than the rigid design strategy. The improvement in ENPV also provides a valuable insight with regard to 'no-regret' anticipatory capacity investments. The `no-regrets-period´ increases from 4 years to 8 and 12 years depending on the tariff level. For example, at tariff level of 0.65 €/tonne, the flexible design strategy performs better for scenarios that S1 joins the network at year 4 or earlier. When the tariff level is increased to 1 €/tonne, the flexible design strategy performs better than the rigid design strategy for a scenario that S1 joins the network at year 8. As the tariff level is increased to 1.5 €/tonne, the no-regrets period for the flexible design strategy increases to 12 years. However, the result shown in Fig.5.6 is only based on uncertainty in future capacity demand. Other factors (e.g. discounting rate, tax) could increase the cost of investment and, therefore, reduce the no-regrets period. The no-regrets period could increase if policies that encourage CCS investment and reduce the capital cost of CCS are in place.

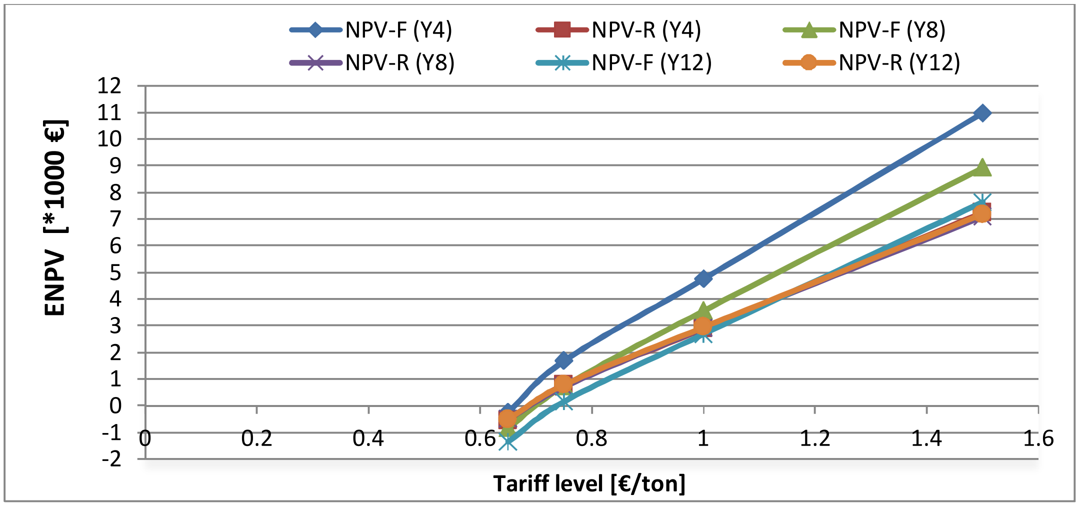

Figure 5.6 Expected net present value of the two design strategies at different tariff level.

The tariff level could also have an effect on capacity shortage. A higher tariff level means that the flexible design strategy becomes economically more viable than the rigid design strategy. In such cases, the network operator could be willing to invest in extra capacity, and that will reduce capacity shortage. However, a higher tariff level may discourage emitters from engaging in CO_2 reduction investments. In such situations, government support in the form of a risk sharing could be necessary.

5.5.3 Comparing physical design strategies with a risk sharing arrangement

Similar to the preceding section, the performances of the two physical design strategies are evaluated for different uncertainty realizations: i.e. the new source (S1) joins the network in years 4, 8, and 12. The connection fee/ tariff level is set at 0.65 €/tonne of CO_2. However, unlike the previous case, the public actor shares revenue risk in the form of minimum revenue guarantee (MRG). If revenue falls below MRG (which is set based on the expected CO_2 flow rate), the public actor will have to pay a subsidy to the network operator. We analysed how each actor is affected under such situations.

Fig. 5.7 shows the effect of MRG rate on the expected profit (ENPV) of the flexible design strategy. It indicates that the MRG rate that is required to satisfy the participation constraint of the network operator depends on the timing of the new source S1. The required MRG rate increases approximately from 9% to 43% when the participation time of S1 increase from 4 years to 12 years. One other hand, the required guarantee rate for the rigid design is between 25% and 30%. Under the rigid design strategy, the network operator enjoys surplus profit above 30% MRG rate.

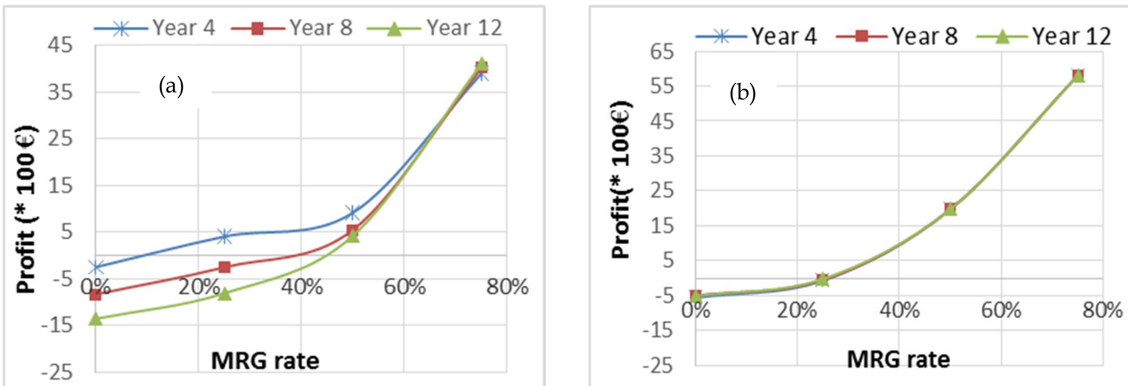

Figure 5.7 Effect of MRG rate on the expected profit (ENPV): (a) the flexible design strategy, (b) rigid design strategy

Although a higher MRG rate implies increased profit for the network operator, it has negative implications for the public actor, specifically, regarding subsidy payments. Fig. 5.8 shows the effect of different MRG rate on the expected subsidy payments for both physical design strategies. It can be seen that subsidy payment depends on the physical design strategies and the level of MRG. For both physical design strategies, there is no government guarantee payment up to 25% MRG rate, implying that the network operator's direct revenue from the tariff is higher than the guarantee level. However, above 25% MRG rate, the guarantee level exceeds the direct revenue from the tariff resulting in subsidy payments by the public actor. For the flexible design strategy, the amount of subsidy payment over the concession period depends on the timing of the new source. For example, for 50% MRG rate, the subsidy payment doubles when connection time of the S1 changes from year 4 to year 12. On the other hand, subsidy payment for the rigid design strategy does not vary with the timing of the new source because the revenue of such design strategy depends only on the flow from the existing two sources. However, for the same MRG rate, the government pays more under the rigid design strategy than the flexible design strategy. Although a higher MRG rate increases the network operator's profit, it presents a huge risk for the public actor. Therefore, if the network operator chooses the rigid design strategy, the MRG rate that would be acceptable by the public actor is expected to be lower than what it would be for the flexible design strategy.

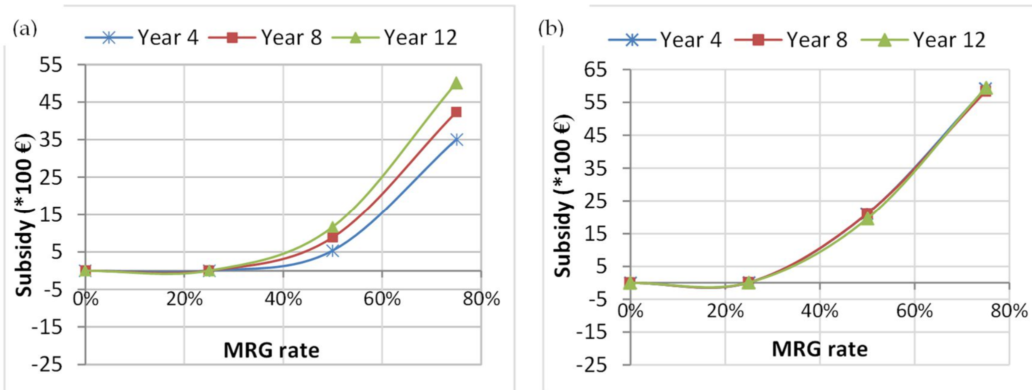

Figure 5.8 The effect of different MRG rate on the expected subsidy payments: (a) flexible design strategy, (b) rigid design strategy

As shown in Eq.5.10 the public actor can guard itself against excessive subsidy payments using revenue cap. For example, in the case of the rigid design strategy, the public actor could negotiate a fixed revenue cap level that will limit the cumulative sum of all government outlays. In such case, the real options pricing method could help the public actor to define a guarantee level that is high enough to allow economically feasible CCS deployment by network operator but low enough not to burden public funds.

So far we have seen the effect of design choices on profit and subsidy payments, but not on capacity shortage. In Fig.5.9, all the three value combinations (i.e. profit, capacity shortage, and subsidy payment) are plotted on one graph. With regard to capacity shortage, Fig.5.9 shows that up to 25% MRG rate the public actor will end up paying nearly the same subsidy under both physical design strategies. However, the flexible design strategy will provide a much higher capacity than the rigid design strategy. The capacity shortage difference between the two design strategies decreases as the timing of S1 increases from year 4 to year 12.

From Fig.5.9 is that it is impossible to recommend an optimal physical and contractual design solution that is best for both actors. For example, a flexible design strategy with 50% MRG rate risk sharing contract would reduce capacity shortage and subsidy payments, which are preferable attributes for the public actor, but results in lower expected profit for the network operator. A higher MRG rate (i.e. > 50%) will increase the expected profit but will also expose the public actor to huge subsidy payments for a small decrease in capacity shortage. A lower MRG rate (i.e. < 50%) will reduce capacity shortage and subsidy payments but will expose the network operator to a revenue risk. Therefore, finding a solution that could satisfy both actors may require value trade-offs.

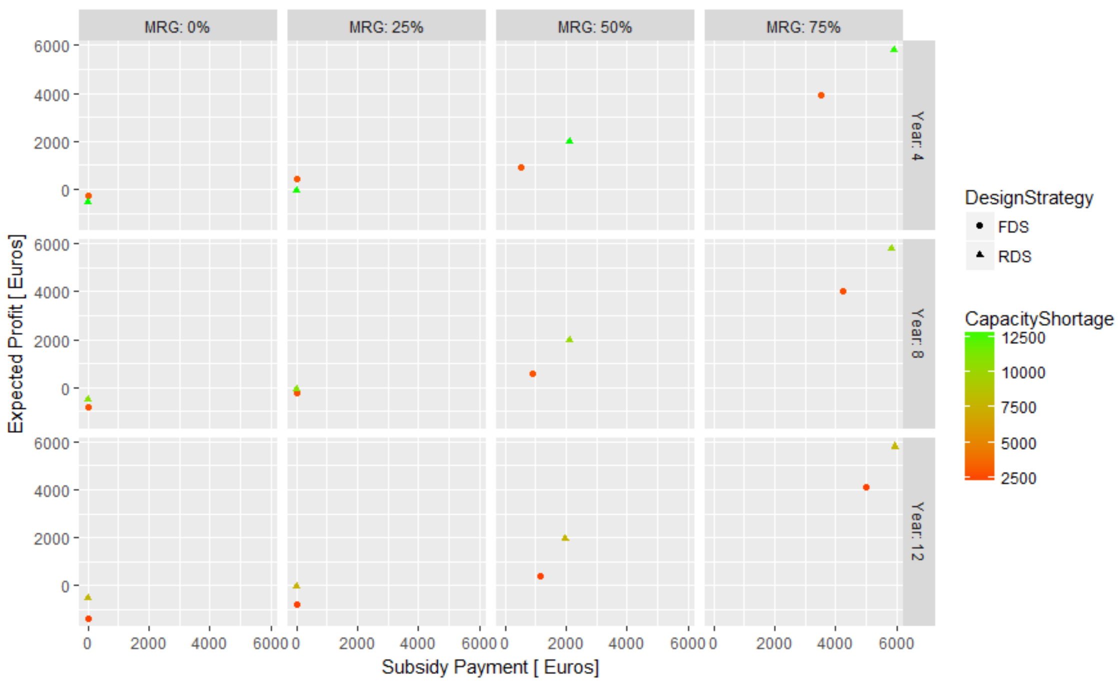

Figure 5.9 Performance measures of the two physical design strategies at different risk sharing contracts. The colour gradient scale shows capacity shortage [in unit of tonne]. FDS and RDS stand for flexible design strategy and rigid design strategy respectively.

A key take away from Fig.5.9 is that it gives an indication into the feasible solution region that could satisfy both actors. Many physical and contractual design combinations deliver intermediate as well as high outcomes, i.e. [high profit, low subsidy payments, and low capacity shortage]. Likely design choices for the actors are those who resulted in a low capacity shortage, low subsidy payment and a positive NP. For example, a risk sharing arrangement with MRG rates higher than 25% but less than 75% with a flexible physical design strategy constitute a set of design choices that could be selected by both actors. Within this set, actors have the opportunity to make value trade-offs and find synergies. Actors can negotiate to decide the ultimate design engineering and contractual choice that is in their mutual interest.

5.6. Conclusions

This chapter discusses the use of flexible design concepts for the deployment of large-scale CCS infrastructures via PPP arrangements under CO_2 supply uncertainty. A framework for a flexible design approach is presented for design and value analysis different physical and contractual design strategies. The approach employs probabilistic and simulation methods to anticipate a range of future CO_2 supply scenarios. Then, Monte Carlo simulation is employed to compare the value effects of design strategies under different CO_2 supply scenarios.

The analysis revealed some valuable insights. It is found that the choice of the physical configuration of the physical network and the contract structure affects values of the two actors differently. For example, oversizing the capacity of critical links of the network favours the public actors objective but comes at the expense of exposing the network operator to high revenue risk. However, the two actors can find design solutions that are not only able to change the risk exposure of the network operator but also enable value-creation and value-exchange with the public actor. For example, by designing the network with flexibility options, i.e. extra capacity, and length, and using option based revenue guarantee mechanism, the two actors are not only able to reduce risk but also to enhance value, in the face of uncertainty. More broadly, the framework enables the two actors to iteratively explore different design solutions in the face of CO_2 supply uncertainty and converge on a design that is acceptable to both of them.

The integrated approach allowed actors to look beyond purely technical or contractual design aspects of the project. It encourages actors to explore flexibility opportunities in both technical and contractual design spaces. By so doing, partners can avoid prematurely locking out benefits and explore technical and contractual flexibilities to shape and secure value trade-offs. However, it must be pointed out that practical deployment of CCS networks depends on other uncertainty factors in addition to CO_2 supply uncertainty. For example, the kind of incentive offered for reducing CO_2 emissions will likely influence the progressive deployment of individual CCS projects and the final layout of the CCS network. An improved cost function (including, for example, pumping cost, the thickness of the material, the terrain of the landscape, and operation and maintenance cost (Knoope et al., 2014)) for the network model would provide better insight regarding design and investment decisions. Future research should take into account these issues.

Chapter 6 Conclusions and Discussions

6.1. Conclusions

This research was focused on the improvement of design and investment decisions involving new energy and industrial infrastructure networks in the face of uncertainty by using the concept of flexibility. Emphasis was given to the concept study phase of the design process, where decisions regarding development layout and formal actor relationships need to be made while significant uncertainty remains regarding the number of participants and the capacity they require.

The research has resulted in the development of theoretical frameworks as well as systematic design analysis procedures that can aid decision-makers to examine and appreciate the value of flexibility in the face of uncertainty. The research results were obtained by answering a number of research questions, which were introduced in chapter 1, serving as a guide in the broad research area. Next, conclusions and discussions of the research findings are presented.

6.1.1 An improved conceptualization of flexibility

The first part of the research was focused on understanding the concept of flexible design and its application to the design of engineering systems in general and the design of energy and industrial infrastructure networks in particular. We conclude that the existing normative flexible engineering system design approaches have a limited conceptual framework and can not fully capture the socio-technical nature of energy and industrial infrastructure networks. It is evident from the literature study that the academic discussion about flexibility in the context of engineering design focuses on the physical elements of the infrastructure system as "the object of design." The social or institutional elements such as contractual relationships, policies are mostly treated as design contexts. The literature that considers actor perspectives to the design of flexible engineering systems is limited to a competitive investment environment by which actors interact to maximize their individual payoff considering the best actions taken by other actors. That means, there is a gap in the scientific discussion regarding flexibility when actors co-development infrastructure networks under uncertainty. To address this conceptual gap a new flexibility conceptualization framework which guides flexibility consideration both in the technical and contractual designs of energy and industrial infrastructure networks is introduced, see (Melese et al., 2017c) for more detail. In general, the proposed conceptual framework encourages flexibility analysis as the main design procedure in both the technical and contractual designs to enhance desired performances by cooperating actors.

6.1.2 Flexibility to improve the lifetime performance of infrastructure networks

The second part of the research was focused on flexibility in engineering design of energy and industrial infrastructure networks with the objective of improving their lifetime performance in the face of uncertain design requirements. We explored the question of how one can improve the lifetime performance of energy and industrial infrastructure networks using flexible design strategies. The conceptual design of flexible energy and industrail infrastructure networks was framed and studied into two main parts.

The first part involves identifying the real options which are the sources of flexbility. The root issue in creating a flexible design is to determine which part of the network should be flexible, and which parts should be configured to provide the real options that will give the network managers the "right, but not the obligation" to change the size or function of a network. In Melese et al. (2015), we explored the question of how one can systematically identify value-enhancing real options (flexibility enablers) that can pro-actively deal with capacity demand and participant uncertainties during conceptual design of infrastructure networks. We proposed an approach based on the concept of real options, graph theory, and Monte Carlo simulation that reckon with future uncertainties. The real options concept guides the design strategy, e.g. options for future expansion and options to wait. The graph theory concept captures the spatial aspects of the physical infrastructure networks. The Monte Carlo simulation technique considers capacity demand uncertainty. By combining these concepts, the proposed approach assesses initial network design layouts and provides insights into potential real options that can enable cost-effective expansion and mitigate the effects of lock-in.

The study demonstrated the approach in the context of a case analysis for the design of a stylized pipeline based CO_2 transportation network. The approach was effective in identifying design elements (e.g. extra most capacity and layout) likely to provide worthwhile flexibilities to mitigate path-dependencies and physical lock-in. Economic analysis has shown that built-in flexibility capabilities (i.e. real options), such as extra pipe capacities and length, provide easy and cost-effective network expansion options compared to the deterministic design strategy. Moreover, the approach has been shown to be effective as it provides easy and fast generation and assessment of various network design architectures under different uncertain scenarios, an important advantage particularly at the exploratory stage of the design process.

The second part involved defining flexible strategies and the conditions that govern when flexibilities are exercised. For this purpose, (Melese et al., 2017d) we explored the question of how one can improve the lifetime performance of energy and industrial infrastructure networks using flexible design strategies. We developed an approach which consists of three major steps: exploratory uncertainty analysis, design flexibility analysis, and sensitivity analysis. The approach allows network designers to systematically identify promising initial designs, identify potential flexibility enablers and strategies for implementing flexibility according to the future evolution of uncertain design requirements. The study demonstrated the approach on a stylized generic gas pipeline network. The demonstration showed that flexible strategies such as having redundant pipe capacity in anticipation of future flow increases can lead to significant increase in value compared to the conventional design strategy which is optimized based on deterministic assumptions. Cumulative probability distribution NPVs has shown that the value improvement comes from a combination of factors: a reduction in the maximum possible loss, an increase in the expected value and an increase in the maximum possible gain.

6.1.3 Risk sharing and flexibility to manage uncertainty in contract designs

Developing a new energy and industrial infrastructure networks involves multiple actors of both commercial and public nature. This means, in addition to the physical design challenges discussed in chapter 3, actors also face uncertainty regarding how risks and benefits are allocated among them and the how the new shared project affect their pre-existing business. These issues are often the cause of indecision and deadlock as actors become risk averse and are afraid to 'bet on the wrong horse' – wrong investment and wrong relationship. In chapter 5 of this thesis, we looked at the question of how risk sharing can serve as flexibility option when actors co-invest in energy and industrial infrastructure networks under uncertain environment.

We proposed a modeling framework that conceptualizes contractual arrangements between actors as a cooperative game and uses the real options concept to study effects of embedding flexibility on the value of contracting parties. The models and numerical analyses provide valuable managerial insights. A numerical analysis was used demonstrated the proposed modeling framework through the analysis of a case study concerning the development of a stylized merchant electric power interconnector between two countries. Based on the modeling framework and numerical analyses we made the following conclusions.

First, actors with divergent risk profile can gain more synergies from risk sharing in uncertain investment environments. This conclusion agrees with earlier works of (Savva and Scholtes, 2005, Ligtvoet, 2013) and implies that cooperating with a partner with a different risk profile can be very beneficial. The model showed that risk-sharing increases the synergy set (i.e. the core of the cooperative game). This could encourage uncertain actors to engage into cooperation to develop vital infrastructures.

Secondly, actors can structure better risk-sharing contracts when compared to conventional approaches. Conventionally, the risk preference of cooperating actors described with their respective risk aversion is used to allocate risk. In this study, we found that the optimal share depends also on the future projection (i.e. volatility) of the new joint project and the actor's pre-existing businesses. Furthermore, the optimal risk share depends on the correlations between the actors' pre-existing businesses and the new joint project. These are new additional insights derived from the model and can help actors in understanding the economic implications of long lasting contractual agreements and build enduring partnerships.

Last, the model can help actors to select the most suitable partner for a co-investment project. As said before, different actors have a different risk preference and background (i.e., pre-existing business). Actors can carry out an exploratory assessment of the value risk sharing with the different prospective partners at the conceptual stage of co-investment projects.

6.1.4 An integrated approach

In the preceding sections, the value effects of considering flexibility during engineering and contractual designs have been discussed in isolation. However, when actors co-develop (e.g. in the form of a joint venture or a public-private partnership) energy and industrial infrastructure networks the desired outcome for individual actors depends not only on how the physical infrastructure is deployed but also on how the contract that defines the allocation of risk and benefit is structured (Sakhrani, 2015). Therefore, as concluded in section 6.1.1, an integrated approach that considers flexible strategies both in the physical and contractual designs could give a better appreciation of the value of flexibility in the face of uncertainty. In chapter 5 of this thesis, we explored the question of how partnering actors, with different and conflicting objectives, can enhance desired performances when they develop new energy and industrial infrastructure networks under uncertainty. We proposed a systematic design analysis approach which allows consideration of value-enhancing flexibility options in technical and contract designs during the conceptual design stage. The proposed approach employs probabilistic and simulation methods to anticipate a range of future circumstances and then enable contracting parties to identify technical and contractual design strategies that provide enhanced desired performance.

The study demonstrated the proposed approach through specific design context of a public-private partnership to develop a CO_2 transportation pipeline network. Application of the approach has shown that the choice of the physical configuration of the CO_2 pipeline network depends on the risk sharing contract between the two actors. This is because the contracting parties have conflicting objectives and trade-offs are necessary. For instance, designing flexibility in the pipeline layout (such as oversizing backbone pipelines) to accommodate future participants (i.e. CO_2 emitters) favors the public actor's objective (i.e. enabling sufficient capacity for future sources) but comes at the expense of exposing the network operator to high investment risk. As a result, risk exchange and value trade-offs are necessary. The application has also shown that partners can find design solutions that enable a reduction in risk exposure for the private actor as well as enable value-creation for the public actor. For example, by designing the network with flexibility options, i.e. extra capacity, and length, and using option based revenue guarantee mechanism, the private actor can be able to reduce investment risk and at the same time keep the objective of the public actor.

More broadly, the integrated approach allowed actors to look beyond purely technical design or purely contractual design aspects of the project. It encourages actors to explore flexibility opportunities in both technical and contractual design spaces. Partners can avoid prematurely locking out benefits and explore technical and contractual flexibilities to shape and secure value trade-offs. By so doing they can preserve system-level objectives such as reliability, a shared interest among private and public actors.

6.2. Reflections and limitations

In this thesis, there is a reliance on illustrative cases to validate proposed frameworks and methods. The cases provide the contextual information without which the design theories and proposed methodologies remain abstract and desolate. Yet, the scale and size of these examples are stylized and do not fully capture the highly complex nature of most energy and industrial infrastructure networks. Moreover, the modeling of the physical infrastructure is abstracted from reality to reach a computationally feasible exploratory study. Similarly, simplifications have been made for risk sharing contract models. While these simplifications provide valuable theoretical insights, they neverthless come at a cost to a full practical applicability. Therefore, legitimate arguments can be raised regarding the applicability of the models and the representativeness of illustrative cases. In this section, we reflect on these issues. We also reflect on the practical applicability of the flexible design approach.

6.2.1 Uncertainty Modelling and Simulation

One of the key components of the design analysis approaches and methodologies presented in this thesis is modeling and simulation of uncertain design variables. With simulation models that capture uncertainty, decision makers and designers can simulate how strategies perform under a variety of circumstances. However, modeling and simulation of the full characteristics of design uncertainties have become a very challenging task. This is particularly true during the conceptual design stage of the design process as information regarding data and parameters are not easy to come by.

In this thesis, we have tried to address this challenge in two ways. Firstly, analytical approaches were used to mitigate the lack of extensive historical data by making initial assumptions on uncertain variables (i.e., type of distribution and the speed of convergence) and then Monte Carlo simulation technique were employed to run multiple trials and define all potential future behaviors of uncertain variables. Using a range of possible values, instead of a single guess, helps to create a more realistic picture of what might the future evolution of uncertain design variables looks like. Secondly, sensitivity analysis technique was employed to examine the effect of assumptions on the outcomes designs.

6.2.2 Graph theory network model

Graph theory was used primarily to model the technical dimension of energy and industrial infrastructure networks. The graph theory model is effective in capturing the network characteristics of these infrastructures. It is especially very useful during the exploratory stage of the design process, as it allows for the fast assessment of low-regret network design options and the quick re-assessment of these options, should new information (e.g. participant or additional capacity) arrive that either narrows down or expands these options. The model combines simplicity of assumptions with relative ease of use, thus attempting to minimize the `black box' approach that quantitative modelers are often accused. Also, the simplicity is an important asset of the model regarding computational requirements.

However, simplicity comes with some degree of effect to full practical applicability. For instance, the key important component of the graph theoretical network model used for CO_2 pipeline network was the generic cost function which was expressed as a function of length and capacity. In practice, the total cost of a CO_2 pipeline project also depends on other factors such as pumping cost, type of the pipeline material, the thickness of the material, the terrain of the landscape, and operation and maintenance cost (Knoope et al., 2014). Moreover, the total cost could depend on environmental and safety regulation and land use regulation. All these factors would likely influence the progressive deployment of individual CO_2 pipeline projects and the ultimately final layout of the CCS network.

6.2.3 Game theory based risk sharing model

In chapter 4, cooperative game theory concept was used to model the relationship between actors during conceptual design of energy and industrial infrastructure networks. Cooperative game theory is effective in modeling payoff allocation between two or more risk-averse actors who cooperate to maximize their joint expected utility under uncertainty. At the center of the model is the expected utility theory that defines the payoff preferences of the two risk-averse actors (Davis et al., 1998). Therefore, the game theory model assumes rational actors. However, studies in experimental economics and psychology indicate that actors are not always rational in their decisions. Furthermore, both individual (e.g. gender), interpersonal relationships (e.g. communication, negotiation), as well as cultural traits all play a role in decision making. These factors, among others, minimize the rational assumptions which are the basis of the game theory model. Moreover, the allocation of risk and benefit is not only the only factor in the decision making of actors. Historical relationship, law, and regulations, networks and alliances, goals and aspirations may also play a factor in the contractual decision making. Therefore, the final agreement between the actors regarding the allocation of risk and benefit could differ from the optimal values derived using the game theory model. Nevertheless, actors can use the optimal allocation as a benchmark when they negotiate contractual deals.

6.2.4 On challenges to adopting a flexible design approach

Throughout this thesis, it has been advocated and shown that flexibility can enhance the expected lifecycle performance of infrastructure networks and improve value for investing actors by reducing exposure to downside risks and enabling the capability to capture upside opportunities. However, some issues remain regarding the practical applicability of the flexible design approach in the infrastructure sector. There can be many reasons for the slow adoption of flexible design approach and low efficacy of flexibility.

One reason raised by practitioners and acknowledged by researchers is the complexity of real options valuation techniques which creates distance to actual project management practices. Lately, real options valuation methods are getting more sophisticated to enhance their applicability to the infrastructure planning and design. Yet, real options analyses have a long way to achieving the level of acceptance NPV analysis has made in infrastructure planning and design. The challenge seems notably greater in public and semi-public infrastructure sector than in the private sector (Herder et al., 2011). Many attribute the slow adoption of real options based engineering design to the mismatch between option analysis and standard project management practice where uncertainty and flexibility are minimized into manageable levels, considered acceptable or bearable by the project owner. Cardin et al. (2016)and Wang and de Neufville (2006) acknowledged that either the modeling assumptions are violated during real applications or that the method requires assumptions that limit the scope of applicability.

Recent efforts have focused on developing practical approaches for assessing the value of flexibility in an engineering setting, to help designers and decision makers implement it and manage it in operations. Cardin et al. (2016) presented an approach that emulates the decision-making process directly and parameterizing the characteristics as well as the physical design variables so that they can be analyzed thoroughly using optimization techniques. In this regard, proposed approaches should go beyond defining a solution by giving greater attention to creating a logical and an intuitive understanding of the design situation and to providing convincing arguments to justify the use of flexible designs as possible improvements over conventional fixed designs based on generally unrealistic requirements.

6.2.5 Capturing the full value of flexibility in engineering design

Designing flexibility into energy and industrial infrastructure networks is the beginning, not the end goal. Designers or decision makers should nurture conditions that will enable future implement ability of the flexibility capability (real options) during the operation phase. Maintaining the capability to operationalize flexibility is more than an engineering/technical issue; it is also a social process. The physical capability to makes use of the flexibility designed in a network is unlikely to vanish. For example, extra pipe capacity built in a CCS pipeline network to allow accommodation of future flow increases will continue to be available for a very long time. Instead, a wide range of non-technical factors such as regulatory changes, market dynamics, and political developments may present owners of the network from using this capacity. These non-technical factors are also the dominant reasons for changes in actors relationships. For instance, new safety regulation may prohibit the installment of new pipeline. New market dynamics may force partners to break up existing alliances in pursuit of new relationships. Financing agencies might not be willing to finance the CCS project due to new developing risk factors. New environmental regulations may create political pressure to close CO_2 emission sources. Therefore, at the conceptual design stage designers and decision makers should extend their thinking beyond the pure engineering aspects of the project.

6.3. Recommendations

6.3.1 For future research work

Based on the main findings of this research and the limitations of the elements of the design analysis approaches discussed in the previous section, recommendations for future research are formulated. The recommendations focus on issues the engineering design of infrastructure networks, the design of contractual arrangements, and integrated design of technical and contractual elements of utility new infrastructure networks, all in the context of uncertainty.

A On flexible design of infrastructure networks

The proposed design analysis procedures for identifying and integrating flexibility during conceptual design of energy and industrial infrastructure networks are parts of an ongoing research stream in the flexible design of engineering systems. There are many opportunities for improvement to further advance this stream of research in the future.

Uncertainty Modeling: stochastic design uncertainty models were used in this research, but the parameter estimates are not based on historical data. One future research topic is to develop more realistic uncertainty models using historical data. For example, CO2 supply uncertainty could be modeled better using a stochastic stepwise function instead of a stochastic random walk process (e.g. GBM). CO_2 supply from an emitter could stepwise increase every time new additional capture units are installed which could take years. Ideally, the uncertainty and learning models need to be calibrated against historical data if available. One possible approach improves uncertainty models developed based on estimates is to apply Bayesian learning approach to update model parameters as actual data becomes available.

Moreover, this study has limited the uncertainty parameters under consideration to flow and participant timing. It is recommended that further research is undertaken to extend the developed models to other uncertain parameters such as regulatory changes (e.g. price of CO_2 emission, tariff changes), economic factors (e.g. interest rate volatility) and technological changes.

<u>Multi-criteria performance evaluation:</u> In this thesis, decision rules are based largely based on economic criteria (e.g. ENPV, capital expenditure). While economics is the dominant criteria, it is not the only for making design decisions of energy and industrail infrastructure networks. Other performance requirements metrics such as reliability, availability and saftey could be considered to the lifetime performance evaluation of flexible design solutions (Ajah, 2009). This is especially the case in public and semi-public infrastructures. For example, Sizhe (2016) evaluated flexibility in emergency services in terms of their expected time responsiveness to incidents over their lifecycle. Future work in this regard could take into account non-financial metrics in their evaluation of flexible design solutions. Flexible design solutions can be evaluated using different performance metrics, and the design solution that dominates across all the criteria could be the preferred solution.

<u>Existing infrastructure networks:</u> The focus of this study has been on flexibility design on new energy and industrial infrastructure networks. However, it is recognized that it is important to consider existing networks and to develop methods for them to transition to a more flexible state. This will include identifying optimal transitional pathways that allow a staged transition from a highly centralized inflexible system to a more decentralized flexible one. The changes happening to the electricity distribution network due to the increasing share of distributed power generations and the flexibility demand of consumers is a timely relevant case for research in this regard.

B Collaborative design as a multi-actor design analysis approach

In a multi-actor setting, the design of energy and industrial networks consists of simultaneously making technical as well as contractual choices. Mostly, cooperating actors have different and mostly conflicting objectives and depending on the choices of technical and contractual design, the values and objectives of the partners will be affected differently (Sakhrani, 2015). For example, in infrastructure public-private partnerships, private agents are mostly concerned with the financial feasibility of the investment as they are especially sensitive to revenue risk. The public agent is also concerned with cost but at the same time want to maintain high reliability of the service provided by the infrastructure. Often, these objectives conflict each other and trade-offs have to be made.

In chapter 5, we proposed a theoretical framework and an analytical method that simultaneously considers engineering and contractual design perspectives to find flexible design solutions in a multi-actor setting. The proposed framework and design analysis approach invite further work. One area of further work in this regard is embedding the concept of flexible design within a collaborative design framework. Collaborative design or commonly called co-design is a process in which project actors simultaneously design technical and contractual features of an infrastructure project. Instead of objective assumptions of the risk preferences of actors, co-design enables understanding and incorporation of subjective values of actors (Sakhrani, 2015). For example, in public-private partnership setting, the private agent can be given greater autonomy to develop an infrastructure project with flexibility without compromising the public actor's objective(s) and the added benefit from flexibility can be shared with the public actor (Cruz and Marques, 2013a). This kind arrangement can be achieved if actors can create a process which allows them to exchange values and in this regard co-design has been shown to be a promising approach (Sakhrani, 2015, Cruz and Marques, 2013a).

6.3.2 Implications for practice

As Keeney (1994) wrote, we do research to lend *some insight* into a complex situation to *complement* intuitive thinking of decision making. In this regard, the primary and perhaps straight forward recommendation is that network designers should build in flexibility into their designs and decision makers should reason through different options before committing to a design strategy. This requires changes in the way they deal with uncertainty and risk – i.e. change from merely a risk minimization perspective which focuses on the downside of events (e.g. a robust design strategy) to a flexible design strategy that enable minimization of loss on downside of events and gain from upside of events.

A second important recommendation is to public actors (e.g. ministry of infrastructure) who promote and invest the development of infrastructures. These actors should be conscious about uncertainty and take pro-active measures to identify and design value-enhancing flexibility options in the way they deploy physical infrastructure. Public actors commonly partner with private actors for development and provision of infrastructure services, for instance in the form of public-private partnerships. In such cases, public actors should explore flexibility options both in the technical design of the infrastructure and in how they structure contractual agreements. By identifying and simulating the several types of flexibility, it is possible to find a contractual structure that will maximise value for money. For this purpose, both public and private actors should communicate early and often in the design process while there is still scope for exploration and learn about the implications of design alternatives.

Partnership contracts structured through open and transparent relationship allow a much better identification of flexibility opportunities and a successful implementation of the project.

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Published Papers

Publication I

A Socio-Technical Perspective to Flexible Design of Energy Infrastructure Systems

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***Abstract*—Systems engineering is the dominant approach for designing flexibility in infrastructure systems. However, the approach merely focuses on physical elements of the system as 'objects of design', whereas hardly any attention is given to the institutional structures (e.g. contracts) required to realize the system. In this paper, the conceptual gaps of systems engineering approach when it comes to infrastructure systems design is discussed. As a way to address these conceptual gaps a theoretical framework that integrates the technical/engineering perspective and the actor/institutional perspective is proposed. The framework promotes design procedures for integrating flexibility, not only in the technical elements of the system but also in the institutional structures.**

***Keywords*— Infrastructure systems; flexibility; systems engineering; engineering systems.**

I. Introduction

Energy infrastructures form the backbone of our energy system as they are essential to supply utilities. Examples include natural gas transmission lines, electricity transmission and distribution networks, and district heating networks. These infrastructures are characterized by enormous investment costs, critical societal dependence. Moreover, along their value chain, they involve multiple actors in their design, ownership, operation, and maintenance. They are socio-technical systems that include not only the physical network, but also the governance, management, and control systems that are needed to make the system meet its functional specifications and it social objectives [1] [2].

One implication of this is that the (re)design of energy infrastructure involves both technical/physical components (e.g., cables, pipelines) and institutional arrangements (e.g., contracts, markets) to coordinate the behavior of the parties that develop and operate them [3]. For example, the design of a district heating network entails both engineering decisions (e.g., the dimensions of the pipes, the number of pipelines, the number and size of pumping stations, the form of the heat carrier) and institutional arrangements between the parties involved (e.g., contracts between waste heat suppliers and network operators or between the public sector and private network operators) [4].

A common feature of energy infrastructure projects is that they all involve multi-domain uncertainties about the design requirements and future operating environment. On the one hand, design requirements change over time due to changes in demand, market prices, technical specifications, and so on. [5]. On the other hand, the technical, economic, political, and institutional environment in which the infrastructure operates is becoming increasingly dynamic [6]. The presence of these uncertainties means that designers and decision makers need to find design solutions that enable these infrastructures to adapt to wide range of future conditions.

Flexibility is a concept that captures the dynamics in uncertainty and the corresponding strategic design and management response to it [7] [8] [9]. In systems engineering field, flexible design describes a design concept that provides an engineering system with the ability to adapt, change and be re-configured, if needed, in light of uncertainty realizations [9] [10]. Flexibility can add significant value to systems as it allows proactive reaction to uncertainties [8] [11]. The concept of flexibility in engineering design have been applied to a range of infrastructures: buildings [9], oil fields [12], power grids [13], water infrastructure [14]. Typical questions of interest are: *how to integrate flexibility in infrastructure systems? How to value flexibility?*

However, the systems engineering perspective to the design of flexibility in infrastructure systems is limited in a sense that it merely focuses on the physical system as 'the object of design' [7], [8]. Often, infrastructure systems are treated as special kinds of engineering systems where efforts have to be made to design them to better accommodate changes and uncertainty [9]. On the other hand, as briefly mentioned before, infrastructure systems are systems that consist of physical elements and social/organizational elements [15] [16]. Therefore, (re)designing of these systems refer not only to the physical infrastructure but also to institutions that coordinate the behavior of the involved multiple actors [3]. In other words, 'the objects of design' is not limited to the physical elements of the system, but includes institutional elements as well. Institutions or institutional elements are thus a set of rules that regulate the interaction between social actors involved in the functioning of a (technological) system [3]. They include contracts, markets, incentives, policies, and norms [17]. Therefore, similar to the technological elements of the systems, flexibility have to be integrated into the institutional[1] structures coordinate the interests of the actors/ organizations. The dual nature (physical and institutional structure) of infrastructure systems means that flexibility needs be designed both in the physical and the institutional architecture. In that respect, the perspective of systems engineering, i.e. the problem formations, design and analysis methods, is limited and has to be extended to include the institutional elements of the system.

II. ENERGY INFRASTRUCTURES AS SOCIO-TECHNICAL SYSTEMS

Increasingly researchers are arguing that infrastructure systems should be treated as socio-technical systems, i.e. systems that have both technical and social/organizational characteristics that are tightly interconnected. The interplay between the social and the technical elements, rather than the individual elements determine the system performance. Technological elements of infrastructure systems, hereafter called- technical subsystem, consists of the functional artifacts, such as machines, factories, pipelines, and wires. The social elements of the infrastructure system, hereafter called- social subsystem consists of social components, such as organizations and institutions that shape and use the technical components and at the same time are shaped by them [18].

At an abstract level, both the physical subsystem and the social subsystem can be conceptualized as networks. The physical subsystem can be described as networks of links and nodes housing a certain amount of flow that moves through the links and is processed in the nodes. It includes facilities for energy production, transmission, distribution, and consumption. Links facilitate the flow of commodities (e.g. electricity, gas, waste heat) and include natural and gas pipelines and power cables.

On the other hand, the social subsystem can be described as a network of interdependent actors (i.e. individuals, firms, organizations, institutions) that design, operate and use the system [19]. Actors use institutional arrangements to safeguard their values and achieve their objectives [17]. Institutional arrangements serve as links and define the relationship between actors [3] [17]. They can be viewed as links that coordinate the behavior of interdependent actors for the proper function of the system. One major form of institutional arrangements is a contract. Contracts are used as a legal framework to enable development and operation of energy infrastructures (e.g. public-private partnerships). They serve as mechanisms to align the interests of actors that often have different objectives [17].

Fig 1 formalizes the different domains common to describe energy infrastructures, if not to all infrastructures. The domains include the following [2]:

- *Technical/ physical network*, nonhuman components of the system to include hardware, infrastructure, software, and information.
- *Social/actor network*, the social network consisting of the human components and the relationships that hold among them.
- *Environment*, the exogenous components that affect or are affected by the system.
- *Functional*, including the goals and purposes of the infrastructure system.
- *Influence*, the actions, both intentional and non-intentional, to shape the state of the system.

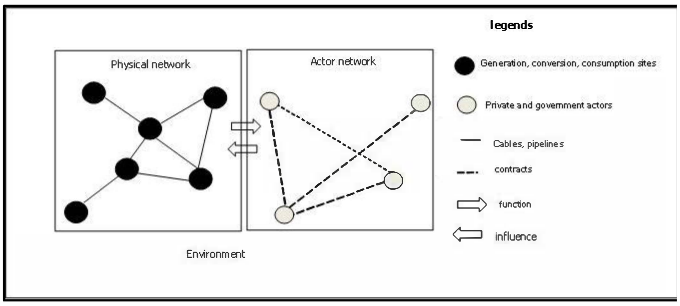

Fig. 1. Representation of energy infrastructures as networks of physical artifacts and networks of actors.

The main difference is that the components of the physical subsystem are technical or physical artifacts governed by rules of nature and created by man, while those of the social system are reflective actors who interact, learn and display strategic behavior [20]. Nonetheless, the complex interaction of the two subsystems between each other and with the environment determines the overall behavior of the system.

III. DESIGNING ENERGY INFRASTRUCTURE SYSTEMS

A. A Technical and Actor Perspective

In the preceding sections, it is established that energy infrastructures have both technical and social characteristics that are tightly bounded and interconnected, and both subsystems can be conceptualized as networks. Therefore, the task of developing energy infrastructures constitute not only designing the technical subsystem but also presumes the design of institutions that coordinate the behavior of the actors involved [3], [21].

Systems engineering is the dominant guiding principle for designing infrastructure systems. Blanchard & Fabrycky [22] defined systems engineering as *" a technologically based interdisciplinary process for bringing systems, products, and structures (technical entities) into being*". According to the 2015 systems engineering proceeding, systems engineering is defined as *" a concept that integrates many of the traditional engineering disciplines to solve large complex functioning engineering systems, dependent on components from all the disciplines*" [23]. Two major observations can be made from the above definitions: (1) there is an 'object of design' that has to be engineered, (2) there is a design approach (engineering process) that has to be executed.

As seen from the above definitions, the social/institutional dimension are considered as design contexts which designers

[1] Some institutions, such as contracts, have to be (re)designed every time an infrastructure systems is (re)designed, while others, such as policy, take longer time period to re(designed). For more refer [3] and [21].

have to consider as requirements and/or constraints. Indeed, some institutions such as norms and values, laws, standards may not be designed on a frequent basis and have to be considered as design inputs. On the other hand, some institutions such as contracts have to be designed every time new infrastructure is developed. Without such institutions being in place, it would be impossible for the infrastructure to be deployed and function properly [24].

Therefore, analyzing and designing infrastructure systems requires using engineering perspective and actors perspective alongside each other. The engineering perspective focuses on the technical subsystem as 'the object of design' and employs largely technical–rational design approaches. The underlying disciplines (mainly engineering disciplines: systems engineering and operations research) apply a phased and structured approach to problem-solving [25]. It involves problem analysis, conceptual design, basic design, detail design, and implementation [22]. Such an approach assumes that problems can be identified and that the information required to model and understand the system is available.

On the other hand, the actor perspective focuses on the design of process so that actors who have a stake in the designed system can address their issues [15]. An important characteristic of the actors within networks is that they are reflective and will display strategic behavior. The existence of many dependencies among actors (each with her/his objective) means, they are obliged to interact and negotiate with each other. To do that actors design new institutional arrangements (e.g. contracts, prices, code of conduct) and/or make use of existing institutions (such as law, regulations, norms and standards). like the design of technical subsystem in the engineering design tradition, process design is based on a solid set of design principles by which the actors core values are protected and there exist open interaction among actors [20] [26].

Table I shows the socio-technical perspective of designing infrastructure systems, adapted from [26] . The socio-technical perspective involves systems engineering approach and process design approach.

TABLE I

A SOCIO-TECHNICAL VIEW OF THE INFRASTRUCTURE SYSTEMS DESIGN

Object of design	Systems engineering	Actors /organizational science
Technical sub-system	Substantive and optimal design of desired system	Rules of the game for designing systems
Social sub-system	Modeling actor behavior	Process design

IV. FLEXIBILITY IN ENERGY INFRASTRUCTURE SYSTEMS DESIGN

Changes in design requirements and operating environment of energy infrastructures represent uncertainty for systems designers and decision makers and come from multiple dimensions: technology, market, economy, regulation, strategic behavior, etc. [27]. Flexibility is a design concept that captures the adaptability of a designed solution in response to uncertainty [11] [8] [28]. It is an attribute of the system, similar to reliability, robustness, availability, and maintainability [29]. The concept has become increasingly important as the emphasis has shifted from rigid designs that are optimized for a narrow set of requirements, towards designs that can better accommodate change and uncertainty. This has been demonstrated in the adoption of the design concept in many fields: manufacturing sector [30], [31], infrastructure sector [8], [9] service sector [32].

However, in many of these fields, the notion of flexibility is ubiquitous. See [33] for reviews of the various concepts of flexibility in different disciplines. Nonetheless, two major features are common to definitions of flexibility in engineering systems. The first is that a design solution (i.e., "object of design") of some sort exists into which flexibility needs to be integrated. The second addresses the level (e.g., strategic, operational, tactical) at which flexibility can be incorporated into the design solution. These features are particularly significant in the context of infrastructure systems, where the design solution requires both technical and institutional elements to be considered, and in which there is a considerable degree of freedom to build in flexibility at the strategic, operational, and tactical levels.

A systems engineering approach for the flexible design of infrastructure systems was presented [9]. The authors presented a process for designing and valuing flexibility for development of infrastructure systems and demonstrated it on a multi-level parking garage built beside the Bluewater commercial center near London in the United Kingdom. Two different types of flexibilities are identified. The first type considers the infrastructure as a "black box" over which some flexibility options (exogenous) might be exercised, e.g., abandon, switch, defer, and time to build [34]. It is basically a managerial flexibility such as abandoning, switching and waiting [35], [13].The second type refers to those flexibilities embedded into the engineering design. It generally involves physical designs such as considering that the system might change and adapt to cope with changes in requirement and the environment [34], e.g. extra column strength.

In both papers, the object of design is clearly the technical/physical infrastructure – the parking garage. Moreover, managerial flexibilities are centralized by which all decisions are from the perspective of a single decision maker (system designer or manager). In other words the management dimension of addressing flexibility purely from a single actor perspective. Even if there are multiple actors, it is assumed that their interests are aggregated into one view, reflected by the manager.

From the actor perspective, contracts are used as an institutional instrument to enable the development of infrastructures. However, these contracts involve large capital investments and long-time commitment in the face of huge uncertainties. As a result, involvement in most energy infrastructure contracts entails significant risk for actors [36], [37]. Risks arise from uncertainty related to the macroeconomic scenarios, technological changes, competition or the emergence of substitute services, regulatory changes, strategic behavior of parties in the contract, and other drivers of uncertainty [38], [39]. The implication of those risks is significant when parties engaged in a contractual relationship with different risk attitude. Therefore, in addition to designing flexibility in the technical structure of infrastructures, actors need to integrate flexibility with the institutional structures that that serve as links between themselves.

[11] attempted to address the concept of contractual flexibility and possibilities for incorporating them in public-private partnership (PPP) contracts. The authors identified two major types of flexibilities that could be considered in PPP contracts: unilateral flexibilities and mutual flexibilities. Unilateral flexibilities are flexibilities exercised by individual partners in order to enhance her/his value within the contract. However, the presented method focuses on the contractual aspects of the system and does not provide a systematic framework for flexibility integration.

V. Proposed Conceptual Framework

While there are individual approaches to integrating flexibility into the physical and institutional structures, an integrated approach is still missing. In this section, a generic framework to design flexibility based on the technical and the actor perspectives is presented.

A. *Technical perspective*

From an engineering perspective, the challenge for designers is: *how to integrate flexibility in physical infrastructure?*

1) *Step 1 - Exploratory uncertainty analysis*

This step consists of two major sub-steps: characterization of major uncertainties and system modeling and simulation. The first sub-step is to characterize the current and future evolution of uncertainty using appropriate models. The future states can take continuous or discrete behavior. Then, the next sub-step is to develop a model of the system to carry out an exploratory analysis of the effects of uncertainties. Top-down optimization models such as mixed integer nonlinear programming, and graph theory and bottom-up approaches such as Agent-Based Modeling, and system dynamics models [40]. The objective of the exploratory analysis is to explore design concepts that are promising for flexibility. Monte Carlo simulation is one technique to achieve that objective. To evaluate and screen valuable design alternatives economic metrics such as net present value, and even techniques such value at risk analysis could be used.

2) *Step 2 - Design flexibility analysis*

The objective of this step is to identify elements of the physical subsystem that could enable flexibility. These elements are flexibility enablers: provide capabilities for the system to change, reconfigure and adapt depending on the evolution of uncertain parameters. Enablers built in the technical system provide flexibility capability [14] and [41].

B. *Actor perspective*

Apart from designing flexibility in the technical elements of the system, actors have to consider flexibility when they design institutions. The central question is: *how to integrate flexibility into the institutional structure?*

1) *Step 1- Exploratory uncertainty analysis*

This step consists of two major sub-steps: identification and characterizations of major uncertainties that would affect the value for parties in the contract, and exploratory analysis. The uncertain factors could be endogenous and/or exogenous. Endogenous uncertainties include technological uncertainty, development uncertainty (cost overruns, capital cost), strategic uncertainty (due to strategic behavior of parties within a contract). Exogenous uncertainties include market uncertainty(demand, interest rate), regulatory uncertainty [42].

Then, the next sub-step is to design a risk and value sharing contract and carry out a preliminary exploratory analysis under different uncertainty scenarios. Common techniques include Monte Carlo simulation [43] and repetitive game analysis [44]. The objective is to identify parameters that affect the contract value for involved parties. By so doing, contracting partners can get helpful information on potential incentive mechanisms to improve the contract structure and manage uncertainty.

2) *Step 2 - Contractual flexibility analysis*

The objective of this step is to identify and integrate flexibility options within the contract. Flexibility options could be exercised either unilaterally or mutually. Timing entry into the contract and opting out of the contract are some of the common forms of unilateral flexibilities. One the other hand, mutual flexibilities are exercised by actors in the interest of enhancing their joint welfare [45]. Renegotiation of contract terms during the life the venture so as to re-adjust optimal joint welfare and mutual exercise of waiting and expansion options are some common forms of mutual flexibilities [46]. To effectively exercise risk sharing re-negotiations, it is crucial to embed contingent claims ex-ante.

VI. Conclusions

Energy infrastructure systems are characterized as socio-technical systems: systems that include networks of technical/physical elements (e.g. cables, pipelines) and networks of interdependent actors (e.g. contracts). However, systems engineering provides a limited perspective by focusing on the technical/physical subsystem as ‘the object of design’, while the social/institutional structure of the system, in some cases, considered as design contexts, or mostly ignored.

The paper proposes an integrated theoretical framework that combines the technical/engineering perspective and the actor perspective to design flexibility during conceptual design energy infrastructure systems. The paper argues that integrating flexibility in the physical design as well as in the institutional structure is a right approach towards flexible infrastructure system.

Finally, energy infrastructure systems are increasingly becoming complex, especially with the integration of information systems with a notable example of smart grids. Therefore, new approaches designing flexibility into the energy infrastructure should take into account information systems in addition to the physical and institutional elements.

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Designing Networked Energy Infrastructures with Architectural Flexibility

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Abstract

Development of networked energy infrastructures (like gas pipe networks), generally requires a significant amount of capital investment under resources, market and institutional uncertainties. Several independent suppliers and consumers are to be connected into these networks. However, the actual commitment of these parties and the capacities they require from the network can remain uncertain for a long time. This is a challenging task for development co-owners because decisions, such as network architectures, have to be made while uncertainty exists. In order to effectively explore through the design space and identify architecturally flexible designs addressing a view of capacity uncertainty, a simulation framework based on a combination of Monte Carlo simulation and Graph Theory is proposed. It integrates a stochastic capacity demand model and network design heuristic algorithm. The framework will be able to evaluate architectural design options and show that architectural flexibility can significantly improve the value of the infrastructure project by reducing downside risks and benefiting from upside gains compared to the deterministic design approach.

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Keywords:networked energy infrastructures, uncertainty,architectural flexibility

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1. Introduction

Energy infrastructures (such as gas pipe and electricity networks) form the back bone of modern society as they provide essential utilities and services. However, society is increasingly challenged with dwindling energy reserves for electricity generation and adverse effects from emission of carbon dioxide from energy use. In response to these challenges several new initiatives are being developed to provide alternatives to fossil fuel and reduce harmful emissions. There are, for example, plans to develop pipeline networks that connect biogas farmers and pool their output for use as alternative fuel, and networks for carbon capture and storage (CCS)[1,2].

In most cases, development of these networks involves several independent organizations to be connected into the network. In the exploratory or design phase of these networks, among others, the capacity of the pipe required by each of the suppliers/consumers is a major uncertainty as the flow from each supplier might change over time. The challenge for the developer, then, is to decide who to connect first and how to develop the network taking the uncertainty into account.

In facing design under uncertainty, the common practice in systems engineering is to find an optimal network that satisfies a fixed set of parameters[3,4]. However, an optimized solution is rigid and does not perform well when uncertainty is high[5]. If the future uncertainty turns out to be favorable, the point-optimized solution is rigid to be expanded and modified, which causes a loss of opportunity. On the other hand if the future turns out to be unfavorable, point-optimized solutions cannot easily be reduced in scale, wasting capital. This calls for an approach that designs networks to be easily changed to adapt to uncertain future conditions.

Flexibility in design is a method to recognize and embrace the effects of uncertainty[6]. The basic premise with introducing flexibility into the design of networks is that it provides the developer with “rights but not obligations” to develop in particular ways[6], given the nature of uncertainty. Flexibility provides “options” in the strict technical sense of the word-these are not just alternatives, they are capabilities to react easily in a number of ways that would not be possible unless designers make intentional choices in the design phase. For example, in the case of biogas network development, flexibility can mean sizing pipe capacity to be able to handle extra flow, anticipating connection to future potential new participants, and so forth. The claim is that flexibility enables the developers to gain from upside opportunities and minimize downside risks[6]. More discussion on the conceptual meaning of flexibility and types of flexibilities in networked energy infrastructures is given in section 3.

In this paper, we propose a computer simulation framework that integrates a stochastic capacity demand model and network design heuristic algorithm to explore network design options. The framework generates and evaluates network designs under capacity uncertainty and shows that flexibility can enhance the value of the network(s) by reducing downside risks and benefiting from upside gains compared to the optimal solution approach which is deterministic.

This paper is organized as follows. Section 2 discusses the characteristics of networked energy infrastructures and conceptualizes them as networks with nodes and links. Section 3 discusses flexibility in energy networks. Section 4 proposes a computational simulation framework for exploring flexible design options under capacity demand uncertainty. Section 5 demonstrates the proposed framework by applying it to the development of a hypothetical network infrastructure. Section 6 concludes this paper.

2. Characteristics of Networked Energy Infrastructures

Energy infrastructures have a socio-technical nature, i.e. both a physical and social/organizational structure[7]. Physically, they are highly engineered technical artifacts and facilities for the production-conversion/treatment, distribution and supply of essential energy needs of society. The social structure implies the organization and institutions that design, operate and make use of the technical artifacts. In this paper, we focus on the design of the physical structure and, on an abstract level, conceptualize it as a network of links and nodes housing a certain flow that moves through the links and is processed in the nodes. Links and nodes are generic components of the network. The links are like pipes, cables which traditionally are referred as “infrastructure” and the nodes are like production, processing, storage and consumption sites. For example, a gas pipe network begins with gas production plant (node); the produced gas is transported through pipe (link) towards consumers (node) for the purpose of energy (heat and electricity) or for chemical processing.

The following are some common characteristics of energy networks that make the designing and development planning process very challenging.

- *Capital intensive*: the design and development of these networks require substantial amount of capital investment (usually in hundreds of millions or billions of dollars).
- *Evolving internal and external uncertainty*: these networks are being designed, developed and operated in uncertain environment. For example, the capacity required by suppliers/consumers of the network might change over time.
- *Long life time*: lifecycle of these networks (i.e. design, development, operation and abandonment) spans several decades.

These characteristics, among others, create uncertainty for the project developers and make decision making difficult. The practice of traditional engineering design focuses on finding an optimal solution given a deterministic assumption of the future environment in which they will be operated. Deterministic optimization often leads to a rigid network design solution that is appropriate if the future condition is relatively stable. Such point-optimal designs without taking into account uncertainty may cause huge financial losses. In this paper, we propose a flexible design approach to enable networks to be easily changed to adapt to uncertain future conditions, which is discussed in more detail in section 3.

3. Flexibility in Networked Energy Infrastructures

In many disciplines, flexibility is intuitively defined as the ability to respond to changes easily. We define flexibility, as the property of the system, endowed by design at initial stage, which gives it the capability to respond to future changes[8]. De Neufville[6] claims with some strong conceptual reasoning and practical case analysis that flexibility can add value over optimization design approaches. The added value could come either from an increase in expected gain, reduction in maximum possible loss, reduction in initial capital expenditure or a combination of those[6].

In general there are two kinds of flexibilities in networked energy infrastructures: architectural and operational[9]. Architectural flexibility is achieved by designs that enable the system to modify configurations or layouts to future uncertainty with relative ease. Operational flexibility is achieved by designs which allow easy modification of operating strategies without major configuration changes. In this paper we focus on architectural flexibility to explore promising design options and show, on a conceptual level, that there is value compared to a deterministic design approach. In the case of networked energy infrastructure, by architectural flexibility we mean it is possible to:

- *Add or delete nodes or connections*: over the life cycle of the infrastructure, nodes or/and connections can be added or abandoned. When such kinds of flexibilities are exercised, the physical configuration of the infrastructure will change.
- *Modify connections among the nodes*: this means changes in the way nodes are connected or different routes for an existing connection. This type of flexibility is referred to as network re-configurability.
- *Modify the designs or properties of nodes or connections*: this flexibility changes the properties of nodes or connections in a network but not its configurations. For example, capacity expansion of links and/or source or sink nodes.

The challenge of exploring and integrating flexibility comes from the large number of possibilities of designing the network and the implementation of flexibility decisions both temporally and specially. The solution to this challenge should enable flexible connectivity within the considered nodes allowing connection and exploitation of nodes (source or sink) which currently doesn't look feasible to consider but in the future become significant to be connected. It is enabled by initial design, such as the ability of the sink node to accommodate possible increase in capacity from other sources or a pipe that can accommodate possible increment in capacity. To facilitate the task of exploring this complex design space and generate promising design options we propose a computational framework based on a combination of Monte Carlo simulation and graph theoretical approach.

4. A Computational Framework

To explore flexibility under capacity uncertainty, this paper proposes a computational framework shown in Fig.1. The key elements of this computational framework include: uncertain variable model, simulation model based on heuristic algorithm, decision rules and evaluation of design options. The loop represents Monte Carlo simulation and each run takes one evolutionary path of an uncertain variable and generates alternative design options and their economic evaluation results. A description of the key elements of the computational framework is provided below.

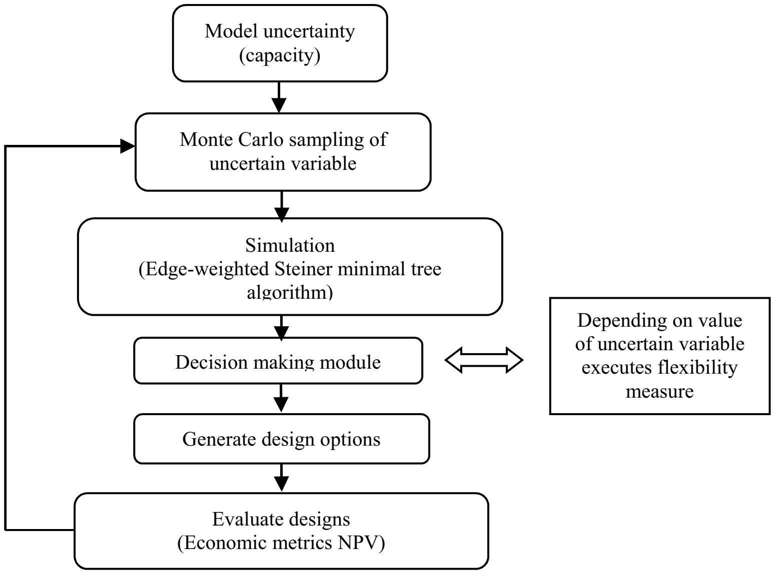

Fig.1. Proposed computational framework to explore flexible design options under capacity uncertainty

- *Modelling capacity demand*: In this research we develop a stochastic capacity demand uncertainty model based on an analytical approach. Capacity required by the participant (node) in the energy infrastructure network can also be otherwise represented by flow from or to that particular node. By making some initial assumptions on flow estimates from nodes (i.e., type of distribution, speed of convergence), this approach avoids requiring large samples of historical data. The first step is to transform an initial flow estimate into a probability distribution, such as, normal distribution characterized by vector D (t0) containing the moments of the distribution (mean and standard deviation). The second step is to generate an ensemble of flow estimate trajectories F (t) given the model, shown in Fig. 2.

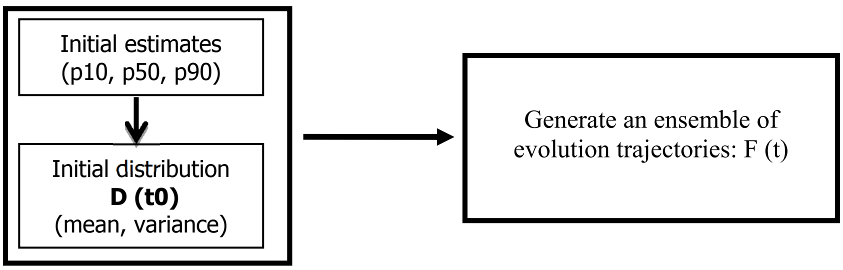

Fig. 2 Model framework for flow uncertainty

- *Simulation model*: this is based on a graph theoretical concept of an edge-weighted Steiner minimal tree, which finds a minimum cost tree-shaped network connecting the nodes. In a graph theoretical representation of networks, the sources of flow are nodes and their connections are edges. The edge-weighted Steiner minimal tree generates the minimal cost connection between the existing nodes taking into account the length and the size of the edges (for example, capacity of pipe in gas network). The cost of building the pipeline e is defined as $C_e = l_e q_e^{\beta}$, as in[10]. Here l_e is the length of e and q_e is the total capacity of pipeline e. The exponent β is the cost exponent for the capacity with $0 \leq \beta \leq 1$. If β=0, the capacity of the pipelines has no influence on the costs. If $\beta = 1$, building two pipelines of capacity 1 is just as expensive as building one pipeline of capacity 2. We took β=0.6 as in[11], indicating that there are cost advantages to building high-capacity pipelines. The total investment cost $C(T)$ of a network T is the sum of all edges costs.

$$C(T) = \sum_{\forall e \in E(T)} l_e q_e^{\beta} \qquad (1)$$

where $E(T)$ is the set of all edges in a network tree T.

Depending on the value of the uncertain variable(s), the simulation model generates multiple architectural layouts (network designs). A detailed explanation of how the minimum cost edge-weighted Steiner minimal tree can be found in[11,10].

- *Decision rules*: these are a set of heuristics which set up the condition for exercising flexibilities. In the simulation, the decision rule determines when and how to exercise flexibilities (i.e. add nodes, modify configuration, increase capacity of edges) according to evolution of the flow.
- *Evaluation of design options*: accumulative distribution of the net present value is used as economic output of different design options. It is calculated based a simplified cost and revenue model. The cost model is represented as $eq\ (1)$. The revenue model calculates the expected income based on the flow from each of the supply sources. It is assumed that the incomes are linear in the used capacity of the network. The expected incomes (EI) for a chosen network N are therefore defined as

$$EI(N) = \alpha \sum_{\forall S} q_{T(N)} \qquad (2)$$

where $q_{T(N)}$ is the used capacity from the source/sink in network N and α is a constant coefficient representing, for instance, the service charge per unit capacity used.

5. Hypothetical network as case study

This section demonstrates the proposed framework by applying it to the development of a hypothetical pipeline network. The case study explores different flexible design options for the network and compares it against the deterministic design. The hypothetical pipeline network could be a typical energy infrastructure, which transports material X[1] from different supply points (physical sources) to demand point(s) (physical sinks) through the links (such as pipes and compressor stations). We specify that the hypothetical network has visible physical links and nodes as in for example gas pipe networks and CCS networks.

In practice, there are several conditions for development of such network infrastructures. Firstly, the benefit from the source points should be able to justify the capital investment needed in their connection to the demand point (physical sink). Secondly, certain physical constraints like distance (pressure and flow assurance limitations) have to be satisfied. The third is the contractual time constraints for investment recovery between the network developer and the suppliers/consumers. All these may result in delaying the investment decision in the network development until the potential sources/consumers have been completely explored and appraised, contractual issues are addressed and the economic viability is justified.

□ By material we mean flowing matter in gas or liquid state

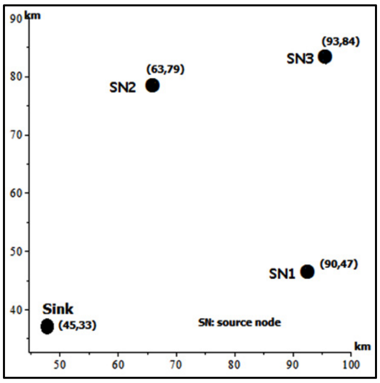

Fig. 3. Layout of a hypothetical network with position coordinates. Black circles represent nodes (source and sink)

We consider a case by which a developer who sees a potential market for X is interested to develop a pipe network connecting suppliers to consumer(s). At the initial stage we assumed the suppliers are interested to sell their X if they have access to pipe network. However, for the developer, the capacity of the pipe required by each of the suppliers is uncertain as the flow from each supplier changes over time. To demonstrate the application of the proposed framework clearly we chose a network that includes three supply points (source nodes) and one sink, see Fig. 3. The situation is hypothetical and the numbers used are stand-ins to permit calculation.

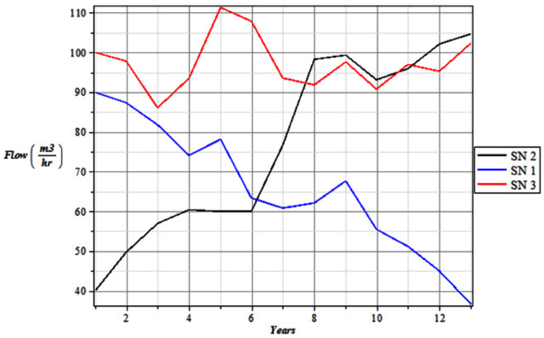

Fig 4. Simulated evolutionary path of flow estimate for hypothetical network

The first task is to model the uncertainty behaviour of flow from each of the suppliers. A normal distribution of initial flow estimate for each source node is defined. The mean of the flows for each of the three source nodes is taken: i.e. SN1= $90m^3/hr$, SN2= $40m^3/hr$, and SN3= $100m^3/hr$. Then, an ensemble of flow evolution trajectory for each source node is generated for a time period of 12 years, shown in Fig.4. The evolutionary flow path curves represent a situation that exists as problem in practical network design that with time supply from a given source could remain relatively unchanged (SN3), or decrease (SN1), or increase (SN2). It shows that, SN2 has a low flow for the first 6 years but drastically increases in the years after and flow from SN1 decreases continuously over time. The sink node is assumed to absorb any amount of flow coming from the three sources.

If the capacity of the pipe connecting to SN2 is designed based on the flow estimate at the beginning, then there will be an opportunity to be lost and designing the pipe network taking into account the initial flow estimate for SN1 will lead to underutilization of pipe capacity. For the network developer, a decision has to be made taking into account the future opportunities from connecting to SN2 and the potential risk from connecting to SN1. This calls for the developer to adopt a flexible strategy that integrates options at the initial stage to make use of upside opportunities and minimize down side risks.

In practice, stage development that involve core (premising) sources and several potential sources with flexible connectivity becomes an attractive strategy for a project with many low flow sources. In the case of oilfield development the connection to small fields is known as tieback[9]. In this research we use the term 'flexible connectivity' for such kinds of connection to potential sources other than core sources. Flexible connectivity allows connection and exploitation of other sources which currently do not look feasible to consider but in the future may become significant. This will change the architecture (topology) of the network. It is enabled by initial design, such as the ability of the sink to accommodate possible increase in capacity from other sources or a pipe that can accommodate possible increment in capacity.

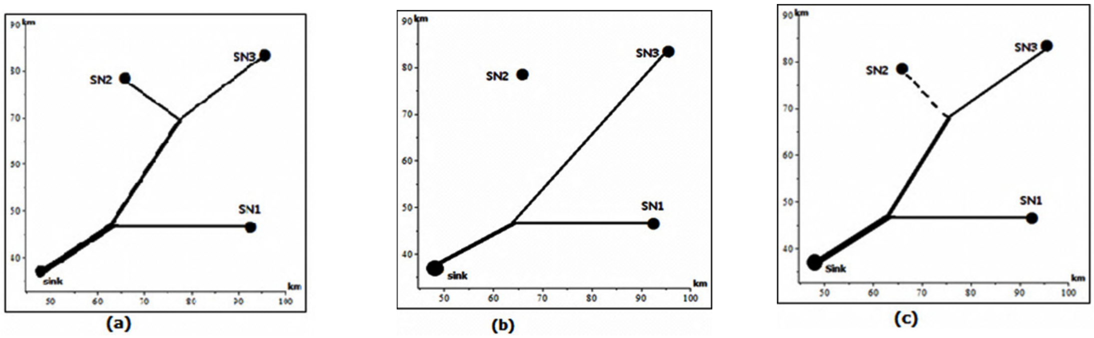

Fig.5. layout of three generic network design strategies

The next step then is to identify and define potential flexible connectivity options and define the triggering conditions governing when we should exercise these flexibilities. Given the trajectory of flow from supply sources (Fig. 4.), three strategies for connecting the networks are identified, shown in Fig.5. (a-c).The first strategy (Fig.5.a) is a deterministic design by which all the supply nodes are connected with capacity based on the distribution of the initial flow estimate (year 1). In this case, only the mean of the flow at initial stage are considered and the capacity of the pipe required by each supply node is fixed. The second strategy (Fig.5.b) is also deterministic by which the decision maker decides to ignore connecting SN 2 because its flow is not significant enough to justify connection just based on year 1 value. The third case (Fig.5.c) is a flexible design connecting nodes which have significant flow at initial stage (SN1 and SN 3) and builds the option of connecting to SN 2, represented in dash line in Fig 6.c. When the flow from SN 2 makes economic benefit the developer will exercise the option (build connection to SN 2). The cost of taking the option in this case is the investment cost of extra pipe capacity and length in design (c) compared to design (b). The option will be exercised when the revenue from SN 2, calculated using equation (2), due to the increase in flow exceeds the cost of its connection. Exercising the option will then change the architecture of the network.

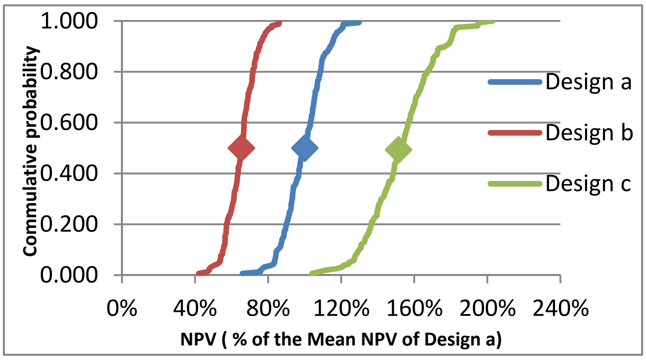

Fig.6. Cumulative probability distribution of NPV

Each of the three design strategies was run through the algorithm shown in Fig.2 for 160 times. Depending on the value of flow from each supply nodes the algorithm provided low cost connections (networks). In each cycle of run, the algorithm also calculated the economic output as net present value (NPV). We then sorted the resulting 160 NPVs calculated for each strategy and plotted them as cumulative distribution function for NPV, shown in Fig.6. To permit comparison between the three designs, we normalize the 160 NPV values for each design against the mean NPV value of design (a).

From Fig.6.we can see that design (c) has higher NPV than the other two deterministic designs. More specifically, the mean NPV of design (c) is 50% higher than the mean NPV of design (b) and 90% higher than mean of design (a). The improvement in expected net present value of design (c) is because of the flexible connectivity, which reduces downside risks and capitalizes on upside opportunities. The downside risks comes from the decrease in flow from SN 1, faced by design (a) and the low initial flow from SN 2 faced by design (b). The opportunities comes from the increase in flow from SN 2, which is missed by design (b) and will not be fully exploited by design (a). From Fig.6.it is also visible that design (a) which connects all source nodes deterministically is better than design (b). This is because the capacity from SN 2 is fully utilized all the time and generates revenue in case of design (a), while both design (a) and (b) are similarly exposed from underutilization of capacity from SN 1.

6. Summary and future work

In this paper, we introduced a computational simulation framework which integrates a stochastic capacity demand model and network design heuristic algorithm. The framework is used to evaluate designs and show that architectural flexibility can significantly improve the value of an infrastructure project by reducing downside risks and benefiting from upside gains compared to the deterministic design approach. Applying the methodology to a hypothetical planned network, it was found that the expected net present value of the network development could be raised through the use of flexible connectivity, that build options at initial stages of the design. The framework can also be applied to practical networked energy infrastructures like carbon capture and storage pipe network and gas network.

Further steps in this research entail considering multi-domain uncertainties, such as adding market price of the material flowing through the network and building other flexibility strategies like operational flexibility. Other future works include improving the decision rule and the triggering condition based on practical experience, using empirical data, and performing sensitivity analysis to improve the understanding on the impact of different decision rules on design outcome.

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Publication III

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Exploring for real options during CCS networks conceptual design to mitigate effects of path-dependency and lock-in

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ABSTRACT

Carbon capture and storage (CCS) networks are expected to grow from small demonstration projects with few emitters to large-scale networks of dedicated carbon dioxide (CO_2) pipelines over the next few decades. Conventional design practices focus on implementing incremental expansions based on deterministic requirements resulting in rigid networks. The design approaches do not proactively recognize future uncertainties in design requirements and operating environments. In this study, we present a design method based on real options, graph theory and Monte Carlo techniques that reckons future uncertainties. The proposed method assesses initial design architectures and provides insights into potential real options and sets of strategies for implementing future expansions. We apply the method to a hypothetical CCS network design. The results reveal that this method helps to appraise the flexibility created by redundant pipe capacity and length in an uncertain future. It also shows that embedding real options in expanding CCS networks could result in more emission reduction by encouraging other emitters to participate.

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1. Introduction

Carbon dioxide capture and storage (CCS) is widely promoted as a promising climate mitigation technology that can significantly reduce carbon dioxide (CO_2) emissions in the transition from a fossil-based economy to a low-carbon future (IEA, 2010). The technology involves capturing CO_2 at large industrial sources, such as coal-based power plants, transporting it in dedicated pipelines and storing it in geological reservoirs, such as depleted oilfields and saline aquifers. Recent projection shows that more than one-sixth of the desired CO_2 emission reduction over the 2015–2050 period can be realised with CCS (IEA, 2014). To achieve this target, large-scale demonstration projects are being initiated and early planning of how the CO_2 pipeline network may be designed in the long term will help to control the total social costs (Austell et al., 2011).

CO_2 pipeline networks, like other large-scale infrastructure networks, are developed in stages. They start with individual CO_2 sources and point-to-point pipeline connections. They expand by adding new sources and over time, a complex pipeline network emerges. In many countries, small-scale demonstration projects are considered starting points for a large-scale CCS. For example, CCS demonstration projects in the Rotterdam area, the Netherlands, are being built for supplying CO_2 to greenhouses (RCI, 2011). These demonstration projects are seen as the essential first steps in the full-scale deployment of the technology.

Conventional CO_2 pipeline-configuration design methods are based on deterministic forecasts and assumptions of fixed design parameters (Flyvjberg et al., 2005; de Neufville and Scholtes, 2011). Designers use the most likely scenarios to generate design concepts and select design parameters that enable the network to perform optimally under those scenarios. Then standard economic evaluation techniques, such as discounted cash flow analysis, optimisation and scenario planning are applied to achieve the best optimal design (de Neufville and Scholtes, 2011).

However, in the real world, this may not provide a design that performs best. First, it does not capture the range of technical, economic, regulatory and social uncertainties that will ultimately affect the effectiveness of CCS networks (Koelbl et al., 2014; IEA, 2012; van Os et al., 2014). A network that is designed to be optimal in future achieves the expected performance only when the predicted scenario is realized. Besides, network expansion is inherently path-dependent (Silver and de Weck, 2007). Path-dependency refers to the notion that the state of an infrastructure at any given point depends on its development path until then. If the predictions used in the design decisions do not realize, it may result in rigid networks that cannot adapt to changing requirements.

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This situation could create 'lock-ins' in pipeline networks like CCS. Lock-in occurs when the cost of modification of an existing configuration exceeds the expected benefit[1]. Therefore, to mitigate lock-ins and sub-optimal performance of CCS networks, one needs a design approach that deals proactively with uncertainty.

In the field of systems engineering, a flexible systems design offers one way to deal proactively with uncertainty (de Neufville and Scholtes, 2011; Silver and de Weck, 2007). Such a design concept provides an engineering system like CCS with the ability to adapt, change and be reconfigured (Cardin, 2014). It involves having a set of strategies on designing the engineering system with the capability to adapt to changing circumstances; and on integrating a set of flexibility enablers into the physical design. Such a design approach, which considers flexibility strategies and flexibility enablers, is called the real options approach (Cardin, 2014; Ling and Ngah, 2009). It offers engineering system designers valuable clues about which flexible design elements are worth the cost (de Neufville, 2003). It thus provides a good rationale for specific types of flexibilities to be designed in a system. However, the core issue in design flexibility, especially in infrastructure networks like CCS, is how to identify the most desirable sources of flexibility enablers (here after also called real options).

This paper aims to provide a useful design method for identifying valuable real options in the conceptual design of CCS networks. The method uses an exploratory uncertainty analysis on a graph theoretical network simulation model. The method allows an easy and quick assessment of low-regret design options and identification of real options that could provide opportunities for flexibility.

The rest of the paper is organised as follows. The next section presents a review of CCS network design methods. Section 3 introduces real options theory and real options-based design strategies that we consider contextually relevant to the understanding of this paper. It also establishes the source of the real options identification problem in the case of CCS networks. The proposed method is presented in Section 4. And in Section 5, the methodology is demonstrated for a hypothetical pipeline-based CCS network. Section 6 concludes the paper.

2. Review of CCS network planning models

In recent years, CO_2 pipeline transport planning methods have become more sophisticated. In a decade, they have evolved from modelling just single pipeline connections to spatially and temporally complex networks. Modelling techniques include simple to complex families of mathematical algorithms, such as linear optimisation, non-linear optimisation and mixed-integer optimisation. Kobos et al. (2007) developed an analytical model to optimise simple networks with multi-stop pipelines using a simple linear optimisation algorithm. It begins with a source and constructs a pipeline of sufficient diameter to carry the entire CO_2 volume to the nearest reservoir. It then finds the next sink nearest to the first reservoir and constructs a pipeline sufficient to carry the remaining CO_2 to it and so on, creating a 'string of pearls'. Most recently, Knoope et al. (2014) have presented an economic optimisation model to design simple networks. This model minimises the cost of pipeline configurations, taking into account inlet and outlet pressure, pipeline length, steel grade and nature of the terrain. The planning models presented in the studies discussed above are applicable for single source-to-sink connections and simple networks. They also assume static situations and, therefore, do not address expansion in time.

[1] In addition to economic reasons, CCS networks could be locked-in due to externalities (due to their externally bounded interface with other sectors) (Economides, 1996).

A compressive and scalable CCS infrastructure model called *SimCCS* was presented by Middleton et al. (2007) and Middleton and Bielicki (2009). It is a geo-spatial economic-engineering model that simultaneously optimises all components of CCS infrastructure, based on a mixed-integer linear programming algorithm. The model allows pipelines to branch and join to avoid duplication and take advantage of economies of scale by creating trunk lines. It also allows for less than 100% of CO_2 to be captured from CO_2 sources and less than 100% of injection capacity to be used at CO_2 sinks if that can reduce costs elsewhere in the system. *SimCCS* was further expanded to integrate multiple independent decisions by Keating et al. (2011). However, *SimCCS* is a static model as it assumes the entire CCS infrastructure network is built all at once and that the amount of CO_2 being managed is constant over time.

Recently, CCS network models have been expanded to take into account expansions over time. Mendelevitch et al. (2010) extended the *SimCCS* model to allow for CCS infrastructure network development decisions over time. van der Broek et al. (2010) has an improved model that takes into account the temporal component of CCS infrastructure development, based on a linear optimisation algorithm. Klokk et al. (2010) introduced a temporal CCS model for delivering CO_2 for enhanced oil recovery. Middleton et al. (2012) introduced an advanced model called *SimCCS^{Time}*, which is an improved version of *SimCCS*. *SimCCS^{Time}* optimises the deployment of CCS infrastructure across multiple periods. Both *SimCCS* and *SimCCS^{Time}* are part of the 'top-down' optimisation approaches that rely on a global optimisation algorithm of some kind and use complete information about the system to find a global optimum. However, the model assumes a pre-defined pattern of future emissions and CO_2 management targets. The model also becomes computationally cumbersome as the number of sources and sinks increase.

A network model based on graph theory technique has been proposed by Heijnen et al. (2014). The model conceptualises, on an abstract level, the design of a physical CCS structure as a network of links and nodes housing a certain flow that moves through the links and is processed/consumed in the nodes. The model helps to find a minimum cost network layout by taking into account pipeline length and capacity. However, the method considers deterministic and discrete scenarios of uncertainty parameters and finds an optimal network configuration for each pre-defined scenario. It does not fully address the stochastic and dynamic nature of uncertainties. It also does not address the issues of flexibility, of real options identification integration as the network expands over time. In a preliminary work, Melese et al. (2014) presented a simple simulation framework based on a combination of Monte Carlo simulation and graph theory to design architecturally flexible networks under capacity uncertainty. The framework uses a simplified flow uncertainty model to generate design alternatives and does not use the concept of real options. Similar to the works by Heijnen et al. (2014) and Melese et al. (2014) this paper uses graph theory to model CCS networks. Stochastic process is used to model current and future flow uncertainty of existing sources and multiple scenarios are used to model the timing of future sources. Moreover, this paper uses the concept of real options to appraise the flexibility created by redundant pipe capacity and length in an uncertain future.

3. Using real options to deal with uncertainty in CCS network planning

The technical concept of an option is a right, but not an obligation, to do something at a certain cost within or at a specific period of time (Myers, 1984). From this definition, it follows that the key feature is exercising the 'option' of using one's right to do an action, and the involvement of a cost that is somehow defined in advance. It is in this sense that an 'option' has value and this feature distinguishes it from a 'choice' or an 'alternative'. The concept first appeared in a field of finance called financial options, and has entered the field of engineering systems in the modelling of design flexibility in realistic uncertain environments.

In engineering systems the term flexibility is widely used and real options are a way to define the basic elements of flexibility (de Neufville et al., 2010; Wang, 2005). Options that involve technical design features are referred to as real options 'in' engineering systems. On the other hand, options that involve financial decisions on engineering projects are referred to as real options 'on' engineering systems (Wang, 2005). Real options 'on' engineering systems refer to managerial flexibility. Both real options 'in' and 'on' engineering systems provide embedded flexibility and enable network developers to minimise downside risks and gain from upside opportunities (de Neufville and Scholtes, 2011; de Neufville et al., 2006; de Weck et al., 2004). However, flexibility capabilities have to be made possible by designers making intentional choices during the conceptual design stage (de Neufville et al., 2010). At this stage, network designers have more freedom to address proactively the varying technical, economic and institutional dynamics.

The core question is: How to identify real options that could enable cost effective expansion of CCS pipeline networks as future capacity requirement increases? There are two key difficulties involved. First, there are the myriad design variables and parameters that make real options identification and valuation difficult. Second, real options in engineering systems often exhibit complex path-dependencies and interdependencies that standard options theory does not deal with de Neufville et al. (2010). They need an appropriate analytical framework. Existing options analysis methods have to be adapted to the special features of real options in pipeline networks like CCS. To the authors' knowledge, there is no previous work on real options based design of CO_2 transportation networks.

4. Methodology

In this paper, we propose a method for identifying valuable real options when designing CCS networks under uncertainty. It builds on existing design methods by giving designers some kind of model for estimating designs benefits and costs in some metric (such as capital expenditure and net present value). The objective is to provide a systematic method for fast and easy assessment of network design options under uncertainty and screen promising designs that could provide cost effective expansion. The method could also provide network designers with important insights so that they can systematically identify flexibility enablers and flexible strategies to mitigate lock-ins.

4.1. Step 1: Specification of the key sources of uncertainty

The first step in the design process is to identify key sources of uncertainties. It includes a comprehensive accounting of all potential sources of uncertainties that, over time, could affect the value of the design. Major uncertainties can be identified through expert judgment and a preliminary sensitivity analysis.

4.2. Step 2: Definition of likely future states over several stages

In this step, the evolutionary behaviour of selected uncertainties is defined. It includes defining the states of uncertain variables over several stages. Stages, in this context, could refer to a suitable planning period and depend on the type of system. For example, in the case of CCS networks, the stages could be long time periods (e.g. five years).

The future states can take continuous or discrete behaviour. To model continuous behaviour, stochastic processes such as Geometric Brownian Motion (GBM) and Wiener processes are often used (Ibe, 2013). To model discrete behaviour, lattice model can be used (Albanese and Campolieti, 2006). An example of a continuous behaviour is the flow rate of CO_2 from power plants with CO_2 capture units that vary power production because of the variability of electricity demand and the increasing use of renewable energy sources in the electricity grid (Cohen et al., 2012; Domenichinia et al., 2013). During variable power production, the amount of CO_2 captured and pumped through pipelines could vary within shorter time periods (hours and days). In addition, emitters could plan their capture targets to increase step by step over a long period of time (years). These scenarios have to be explored in detail.

4.3. Step 3: Explorative uncertainty analysis

The objective in this step is to identify elements of the network that seem most promising for flexibility. This requires employing some kind of network model to generate design concepts. In this study, we employ a graph theoretical network model (explained in Section 5.4.1). Scenarios of the selected uncertain variables are used as inputs to simulate the network model. The outputs of the model include network configurations and their economic performance parameters (e.g. NPV and investment cost) for each set of the uncertainty scenarios. Design elements that vary across these sets of uncertain scenarios are those that may be good as real options. Conversely, those design elements that are insensitive to uncertainty do not present interesting real options.

This step is a preliminary stage for the identification of the best opportunities for flexibility. The search for a valuable design could involve many thousands of possibilities. For a proper search of the promising configurations of the network, it is necessary to use low-fidelity models that can be run much faster than detailed, high-fidelity models.

4.4. Step 4: Identification and valuation of the real options

The goal here is to map real options to the sources of uncertainty, based on the results of the exploratory analysis. There are several real options strategies that might lead to flexibility. Some of the strategies relevant in the context of CCS networks include *option to expand*, *option to defer, option to abandon, and option to switch*. Analysis of design alternatives is required to assess the above-mentioned strategies.

The focus in this work is not to price the options. The focus is on the improved design; i.e. determining which parts of the network should be configured to provide the real options that will give the network operators/designers the '*right, but not the obligation*' to change the size of the network. Such an analysis can aid network designers in making rational (though optional) decisions as to which flexible design elements can be incorporated into the design. It can also help designers and decision makers to determine the relative cost of incorporating such flexible design element into networks.

5. Application

Our case study concerns the development of a hypothetical pipeline-based CCS network. The hypothetical network is inspired by a CCS project in the Rotterdam area, The Netherlands. The Rotterdam CCS project is part of the national goal to reduce CO_2 emission from the port and other industrial activities. An effective and comprehensive method to achieve this goal is to develop a large-scale pipeline network that connects spatially distributed emitters and store CO_2 in depleted offshore oil-and-gas fields in the Northern

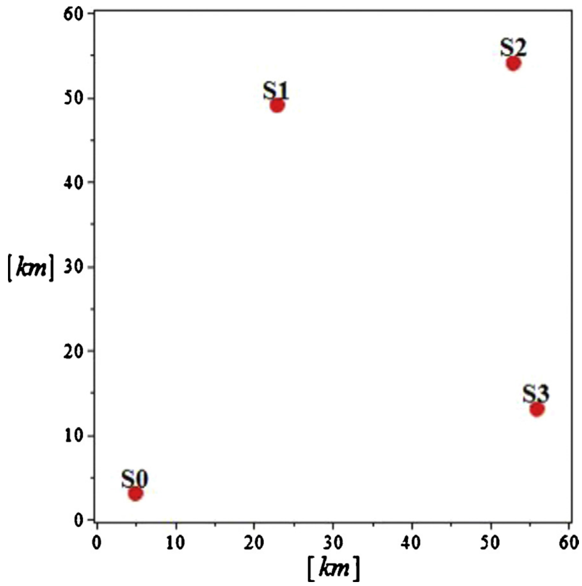

Fig. 1. Layout of our hypothetical field.

Sea (RCI, 2011). However, the CCS project faces a range of technical, economic, regulatory and social uncertainties resulting in slow progress. The current practice is to encourage demonstration projects with few emitters and gradually evolve to a full-scale CCS network. For example, E.ON Benelux and GDF SUEZ Energie Nederland are installing a CO_2 capture unit at a new coal fired power plant worth millions of Euros and are in process of building a pipeline to the Northern Sea as part of the CCS demonstration project (Read et al., 2014). However, the installed capture unit is only sufficient for 25% of the total CO_2 emission. If new environmental policies are introduced regarding the CO_2 limit, additional capture units may have to be installed, requiring building new pipelines.

The problem with staged CCS developments, as is common with other similar networks, is that every incremental development is being optimised based on a set of currently conceived design parameters. Experiences from oil, gas and water distribution developments shows that such designs often result in sub–optimal networks as a result of lock-ins (Lin, 2008; Marques et al., 2014). This study aims to provide a systematic method to mitigate path-dependency and lock-in effects by identifying the most potential flexibility enablers at the conceptual design stage.

5.1. *The design problem*

The hypothetical field for this demonstration has three sources, S1, S2 and S3, and one sink, S0. It is a multi-source, single-sink network design problem. Fig. 1 shows the position of the three sources and the sink on a 60 by 60 km field. The plan is to transport CO_2 from the three sources through links, such as pipes and compressor stations, to the sink. By demonstrating the proposed method in the context of the hypothetical case, this study answers the following basic design decisions:

- What is the most cost-effective strategy for phasing a CCS network to meet increasing capture targets from emitters?
- How can the network be strategically designed so that it is able to coordinate the capacities of capture facilities, pipelines and the sink as the network expands over time?
- Does it make economic sense to overbuild capacities, with large-diameter pipelines, early in the design in order to have flexible networks later, when volumes increase?
- Is it worth waiting for a new capture-ready source to come online?
- Is having bigger pipeline capacities that collect from several sources better than having smaller pipelines that connect each source to a sink?

To answer these questions, we narrow the problem by looking at a situation where S2 and S3 take the initiative to start developing the network and S1 joins at some time in the future. The rest of the case study applies step-by-step the methodology developed previously to identify potential real options that could mitigate future lock-ins.

5.2. *Step 1: Specification of the key sources of uncertainty*

During the design exploration stage, designers and managers need to identify and incorporate major uncertainties into the design decisions. The uncertainties present during CCS network development include, among other things, the number of emitters who will partake of the CCS venture, the capacity required by each participant, the cost per unit capacity (e.g. for material and digging) and the regulatory policy regarding CO_2 emissions, including the CO_2 price. In this work, we focus on two major uncertainties: (1) the uncertainty with respect to new participants who could join the network, and the capacity they may require—hereafter called participant uncertainty; and (2) uncertainty in the capacity requirements of all existing sources over time—hereafter called capacity uncertainty. Participant uncertainty represents the time a new source may join the network and the capacity it may require from then. Capacity uncertainty represents the changes in future capacity requirements of existing sources, for example, when the capture target by emitters increases.

5.3. *Step 2: Definition of likely future states over several stages*

In this step stochastic capacity uncertainty and participant uncertainty models are developed using analytical approaches.

5.3.1. *Capacity uncertainty*

Capacity uncertainty is modelled using an analytical approach based on some initial assumptions of the flow behaviour from sources (i.e. types of distribution, speed of convergence) to generate the full characteristics. The initial flow estimates are then transformed into normal distribution curves. Initial flow estimate parameters for the two sources in this case study are as follows:

- S2 (mean = 350,000 tCO_2/year and standard deviation = 40,000 tCO_2/year).
- S3 (mean = 400,000 tCO_2/year and standard deviation = 50,000 tCO_2/year).

The situation is hypothetical and the numbers used are stand-ins to permit calculation. The next step is to generate an ensemble of future trajectories of flow over several stages or design periods in the future. A 20-year planning period is chosen for this demonstration. Within this period, flow from a given source could increase due to increasing capture targets over time, or remain the same. There are cases where the flow from a given source could decrease due to changes in the internal operation of the emitting source or even a shutdown of the emitting source is possible. In this study, the Geometric Brownian Motion process is used to model future flow evolutionary paths using similar drift rate = 1%, volatility = 30%. In a given scenario one floe path is generated for each source and it contains yearly flow rate data over 20 years period. Fig. 2 shows a normal distribution model of the initial flow behaviours of S2 and S3 and three instances of their future flow evolution.

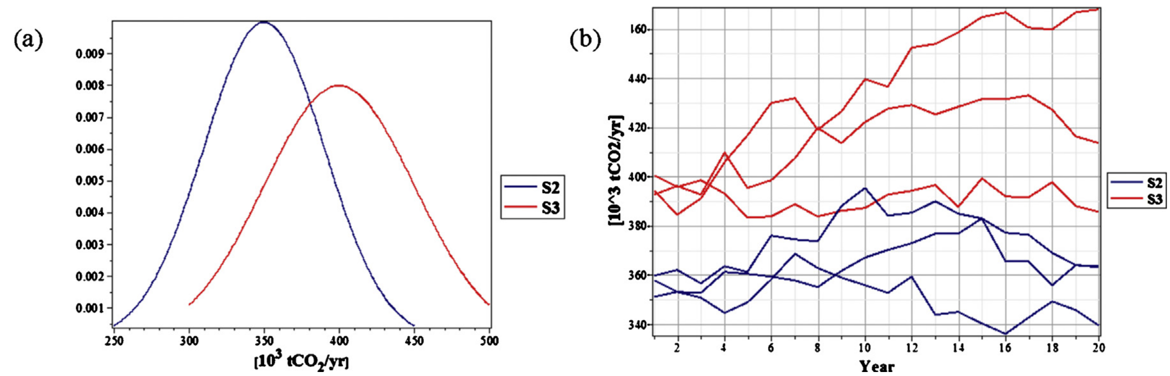

Fig. 2. Capacity uncertainty model of S1 and S2; (a) initial flow estimate model of sources; and (b) three instances of the evolution of flow from S2 and S3 over a 20-year period.

5.3.2. Participant uncertainty

To account for the uncertainty in the timing that S1 will join the network, we choose four scenarios over a 20-year investment period: Year 4, Year 8, Year 12 and Year 16. In this case study, we choose four years as a reasonable time for an emitter to install capture units and be ready for connection. Similar to S2 and S3, the initial flow estimate of S1 is modelled as a normal distribution based on an initial estimate (mean = 300,000 tCO_2/year and standard deviation = 50,000 tCO_2/year), as shown in Fig. 3a. The future evolution of CO_2 flow from S1 is modelled using the GBM process with the same drift rate = 1% and volatility = 30%, see Fig. 3b.

Similar to S2 and S3, the future flow of S1 could increase, decrease, remain the same, or present a combination of all three. Multiple scenario representations of uncertain variables over time allow one to generate and analyse multiple design possibilities and can help arrive at a better decision.

5.4. Step 3: Explorative uncertainty analysis

To perform an exploratory analysis, the selected uncertain variables have to be simulated using a network optimisation model. In this paper, we employ a network optimisation model based on graph theory (Heijnen et al., 2014). The main inputs for the model are flow rates from sources and the spatial positions of sources and sink nodes. The model generates minimum-cost tree-shaped network configurations connecting the sources to the sink. The resulting networks are edge-weighted Steiner minimal trees. An edge-weighted Steiner minimal tree network is a minimal cost network that takes into account the influence on the cost of both the capacity and the length of the pipeline. Next, the core concepts of the model are presented.

5.4.1. Graph theoretical network model

In a graph theoretical representation of networks, the sources and sinks are nodes (e.g. emitters) and their connections are edges (e.g. pipelines). To generate an edge-weighted Steiner minimal network, the network algorithm uses the following cost function of edges.

$$C_e = 1_e q_e^{\beta} \tag{1}$$

In Eq. (1), l_e is the length and q_e is the capacity of an edge e. β is the cost exponent for the capacity with $0 \le \beta \le 1$ If β=0, the capacity of the pipelines has no influence on the cost. If β=1, building two pipelines of capacity 1 is just as expensive as building one pipeline of capacity 2. A value of β=0.6 is commonly used (Heijnen et al., 2014), indicating that there are cost advantages to building high-capacity pipelines. Then, the total investment cost $C(T)$ of a network T is the sum of all connection (pipeline) costs as given in the following equation:

$$C(T) = \sum_{\forall e \in E(T)} l_e q_e^{\beta} \tag{2}$$

where $E(T)$ is the set of all edges in a network tree T.

In addition to cost, it is also necessary to calculate the expected income of the network. A revenue model that calculates the expected income as a linear function of capacity is used. The assumption is that the network developer generates income by charging a certain fee per unit capacity. The expected income (EI) from a network T is then given as

$$\mathrm{EI}(T) = \alpha \sum_{i \in V(T)/\{s\}} q_i \tag{3}$$

In Eq. (3), q_i is the used capacity by a source i in a network T, $V(T)$ is the set of all nodes in the network T, s is the sink and α is the constant coefficient representing a constant price charged per unit capacity of pipeline. In this demonstration, we assume α=1.

The total income from a given network in its lifetime is calculated as a summation of discounted (using a certain interest rate, r) yearly income flows over a certain investment period. The summation of discounted future cash flows (revenues) gives the present value of income (PVI), see the following equation:

$$\mathrm{PVI}(T) = \sum_{t=0}^{n} \frac{\sum \mathrm{EI}(T)}{(1+r)^t} \tag{4}$$

The Net Present Value (NPV) is used to evaluate the lifetime performance of a network under a given scenario of uncertain parameters as shown in the following equation:

$$\mathrm{NPV}(T) = \mathrm{PVI}(T) - \mathrm{C}(T) \tag{5}$$

5.4.2. Simulation outputs

In this step the network model is simulated using different uncertain future scenarios. In one scenario 20 network configurations are generated (based on 20 yearly flow rate inputs from each source). Fig. 4a shows a density diagram consisting of 20 different edge-weighted Steiner minimal network layouts. It shows the layout of the network in phase 1. In phase 1 only S2 and S3 are available to develop the CCS network. Fig. 4b shows network layouts if all the sources are available at the beginning. However, since S1 joins the network later S1. Each network layout represents the lowest cost connection between the sources and the sink. The capacities and the lengths of the edges and the points of connection (Steiner points) between edges is different for each layout.

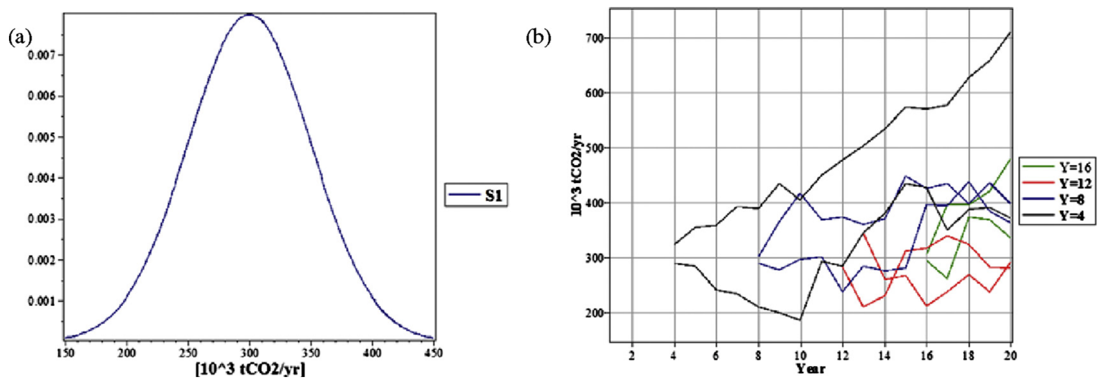

Fig. 3. Flow model of S1: (a) initial flow estimate model of S1, (b) instances of evolutionary flow model of S1 over time. Each line indicates one instance of S1 flow path under the four scenarios (*Y* stands for Year).

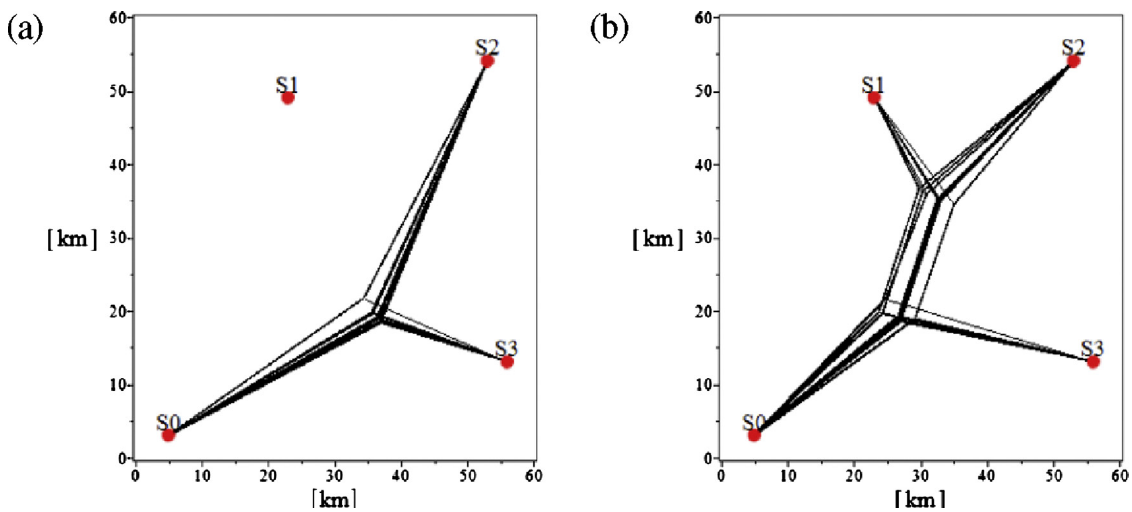

Fig. 4. Optimal network layouts of the CCS network in phase 1 (a) and phase 2 (b).

To determine the optimal network out of several design alternatives in a given scenario, the Present Worth Ratio (PWR) metric is used, see Eq. (6). PWR is the ratio of the expected revenue of the network to the initial outlay required for it. It illustrates the efficiency in the invested capital.

$$\text{PWR} = \frac{\text{Expected } Revenue - \text{Investment cost}}{\text{Investment cost}} \tag{6}$$

Out of the 20 network layouts in each scenario, the layout with the maximum PWR is selected. To generate multiple scenarios, Monte Carlo simulation is carried out. By simulating the network model with several scenarios multiple layouts are generated for both phase 1 and phase 2. We limit the number of simulation runs to 200. 200 simulation runs result in 200 network configurations with their corresponding maximum PWR values. In phase 1, the PWR values follow a lognormal distribution with a mean of 2.7 and standard deviation of 0.3. Similarly, in phase 2, the PWR values follow a lognormal distribution with a mean of 3.5 and standard deviation of 0.4. During the conceptual design stage, Monte Carlo simulation enables designers and decision makers to explore several scenarios and generate several design candidates. Therefore, the exploratory uncertainty analysis step serves a screening step to identify promising network design concepts for the detail design stage. In the next step, the network with a maximum PWR, 2.7 in phase 1 and 3.5 in phase 2, are selected to identify best opportunities for flexibility.

5.5. Step 4: Identification and valuation of real options

The objectives in this step are (1) to map uncertainties to part of the network that should be configured to provide network designers the 'right, but not the obligation' to change the network in the future; (2) to calculate the value of having real options in the network.

Based on the simulation outputs in the previous stage, the following two design strategies are identified.

- Design strategy 1, (the baseline strategy). Under this strategy the network will be developed by connecting S2 and S3 without taking into account the future connection of S1. Expected capacity estimates of S2 and S3 are used to design the network.
- Design strategy 2. Under this strategy the network will be developed after taking into account the possibility that S1 will join in the future.

Fig. 5 shows design concepts based on design strategy 1 and design strategy 2.

In both design strategies the decision makers analyze two major options: the option to defer (wait) and the options to expand. Table 1 shows the different types of uncertainties and the real options to mitigate their effect for both design strategies.

Developing the network based on design strategy 1 represents an investment opportunity. Therefore, it is a real option by itself. If a manager decided to invest, then the option is exercised by committing to an initial cost in exchange for a real asset that may pay a

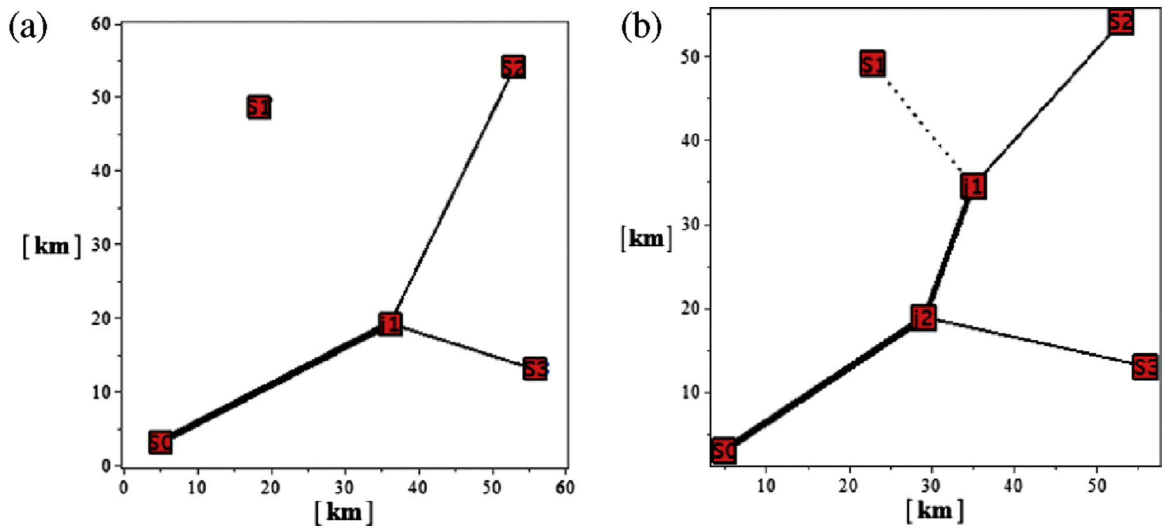

Fig. 5. Network layout concepts based on design strategy 1 (a) and design strategy 2 (b).

Table 1
Mapping sources of uncertainty to real options strategies.

Uncertainty type	Option to defer		Options to expand	
	Design strategy 1	Design strategy 2	Design strategy 1	Design strategy 2
Participant uncertainty	Yes (default)	Yes	No	Yes
Capacity uncertainty	Yes (default)	Yes	No	Yes

stream of future cash flows. In the case of design strategy 2, there is a freedom to exercise both real options. Similar to design strategy 1 the deferral option can be exercised in phase 1 and phase 2. In phase 2, if the investment opportunity of connecting S1 is not worthy, then it can be deferred.

As can be seen in Table 1 the major difference between the two design strategies is the expansion option. The expansion option is made possible by embedding real options in the initial network design. Real options require extra cost but could provide the network manager the right to accommodate S1 at lower overall cost. One real option can be embedded in the network by committing large-size pipes between nodes S0 and J2. Another real option can be embedded by laying out pipeline J1–J2–S2 instead of J2–S2. This option requires extra pipe capacity on line J2–J1 and extra length (i.e. the difference between J2–J1–S2 and J2–S2). Real options can also be considered in edge S2–J1 and edge S3–J2 by having extra capacity.

5.5.1. *Real options valuation*

To value the expansion option both design strategies are simulated using multiple scenarios of uncertain variables. The analysis takes the perspective of a network developer who invests in developing the CCS network for a profit. NPV is used to measure the performance of both design strategies. As shown in Eq. (5), NPV depends on the flow from each source and the total cost of the network. The present value of revenue is calculated using Eq. (4). It is a function of the total flow rate of CO_2 which is uncertain. The total flow model is obtained by adding the distribution of the three sources defined in step 2 (as shown in Figs. 2 and 3). Let S_t represent the distribution of the total flow. Since the sum of the independent normal distributions is again a normal distribution, S_t has normal distribution. The mean μ_t and variance var_t of S_t are given as

$$\mu_t = \frac{1}{n}\sum_{i=1}^{n}\mu_i \quad \text{and} \quad var_t = \frac{1}{n^2}\sum_{i=1}^{n} var_i, \quad i \in (1, 2, 3) \qquad (7)$$

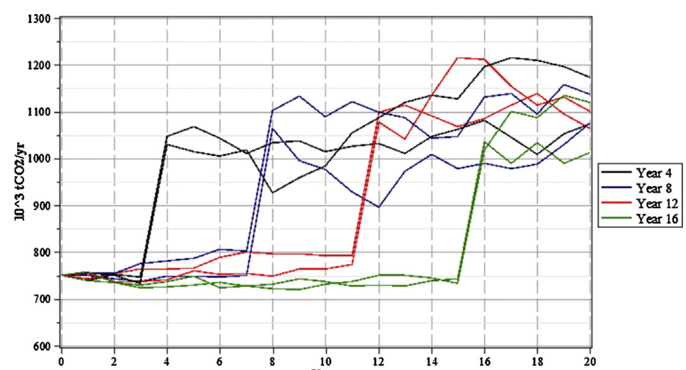

Fig. 6. Flow paths of S_t for the four scenarios (S1 joins at Year 4, Year 8, Year 12, or Year 16).

n=2 in phase 1 and n=2 in phase 2. Fig. 6 shows simulation of paths of S_t (out of 200 paths, single sample paths are shown for clarity).

In phase 1, the total cost of the worth maximizing networks of both design strategies is calculated using Eq. (2). In phase 2, if the deferral option is not exercised, additional costs are made to connect S1 to the network. Let C_{t1} represent the cost of the worth maximizing network in phase 1 and C_{s1} represent the present value of the cost made to connect S1. Then, the total cost of the network in phase 2, CT_{t2} is calculated as

$$CT_{t2} = C_{t1} + (C_{31})_Y, \qquad Y \in (4, 8, 12, 16) \qquad (8)$$

In design strategy 1, C_{31} is the cost of edge S1–S0 and in design strategy 2, C_{31} is the cost of S1–J1 (the dotted line). The value of C_{31} depends on the year (Y) in which S1 is connected to the network.

The two design strategies are evaluated by simulating the network model using different scenarios of S_t. Both design strategies were simulated for 200 times. We sorted the 200 NPV results of each design strategy and plotted them as cumulative probability distribution curve, see Fig. 7. For this analysis we assume connection cost

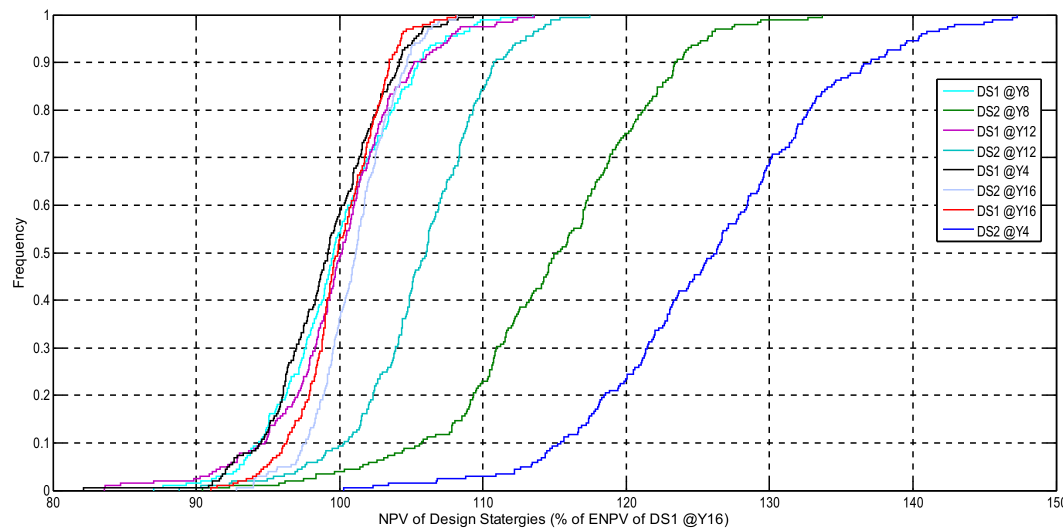

Fig. 7. Cumulative probability distribution curve of NPVs (*Y* stands for Year, DS1 and DS2 stands for design strategy 1 and design strategy 2, respectively. For example, DS1@Y4 mean design strategy 1 and S1 join the network at Year 4)

Table 2
ENPVs of design strategies 1 and 2 and EVRO (in 10^3 Euros) under the four time scenarios.

	Year 4	Year 8	Year 12	Year 16
ENPV design strategy 2	126 ± 8	115 ± 7	106 ± 6	101 ± 3
ENPV design strategy 1	103 ± 4	102 ± 5	101 ± 4	100 ± 3
EVRO	23 ± 9	13 ± 8	5 ± 7	1 ± 3

of $\alpha = 1$ €/t and a real (i.e. excluding inflation) discount rate of 7%, a figure commonly used by the World Bank (Blanchard, 1993). From the distribution of NPVs, the expected NPV (ENPV) is calculated. The ENPV based valuation technique adjusts for uncertainty by calculating NPVs under different scenarios and probability-weighting them to get the most likely NPV. For the purpose of comparison the NPVs of the two designs are normalized against the expected net present value (ENPV) of design strategy 1 at year 16.

The expected value of the real options (EVRO) is calculated using Eq. (9). It is defined as the difference between the ENPV of design strategy 2 and the ENPV of design strategy 1. Table 2 shows the normalized ENPVs of the two design strategies and the expected value of real options.

$$\mathrm{EVRO} = \mathrm{ENPV}_{\text{design strategy 2}} - \mathrm{ENPV}_{\text{design strategy 1}} \tag{9}$$

From Table 2 and Fig. 7, it can be seen that the ENPV (frequency = 0.5) of design strategy 2 is higher than design strategy 1 in each of the four scenarios. This indicates that embedding real options in the physical design enables cost effective expansion as future capacity requirement increases. The real options are the redundant pipe capacities in the edges and their extra lengths which enable cheaper expansion. However, the difference between the two strategies decreases if S1 is connected later. For example, the EVRO decreases from 23 ± 9 at year 4 to 5 ± 7 at year 12. The decrease suggests that the economic value of those real options diminish with time. Embedding extra capacity and length at the beginning to connect S1 after 12 years becomes less worthy and even could result to a loss. As the time horizon for considering extra capacity requirement increases, the opportunity of cost of the real options investment (the premium) increases exceeding the expected return.

In Fig. 7, it can be seen that the difference between the two design strategies increases when we move up from the expected value. Since NPV is directly related to flow rate, the increasing difference suggests that the value of the real options increases if flow from sources is higher than expected. The lower part of the curves shows that the difference between the two strategies continues to decrease when flow is lower than expected. When flow rate is lower than expected there will be unused physical capacity and that decreases the value of the real options. In such cases, a valuable decision could be to decrease the size of extra capacity or deferring the investment. Waiting until better information is available about the future flow of existing sources and the timing of new sources could be worthy. However, it is also important to mention that the value of waiting could be at odds with the value of early strategic commitment. Decision makers also take into account other strategic advantages in addition to the distribution of NPVs. For example, by investing in demonstration projects, 'early movers' could take a strategic advantage on future opportunities related to CCS technology compared with 'late comers', even though ENPV tells otherwise.

The expected values of real options in Table 2 provide some insight with regard to having expansion option decision without regrets. In commercial CO_2 pipeline design the 'no-regrets-period' of 10 years is used as a bench mark (Austell et al., 2011). Table 2 shows that the 'no-regrets-period' could be between 8 and 12 years. However, this study considers only uncertainty in future capacity requirements while other uncertain factors (e.g. discounting rate) are assumed as constant. If other uncertain factors, in addition to flow, are considered the 'no-regrets-period' is expected to decrease. On the contrary, the 'no-regrets-period' could increase, for example, if favourable governmental policy is in place and the cost of CCS technology reduces in the future.

So far, the value of having real options is measured using economic metrics, which is commonly used by project managers. However, the flexibility value of a CCS network can be more than its economic benefit to a single project owner. There can be added benefits for other subordinate stakeholders. For example, a flexible CCS network that is able to accommodate future emitters could mean less costly connections for the new emitters. In the case of design strategy 2, when S2 and S3 design the pipeline S0–J2–J1 with extra capacity to accommodate future flow increases, it reduces the cost to connect S1 to the sink. At the same time, the real option built into the network (i.e. the extra pipe capacity) will encourage the participation of new emitters like S1 by reducing some of the barriers, such as obtaining land permits for an independent pipeline. The participation of more emitters in the CCS network can be considered an added value for an environmental agency like the Rotterdam Climate Initiative whose objective is to reduce CO_2 emissions by creating a large-scale CCS network. If more emitters participate in the CCS network, it will lead to a reduction in the total CO_2 emissions.

6. Conclusions

The main aim of this paper is to provide a systematic design method to explore valuable real options in CCS networks to mitigate the effects of lock-ins as they expand over time. By referencing relevant literature, we show that the typical design and planning approach tends to focus on pre-defined requirements and often leads to inflexible and sub-optimal networks. This paper argues that one way to deal with less inflexible CCS networks is to adopt a real options-based design approach. In order to explore valuable real options, the paper presents an exploratory uncertainty analysis of network design architectures using a graph theory-based network model. This model provides easy and fast generation and assessment of various network design architectures under different uncertain scenarios. This is an advantage over most of the CCS network planning models, as were presented in Section 2 of this paper. This aspect of the network model is very helpful when designers have to assess thousands of design concepts under a combination of uncertain design parameters.

The proposed method helps to identify design elements and design strategies most likely to provide worthwhile flexibilities to mitigate path-dependencies and lock-in effects. Using a hypothetical CCS network for demonstration purposes, the method provides valuable insights to designers and decision makers on how to design CCS networks under capacity and participant uncertainty. It also helps to identify a need for extra capacity to accommodate future increases in capture targets by emitters. In our specific case study, we found out that building higher pipe capacity is valuable if there is an increase in future capture by emitters. Our analysis also shows that the method proposed could provide valuable insight into which parts of the network should include real options to accommodate future emitters. Physically built-in capabilities, such as extra pipe capacities and length, provide easy and cost-effective expansion option of the network when compared with a deterministic design approach (baseline). Another conclusion is that the value of identifying and imbedding real options in expanding CCS networks could extend beyond an improvement in an economic metric (e.g. an environmental value, by encouraging more emission reduction) and beyond a single stakeholder (i.e. not only to initial developers of the network but also to future participants).

The framework and methods introduced in this study can be generalized to the application of other pipeline-based network design problems such as gas pipeline networks, water distribution networks and district heating networks. These different networks are subject to distinct costs and benefits and faced with their respective sources of uncertainties; as a result, details of modelling and computation may need to be adjusted to suit the particular network at hand.

The network model could be expanded at the moment to accommodate multi-source, multi-sink CCS network design problems. In large CCS networks, multiple storage sites could be used, i.e. CO_2 could be stored in abandoned oil fields, consumed for enhanced oil recovery and consumed for agricultural and industrial purposes. Moreover, the utility of the network model can be improved by including CO_2 and pipeline properties, and taking into consideration no-go areas such as parks and residential areas.

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An Approach for Integrating Valuable Flexibility During Conceptual Design of Networks

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Abstract Energy and industrial networks such as pipeline-based carbon capture and storage infrastructures and (bio)gas infrastructures are designed and developed in the presence of major uncertainties. Conventional design methods are based on deterministic forecasts of most likely scenarios and produce networks that are optimal under those scenarios. However, future design requirements and operational environments are uncertain and networks designed based on deterministic forecasts provide sub-optimal performance. This study introduces a method based on the flexible design approach and the concept of real options to deal with uncertainties during conceptual design of networks. The proposed method uses a graph theoretical network model and Monte Carlo simulations to explore candidate designs, and identify and integrate flexibility enablers to pro-actively deal with uncertainties. Applying the method on a hypothetical network, it is found that integrating flexibility enablers (real options) such as redundant capacity and length can help to enhance the long term performance of networks. When compared to deterministic rigid designs, the flexible design enables cost effective expansions as uncertainty unfolds in the future.

Keywords Energy and industrial networks · Uncertainty modeling · Flexibility · Real options · Graph theory

1 Introduction

Networked energy and industrial infrastructures, such as district heating systems, pipeline-based carbon capture and storage infrastructures and LNG distribution

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networks, are often characterized by their long life span and huge societal impact as they are intended to provide essential goods and services for society. They transport a commodity (in this case liquid and/or gas) from one or several sources to one or several sinks. In some cases there are several sources and sinks involved and finding a configuration that maximizes value (e.g. lower cost) for developers is very difficult. In addition, during design exploration stage, not all participating sources and sinks nor the capacities they require are fully known. On the other hand, important decisions such as network architecture have to be made at the early stage and the presence of uncertainties makes this task very challenging.

When designing infrastructure networks under uncertain situations, there are two major systems engineering approaches: robust design and flexible design (de Neufville 2004). The robust design approach is a set of design methods intended to improve the consistency of an engineering system function across a wide range of conditions. One of these methods is robust optimization which aims at finding a solution that is robust or insensitive to the uncertainty considered and is thus an efficient solution practice (Mulvey et al. 1995; Ordóñez and Zhao 2007; Chung et al. 2011). The focus of robust optimization is to search for an optimal network that satisfies a fixed set of objectives such as shortest path and minimum cost (Desai and Sen 2010; Roy 2010; Chen et al. 2013; Tarhini and Bish 2015; Li et al. 2011). The method is widely applied to design infrastructure networks such as pipeline networks (Heijnen et al. 2014; van der Broek et al. 2010) and road networks (Szeto et al. 2013; Li et al. 2015). While optimization for cost is a required objective, a solution that is optimized based on fixed requirements is often found to be rigid and does not perform well when uncertainty is high (Goel et al. 2006; Zhao et al. 2015). On one hand, if future uncertainty turns out to be favorable, it will be difficult to easily expand and modify point-optimized solutions, which will amount to a lost opportunity. On the other hand, if the future turns out to be unfavorable, point-optimized solutions cannot easily be reduced in scale, which will amount to a waste of capital.

Another approach that recognizes and embraces the effect of uncertainty is flexible design (de Neufville and Scholtes 2011). Flexible design approach is a design concept that provides an engineering system with the ability to adapt, change and be reconfigured, if needed, in light of uncertainty realizations. The concept could be of help in the design of networks with the capability to pro-actively deal with uncertainties. In such sense, the concept of flexibility is similar to the concept of real options, which is defined as “the right, but not the obligation, to change a project in the face of uncertainty” (de Neufville 2003). Real options are flexibility enablers that provide capabilities to operationalize flexibility. When real options are embedded in the physical design of the network, they enable network developers to adapt the network in the face of uncertainty by utilizing the upside opportunities and minimizing the downside risks (de Neufville et al. 2006; de Neufville and Scholtes 2011). Moreover, (Cardin et al. 2015) real options analysis provides analytical tools to quantitatively assess the value of flexibility by allowing for objective evaluation of design concepts (de Neufville 2003). Therefore, unlike the robust design approach, which de-sensitizes design to future fluctuations and inherently encourages a reactive response, the flexible design approach is characterized by considering a wide range of possible future scenarios and by taking pro-active actions to mitigate and exploit uncertainty. There are several examples on applications of the flexible design approach in large-scale infrastructure systems (Babajide et al. 2009; Buurman et al. 2009; Deng et al. 2013; Lin et al. 2013; Cardin et al. 2015), thus demonstrating that incorporating flexibility considerably improves life cycle performance of engineering systems.

While the flexible design approach using the concept of real options is philosophically appealing and has been applied to various engineering systems, an efficient and effective flexible design generation and evaluation method is not apparent or readily available in the case of energy and industrial infrastructure networks. Networks have a special character in that they develop in stages and grow from simple to complex networks over several years. Therefore, network development is inherently path dependent. To this end, this article presents a method to systematically integrate flexibility in energy and industrial infrastructure networks based on the real options perspective. The method proposed involves three steps: exploratory uncertainty analysis, design flexibility analysis and sensitivity analysis. The three steps are based on simulation of a graph theoretical network model. The proposed method should be able to provide designers and decision makers with insights, early in the conceptual design stage, into how to design better (in economic value) networks in the face of uncertainty.

The rest of the paper is organized as follows. Section 2 discusses the motivation for applying the real options perspective to design flexible networks by reviewing the relevant literature. Section 3 presents the details of the proposed methodology. In section 4 the proposed methodology is demonstrated on a hypothetical pipeline-based network. Section 5 concludes the paper.

2 Literature Review

2.1 The Real Options Framework for Enabling Flexibility

As pointed out in the introduction section, energy and industrial networks have long life time and the future is more uncertain and difficult to forecast in long-term projects. On one hand, forecasts on long-term projects are 'always wrong' in that actual design requirements and the future environment will always vary from what has been anticipated (Flyvjberg et al. 2005). On the other hand, development activities that last long time give network developers considerable scope to decide on the size and timing of investments and to thus optimize and increase the targeted value of the project. The real options concept is based on a rationale that when the future is uncertain there is a value in having the "right, but not the obligation" to adapt future changes without making deterministic early commitments (de Neufville 2003). It provides a systematic framework for designers to make rational (though optional) decisions as to which flexible design elements and specific or combined flexibility types can be incorporated into the engineering system. (Zhao and Tseng 2003) apply the real options concept to the size the foundation of a parking garage when future demand is uncertain. The value of the parking garage with extra sizing includes not only its present value, but also the value associated with the option to add the extra floors (Wang 2006) used the real options concept to define the basic elements of flexibility in hydropower design (de Neufville et al. 2008) used the real options framework to increase the value of transportation systems.

Designing for flexibility involves defining a strategy and an enabler in design and management (Cardin 2014). A strategy represents aspects of the design concept that captures flexibility, or how the network is designed to adapt to changing circumstances. An enabler represents what is done to the physical infrastructure design and management to provide and use the flexibility in operations. In the context of engineering systems enablers are the real options. There are two major types of real options (Wang 2006). Options that involve technical design features are referred to as real options ‘in’ engineering systems and options that involve financial decisions on engineering projects are referred to as real options ‘on’ engineering systems (Wang 2006).

2.2 Identifying Valuable Real Options

Multiple sources of flexibilities (real options) exist in the design and management of infrastructure networks. These real options should be integrated into the network at the early stage of the design process to enhance the value of the network. The task of identification and integration of real options requires exploring and evaluating large sets of potential design configurations by generating different scenarios of uncertain variables. Depending on the scenarios, huge number of design alternatives can be generated. In networks, the temporal and spatial dimensions of future scenarios produce a large number of possibilities of designing the network and implementing flexibility decisions. Therefore, a method that enables designers to generate several initial design architectures before the final detailed design is required.

A set of procedures has been proposed in relation to designing and evaluating flexibility from real options perspectives (Ajah and Herder 2005) presented the adoption of the real options approach in the conceptual design stage of energy and industrial infrastructures, and provided a systematic procedure for real options integration. However, the paper does not provide a clear method on how to identify and screen the real options and how to define the added value of flexibility (Hassan and de Neufville 2006) presented a practical procedure for using real options valuation in the design optimization of multi-field offshore oil development under oil price uncertainty. To manage the large number of possible combinations and fine the optimal configuration a Genetic Algorithm is used. However, the procedure results in an optimal design, which tends to be robust for uncertainties and focuses very much on the value (price) of the options to select designs and only a little on how to identify and integrate the options.

A two-step procedure for identifying real options for offshore multi-oilfield development is presented by (Lin 2008). The procedure involves developing a screening model and a simulation model. The screening model is a non-linear programming, low fidelity model for identifying the elements of the system that seem most promising for options. The simulation model tests the candidate designs from runs of the screening model. It is a high fidelity model whose main purpose is to examine candidate designs under technical and economic uncertainties, the robustness and reliability of the designs, and their expected benefits. Both ways of identifying real options are meant simplifying the task of an early search for the most promising flexible design. More pertinent to our work, in terms of their approach for integrating flexibility, are the methods proposed by (Deng et al. 2013) for urban waste management system and for on-shore LNG production design. At the center of the proposed methods by the two papers is a design flexibility analysis procedure to improve the lifecycle performance of the design under uncertainty. However, both works deal with design problems that do not have network characteristics and do not provide enough insight for the kinds of problems that have spatial and temporal characteristics.

A method for addressing the problem of design under uncertainty for energy and industrial networks is presented by (Heijnen et al. 2014). The method proposed is a novel combination of graph theory and concepts of exploratory modelling for the analysis of most likely paths that maximizes the value of network designs. The method conceptualizes the design as a network problem by which the physical infrastructure is abstracted as consisting of nodes (e.g. producers and/or consumers) and links (e.g. pipelines). It takes into account uncertainty about the participants (participating or not), the location of participants and the capacity they require. The most important utility of the method is that it allows easy and fast assessment of low-regret options and quick re-assessment of these options should new information arrive that narrows down or expands these options. However, the method considers deterministic and discrete scenarios of uncertainty parameters and finds an optimal network configuration for each pre-defined scenario. Moreover, the method does not fully address the stochastic and dynamic nature of uncertainties and most importantly does not address the issue of flexibility: i.e. defining flexible strategies and identifying flexibility enablers.

In summary, a systematic methodology to integrate flexibility based on the concept of real options is missing in network design and management. Building on the network model developed by (Heijnen et al. 2014), this paper expands it by adding a more sophisticated uncertainty analysis and a design flexibility analysis procedures. The details of the method are presented in the next section.

3 Methodology

This paper introduces a method to integrate flexibility in the design of energy and industrial networks. The procedure consists of three concrete steps: exploratory uncertainty analysis, design flexibility analysis and sensitivity analysis. The objective of the proposed method is to enhance the value of networks by identifying and integrating valuable flexibility elements. Figure 1 shows the proposed method.

3.1 Step 1: Exploratory Uncertainty Analysis

This step consists of characterization of major uncertainties, modelling and simulation the network, and design analysis.

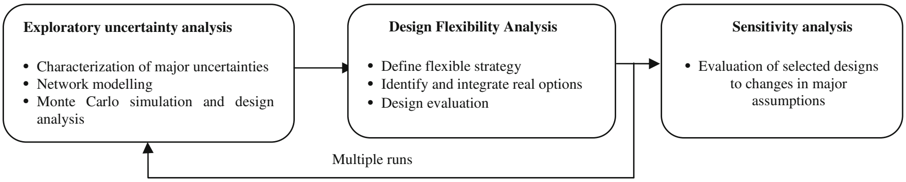

Fig. 1 Proposed method for flexible design of networks

3.1.1 Characterization of Major Uncertain Variables

The objective of uncertainty characterization is to model initial distributions and future trajectories of selected uncertain variables. In order to define initial distributions of selected uncertain variables two approaches are often employed: data-driven and an analytical. Data-driven approach requires large quantity of historical data and applies statistical methods (e.g. regression) to fit the empirical model. The analytical approach is more useful in the absence or limitation of full historical data the analytical. It requires making initial estimations on the behavior of uncertain variables (i.e. types of distribution and speed of convergence). The initial estimates are then transformed to a probability distribution, such as a normal distribution, characterized by a vector containing the moments of the distribution (means and variances).

Modelling the future trajectories of uncertain variables requires defining their states over a planning period of the network. The future states can take continuous or discrete behavior. To model continuous behavior, stochastic processes such as Geometric Brownian Motion (GBM) and Wiener processes are often used (Ibe 2013). To model discrete behavior, lattice model can be used (Albanese and Campolieti 2006).

3.1.2 Network Modeling, Simulation and Design Analysis

To generate network design concepts a network model is developed and exploratory simulations of uncertain variables are carried out. In this study a graph theoretical network model (Heijnen et al. 2014) is employed. The model is effective in conceptualizing energy and industrial infrastructures as networks consisting of nodes (e.g. production and/or consumption sites) and links (e.g. pipelines). Monte Carlo simulation of uncertain variables over the network model is carried out to generate multiple network design concepts. The main inputs of the model are the spatial positions of source and sink nodes and flow rate from sources. The outputs of the simulation are minimum-cost tree-shaped network configurations. The resulting network configurations are edge-weighted Steiner minimal tree-shaped networks. An edge-weighted Steiner minimal tree network is a minimum cost network that takes into account the effect on the cost of both the capacity and the length of edges. The details of the graph theoretical network model employed are explained in section 4.2.2.

3.2 Step 2: Design Flexibility Analysis

In this step the concept of flexibility is employed to improve the life cycle performance of network designs selected in step 1. It involves defining flexible strategies, identifying real options to enable these flexible strategies and evaluating designs. Flexible strategies are the actions decision makers can take when a particular path of uncertainties is realized (e.g. expand the capacity of a network if a new participant joins the network in future) (Jablonowski et al. 2011). The actions of decision makers are defined as decisions rules in the network model. The decision rules are triggering mechanisms or "if" statements that specify clearly when flexible strategies will be exercised depending uncertainty realizations (Cardin et al. 2013).

To enable flexible strategies, it is necessary to identify and integrate valuable real options. There are several real options that might lead to flexibility. We listed some of the real options relevant in the context of networks.

- **Option to expand/contract**: the option to expand/contract seems useful vis-à-vis the flexibility needs of infrastructure networks as they are often developed in phases. For example, overbuilding the capacity of a large-diameter pipeline in earlier period in order to have the flexibility to accommodate increasing capacity requirements in later period.
- **Option to defer**: in the presence of irresolvable uncertainty (at least within the decision time frame) it could be interesting to wait and invest later. This is a typical (wait and see) real option which projects managers exercise often when information about important uncertain variable(s) is not well known.
- **Options to abandon**: is it at any point in time possible to abandon the investment? This includes options not to commit further assets.
- **Options to switch**: What are the main inputs and outputs of this project? Is it possible to accommodate multiple inputs or outputs so that it is possible to switch later? For example, is the pipeline material able to handle liquid and gas phase substances as required?

The final activity in this step is to evaluate designs with real options. The evaluation helps to determine the cost of implementing real options for the desired flexibility and to decide the appropriate time to exercise the real options. In literature, different kinds of methods are proposed to evaluate real options (de Weck et al. 2004) applied binomial tree approach to obtain the value of real options in stage deployment of communication satellites (Babajide et al. 2009) used decision tree method to evaluate the value of flexibility in oil deployment projects. The binomial approach has limitations in that it assumes path-independency which does not hold in engineering systems and decision tree analysis suffers from intractable computations as the number of decision-making periods and states increases. Recently, simulation based methods are being adopted for valuing flexibility in oil field developments (Lin 2008; Jablonowski et al. 2011), and water management systems (Deng et al. 2013). In this work a simulation approach is adopted as it can be more generally applied, since it has fewer restrictions on the number of time periods and the distribution of uncertainties. Besides, the simulation approach considers decision rules as explicit variables in the modelling framework, so that the model itself can be more easily modified to capture more diverse design configurations.

3.3 Step 3: Sensitivity Analysis

In this step, sensitivity analysis is performed in order to examine how the results obtained following the above steps respond to changes in underlying assumptions. This step can be seen as a way to test the robustness of the design alternatives in response to the variation that may happen to the assumptions. There are standard mathematical (Czitrom 1999), statistical (Saltelli et al. 2000) and graphical (Canon and McKendry 2002) methods to perform sensitivity analysis. These sensitivity analysis methods can be carried out on global or local variables. One-factor-at-a-time method (Czitrom 1999), which addresses the parameter sensitivity relative to the point estimates chosen for the parameters held constant, is used in this work. The one-factor-at-a-time method is more convenient than the other methods because it enables to analyze the effect of one parameter on the dependent variable at a time by keeping other parameters constant.

4 Application

This section demonstrates the proposed simulation framework by applying it on a hypothetical pipeline based network. The hypothetical case is inspired from an initiative to collect carbon from distributed emitters using pipeline network in Rotterdam area, the Netherlands. However, the case could represent any network consisting multiple sources and a single sink such as district heating networks and (bio)gas networks to mention a few.

4.1 Description of the Design Problem

The hypothetical field has three sources S1, S2 and S3 and one sink S0. Figure 2 shows the position of the three sources and the sink on a 60 by 60 Km field. The objective is to build a pipeline network which transports material X[1] from supply points (sources) to a single demand point (physical sink). The design problem takes the perspective of a private developer whose objective is to make profit by connecting the spatially distributed sources to a sink. During the design exploration phase the future flow rates of existing sources and the capacities they require are uncertain. Moreover, the timing and flow rate of future sources is also uncertain. For example, in carbon capture networks, connected emitters increase their CO_2 capture targets with time. Moreover, most carbon capture networks are expected to expand by adding more emitters in the future.

The demonstration tries to answer the following design questions that could be asked by network designers and network developers.

1. What is the most cost-effective strategy for phasing the network to meet increasing flow from existing and future sources?
2. How to strategically design the network to be able to coordinate the capacities of source facilities, pipelines, and the sink as the network expands over time with new sources joining the network?
3. Is overbuilding capacities with large-diameter pipeline early in the design in order to accommodate future flow increase from sources making economic sense?
4. Is it worthy to wait a new source to join the network and for how long?

The objective of this work is then to design networks that provide enhanced value for the investor given the uncertainty in flow rate from existing sources and future new sources.

[1] By material we mean flowing matter in gas or liquid state.

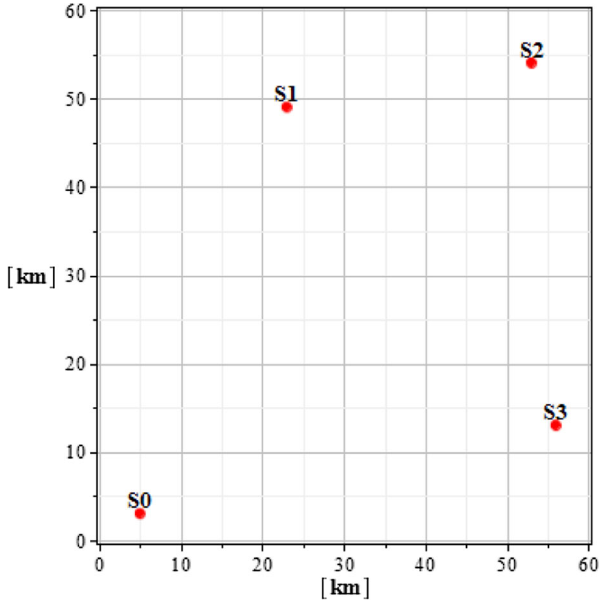

Fig. 2 Layout of the hypothetical field

In order to answer the above questions we specify the design problem scenario such that S2 and S3 are existing sources and S1 will join at some unspecified future time. The economic lifetime of the network is limited to 10 years. The rest of this demonstration is to apply the methodology proposed in the previous section with the aim to design a network that provide enhanced value for the investor given the uncertainty (1) in flow rate from existing sources (i.e. S2 and S3); and (2) timing and flow rate of the future new source (i.e. S1).

4.2 Step 1: Exploratory Uncertainty Analysis

The objective of this step is to model the major uncertainties and explore their effect on the performance of design alternatives. In this study we focus on two major uncertainties: (1) stochastic behavior of flow rate from existing sources, hereafter called flow uncertainty, and (2) the uncertainty in new source(s) that may join the network in the future called participant uncertainty. Flow uncertainty represents flow rate changes from existing sources over the economic lifetime of the network, for example, increase in capture targets from CO_2 emission sources. Participant uncertainty represents the uncertainty in the timing of new sources and their flow rates.

4.2.1 Characterization of Major Uncertainties

Flow Uncertainty Flow uncertainty is due to the stochastic nature of volume flow rates of sources over the life time of the network. An evolutionary path of volume flow rate over time is an external variable that can influence the capacity of the pipe required for connecting a source. It could vary with time given the long life time of such projects. For example, flow from a CO_2 producing power plant may increase due to stage-wise increases in emission reduction targets; and flow from a bio-gas producing field could decease due to reduction of substrate. Flow uncertainty model is used to generate possible future trajectories of volume flow rates from sources. First, the flow behavior of the three sources at a given instant in time is modelled using a normal distribution. Initial flow estimates of sources are:

- S1: mean 100 m^3 tone/year and standard deviation 20 m^3 tone/year.
- S2: mean 400 m^3 tone/year and standard deviation 100 m^3 tone/year.
- S3: mean 350 m^3 tone/year and standard deviation 70 m^3 tone/year.

Next, Geometric Brown Motion (GBM) process is used to model the evolution of flow rate from the three sources over an investment period life time of 10 years. Initial values are taken by randomly sampling from the initial. To generate the evolutionary paths the expected drift rate of 1 % and volatility of 30 % are assumed for all the three sources. In each simulation, the GBM model produces future flow evolution volume flow rate values. Figure 3 shows initial flow estimate model of the three sources and one instance of the future flow rates of the three sources over a 10 year time period. The sink is assumed to have significant capacity to absorb all flows from existing as well as future new sources.

Participant Uncertainty Participant uncertainty represents the uncertainty arising from new source(s) that may join the network in the future. The uncertainty originates from two dimensions: spatial and temporal. Spatially, the new participant could assume any geographical position relative to the existing network. Temporally, the new source could join the network at any time within the technical life time of the network. For designers, both dimensions of participant uncertainty could result in infinite possibilities of network configuration alternatives. As a result, the identification and evaluation of design options is extremely difficult, if not computationally intractable. For simplification, we assume that the new participant will be S1 and this will avoid the spatial uncertainty. With this simplification the uncertainty will be in the time S1 will join the network.

Figure 4 shows 3 instances (years 3, 5 and 7) of the flow evolutionary path of S1. It represents a model of the uncertainty in the year S1 may be connected to the network. The objective is to explore for value maximizing configuration of the network if S1 does not exist at the beginning but appear after sometime within the 10 years period.

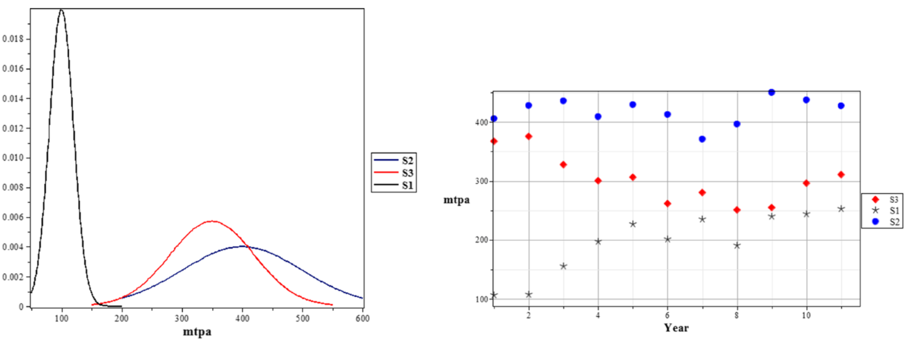

Fig. 3 Initial flow estimate model of sources (*left*) and one instance of the evolution of flow of the three sources over a 10 year period (*right*)

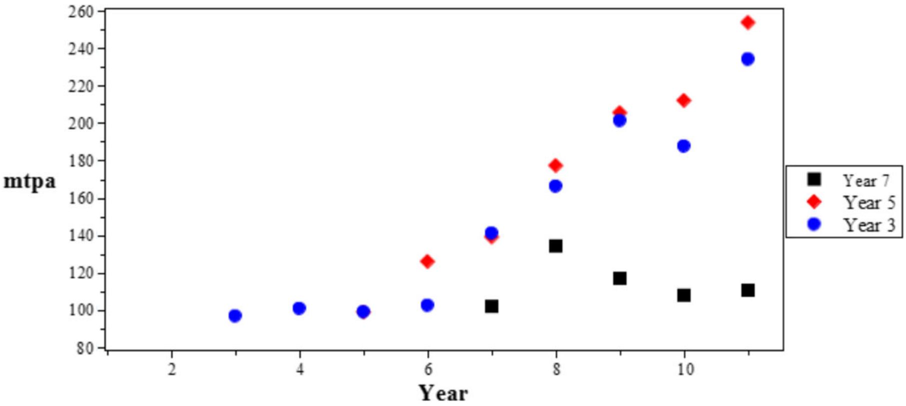

Fig. 4 One instance of S1 joining a network at year 3, 5 and 7 and its flow evolutionary path

4.2.2 Network Modelling

As indicated in the methodology section, in this study we developed a network model based on the concept of graph theory. In a graph theory representation of networks, sources and sinks are nodes (e.g. bio-gas fields and gas consumption sites) and their connections are edges (e.g. pipelines). To determine the investment cost of the network the model uses flow-dependent model, as in (Heijnen et al. 2014). Hence, to generate a minimum-cost edge-weighted Steiner minimal network, the network algorithm uses the following cost function of edges as in.

$$C_e = l_e q_e^{\beta} \tag{1}$$

In Eq. 1, l_e is the length and q_e is the capacity of an edge e. β is the cost exponent for the capacity with $0 \leq \beta \leq 1$. If $\beta = 0$, the capacity of the pipelines has no influence on the cost. If $\beta = 1$, building two pipelines of capacity 1 is just as expensive as building one pipeline of capacity 2. A value of $\beta = 0.6$ is commonly used (Heijnen et al. 2014), indicating that there are economies of scale to building high-capacity pipelines. Then, the total investment cost $C\ (T)$ of a network T is sum of all connection costs as given in Eq. 2.

$$C(T) = \sum\nolimits_{\forall e \in E(T)} l_e q_e^{\beta} \tag{2}$$

where $E\ (T)$ is the set of all edges in a network tree T.

In addition to cost, it is also necessary to calculate the expected income of the network. A revenue model that calculates the expected income as a linear function of capacity required by the source is used. The assumption is that the network developer generates income by charging a certain fee per unit capacity. The expected income (EI) from a network T is then given as:

$$EI(T) = \alpha \sum\nolimits_{i \in V(T)\%\{s\}} q_i \tag{3}$$

In Eq. 3, q_i is the used capacity by a source i in a network T, V(T) is the set of all nodes in the network T, s is the sink and α is the constant coefficient representing, for instance, a constant fee per a unit volume of liquid/gas charged by the network developer. In this demonstration we assumed $\alpha = 1$ (see section 4.4 for a sensitivity analysis with varying α).

The total income from a given network in its life time is calculated as a summation of discounted yearly income flows over the 10 years period. The interest rate of $r = 8\ \%$ is used for this demonstration. The sum of the discounted cash flows is the present value of income (PVI).

$$PVI(T) = \alpha \sum_{t=0}^{n} \frac{\sum q_i}{(1+r)^t} \tag{4}$$

The life time performance of a network under a given scenario of an uncertain parameter is evaluated using the Net Present Value (NPV) metric.

$$NPV(T) = PVI(T) - C(T) \tag{5}$$

4.2.3 Monte Carlo Simulation and Design Analysis

In this section, Monte Carlo simulation of the network model is carried out by varying flow scenarios. Given the low flow rate from S1 at the beginning and the uncertainty in the time it may join the network, the following two design strategies are proposed: committing design strategy (CDS) and abandoning design strategy (ADS). Under the CDS the network will be designed by connecting all the three sources and in the case of ADS the decision is to connect S2 and S3 only by abandoning S1. The inputs of the model are yearly flow rate values from each sources over 10 year period and the spatial position of the sources and the sink. The simulation results in minimum-cost tree-shaped network configurations connecting source nodes to the sink.

Figure 5 (left) and Fig. 6 (left) show density diagrams of 10 network configurations based on a single flow evolutionary path (scenario) under CDS and ADS respectively. Each network configuration is an edge-weighted Steiner tree generated by taking flow rate values at each year of a single flow evolutionary path. The simulation outputs provide designers a better insight into what would be the optimal configuration of the network, not only based on the values of design variables at the time of design but also in multiple future stages.

However, in practice networks are path-dependent, i.e. the state of a given network at later stage is dependent on the decisions made in earlier stage. Network developers will not build one network in year 1 and another network in years after that. Then, the question becomes, how to select the network that provide maximum value over a given scenario?

One way to select the network that maximizes value among several design alternatives is to use a preliminary economic evaluation technique the Present Worth Ratio (PWR), as in (Heijnen et al. 2014). The PWR illustrates the efficiency in the invested

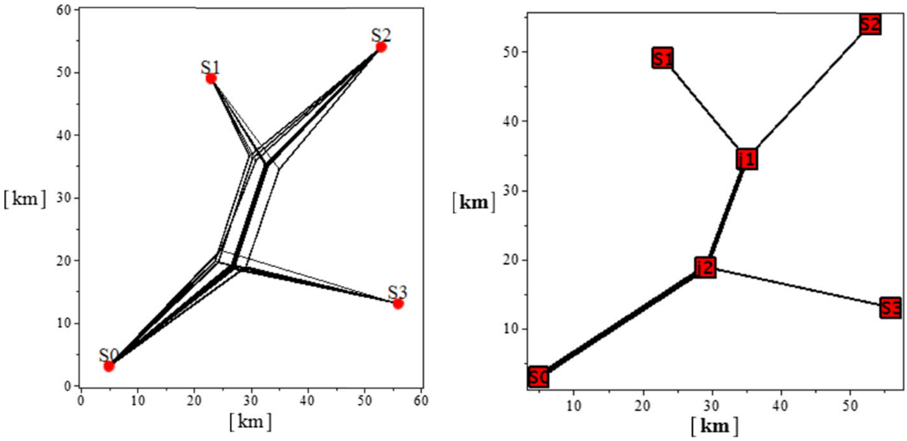

Fig. 5 Network configurations under the committing design strategy: density diagram of multiple network configurations (*left*) and the value maximizing network (*right*)

capital by taking into account the investment cost and the expected revenue of a network over a fixed period of time.

$$PWR = \frac{Expected\ revenue - Investment\ cost}{Investment\ cost} \tag{6}$$

Figure 5 (right) and Fig. 6 (right) show the network that maximizes value out of the 10 configurations under CDS and ADS respectively. The thickness of edges indicates their capacity. Monte Carlo simulations of the network model results in multiple value maximizing networks and their respective economic performances (i.e. cost and PWR values). 200 different flow path scenarios are simulated resulting 200 optimal networks for each design strategy. Then, the value maximizing network with a highest PWR is selected. This step is used to screen network design alternatives that make economic sense given the future evolution of flow. It serves a preliminary design exploration step

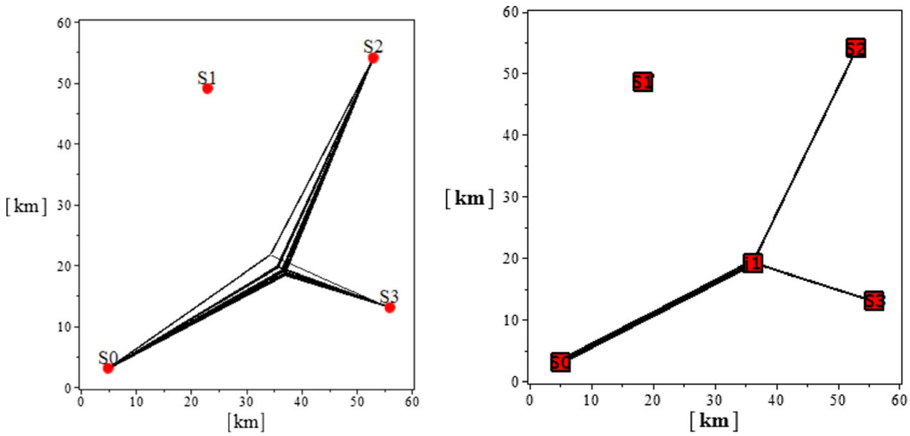

Fig. 6 Network configurations under the abandoning design strategy: density diagram of multiple network configurations (*left*) and value maximizing network (*right*)

by simulating different uncertain scenarios. Exploring multiple design concepts using multiple scenarios provides decision makers with a better insight into the effects of uncertainty compared to a deterministic design based on a single scenario or a few pre-defined scenarios.

Once the networks with the highest PWRs are selected for both design strategies, their life-time economic performances are evaluated over multiple uncertain scenarios. Net Present Value (NPV) metric is used to evaluate the economic performance in this study. 200 Monte Carlo simulation runs were carried out to compare the economic performance of both design strategies. The 200 NPVs of both design strategies are plotted as cumulative distributions, or also known as target curves, see Fig. 7. Moreover, from NPVs of each design strategy, the corresponding expected net present values (ENPVs) are calculated. The ENPV is the most likely NPV (i.e. NPV at 50 % probability in the cumulative distribution curve) calculated by probability-weighting NPVs. The two design strategies are also compared using other economic metrics as shown in Table 1. For the purpose of comparison, the NPVs of the two designs are normalized against the expected net present value (ENPV) of the abandoning design strategy.

From Fig. 7 and Table 1 it is clear to see that the committing design strategy results in a better NPV than the abandoning design strategy. The value enhancement suggests that the revenue obtained from S1under the committing design strategy outweighs the avoided cost of connecting S1 under the abandoning design strategy. Even though abandoning design strategy helps to avoid revenue risk due to the low flow rate of S1 at the early years, it loses the opportunity that may be obtained due to future flow rate increases. However, this conclusion is only valid under flow uncertainty. Under participant uncertainty abandoning design strategy is the only realistic solution of the two strategies. If the network is developed based on abandoning design strategy and a new source wants to join after some years, then the design will not be able to accommodate it. The only possibility is to make a connection directly to the sink. In such a case, the cost will increase and the overall performance of the network will even further decrease.

In addition to NPV (ENPV, minimum NPV and maximum NPV), Capital expenditure (CAPEX) can provide valuable insight during decision making. For example, the NPV of the network under CDS is higher than ADS. However, ADS requires a lower CAPEX than CDS and that can be a factor in decision making.

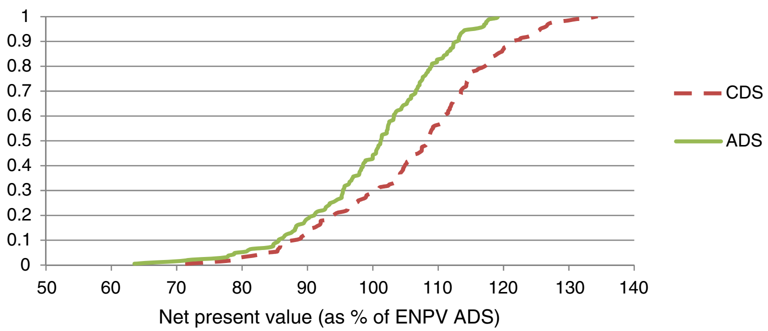

Fig. 7 Target curves for the two design strategies (connection fee $a = 1$)

Table 1 Summary of statistics for the two designs strategies (% of ENPV or as % of initial CAPEX of ADS)

Parameters	ENPV	Min NPV	Max NPV	Initial CAPEX	Min CAPEX	Max CAPEX
Committing design strategy	106 ± 6	72 ± 6	134 ± 6	116 ± 8	110 ± 8	128 ± 8
Abandoning design strategy	100 ± 4	64 ± 4	119 ± 4	100 ± 5	95 ± 5	108 ± 5

4.3 Step 2: Flexibility Analysis

The objective of this step is to further enhance the life time performance of the network given the two uncertainties defined in step 1. It involves defining flexible strategies, identifying real options to enable these flexible strategies and evaluation of designs with real options. A stage-wise development of the network with expansion options is defined as a flexible design strategy (FDS).

4.3.1 Identification of Real Options

To enable the flexible design strategy two real options are identified: expansion option to accommodate future flow increases from all sources and an option to delay the connection of S1. The two real options enable the network to pro-actively manage flow and participant uncertainties. If S1 exists but its flow rate remains low in the future delaying its connection could be valuable. If S1 exists and its flow rate increases in the future or if S1 does not exist at the beginning but appear later in the future the expansion option could be valuable. The expansion option is made possible by embedding redundancy in the length and capacity of the network. Having the expansion option may require more initial capital but could give the network manager the right to accommodate future connection of S1 at lower overall cost.

Figure 8 (left) shows 10 different layouts of the network connecting the three source points with the sink. It can be seen that S1 is not connected to the network all the time. The simulation showed that connecting S1 is not worthwhile before year 5 given its low flow rate. One strategy to design the network is to start by connecting S2 and S3 with an option to connect S1 in the future. We call this strategy as the flexible design strategy. Figure 8 (right) shows the layout of the network under the flexible design strategy. A dotted line is used between node S1 and node J1 to represent future connection of S1. Real options are embedded in the network by committing large-size pipes between nodes S0 and J2, i.e. laying out line J1-J2-S2 instead of J2-S2. Both options require extra pipe capacity on line J2-J1 and extra length (i.e. the difference between J2-J1-S2 and J2-S2). Real options can also be considered in line S2-J1 and S3-J2 by having extra capacity to handle future flow rate increases. When the flow from S1 makes an economic benefit the developer can build the pipeline J1- S1. The redundant pipeline capacities and lengths embedded in the network enable the network developer to exercise stage-wise expansion strategy.

4.3.2 Design Evaluation

The performance of the three design strategies is evaluated using flow and participant uncertainty scenarios define in step 1. NPV is used to compare the

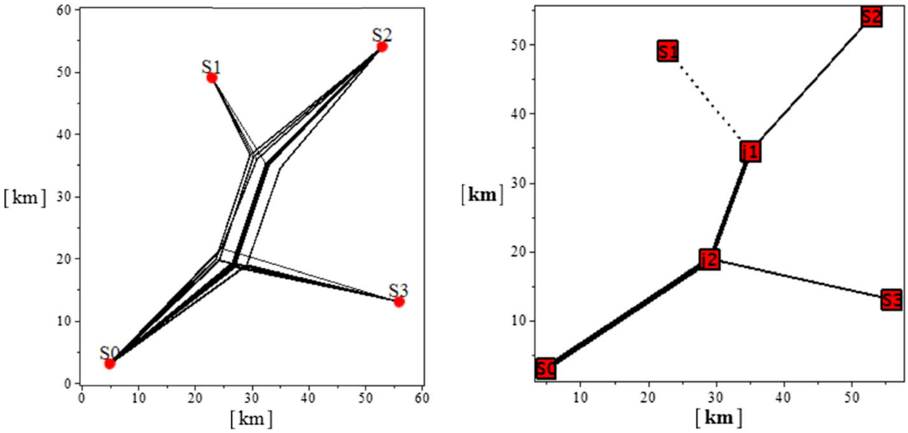

Fig. 8 Density diagram of network layouts (*left*) and the layout of the network under the flexible design strategy (*right*)

performance of the three design strategies. 200 Monte Carlo simulations are carried out resulting in 200 NPVs for each design strategy. Then, target curves are plotted based on the 200 NPVs. Moreover, from NPVs of each design strategy, the corresponding expected net present values (ENPVs) are calculated. The ENPV is the most likely NPV (i.e. NPV at 50 % probability in the cumulative distribution curve) calculated by probability-weighting NPVs. In addition to ENPV, decision makers also use capital expenditure (CAPEX) to evaluate design strategies. Table 2 shows ENPV and CAPEX of the three design strategies.

Under Flow Uncertainty From Fig. 9 and Table 2 it can be seen that the flexible design strategy performs much better than the two rigid design strategies. The sources of improvement in performance are from the flexibility that enabled by the real options built in the edges and lengths of the flexible design strategy. The real options help to reduce down side risks such as commitment to big pipeline capacity when flow from S1 is low. They also help to capitalize on the upside opportunity when the flow from S1 increases. Therefore, the improvement in performance of the flexible design strategy when compared to the other two design strategies can be considered as the value of the real options (*VoRO*). The value of the real options is calculated by subtracting the ENPV of the rigid design

Table 2 Summary of statistics for the three designs strategies (expressed as % of ENPV ADS or as % of initial CAPEX of ADS)

Parameters	ENPV	Min NPV	Max NPV	Initial CAPEX	Min CAPEX	Max CAPEX
Flexible design strategy	144 ± 10	111 ± 10	174 ± 10	105 ± 6	98 ± 6	112 ± 6
Committing design strategy	106 ± 6	72 ± 6	134 ± 6	116 ± 8	110 ± 8	128 ± 8
Abandoning design strategy	100 ± 4	64 ± 4	119 ± 4	100 ± 5	95 ± 5	108 ± 5

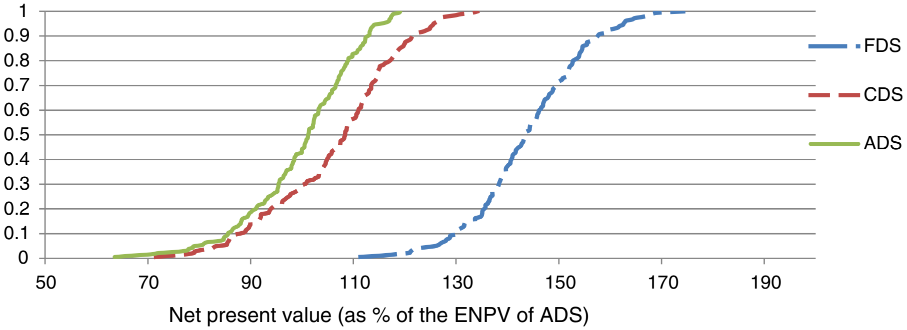

Fig. 9 Target curves of NPVs of the three design strategies (connection fee $a = 1$)

strategies from the flexible design strategy, see Eq. 7. Appendix shows how cost and revenue are calculated to decide the value of real options.

$$VoRO = ENPV_{flexible\ design} - ENPV_{rigid\ designs} \tag{7}$$

From Table 2 it can be seen that the flexible design requires a lower initial CAPEX when compared to the committing design strategy but a higher initial CAPEX when compared to the abandoning design strategy. The committing design strategy is the most expensive of the three. Initial CAPEX could be an important factor when evaluating designs and the flexible design strategy reduces costly initial commitments when uncertainty about the future flow evolution of S1 is higher.

The initial CAPEX of ADS is comparatively smaller than the other two design strategies largely due to the fact that there is no connection to S1. Even though, the strategy minimizes investment cost in the early years compared to the CDS and FDS, it loses significant revenue from future increases in flow rate of S1. However, in ADS S1 may join the network when information about S1 is known. However, under such scenario connecting S1 requires building dedicated pipeline directly to sink. As a result of such practice, the network could provide much inferior value when compared to the FDS and the CDS.

Under Participant Uncertainty The time a new participant could join the network has an effect on the value of the overall network. A comparison is made between the FDS and ADS, as the CDS is not realistic solution, in this case. The analysis is carried out for scenarios on which the new source (S1) joins the network in years 3, 5 and 7. The performance of the two design strategies is shown using cumulative probability distribution of NPV, see Fig. 10.

It can be seen from Fig. 10 that the ENPV of the FDS is higher than the ADS in each of the three scenarios. However, the superiority of FDS over ADS diminishes as the time for connecting S1 is delayed. The curve below P50 (i.e. the lower half of the target curve) shows that the risk of FDS increases faster than the risk of ADS if the connection to S1 is further delayed from Y5 to Y7. In such cases, it does not make economic sense to build a real option that can be exercised only after a long period of time as the value of the option diminishes with time.

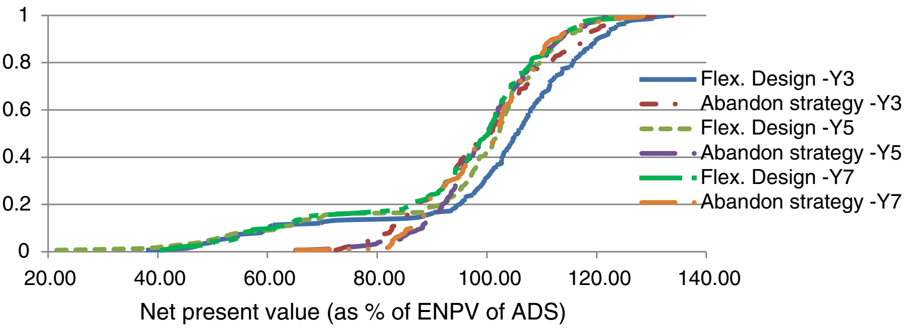

Fig. 10 Target curves for the two design strategies for year 3, 5 and 7. (NB: Y3 – year 3, Y5-year 5, Y7-year 7)

In real pipeline network design, decision regarding the time period to consider extra capacity to accommodate future new sources is called 'no-regrets-period'. The 'no-regrets-period' depends on the profitability of the fluid flowing through the network and varies from one case to another. In carbon capture networks, the 'no-regrets-period' for having redundant pipe capacity extends up to 10 years based on the current CO_2 price (Austell et al. 2011). In natural gas networks, the 'no-regrets-period' can extend beyond 15 years.

The analyses of the design strategies under flow uncertainty and participant uncertainty show that there are values to be gained from flexibility. Mainly, there are two flexibility enablers (real options) that can built in the physical design. The first is the extra diameter in edges, required for accommodating future flow rate increases from existing sources and new connections. The second is the extra length that is built in the configuration. These real options anticipate increases in flow rate from existing sources that are not financially feasible to connect at the beginning due to their low flow rate and from new sources that could join in the future. Flexibility would not be possible if designers do not plan and embed those real options at the early stages of the design process.

4.4 Step 3: Sensitivity Analysis

In this step sensitivity analysis is carried out to examine how the three design strategies depend on assumptions. Specifically, the sensitivity of the performance of the three design strategies to the connection fee (α) and the initial flow estimate are considered.

4.4.1 Sensitivity to the Connection Fee

The connection fee value is varied to check its effect on the performance of the flexible design compared to the rigid designs. The connection fee is the amount paid by sources per unit capacity. In other words the connection fee is the price that is charged by the network developer. Figure 11 shows the relative performance (in terms of NPV) of the three design strategies at various connection fee values. The network model is simulated 200 times for each connection fee values. For the purpose of comparison the NPVs of the three designs are normalized against the ENPV of the abandoning design strategy at $\alpha = 1$.

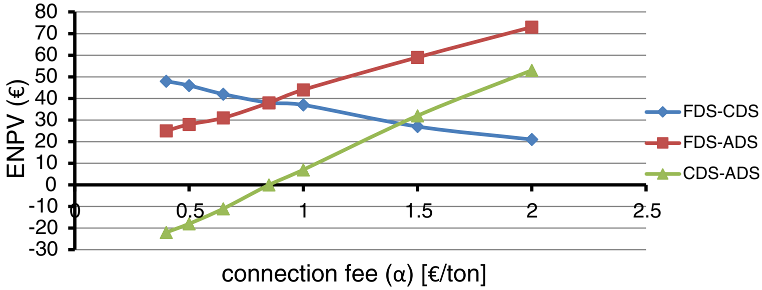

Fig. 11 Effect of connection fee on the performance of design strategies

Figure 11 it is clear to see that the difference between the flexible design strategy and the abandoning design strategy increases when the connection fee increases. The cause of this relationship is mainly due to the increase in revenue as α has a linear relationship with revenue. At low α the difference between the committing design strategy and the abandoning design strategy becomes negative. The negative value implies that, as the connection fee decreases, the abandoning design strategy becomes more valuable than the committing design strategy for the network developer. On the other hand, the flexible design strategy performs better than the abandoning design strategy on all α values. However, as α decreases the difference between the flexible design strategy and the abandoning strategy decreases. Another observation from Fig. 11 is that the difference between the flexible and the committing design strategies decreases when the connection fee increases. The decreasing trend is due to the fact that as α increases its effect on the revenue increases. That means the value of early commitment increases with increasing α.

4.4.2 Sensitivity to Initial Flow Estimate

In this section the effect of initial flow estimates is analyzed. Specifically, the mean value of S1 is varied as S1 is used to make the case for uncertainty analysis in previous steps (low flow rate in case of flow uncertainty and new source in case of participant uncertainty). As the abandoning design strategy does take into account S1, the analysis is focused on the flexible and the committing design strategies. The analysis carried out for flow uncertainty and participant uncertainty.

Figure 12 shows the performance of the flexible and the committing design strategies versus the mean value of S1. It is clear to see that both design strategies increase

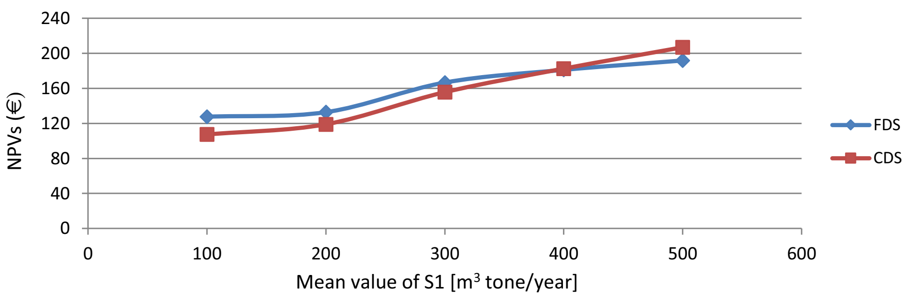

Fig. 12 Sensitivity of flexible and committing design strategies to the mean value of S1

with increasing mean value of S1. This is due to the linear relation between flow rate and revenue. Up to a mean value of 400 m^3 tone/year, the flexible design strategy performs better than the committing design strategy. However, above 400 m^3 tone/year the committing design strategy appears to be better than the flexible design strategy. The above observations indicate that at higher mean value of S1 early commitment is valuable than investing on real options.

One the other hand, one can expect that the abandoning design strategy to have constant value since there is no connection to S1. However, the lost opportunity due to a potential increase in flow rate of S1 or avoided risk due to low flow rate from S1 by the abandoning design strategy can be implicitly inferred by comparing it against the other two design strategies. If the mean value of S1 increases, then the opportunity lost by the abandoning design strategy increases. Conversely, if the mean flow of S1 decreases the risk avoided by the abandoning design strategy increases and at much lower mean value, the abandoning strategy can become better than the committing strategy.

The effect of the initial estimate is very strong for the case of participant uncertainty. Figure 13, shows the effect of initial mean value of S1 on the performance of the flexible and the abandoning design strategies. The performance of the flexible strategy compared to the abandoning strategy largely depends on the time S1 is connected. If S1 joins the network early in the investment period, the value of the flexible strategy increases or decreases proportional to the mean value of S1. Conversely, if S1 joins the network later in the investment period, the value of the flexible design strategy diminishes with increasing mean value of S1. For instance, if S1 joined the network in year 7, the flexible strategy provides inferior value compared to the abandoning strategy. The cost of having the real options for flow rate of 500 m^3 tone/year is higher than the cost for 100 m^3 tone/year. At higher flow rate, the size of extra capacity to accommodate flow increases will be larger. Moreover, as shown in Fig. 10, the value of having the real options would be higher if S1 joins the network at year 3 than at year 7. As a result, the value of the option with higher initial flow rate at year 7 becomes lower than with lower initial flow rate. On the other hand, the performance of the abandoning design strategy is the same as it does not depend on S1. Therefore, at year 7, the difference between the flexible design strategy and the abandoning design strategy decreases with increasing initial flow rate of S1.

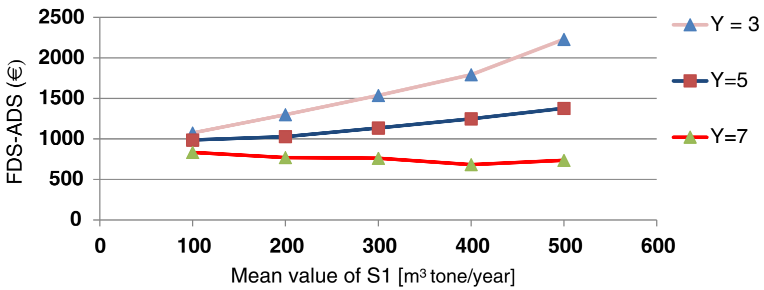

Fig. 13 The effect of the initial estimate of S1 on the performance of the flexible and the abandon design strategies

5 Conclusions

This paper introduces a method to enhance the value of networks by identifying and integrating flexibility enablers under uncertainty. In the paper, we argued that one way to design flexible networks is to adopt a real options-based design approach. The proposed method uses a graph theoretical network model to carryout out exploratory uncertainty analysis of design alternatives. The aim of the exploratory analysis is to screen out promising design concepts out of several alternatives. Once candidate designs are selected, design flexibility analysis is carried out to improve the life cycle performance of networks by considering uncertainties. The design flexibility analysis uses the concept of real options to enhance the value of the network. The proposed design approach contrasts with the typical design and planning approach which tends to focus on pre-defined requirements and often leads to inflexible and sub-optimal networks.

Using a hypothetical pipeline-based network for demonstration purposes, the method provides valuable insights to designers and decision makers on how to design flexible networks under capacity and participant uncertainty. We found out that building higher pipe capacity is valuable if flow rate increases from existing sources and/or if new sources join the network in the future. Moreover, the proposed method could provide valuable insight into which parts of the network should designers include real options. Results reveal that physically built-in capabilities, such as extra pipe capacities and lengths, provide easy and cost-effective expansion option of the network when compared with a deterministic design approach.

The procedure introduced in this study generally can be applied to most pipeline-based network design problems including natural and bio gas pipeline networks, water distribution networks and district heating networks. However, different networks are subject to distinct costs and benefits and faced with their respective sources of uncertainties; as a result, details of modelling and computation may need to be adjusted to suit the particular network at hand.

Future works in this research include expanding the network model to multiple sources and multiple sinks, cases other than pipelines such as electricity transmission lines which have a different governing physics. Moreover, the utility of the proposed method could be further increased by applying it on real case studies, and by taking into consideration no-go areas such as parks and residential areas.

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Appendix: Cost and Revenue calculations

Investment cost and revenue calculation is required for making decisions weather to make a connection to a given source or not.

Cost Calculation

If a connection to S1 is delayed to year t, the present value of the cost of building the network is the summation of the cost of edges in year 1 and the discounted value of the cost for connecting S1 at year t as shown i'n Eq. A.1.

$$C(T) = C(T)_{y=1} + C_{y=t} \tag{A.1}$$

where y stands for year, $C(T)_{y=1}$ is the summation of the costs of edges in year 1, and $C_{y=t}$ is the cost of pipeline from S1 to junction point j1 at time of connection t. $C(T)_{y=1}$ and $C_{y=t}$ are mathematically expressed as follows:

$$C(T)_{y=1} = \sum l_e * q_e^{\beta} \tag{A.2}$$

$$C_{y=t} = l_{S1,j1} * q_{S1,j1}^{\beta} \tag{A.3}$$

Expected Revenue Calculation

Revenues are calculated as the product of the volume flow rate and the price per volume flow rate. The price could also be the service charge (e.g. connection fee) for a unit pipe capacity required for connection. Revenues are calculated every year and discounted to a present value using a discount rate of r. The summation of the

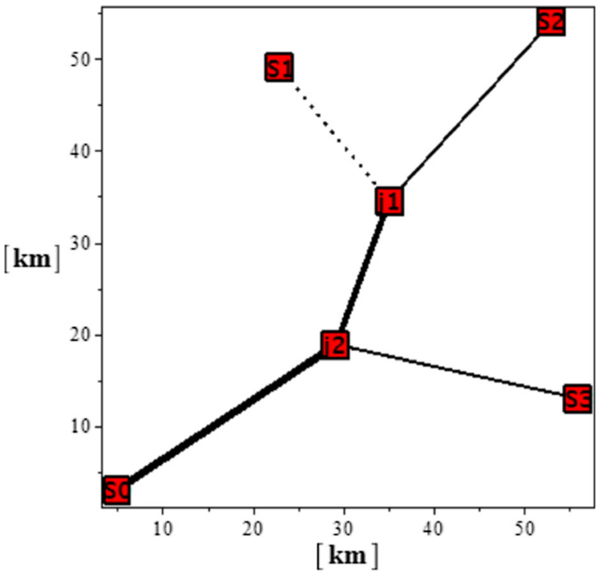

Fig. 14 Configuration of a network with option for future expansion

discounted revenues from all sources over investment time of the project gives the expected revenue of the network, Er.

$$Er = \alpha \sum\nolimits_{1}^{y} \frac{F_t}{(1+r)^y} \tag{A.4}$$

where F_t is the summation of flow rates from all existing sources.

As noted, the decision rule checks if the connection to S1 is worthy by comparing the cost incurred for enabling connection of S1 (summation of cost of the edge from junction point to S1 and the extra cost of pipeline from junction point to the sink to accommodate S1) with the expected revenue from S1. If the expected revenue from S1 is greater than the cost for its connection, then S1 will be connected. However, if the flow is small in early years, a case for differing the connection to S1 may be relevant. This means that the algorithm has to check for delaying and abandoning strategies. In the cases of delaying strategy, the algorithm checks for building real options in the capacity and the length of the pipe. This requires calculating the cost of the options and comparing it against the expected revenue from S1. The cost of taking real options for enabling the network to be flexible for future connections and increases in flow rate is given as:

$$C_{option} = C(T)_{y=1} + \frac{C_{y=t}}{(1+r)^t} \tag{A.5}$$

where C_{option} is the cost of the option.

The expected revenue from S1 (Er_{s1}) is calculated as

$$Er_{s1} = \alpha \sum\nolimits_{y=t}^{y=n} \frac{F_{s1}}{(1+r)^y} \tag{A.6}$$

where F_{s1} is the flow from S1.

If the expected revenue is greater than the cost of the real option built in, the algorithm results in a network configuration with an option for future expansion. If the delaying strategy is not worthy, the algorithm will choose the abandoning strategy. That means:if $C_{option} > (Er)_{s1}$, do not built an option, else if $C_{option} < (Er)_{s1}$, build the option.

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Cooperation under uncertainty: Assessing the value of risk sharing and determining the optimal risk-sharing rule for agents with pre-existing business and diverging risk attitudes

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Abstract

The allocation of risk among the cooperating parties in a shared project is an important decision. This is especially true in the case of large infrastructure investments. Existing risk allocation methods are either simplistic or do not consider the effect of the agents' pre-existing businesses. In this paper, we model and analyse the effect of risk sharing when two agents want to co-develop an energy infrastructure project in an uncertain environment. The cooperating agents have a pre-existing risky business, and the new common project has a deterministic initial cost but random revenue potential. Our analysis shows that the optimal risk-sharing rule depends not only on the agents' risk aversions but also on the volatility of the common project profit, the volatilities of the agents' pre-existing businesses and the correlation of each agent's pre-existing business with the common project. An illustrative example based on energy infrastructure is used to show the implications of the sharing rule for partners.
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Keywords: Energy infrastructure investment; Risk sharing; Cooperation; Contracts; Uncertainty; Risk averse agents

1. Introduction

The selection of partners in a joint venture and the allocation of risk among them are important decisions that have a deep impact on the success of the project. However, the existing methods in the literature only consider the agent's risk aversion, leading to the least risk-averse agent taking a higher share of the risk. However, determining the best risk-sharing approach should take other factors into account such as the agent's pre-existing businesses. This paper answers this question, developing a model to determine the value of risk sharing – that is, how much value the coalition brings with respect to the project being developed by a single partner. Contrary to existing approaches, our developed value of risk sharing considers the agents' pre-existing business and their correlation to the joint venture, together with their risk attitudes. The model provides valuable insights for the most favourable design of a coalition and the risk-sharing contract in order to get the most of the benefits of cooperation.

Cooperation is even more important in infrastructure projects given their high capital intensity, which makes it necessary to form partnerships face the needs for investment in an efficient way. Specifically, the energy sector has recently experienced an increased need for cooperation which we would like to highlight, as it provides a further specific context for this need. Agents in the energy sector are increasingly seeking cooperation to cope with the competitive and complex energy landscape caused by forces such as liberalization, deregulation, renewable energy integration, and climate policies (Ligtvoet, 2013). This can be seen in several large scale joint infrastructure project

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initiatives and plans. For example, in the USA, regional transmission operators are cooperating to develop inter-regional electricity transmission lines to facilitate the integration of renewable energy sources that span across multiple regions (MIT Energy Initiative, 2011). In Europe, bordering transmission operators are cooperating to invest in cross-border transmission to facilitate electricity market integration (Brancucci Martínez-Anido, 2013). Moreover, new regulatory frameworks are being introduced to encourage cooperation in electricity markets integration (Böckers et al., 2013), renewable energy integration (EU Commission, 2006), electricity and gas infrastructure development and upgrade (Henry et al., 2014; Brancucci Martínez-Anido, 2013), energy efficiency (Nauleau et al., 2015), and CO_2 emission reduction (RCI, 2011).

The rationale for cooperation in infrastructure projects is multiple: it enables agents to minimize the effects of uncertainty by aligning their interests (Ligtvoet, 2013); provides strategic advantages such as the ability to achieve objectives faster, getting access to know-how or to markets, cost advantages, transfer or complementarity of technologies, and economies of scale (Williamson, 1979; Bronder and Pritzl, 1992; Guoa et al., 2014). However, cooperation is not always straightforward, and various uncertain factors expose parties to different kinds of risks (Lam, 1999; EU Commission, 2006). On the one hand, large-scale infrastructure projects are particularly subject to risk due to large initial costs, high irreversibility (sunk costs), and long-term durability of assets (Lam, 1999; Boatenga et al., 2015). On the other hand, cooperation involving infrastructure (and energy infrastructure in particular) is complex as multiple agents are involved with different objectives and constraints. By its own nature, cooperation is a multi-motive game. Because each party displays a rational behaviour, there are considerable costs and risks involved in the decision to join a project (Williamson, 1979; Nooteboom, 2000). The presence of endogenous uncertainty (e.g. strategic behaviour) (Berger and Hershey, 1994; Grundy, 2000) and exogenous uncertainty (e.g. technology, market, regulatory changes) often lead to a deadlock in which decision-making stagnates as parties become increasingly risk averse and are afraid to 'bet on the wrong horse' (McCarter et al., 2010; Gong et al., 2009). Therefore, with incentives on one hand and costs and risks on the other, the challenges in most infrastructure development cooperation projects are: (1) How will the associated risk and value be shared among the partners? (2) How should we structure contracts to enhance synergies at an acceptable level of risk?

In the strategic management literature, the discussion on the allocation of benefits and risks from cooperation under uncertainty is based on two perspectives: a value-creation perspective and a risk-sharing perspective. The value-creation perspective takes the view that agents cooperate to gain value and hence focuses on the allocation of value from cooperation (Folta and Miller, 2002; Holta et al., 2000). In that respect, real-options valuation is receiving increasing attention as a tool to analyse the value of cooperation, see for example (Kogut, 1991; Liu et al., 2014; Park et al., 2013). The risk-sharing perspective uses the concept of risk sharing to explain the motive for cooperation and allocation of risk among cooperative agents (see for example Allen and Lueck, 1999; Medda, 2007; Blenman and Xu, 2009).

Regarding the allocation of value from cooperation, the literature has also come a long way from deterministic cooperative game theory models of Nash (1950), Nash (1953) and Shapley (1953) to models for stochastic payoffs (Suijs et al., 1999; Savva and Scholtes, 2005). The literature on optimal risk sharing between two parties was first analysed by Borch for the specific case of insurance contracts (Borch, 1962). Later, Wilson led the research for efficient risk sharing in syndicates (Wilson, 1968) and more recently this was advanced by Pratt (Pratt, 2000). Various risk-sharing allocation techniques have been presented for infrastructure investments. (Lam et al., 2007) used qualitative risk allocation for construction projects using a fuzzy inference mechanism. Medda (2007) used a game theoretical approach to the allocation of risks in transport public-private partnerships. Other techniques applied to this problem include Artificial Neural Networks (Jin and Zhang, 2011) or fuzzy system dynamics (Nasirzadeha et al., 2014). However, all these previous works largely focus on closed contracts where the only payoff comes from the joint investment, and the effects of the agents' pre-existing businesses are ignored. Moreover, the methods used to model the uncertainty in the future performance of the common project are either deterministic or relatively simplistic, while the future revenues from most infrastructure investments are stochastic.

In this study, we deal with stochastic revenue and consider the correlation of the pre-existing businesses of cooperating agents with the common project. We use concepts from the risk-sharing literature to model a risk-sharing contract between two risk-averse agents who invest in a common project. Then, we apply cooperative game theory to analyse the synergy effects of risk sharing. A stylized case example loosely inspired by a joint venture created to develop a merchant electricity interconnector between the Netherlands and the UK, known as BritNed (BritNed, 2015) is used to illustrate the implications of this research.

This paper adds to the existent literature in two ways: we study the value of cooperation considering that the participants have pre-existing businesses that are correlated with the joint venture and that these agents can have diverging risks attitudes. We also develop the rule for optimal risk sharing –i.e. how much of the risk should be borne by each agent-. These results can be used to select among possible partners so that the value of cooperation is better and to support negotiations.

The paper is organized as follows. Section 1 introduces the work. Section 2 provides the basic model set-up and assumptions. Section 3 solves for the optimal linear contract between the two agents. Section 4 introduces uncertainty in the form of difference in contract design between cooperating parties and solves for the real option value of risk sharing. Section 5 presents computational results and analysis of optimal risk share and values of risk sharing.

2. Modelling revenue and profit

Let's take two agents ($i = 1, 2$) who intend to create a joint venture to share the development cost and future profit of an energy infrastructure project. Each agent has a pre-existing risky business before the possibility of investing in the common project is considered. Moreover, agents agree to share the profit risk associated with the common project. We assume that cooperating agents observe the evolution of the joint cooperative project's value and they have symmetric information. All parties have access, ex-post, to the true realized returns of the common project. All profits of the new venture will be shared between the two agents. The applicability of the proposed model is general but throughout the paper a joint project to develop a merchant transmission line is used as an illustrative case.

We assume that the future performance of the common project is uncertain and follows a stochastic process. For example, in merchant power interconnectors[1], the daily revenue is stochastic due to the random nature of congestion revenue, which depends on daily electricity demand and nodal prices (Salazar et al., 2007). There is an array of approaches (e.g., Brownian motion, mean reverting process) that can be used to model the revenue time series (Dixit and Pindyck, 1994). Geometric Brownian Motion (GBM) processes are frequently applied to model stochastic price and revenue behaviours. Salazar et al. (2007) and Fleten et al. (2011) employed a GBM process to model electricity prices for an economic analysis of merchant power interconnectors. Brandao and Saraiva (2008) and Carbonara et al. (2014) used GBM process to model revenue in infrastructure projects.

Although GBM is preferred for the purposes of price modelling, it fails to effectively model profit and cash flows as it does not allow for negative realizations. Arithmetic Brownian Motion (ABM) processes are frequently used to model economic performance measures that can become negative (e.g. profits) (Copeland and Antikarov, 2001). Since the revenue of merchant interconnector project depends on price differences between the connected markets, ABM can be used to model its dynamics over time. Moreover, if the price of each individual price region is modelled using a GBM process, the dynamics of the difference can be reasonably approximated using an ABM process (Carmona and Durrleman, 2003). Therefore, in this study, we assume that the investment-flow returns follow an ABM process.

An ABM process representation of profit $p(t)$ at any time is given by

$$p(t) = p_0 + \mu t + \sigma W(t), \tag{1}$$

where p_0 is the initial value, μ is the expected return (the drift), and σ is the volatility of profit.

To illustrate the risk-sharing rule, we consider the following cooperation scenario. The agents agree on creating the joint venture S at time $t=0$. Then, at time $t=\tau<T$, the partners decide to sign a risk-and-profit-sharing agreement based on the discounted value[2] of the common project's profit for the period $[\tau, T]$. Therefore, we are interested in the distribution of the present value of the profit of the three entities: i.e. the common project and the two pre-existing business of the agents. Mathematically, the present value of an ABM process can be reasonably approximated using a normal distribution (Ross, 1999; Cartea and González-Pedraz, 2012). Therefore, a time = $\tau < T$, the profits of the common project and the agents' pre-existing businesses are denoted as follows:

- $x_i^0(\tau)$ = the discounted value of the profit from agent i's existing business.
- $x_i^1(\tau)$ = the discounted value of the profit if either of the agents invests on the joint venture alone.
- $x(\tau)$ = the discounted value of the profit from the common project.
- $x_i(\tau)$ = the discounted value of the profit from the joint venture received by agent i.

The expressions of the distributions of the pre-existing business and the common project are shown as follows.

$$x_i^0(\tau) \sim N\left(\mu_i^0, \sigma_i^0\right) \tag{2}$$

$$x(\tau) \sim N(\mu_s, \sigma_s) \tag{3}$$

Whether the agents decide to take up the new project as a single investor or together as a joint project, it is important to define the relationship between the joint venture and their existing projects. Since the two agents have some existing risky businesses, their decision whether to invest in the shared infrastructure project or not depends on their pre-existing business and the characteristics of the new shared project. For example, if two neighbouring countries jointly invest in an electricity interconnector, the electricity prices in both countries will be affected and that in turn will affect the revenue of transmission operators and generators in each country (Parail, 2009). As a result, neighbouring countries (at least the transmission operators and generators in the high electricity price market) have the interest to keep the two electricity markets separate (Kristiansen and Rosellón, 2010; Parail, 2010). In order to take into account the influence of the new common project, we consider its correlation with the pre-existing businesses of the two agents.

The dependence between the pre-existing businesses and the common project is determined by a linear correlation coefficient ρ_i (Pastore, 1988). This correlation coefficient takes a value between 0 and 1, i.e. $-1 \le \rho_i \le 1$. If $\rho_i = 0$, then the common project and the pre-existing business are independent. If $0 < \rho_i < 1$, then the two are positively correlated and if $-1 < \rho_i < 0$, then they are negatively correlated.

The sum of two dependent normal distributions (which can each describe the present value of an ABM-cash-flow) is

[1] Merchant electricity interconnector, also called non-regulated transmission investment, is an arrangement where a third party constructs and operates electric transmission lines between unrelated electricity markets, often across borders. Interconnectors are the physical links which allow the transfer of electricity across borders.

[2] In a continuous-time game the payoffs are realized along the time of the cooperation. However, we assume that agents evaluate the worth of cooperation (i.e. their individual share) by discounting the sum of future payoffs at the time of entering into the cooperation.

a normal distribution (Pastore, 1988). By this principle, we can define the distribution parameters of $x_i^{\,1}$ and $x_i(\tau)$ based on Eqs. (2) and (3).

If one of the agents carries out the investment alone[3], the total uncertain payoffs can be obtained by adding the payoff from the existing business and the payoff from the common project.

$$x_i^{\,1}(\tau) = x_i^{\,0}(\tau) + x(\tau) \tag{4}$$

Therefore, $x_i^{\,1}(\tau)$ is given as

$$x_i^{\,1}(\tau) \sim N\left(\mu_i^1, \sigma_i^1\right) \tag{5}$$

where $\mu_i^1 = \mu_i^0 + \mu_s$ and $\sigma_i^1 = \sqrt{\left(\sigma_i^0\right)^2 + \sigma_s^2 + 2\rho_i\sigma_i^0\sigma_s}$.

Similarly, if the agents cooperate the total value of each agent's payoff from engaging in the joint venture is the sum of the uncertain payoff from the existing business and a share $\varphi_i \in [0, 1]$ of the uncertain payoff from the joint venture. Here we define the risk-sharing contract to be a rule to calculate the percentage share of the equity stake in the common project. Therefore, if the agents cooperate in developing the project the cash flow depends on the contractually agreed share rule φ_i.

$$x_i(\tau) = x_i^{\,0}(\tau) + \varphi_i x(\tau) \tag{6}$$

$$x_i(\tau) \sim N(\mu_i, \sigma_i) \tag{7}$$

where $\mu_i = \mu_i^0 + \varphi_i\mu_s$ and $\sigma_i = \sqrt{\left(\sigma_i^0\right)^2 + \varphi_i^2\sigma_s^2 + 2\rho_i\varphi_i\sigma_i^0\sigma_s}$.

The probability density distribution of a normal distribution function x with mean μ and variance σ^2 is expressed as

$$f(x; \mu, \sigma) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \tag{8}$$

Inserting the mean and variances of Eqs. (5) and (7) in Eq. (8) we get a probability density distribution of for $x_i^{\,1}(\tau)$ and $x_i(\tau)$.

$$f\left(x_i^{\,1}(\tau)\right) = \frac{1}{\sqrt{2\pi\left(\sigma_i^2 + \sigma_s^2 + 2\rho_i\sigma_i\sigma_s\right)}} e^{-\frac{\left(x_i^{\,1} - (\mu_i + \mu_s)\right)^2}{2\left(\sigma_i^2 + \sigma_s^2 + 2\rho_i\sigma_i\sigma_s\right)}} \tag{9}$$

$$f(x_i(\tau)) = \frac{1}{\sqrt{2\pi\left(\sigma_i^2 + \varphi_i^2\sigma_s^2 + 2\varphi_i\rho_{is}\sigma_i\sigma_s\right)}} e^{-\frac{\left(x_i^{\,1} - (\mu_i + \varphi_i\mu_s)\right)^2}{2\left(\sigma_i^2 + \varphi_i^2\sigma_s^2 + 2\varphi_i\rho_{is}\sigma_i\sigma_s\right)}} \tag{10}$$

The expressions in Eqs. (9) and (10) respectively show the probability distribution of profit for each agent if they invest in the common project alone and if they invest jointly. Determining the profit distributions in Eq. (9) requires only calculating the correlations (ρ_i) between the profit from the agents' pre-existing businesses and the profit from new common project, given their distribution is known. However, determining the profit distributions in Eq. (10) requires deriving the optimal risk sharing ratio (φ_i) in addition to correlation. In the next section we use utility theory to derive the optimal risk share ratio.

3. Optimal risk-sharing rule

In the previous section, we define the uncertain profit agents will receive when they engage into a shared investment. However, the value of the uncertain payoff depends on the risk preference of the agent. Without loss of generality, we assume both agents are risk averse. A risk-averse agent is reluctant to accept a bargain with an uncertain payoff compared to another bargain with a more certain, but possibly lower, expected payoff (Pratt, 2000). We model the payoff preference of agents using expected-utility functions (Schoemaker, 1982), i.e. party i prefers an uncertain payoff X over an uncertain payoff Y if $E[U_i(X)] > E[U_i(Y)]$ where U_i is a suitable utility function (Pratt, 1964). The underlying assumption is that the agents' perception of risk can be fully captured by the expected utility function, which reflects the value of the payoff share from the common project. Utility function translates each of the possible payoffs into a non-monetary measure known as utility. For tractability reasons, we consider a negative exponential utility function assuming the agents that the risk preference of each firm is governed by a constant absolute risk aversion (CARA)[4] utility function.

$$U(X) = -e^{-\gamma X}, \tag{11}$$

where $U(X)$ represents the utility function, X is the evaluation measure (such as profit or cost), γ is a constant that describes risk aversion. The degree of risk aversion that is appropriate depends, for instance, on the nature of the agent or on its asset position (Pratt, 1964). CARA means that, if we change a uncertain payoff X by adding a fixed additional amount of money to the agent's payoff in all possible outcomes of the gamble, then the certainty equivalent of the gamble should increase by this same amount. Constant risk aversion is widely used for practical decision analysis due to its convenience (Myerson, 2004). Moreover, constant risk aversion allows us to evaluate independent uncertain payoffs (i.e. P(t) and $P_i^{\,0}(t)$) separately.

For a CARA utility function shown in Eq. (11), the expected utility of Eq. (8) is given by[5]

$$EU(x) = -e^{-\gamma\left(\mu - \gamma\frac{\sigma^2}{2}\right)} \tag{12}$$

Using the same formulation $x_i(\tau)$ can be given by

$$E(U(x_i)) = -e^{-\gamma_i\left(\mu_i^0 + \varphi_i\mu_s - \gamma_i\frac{\left(\sigma_i^0\right)^2 + \varphi_i^2\sigma_s^2 + 2\rho_i\varphi_i\sigma_i^0\sigma_s}{2}\right)} \tag{13}$$

Eq. (13) shows that the expected utility of the discounted value of the joint venture for agent i is a function of her share

[3] However, for reasons of risk and other regulatory barriers, they are not willing to do it alone or not allowed by law. This is often the case for cross-border power transmission investment.

[4] The assumption of CARA utility function may seem far from reality compared to constant relative risk aversion (CRRA). However, the kind of utility function that describes the average is still controversial.

[5] See Sargent and Heller (1987) for the proof.

from the joint venture and the correlation of her existing business to the new joint venture.

For CARA utility function, $\gamma_i > 0$ implies that agents are risk averse. Therefore, for each random x_i, an agent prefers receiving the expected payoff $E[x_i]$ with certainty to receiving the random payoff x_i. Moreover, agent 1 is more risk averse than agent 2 if $\gamma_1 > \gamma_2$[6].Therefore, we can define the certainty equivalent (CE) of a random payoff x_i by $CE_i(x_i) = U_i^{-1}(E(U_i(x_i)))$, provided that the expected utility exists. Then, for all these random payoffs x_i, $E(U_i(CE_i(x_i)) \equiv U_i(CE_i(x_i)) = E(U_i(x_i))$ holds. Since the expected utilities equal one another, agent i is indifferent between the random payoff x_i and the deterministic payoff $CE_i(x_i)$. Therefore, the certainty equivalent expression of distributed x_i is given by

$$CE_i(x_i) = \mu_i^0 + \varphi_i\mu_s - \gamma_i\frac{(\sigma_i^0)^2 + \varphi_i^2\sigma_s^2 + 2\rho_i\varphi_i\sigma_i^0\sigma_s}{2} \tag{14}$$

Individual rationality dictates that each agent will try to maximize their expected utility. Then the question becomes: what is the optimal contract for two agents to efficiently share the risks involved in a cooperative project?

To derive the optimal risk-sharing rule, we assumed that parties act cooperatively and have symmetric information about the characteristics of the venture. The returns to the venture are also verifiable ex-post, and the management of the joint venture acts to maximize the joint venture profits. It is also rational to think that both firms prefer to take up as little risk as possible while trying to increase their own gain. However, for risk-averse firms with a concave utility function, marginal gains decrease as risk taking decreases. Furthermore, this rate of reduction of marginal gains will be different for both players in view of their differing risk aversion levels. Therefore, the task for a rational firm in such situation is to optimize the amount of risk-taking in relation to the amount of gain.

The maximum total value of the joint venture will be obtained at a risk-sharing rule where the marginal value of taking up some infinitesimal fraction of the risky venture is the same for both agents (Bolton and Dewatripont, 2005). If the marginal gains were different for the two agents, it would be possible to add to the total value by taking away an infinitesimal amount of risk from the firm with the smaller marginal gain and giving it to the firm with a larger marginal gain. Therefore, the first optimality condition equates the marginal gains of the uncertain payoff of the two agents (Borch, 1962).

$$\begin{gathered}\frac{d}{d\varphi_1}CE_1(x_1) + \frac{d}{d\varphi_2}CE_2(x_2) = 0\\ \sum_{i=1,2}\varphi_i = 1\end{gathered} \tag{15}$$

where, φ_1 is the share of agent 1 and the share of agent 2 is $1-\varphi_1$. The expression in Eq. (15) means that the risk sharing problem is given as a maximum of the sum of the certainty equivalents of the two agents.

$$x(\tau)^* = \max_{\varphi_1}[CE_1(x_1) + CE_2(x_2)] \tag{16}$$

Inserting Eqs. (14) in (15) and rearranging, we get the optimal share of the risk φ_1^* for agent 1.

$$\varphi_1^* = \frac{\gamma_2}{\gamma_1+\gamma_2} + \rho_{2s}\frac{\gamma_2}{\gamma_1+\gamma_2}\frac{\sigma_2^0}{\sigma_s} - \rho_{1s}\frac{\gamma_1}{\gamma_1+\gamma_2}\frac{\sigma_1^0}{\sigma_s} \tag{17}$$

With $0 < \varphi_i^* < 1$ and $\sum_{i=1,2}\varphi_i^* = 1$.

Note that the optimal risk-sharing rule does not depend on the mean rate of the returns of the pre-existing businesses ($\mu1$ and $\mu2$). Only the risk aversion of the two parties, the volatilities of the pre-existing businesses and the correlations of the pre-existing businesses with the joint venture affect the optimality conditions. There is no risk-sharing agreement when $\varphi_1^*=0, \varphi_2^*=1$, or equivalently $\frac{\gamma_1}{\gamma_2} = \frac{\sigma_s+\rho_{2s}\sigma_2}{\rho_{1s}\sigma_1}$; or $\varphi_2^*=1, \varphi_2^*=0$, or equivalently $\frac{\gamma_1}{\gamma_2} = \frac{\rho_{2s}\sigma_2}{\rho_{1s}\sigma_1+\sigma_s}$. The condition that $0 < \varphi_i^* < 1$ can be equivalently expressed as $0 < \gamma_2(\sigma_s + \rho_{2s}\sigma_2) - \gamma_1\rho_{1s}\sigma_1 < (\gamma_1+\gamma_2)\sigma_s$. This condition is expressed with the parameters that represent the distribution of profit from the agents' existing businesses and the common project, and the agents' risk aversions.

Let us define the following variables that depend on risk aversion, correlation, and volatility:

$$K_1 = \frac{\gamma_2}{\gamma_1}, K_2 = \rho_{1s}\frac{\sigma_1}{\sigma_s}, \text{and } K_3 = \rho_{2s}\frac{\sigma_2}{\sigma_s}, \text{for } \forall\gamma_1, \forall\sigma_s \neq 0$$

Then, the condition for the existence of a feasible risk sharing agreement is given as:

$$\begin{aligned}&K_1 > 0\\ &K_2 < K_1(1+K_3)\\ &K_2 > K_1K_3 - 1\end{aligned} \tag{18}$$

An important feature of expression (17) is that it is time-invariant. This implies that after the risk-sharing contract has been agreed neither party will have an incentive for dynamic re-negotiation of their respective risk share unless these correlations and volatilities change.

3.1. The effect of correlation

In expression (17) we can see that the optimal amount of risk an agent is willing to take partly depends on the correlation of the agents' existing projects with the common project. If there is no correlation between the common project and the agents' existing businesses the optimal risk share is only a function of the agents´ risk aversions (for instance for agent 1, $\overline{\varphi}_1^* = \frac{\gamma_2}{\gamma_1+\gamma_2}$). In such case, the certainty equivalent of agent i is given by:

$$\overline{CE}_i = \mu_i^0 + \overline{\varphi}_i^*\mu_s - \gamma_i\frac{(\sigma_i^0)^2 + (\overline{\varphi}_i^*)^2\sigma_s^2}{2} \tag{19}$$

[6] By changing the signs of the parameter γ_i, the utility function becomes convex and, as a consequence, the player will be a risk-seeker.

If the pre-existing businesses and the new common project are correlated the agents' certainty equivalents can be found by using Eq. (20).

$$CE_i = \mu_i^0 + \varphi_i^* \mu_s - \gamma_i \frac{(\sigma_i^0)^2 + (\varphi_i^*)^2 \sigma_s^2 + 2\rho_i \varphi_i^* \sigma_i^0 \sigma_s}{2} \tag{20}$$

Then, the effect of correlation can be obtained by subtracting Eq. (19) from Eq. (20) as shown in Eq. (21).

$$CE_i - \overline{CE}_i = \mu_s(\varphi_i^* - \overline{\varphi}_i^*) - \frac{\gamma_i \sigma_s^2}{2}\left((\varphi_i^*)^2 - (\overline{\varphi}_i^*)^2\right) - \gamma_i \rho_i \varphi_i^* \sigma_i^0 \sigma_s \tag{21}$$

It can be seen that the correlation coefficient (i.e. $\rho_i > 0$ or $\rho_i < 0$) affects the value of the right-hand side of Eq. (21). Using expression (21) agents can get valuable insight, at least at exploratory stage of cooperation, about the effect of the new project to their overall expected utility.

3.2. The value of risk sharing

In this section, we derive the value of risk sharing that can be obtained from cooperation. We treat cooperation in the joint venture as an investment option that can be exercised by committing some given capital. As with any investment, cooperation in the joint venture comes with its own risks. As a result, at the conceptual stage of the cooperation agents have three options: exercise the investment in the project through cooperation, invest in the project alone or do nothing. We refer to the first one as *cooperation option*. The solo investment and the abandoning options are referred as *non-cooperation* options.

If agent i neither cooperates or invests alone (i.e. carry out only existing project), the certainty equivalent of the uncertain payoff from the existing project x_i^0 is given by

$$CE_i^0 = \mu_i^0 - \gamma_i \frac{(\sigma_i^0)^2}{2}. \tag{22}$$

If either of the agents invests alone, then the certainty equivalent of the uncertain profit x_i^1 is given by

$$CE_i^1 = \mu_i^0 + \mu_s - \gamma_i \frac{(\sigma_i^0)^2 + \sigma_s^2 + 2\rho_i \sigma_i^0 \sigma_s}{2}. \tag{23}$$

In this case, the value of risk sharing for each agent, $\mathrm{VoRs_i}$, can be obtained by comparing the utility agent i gets from the cooperation option with that of the non-cooperation options. The value of cooperation via risk sharing can be obtained by subtracting the maximum of the certainty equivalent values of the two non-cooperation options from the cooperation.

$$\mathrm{VoRs_i} = CE_i - \max\left(CE_i^1, CE_i^0\right) \tag{24}$$

Expression (24) allows us to define the condition under which partners will choose cooperation to undertake a project when there is a background risk (from their existing business) and project risk (from the common project), provided that they can also consider investing on their own. It shows the minimum of the value that the agent gets as a result of cooperation. Theoretically, the minimum $VoRs_i$ should be greater than zero for the agent to engage into cooperation. Otherwise, the agent could compare the maximum of CE^1 and CE^0 to either invest in the project alone or not invest at all. Expression (24) can also be used by individual agents to select a cooperating partner to set up a joint venture for a project. Different agents are most likely to have different background risks, resulting in an increase in the value of risk sharing. Using expression (24), agents can compare the amount of value they obtained by sharing the risk of the common project with the different kinds of prospective partners who have different background risk.

3.3. The risk-sharing zone

In expression (24), we present a model to determine the value agents get if they take an optimal share of the risk. The direct takeaway from Eq. (24) is that depending on the VoRs agents can decide whether to engage in cooperation or not. However, cooperation could be possible if one agent has a positive VoRs and can transfer a portion of the surplus to the other agent with negative VoRs. In this section, we check whether cooperation is possible via a side payment. We assume that agents agree on the cooperation at time $t=0$. Then, after uncertainty is resolved, they decide to exercise the cooperative option $t=\tau<T$ and receive an instant payoff. The core of a cooperative game is the set of payoff allocations that make both partners better off than if they were to go it alone. i.e.

$$CE_i \geq {CE_i}^1$$
$$\sum_{i=1,2} CE_\mathrm{i} = CE.$$

A payoff for either firm is in the core if

$${CE_i}^1 \leq CE_i \leq CE. \tag{25}$$

The focus now is to define the risk-sharing-value core in which cooperation is possible. In this core, partners can agree to maximize the sum of their certainty equivalents by sharing the risky returns in proportion to their respective risk tolerances. We will focus on linear contracts, i.e. agreements involving a deterministic cash payment D_i and a share φ_i of an uncertain payoff CE at $t=\tau$. The total payoff of agent i from the joint project will be

$$CE_i = D_i + \varphi_i CE. \tag{26}$$

Linear contracts are very common in most joint-venture revenue-and-cost-sharing arrangements (Bolton and Dewatripont, 2005; Savva and Scholtes, 2005). In Eq. (17) we derived the optimal share of risk when two agents cooperate to maximize their joint certainty equivalents. However, the optimal risk-sharing rule only specifies how much risk each player will take and does not determine the optimal payoff for each agent from the cooperation. This is because the deterministic amount D_i that the two agents exchange is not constrained and is determined through negotiation.

To know the amount of D_i let us define the sharing rule in a situation where agent 1 owns the option to develop the project alone. For agent 2, there is always the alternative of not participating in the project with a zero payoff. The best sharing rule for agent 1 would be one that maximizes 1's certainty equivalent subject to the constraint that 2's certainty equivalent should not be less than zero. The best sharing rule can be achieved by sharing in the optimal proportions, to maximize the sum of the each agent's certainty equivalents, with an additional payment from agent 2 to agent 1 on the condition that 2's certainty equivalent should be equal or greater than zero. The best possible sharing rule for agent 1 would be to sell agent 2 an optimal share of the project which is φ_2^*. The maximum price of the optimal share of the investment is equal to $\varphi_2^* * CE$. Agent 1´s overall certainty equivalent is equal to $(\varphi_1^* * CE)+(\varphi_2^* * CE)$. This value is the maximum sum of certainty equivalent that the two partners can get from the project and it is allocated to agent 1.

However, agent 2 would prefer to pay less than $\varphi_2^* * CE$ for an optimal share φ_2^*. Agent 2 may try to negotiate for lower price. The negotiated price that is given from agent 2 to agent 1 for an optimal share of the project is the cash D. Although D is determined through negotiation it has minimum value that agent 1 can accept. At the minimum, D should make agent 1´s certainty equivalent better than owning 100% of the project alone. Hence, the conditions for the core of the cooperation game, subject to optimal sharing, is given as

$$CE_1 + D \geq CE_1{}^1$$
$$CE_2 \geq D$$
$$\sum_{i=1,2} \varphi_i^* = 1.$$

The first two conditions guarantee that the optimal share value, as estimated by each agent, is at least as good as going it alone and the third condition will ensure efficient risk sharing. Then, the core of the cooperation game captures the risk exchange zone. In this case, the risk exchange zone is determined by the amount of D that is exchanged between the two agents. It is given as follows:

$$CE_1{}^1 - CE_1 \leq D \leq CE_2 \tag{27}$$

It can be seen from Eq. (27) that the core of the cooperation game is non-empty as long as D is positive[7]. A non-empty core indicates that there are gains to be made by cooperating via risk sharing. In other words, the risk-sharing zone is the risk-sharing core of the contract. It can also be seen from expression (27) that the size of the risk sharing core depends on the risk aversion γ_i of the two agents in addition to the variances σ_1, σ_2 of the pre-existing businesses and the correlations ρ_1 and ρ_2 of the pre-existing businesses with the joint venture.

[7] Individual rationality is the boundary condition for having non-empty core of the cooperative game.

So far, we have seen the value that risk sharing provides for risk-averse agents seeking cooperation. We showed that for a stochastic cooperative joint venture between agents with a CARA utility function, linear contracts provide Pareto-efficient payoff allocation and allow an optimal risk-sharing rule. We assumed that agents maximize their joint welfare and under that assumption, linear contracts can provide optimal risk sharing mechanism. The optimal risk sharing contract is determined by the exchange of a negotiated cash payment from one party to another. It is dependent not only the parameters that affect the optimal risk share (i.e. risk aversion γ_i, volatilities σ_1, σ_2 of the pre-existing businesses and the correlations ρ_1 and ρ_2 of the pre-existing businesses with the joint venture), but also the agents' relative bargaining power (Choi and Triantis, 2012; Murnighan et al., 1988).

4. Illustrative example

In this section, we provide an example of our results for illustration purposes. Specifically, we present analyses of the effect of correlation on the optimal risk share and the value risk sharing for cooperating partners. A stylized joint investment on merchant electricity interconnector is used for demonstration. We provide some background that presents the need for analysing the value of risk sharing in this specific situation. However, the example should be taken only as an illustration rather than a numerically accurate case study. Fitting model parameters would require access to confidential information and interactions with the agents in order to extract accurately their risk preferences, and it would not add to the illustration intended, which considers many different possible values for the parameters.

4.1. Problem background

The current electricity infrastructure across the EU is outdated and inefficient and bottlenecks prevent efficient transmission of electricity from one part of Europe to the other and from one country to another (Norton Rose Fulbright, 2014). The lack of much new public interconnection investment has induced the European legislator to opt for merchant transmission projects (Parail, 2009). Merchant projects could be carried out by new actors as in the case of *East–West cables* and by incumbent transmission system operators (TSOs) as in the case of *BritNed* (Supponen, 2011). However, investment by new actors to connect different market regions is discouraged by the protection tendencies of incumbent TSOs on both sides of the market (Kristiansen and Rosellón, 2010). As a solution, regulators allow incumbent TSOs of both regions to invest in the interconnection as merchant project. A notable example is BritNed merchant interconnector between the UK and the Netherlands (BritNed, 2015).

There is a conflicting choice between national and company interests in cross-border transmission investments (Supponen, 2011). From the national perspective, the motivation for interconnector investment originates from a need to improve the security of supply, facilitate renewable energy integration or electricity price reduction (Kristiansen and Rosellón, 2010). For example, the major motivation for expanding the Germany-Netherland interconnector capacity is Germany's increasing share of electricity from wind which can be exported to Norway. The major motivation for constructing the NorNed cable is the security of supply, since Norway is almost entirely dependent (99%) on hydro generation, and the Nederland is predominantly thermal. BritNed has been undertaken because of security-of-supply issues and the European Commission's desire to link electricity markets. However, from a TSO perspective, the project is risky. For instance, historically the Netherlands has been a higher-priced country (especially during peak hours) relative to its neighbours. From an organizational perspective Tennet (the Dutch TSO) has an incentive to isolate the market, while the Dutch regulator's objective is to introduce renewable energies in an otherwise thermal-dominated system. On the one hand, there are national interests and associated incentives to cooperate. On the other hand, there are costs and associated risks. Therefore, TSOs need to understand the effect of cooperation: i.e. the share of risk during cooperation, the potential value of cooperation and the effect of the interconnector on their existing business. Next, a simplified Numerical analysis is presented to demonstrate these issues.

4.2. Major assumptions of the case study

The main parameter values defining the performance of the three entities and the risk aversion of the agents are shown below, in annual terms.

- Initial cost of the common project $C_s = 15$
- Distribution of revenue of the common project $\mu_s = 40$, $\sigma_s = 20$
- Distribution of revenue of the agent 1 $\mu_1 = 400$, $\sigma_1 = 100$
- Distribution of revenue of the agent 1 $\mu_2 = 250$, $\sigma_2 = 50$
- Risk aversion of agent 1 = 0.1
- Risk aversion of agent 2 = 0.3

As highlighted above, although this case study is inspired by BritNed, the situation is hypothetical, and the estimated parameter values are intended for illustration only.

4.3. Effect of correlation on the risk sharing ratio

Fig. 1 shows agent 1's optimal share of risk as a function of correlation coefficients assuming constant risk aversion. In Fig. 1a it can be seen that, for $\rho_{1s} > 0$, agent 1's share of risk decreases linearly as the correlation between its pre-existing business and the common project increases. On the other hand, for $\rho_{1s} < 0$, the optimal share of risk for agent 1 increases as its correlation increases. Fig. 1a also shows that the risk share of agent 1 depends on ρ_{2s} as well. It can be said that the risk share of agent 1 increases as the correlation of agent 2 shifts from negative to positive. However, it is important to notice that for a given correlation coefficient of agent 2, the correlation coefficient of agent 1 should be between certain value range for optimal risk sharing to exist. For example, if $\rho_{2s} = 0.5$, the optimal risk sharing between the two agents, is possible when $0.2 \le \rho_{1s} \le 1$ for the assumed risk aversion and volatility parameters. The optimal risk share of agent 1 steeply decreases from 90% at $\rho_{1s} = 0.2$ and $\rho_{2s} = 0.5$ to 10% at $\rho_{1s} = 1$ and $\rho_{2s} = 0.25$. In Fig. 1b it can be seen that the risk share of agent 2 linearly varies with the correlation of its pre-existing business with the common project.

In a particular case where the correlations coefficients of both agents are equal to zero agents 1 and 2 take 75% and 25% of the risk respectively. The more risk-averse agent takes a smaller share of the risk and vice versa. However, Fig. 1 shows that the agents can take a higher or lower share of the risk when the correlations of their pre-existing businesses are considered. If agent 1's pre-existing business profit is positively correlated to the projected revenue of the common project and agent 1 knows that agent 2's pre-existing business is negatively correlated to the common project revenue, then it is optimal for agent 1 to take a lower share of the risk than the one obtained at zero correlation.

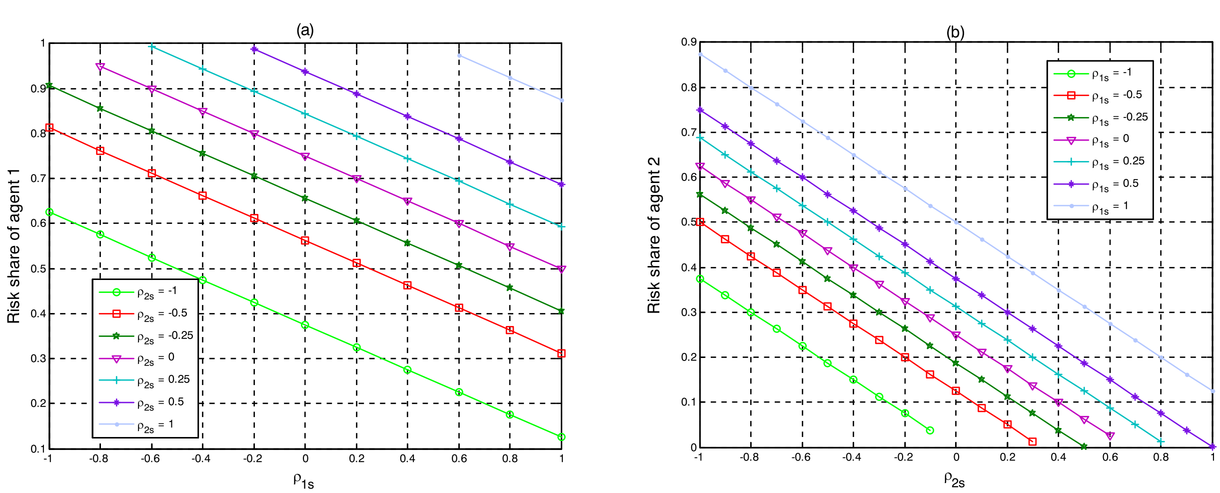

Fig. 1. Optimal risk share as function of correlation coefficients: (a) agent 1, and (b) agent 2.

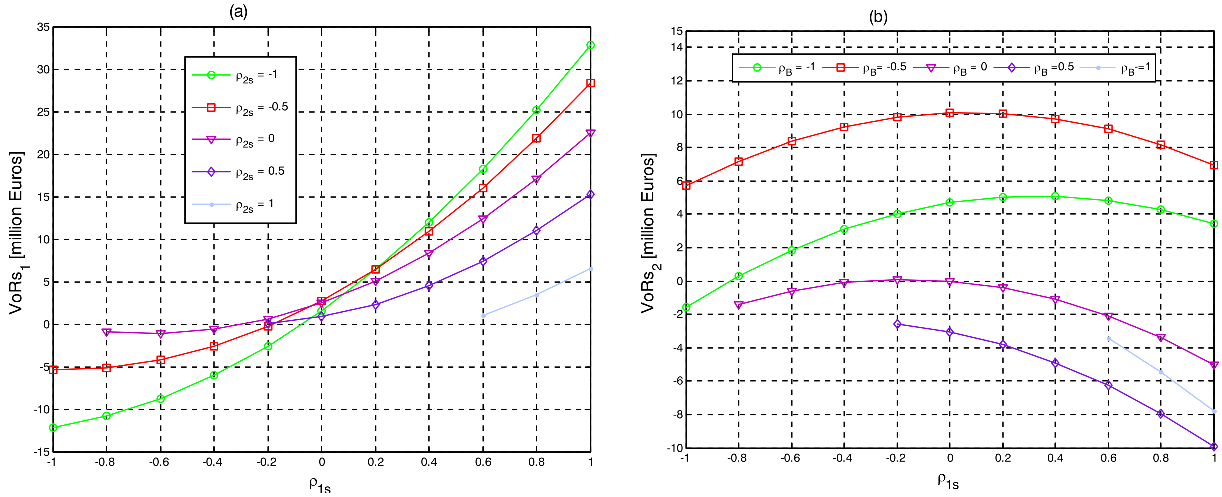

Fig. 2. Values of risk sharing as function of correlation coefficients: (a) agent 1, (b) agent 2.

Therefore, considering correlation provides a deeper insight for agents regarding their optimal share of risk in cooperative ventures. Previous approaches only considered that the share of risk taken by a partner is higher for lower risk aversion. However, we show how the optimal risk share depends greatly on the correlation of the joint venture with the agent's pre-existing businesses.

4.4. The value of cooperation via risk sharing

In the previous section, we showed that the optimal stake of risk is influenced by the correlation of the pre-existing businesses with the common project. However, the optimal risk ratio only informs how much stake of the risk each player will take and does not provide information about the value of cooperation via risk sharing. Fig. 2 shows the value of cooperation via risk sharing (VoRs) as a function of correlation coefficients. In Fig. 2a it can be seen that the value of cooperation for agent 1 is positive when her pre-existing business is positively correlated to the common project. However, the value of risk sharing depends also on the correlation coefficient of agent 2. If agent 1 has a positive correlation, the value of risk sharing increases as agent 2's correlation increases. The effect of the correlation of agent 1's business on its value of risk share can be clearly observed when the correlation coefficient of agent 2 is fixed. For example, in Fig. 2a it can be seen that for $\rho_{2s}=0.5$ the VoRs1 increases from close to zero at $\rho_{1s}=-0.2$ to 27.5 million Euros at $\rho_{1s}=1$.

Similarly, for agent 2, the value of risk sharing is influenced by the correlation of its pre-existing business with the common project, in addition to the correlation coefficient of agent 1. In Fig. 2b it can be seen that for $\rho_{1s}<0$ the value of risk sharing for agent 2 decreases as his pre-existing business is more negatively correlated to the common project. On the other hand, if $\rho_{1s}>0$, the value of cooperation for agent 2 decreases as her/his existing business is more positively correlated to the common project. If the VoRs for both agents is positive, it indicates that partners with divergent risk attitudes and correlation coefficients can gain more synergies from risk sharing in uncertain environments.

It is likely that different agents have different background risk from their pre-existing businesses. If an agent knows about the performance of the co-partner's businesses profit, then it is possible to calculate the share of risk and the value of cooperation with another agent. However, symmetry information among partners is required regarding the performance of the common project and their pre-existing businesses. If an agent has information about the pre-existing businesses of potential candidate partners, she/he can use that information to determine worthy co-investors. This is particularly important at the exploratory stage of the co-investment and during contract negotiation stages. Having a better understanding of the economic implications of committing contractual agreements, especially when the new venture has implications on the performance of the pre-existing business, could help build resilient partnerships and avoid problems.

5. Conclusions

The exploratory phase of a joint infrastructure project entails uncertainties to cooperating agents with respect to the value of the project and the optimal share of risk. Uncertainty often leads to a deadlock situation in which decision-making stagnates. To address uncertainty in such situations, an approach is required that allows the assessment of the risk and gain of cooperation for each agent. In this paper, we analyse the effect of risk sharing when two risk-averse agents co-develop an energy infrastructure project under uncertain environment. The two agents have background risks from their pre-existing businesses, and the joint project is represented by a risky cash flow. The cooperating partners are risk-averse but need not have the same risk aversion. We assume that the partners will act cooperatively to maximize their joint welfare and there is information symmetry on the common project performance. The models and numerical analyses provide valuable managerial insights.

First, agents with divergent risk attitude can gain more synergies from risk sharing in uncertain investment environments. This is in agreement with earlier work (Savva and Scholtes, 2005) and implies that cooperating with a partner with a different risk attitude can be very beneficial. As shown in Eq. (27), risk-sharing opportunities increase the risk exchange zone (i.e. the synergy set) from traditional economies of scale and scope. This could encourage uncertain agents to engage in cooperation to develop vital energy infrastructures.

Secondly, agents can structure better risk-sharing contracts. Conventionally, the risk preference of cooperating agents described with their respective risk aversion is used to allocate risk optimally. In this study, we found that the optimal share depends also on the future projection (i.e. volatility) of the new common project and the agent's pre-existing businesses. Furthermore, the optimal risk share depends on the correlations between the agents' pre-existing businesses and the new common project. These additional insights can help agents understand better the economic implications of long lasting contractual agreements and build enduring partnerships.

Last, the model can help agents to select the most suitable partner for a project. Agents can carry out an exploratory assessment of the value risk sharing with the different prospective partners. Different agents have a different background (pre-existing business) and risk attitudes, and the developed model can support the selection of a partner.

Finally, the modelling framework and the numerical analysis presented in this paper invite opportunities for future work. One area of future work could involve extending the model for multiple agents and considering the relative negotiation power of agents. Moreover, a real case study would make the model more relevant for practical deal negotiations.

Conflict of interest statement

There is no conflict of interest.

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An approach for flexible design of infrastructure networks via a risk sharing contract: The case of CO_2 transport infrastructure

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ABSTRACT

This paper presents a systematic design analysis method based on the flexible design approach and the concept of real options to support decision-makers during conceptual design of infrastructure public–private partnership projects under uncertainty. It employs probabilistic and simulation methods to model uncertainty and flexible design concept to generate flexible design strategies within the physical layout and the contractual structure. Monte Carlo simulation is used to compare the value effects of design strategies. Illustrated on a stylized public–private partnership to develop a carbon capture and storage infrastructure, it was found that partners could find design solutions that not only reduce risk exposure but also enable value-creation. For example, by designing the physical network with flexibility options such as extra capacity and length coupled with flexible revenue guarantee contract, partners can be able to reduce risk and enhance their respective value in the face of capacity demand uncertainty. Such a design strategy can be a promising way to realize multi-user carbon capture and storage investments.

1. Introduction

Carbon capture and storage (CCS) is considered as one of the best options currently available for mitigating global greenhouse gas emissions, especially given the reality that fossil fuels will remain the primary sources of energy for the foreseeable future (IEA, 2015). For example, the EU climate and energy framework stated CCS as the "only option available" to reduce direction emission at large scale (European Commission, 2014). The framework also considers CCS as key technology for emisison reduction from fossil fuel-based power generation (European Commission, 2014). Yet, currently, carbon capture and storage (CCS) is not being deployed on a commercial scale.

One of the key challenges to achieving large-scale deployment of CCS is the development of the infrastructure necessary to transport and permanently store CO_2 (Austell et al., 2011). Several techno-economic studies have demonstrated that the most cost effective way to develop large-scale CCS networks is to connect multiple CO_2 sources and storage sites via networks of pipelines (Middleton et al., 2012; Melese et al., 2015; Chrysostomidis and Zakkour, 2008). Multi-user pipeline networks facilitate more CCS projects deployment, as CO_2 emitters that do not have the capacity (technically and/or financially) to build their front-to-end pipeline will be able to gain access to a network (Austell et al., 2011). By reducing unit transportation costs as well as entry costs for new entrants, multi-user pipeline networks will especially help smaller emitters which may not able to bear the cost of building an individual pipeline (Austell et al., 2011).

However, in the current situation, developing multi-user CO_2 pipeline networks would expose developers to significant first-mover risk and additional up-front costs (Chrysostomidis and Zakkour, 2008; Bowen, 2011). The first-mover risk is greater during the demonstration stage of CCS (Bowen, 2011). But, the risk could gradually phase out as the pipeline networks start to develop by adding new emitters. Nevertheless, at its current stage, CCS investment faces substantial risks and uncertainties (Lupion and Herzog, 2013; Global CCS Institute, 2014). As a result, currently, CCS network deployment projects are mostly limited to point-to-point connections.

The high risk of building CCS raises an argument that government support may be required. Risk sharing in the form public-private partnership (PPP) is a common form of public support mechanism used to improve the financial viability of infrastructure investments (Cruz and Marques, 2013a,b). An infrastructure PPP bundles investment and service provision in a single long-term contract (Engel et al., 2013). The contract allows the concessionaire (the private actor) to manage and control the assets, usually in exchange for user fees and government payments (e.g. subsidy), which compensate for investment and other costs. In the case of CCS, government support for multi-user CO_2 pipeline network investments can be justified on the basis that taking advantage of economies of scale can reduce the overall cost of

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mitigating greenhouse gas emissions to society (Mikunda et al., 2011). Furthermore, public support can be justified on the basis that mitigation of CO_2 emissiones is a form of public good in which governments have a vital role to play (Chrysostomidis and Zakkour, 2008). Studies substantiate the use of public funds to realize large-scale deployment of CCS technology (DECC, 2010; Chrysostomidis and Zakkour, 2008; Groenenberg and de Coninck, 2008). A study done by Boston Consulting Group (BCG) for Global CCS Institute suggests that considerable government involvement is required to overcome the current commercial realities of CCS (Global CCS Institute, 2010). The same view is supported by the evidence from the case study by Environmental Resource Management (Chrysostomidis and Zakkour, 2008).

Deployment of CCS infrastructure PPPs is very challenging for number of reasons. Firstly, infrastructure PPPs are generally long lasting contracts involving massive and irreversible capital investments under a highly uncertain environment. Secondly, infrastructure PPPs have intrinsic characteristics that make them particularly vulnerable to exogenous uncertainty related to the macroeconomic scenarios, technological changes, regulatory changes, competition or emergence of substitute services (Shen et al., 2006). Finally, infrastructure PPPs are vulnerable to opportunistic behavior as they require cooperation between actors with different and often conflicting objectives (Williamson, 1979; Hart, 2003; Guasch and Straub, 2009). Private actors are mostly concerned with the financial feasibility of the investment as they are particularly susceptible to revenue risk, whereas the public actor is concerned with cost overruns, guarantee payments, and reliability of the service provided by the infrastructure.

Related to the last reason, synchronizing the interest of the public actor with that of the private actor is important factor for effective deployment of multi-user CCS. Private network operators usually invest in smaller capacity to save the sunk cost (Global CCS Institute, 2010). Moreover, private network operators charge a very high tariff and that is considered as one of the reasons that discourage emitters from participating in a CCS project (Global CCS Institute, 2010). On the other hand, public actors want to ensure that sufficient capacity is available for existing and future emitters (Austell et al., 2011). Therefore, from a design perspective, deployment of CCS via public-private partnership involve both engineering and contractual design dimensions that may lead to conflicts. These design issues are more visible and impactful at the initial stage of the design process commonly called the conceptual design stage (de Neufville, 2004).

Conventionally, PPP contractual arrangements involving large infrastructure projects are based on deterministic demand forecasts and cost estimations (Cruz and Marques, 2013a,b). However, several studies have shown that demand forecasts and cost estimations are often inaccurate (de Neufville, 2004; Flyvjberg et al., 2005). As a remedy, contracting parties 'overwrite' contracts in order to reduce the degree of exposure to situations out of the forecast (Marques and Berg, 2010). However, such kind of contract design approach emphasizes risk minimization and in the process undermines the ability to adapt to changing circumstances (Cruz and Marques, 2013a,b). Moreover, the dynamic nature of uncertain factors and the inability of contracting parties to write complete contingent contracts, in essence, underscores that risk management activity should be dynamic (Chiara and Kokkaew, 2009).

Flexibility is a design concept that captures the adaptability of a designed solution to uncertainty (de Neufville and Scholtes, 2011; Cruz and Marques, 2013a,b). It is an attribute of the designed system (i.e. a physical infrastructure or a contract), alongside reliability, robustness, availability, and maintainability (Saleh et al., 2003). The concept of flexible design has gained increasing attention for designing large-scale engineering systems that can better accomodate uncertainty (Cardin, 2014; Melese et al., 2016). Similarly, the idea of contractual flexibility is gaining momentum in contracts involving large-scale infrastructures (Chiara and Kokkaew, 2009; Tan and Yang, 2012; Cruz and Marques, 2013a,b; Domingues et al., 2014).

Infrastructure PPPs involve engineering and contractual dimensions that may provide opportunities to design flexibility. From an engineering design perspective, the physical infrastructure can be designed with flexibility capabilities that will allow it to adapt to changes, e.g. demand (de Neufville and Scholtes, 2011; Zhao and Tseng, 2003). From a contractual design perspective, opportunities exist to incorporate flexibilities, e.g. flexible concession period, revenue guarantees, options to defer or abandoning the project (Cruz and Marques, 2013a,b).

To date, several CCS infrastructure models have been proposed in the literature that tried to address the spatial and temporal uncertainty facing large-scale CCS deployment. (Mendelevitch et al., 2010) developed a model that considers multi-stage deployment of the CCS network. (Middleton et al., 2012) introduced an improved model that allows an optimal deployment of CCS over multiple periods. The model is designed to be flexible regarding how much CO_2 is captured, transported, and stored in each period. (Melese et al., 2015) introduced a design procedure that deals with temporal and spatial uncertainties facing the deployment of CCS networks. The design procedure uses graph theory to model CCS networks and uses exploratory modeling and the concept of flexible design to search for design strategies that would allow cost-effective expansion of a multi-user network. The works above represent advanced approaches that provide insights into the economics of integrated CCS deployment. However, all these methods focus on the physical design of the infrastructure and implicitly or explicitly assume a single actor (investor), whereas a CCS PPP involves multiple actors and requires modeling of both the physical and the contractual structures.

To this extent, in this study, an integrated design analysis framework that models both engineering and contractual structures of infrastructure PPPs is presented. The framework is used to explore the value effects of different physical and contractual design strategies by simulating the model under different uncertain scenarios. A public-private partnership for deployment of CCS networks is used as a case study to demonstrate the proposed framework.

The rest of the paper is organized as follows. In Section 2, the proposed methodological framework is presented. In Section 3, the proposed method is demonstrated on a PPP arrangement for deployment of a hypothetical CCS network. Section 4 concludes the paper.

2. Proposed methodological framework

By blending ideas presented in (Melese et al., 2015) on engineering design of CCS networks with those of (Brandao and Saraiva, 2008) and (Engel et al., 2013) on concession contractual design, this paper presents a systematic design analysis framework for a conceptual design of a CCS PPP. The framework is used to study the value effects of different design stratgies at the conceptual stage of the design process. It involves three major steps as shown in Fig. 1: Identify and characterize relevant uncertain design variables; generate technical and the contractual design concepts of the PPP; and Monte Carlo simulation and design analysis.

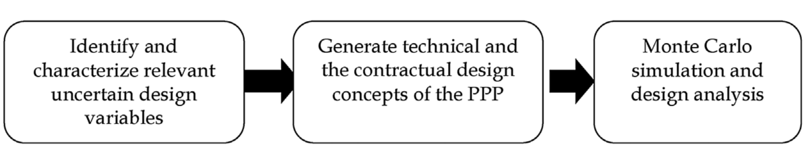

Fig. 1. Proposed framework for systematic design analysis.

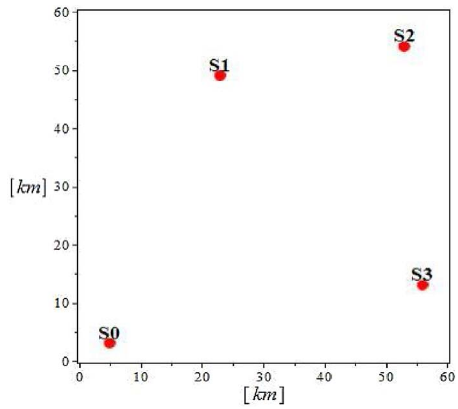

Fig. 2. Layout of the Field.

2.1. Step 1:- identify and characterize relevant uncertain design variables

As highlighted in the introduction section, uncertainty, in the context of infrastructure PPP design, reflects the fact that many assumed inputs could change over time. Therefore, the first task in the design process is to identify uncertain design variables that could affect the performance of the PPP and the values of partners. These include market uncertainty, raw material input uncertainty, cost uncertainty, productivity uncertainty, technological uncertainty, regulatory uncertainty, etc.

Once the relevant uncertain variables are identified, they must be characterized appropriately. Characterization involves modeling initial distributions and future states of the selected uncertain variables. Uncertainties can be modeled using a number of different methods, and the choice of a particular method depends on the information available. When sufficient historical data is available, statistical methods (e.g. regression) can be used to fit empirical data and derive future states (Agarwal and Aluru, 2010). When there is a lack of historical data, analytical approaches could be more helpful as they allow the use of assumptions on the initial behavior of the uncertain variable (i.e. types of distribution and speed of convergence) (Sankararaman et al., 2014).

Once the initial distribution of the selected variable is defined, future states over several stage or design period should be modeled. A stage or design period in this context would be a suitable planning period (i.e. months, years). The future states can be generated using continuous stochastic models such as Geometric Brownian Motion (GBM) and Wiener processes, or discrete models such as the binomial trees (Lin, 2008).

2.2. Step 2:- generate technical and the contractual design concepts of the PPP

In this step, designers generate flexible design concepts of both the physical and the contractual structures to deal proactively with changing design requirements identified in step 1. Flexible design concept generation involves defining strategies necessary to determine how the physical network and contractual arrangement will adapt in the face of uncertainty (Cardin et al., 2013). Examples of flexibility strategies in technical design and management include (Trigeorgis, 1996): (1) defer investment until favourable conditions arise, (2) staged or phased deployment of asset, (3) change operation and management by expanding or contracting production capacity, (4) abandon or opt-out of a project, (5) switch inputs and/or outputs to capture emerging new requirements, (6) or combination of the above. Flexible duration contract, flexible revenue guarantee, step-in rights are some common forms of flexible design strategies for contracts (Cruz and Marques, 2013a,b).

Generating flexible design concepts require developing a model of the designed system at hand. Therefore, designers need to develop a model of the PPP including the configuration of physical infrastructure and the contractual relationship between the partners. In the case of CCS networks, the physical configuration of the network includes design variables such as capacity, length, and flow rate. Contractual design variables include tariff, contractual period and the share of risk and benefits.

2.3. Step 3:- Monte Carlo simulation and design analysis

The objective of this step is to evaluate, analyze and compare the performance of different combinations of physical and contractual design strategies by simulating them under different uncertain scenarios. Monte Carlo simulation is a commonly used means to assess the value of design concepts to distributions of uncertainty. The inputs are the evolution of the uncertain parameters and the flexible design strategies. The result is a distribution of the project value, for example, its net present value (NPV). Then compare the resulting distributions, along with aggregate statistics of interest, to get an understanding of the value effect of the different design solutions for the partners.

3. Illustration – carbon capture and storage networks

3.1. Design problem

For the purpose of illustration, we formalized a stylized design problem that resembles a real-world network design context but is more abstract and general. The problem involves the conceptual design of a CCS network. The field has two existing CO_2 sources, S1 and S2, and one potential source, S3, that could join in future. All existing and future new sources will be connected via a pipeline network to a single sink S0 (e.g. storage site). Fig. 2 shows the spatial location of the three sources and the sink.

A partnership is created between a private firm who will own and operate the network, hereafter called, network operator; and a government agent, hereafter called, public actor to develop the CCS network. The network operator invests in the network and the public actor shares investment and operational risk with the network operator via a long-term concession contract. It is assumed that the network operator will not invest in the network without the risk-sharing contract. The network operator will build and operate the network for the period of the concession.

The two actors have different objectives which define their value in the partnership. The objective of the public actor is to ensure the public interest- reduction of CO_2 emission by facilitating the availability of a pipeline based CO_2 transport infrastructure which can provide sufficient capacity for existing and future CO_2 sources. To meet its objective, the public actor provides subsidy payments for the network operator in the form of minimum revenue guarantee (MRG). On the other hand, the network operator's objective is profit. Therefore, there are three dimensions of value in this design problem: contractual payments (public actor's view of the problem), profit (network operator's view of the problem), and availability of sufficient capacity which trades off the other two values and relates the outcomes to both actors.

The values of the two actors in the partnership depend on the physical configuration of the network and the contract arrangement between them. Under CO_2 supply uncertainty, the reliability of the network is its ability to provide the required capacity as and when CO_2 supply increases over time. Therefore, the design strategy will influence the reliability as some design configurations may be more reliable than others.

The concession contract is used as a mechanism for the exchange of values for the actors. It also provides a legal framework for the risk allocation provision to manage the CO_2 supply (or capacity utilization) risk. For example, the contractual connection tariff term and other risk sharing provisions determine the payments that the public actor makes to the network operator.

By integrating the physical and contractual design, this case study investigates the effects of architectural flexibility, i.e. extra capacity, and length, in the physical domain and connection fee/tariff and revenue guarantee in the contractual domain. Each of these design dimensions presents difficult choices given the uncertainty in CO_2 supply and changing regulations. In this context, the goal of this paper is to propose a systematic design analysis framework that enables value creation through improved physical design of the CCS network and value exchange (risk sharing) through improved contractual design. As pointed out in the introduction, the literature often treats these two types of designs separately, and in this study, we demonstrate how an integrated design approach that considers both physical and contractual structures shapes value creation and exchange during conceptual design of CCS networks. A step by step illustration of the framework is presented next.

3.2. Step 1 – identify and characterize uncertain design variable

Designers face a number of uncertainties in the initial design stage of a multi-user CO_2 pipeline network. Some of the prevalent uncertainties are: the exact number of emission sources who are willing to join network and the capacities they require, the cost per unit capacity (e.g. material and digging costs), the availability and capacity of storage sites, competition from alternative technologies, and regulatory policy regarding CO_2 emissions including the CO_2 price. Collectively, these uncertainties have an impact on the investment decision of the network operator. They also have an effect on the decision to invest in the integrated network or just point-to-point pipeline (Knoope et al., 2015).

In this study, we focus on capacity demand uncertainty, a major design variable, that makes the deployment of an integrated CCS network very challenging (Austell et al., 2011). The uncertainty over capacity demand originates from two sources: (1) from existing participants whose demands may change over time; and (2) from participants who may be interested in joining the network in the future. The profitability of the CCS network investment highly depends on the capacity requirement as well as the tariff charged by per unit volume of CO_2. Therefore, the uncertainty of capacity demands of future and existing sources should be clearly quantified and considered in the investment decision.

3.2.1. Capacity demand uncertainty of existing sources

Analogous to (Melese et al., 2015), the uncertainty over the capacity demand of existing sources is modeled using an analytical approach. The capacity demand of a CO_2 source is related to its CO_2 flow. Therefore, to model the initial capacity demand uncertainty of the two existing sources (S2 and S3) a normal distribution model is used.

- S2 (mean = 350 kt CO_2/year and standard deviation = 40 kt CO_2/year)
- S3 (mean = 400 kt CO_2/year and standard deviation = 50 kt CO_2/year)

Next, future states of CO_2 flow over several stages of the planning period is quantified. In this study, the planning period is set for 20 years, which is a reasonable time horizon for a progressive CCS deployment strategy (Asian Development Bank, 2015). To model the future states of CO_2 flow, Geometric Brownian Motion (GBM) process is used. The parameters of the GBM process for both sources are drift rate = 5% and volatility = 7.5%. With the initial assumptions, drift rate and volatility, the GBM process generates yearly flow data over the planning period. Fig. 3 shows initial flow estimate model and flow evolution pathways for sources S2 and S3.

3.2.2. Capacity demand uncertainty of future sources

Timing and capacity demand of future sources present another challenge for an integrated CCS network deployment. In this study, we only consider one future source, S1.

Theoretically, S1 could be CCS ready and join the network at any time over the planning period. However, in reality, it takes years to install a CO_2 capture unit and to be ready to join a CCS network. In this study, four timing scenarios are considered with a time step of four years: Year 4, Year 8, Year 12 and Year 16. A time period of four years is considered reasonable for an emitter to install a capture unit and connect to a network.[1] The capacity demand of S1 is modeled in a similar way to that of S2 and S3 with initial flow estimate modeled as shown in Fig. 4a with mean = 300 kt CO_2/year and standard deviation = 50 kt CO_2/year. Then, GBM process is used to model future yearly CO_2 flow rates. Parameters of the GBM process are, drift rate = 5% and volatility = 7.5%.

3.3. Step 2 – generate technical and the contractual design concepts of the PPP

The objective of this step is to generate flexible design concepts of the physical CCS network as well as the risk sharing contract. To facilitate the generation of flexible design concepts models of the physical CCS infrastructure and the contractual relationship is developed. These models help to analyze the value effects different design concepts under different uncertainty scenarios.

3.3.1. The physical network design model

A graph theory-based network modeling technique is used to model the physical layout of the CO_2 transport infrastructure. The technique is effective in modeling the layout of spatially distributed and connected infrastructures as networks consisting of nodes and links (Heijnen et al., 2014). CCS involves transporting CO_2 from of CO_2 capture stations (source nodes) to an injection site (sink node) through pipelines (links).

In CCS pipeline network design, various goals may be pursued. Minimization of investment cost and availability of sufficient capacity are probably the most important and evident. In this study, the goal is to maximize the present worth ratio (PWR) the network investment. The PWR of the network will be maximized when investment cost of building the network are low and expected revenues are high.

$$\mathrm{PWR} = \frac{\text{expected revenue} - \text{investment cost}}{\text{investment cost}} \tag{1}$$

The investment cost of the CCS network depends on the length and capacity of the pipeline. The inputs of the model are flow rates of sources to determine capacity and the spatial positions of sources and sink nodes to determine length. The spatial positions of the three sources and the sink node are fixed as shown in Fig. 2. The total cost of a network N is the sum of all the costs of edges

$$C(N) = \sum_{e \epsilon E} l_e f(q_e) \tag{2}$$

where E is the set of all edges in a network N, l_e is the length of an edge e and $f(q_e)$is the cost per unit length of building an edge e with a flow capacity of q_e. The flow capacity is assumed to be given by

$$f(q_e) = q_e^{\beta} \text{ with } 0 \le \beta \le 1. \tag{3}$$

where β is the exponent taking account capacity variation on the cost.

The cost exponent takes into account the capacity factor in the cost calculation. The lower the cost exponent, the more beneficial it is in terms of construction costs. An empirical cost exponent value of 0.6 is commonly used in pipeline networks models (Heijnen et al., 2014). The cost exponent indicates that building high-capacity pipelines have cost advantages. The network model then produces edge-weighted Steiner

[1] The actual instllation time of a capture ready plant could vary depending on the size of the capture unit, the type of capture technology, and other project specific factors (IEA GHG, 2007).

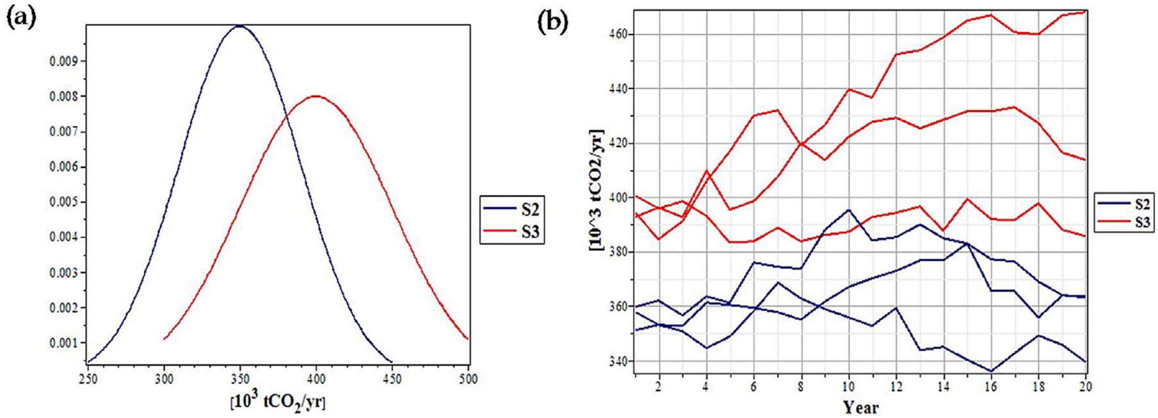

Fig. 3. Sources capacity demand model. Initial flow estimate model (a) and three instances of future trajectories of flow (b).

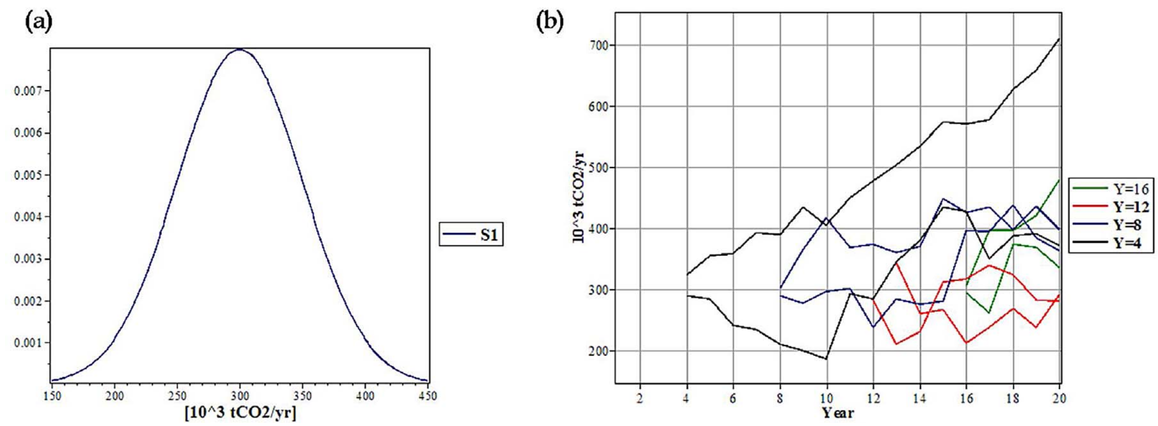

Fig. 4. Capacity demand model of S1: (a) initial flow estimate, (b) instances of flow trajectories over time. Each trajectory represents one instance of S1 flow path. Y stand for Year.

minimal trees[2] that take into account both the capacity and the length of the pipeline.

In addition to cost, expected revenue over the planning period should also be modeled. For this purpose, the expected revenue is modeled as a linear function of flow rate. It is assumed that the network operator generates revenue by charging a connection tariff from CO_2 sources. Hence, the revenue R_t of a network N in year t is given as,

$$R_t(N) = \alpha \sum_{i \in V(N)\backslash\{s\}} q_i \tag{4}$$

where q_i is the used capacity by CO_2 supplier i in a network N, $V(N)$ is the set of all nodes in the network N, s is the sink and α is the constant coefficient representing the tariff.

Searching for the worth maximizing network involves simulation of the network model with different uncertainty scenarios. The simulation will result in thousands of design possibilities. Advantage of the network model is that it is simple low-fidelity and therefore can be run much faster than detailed high-fidelity models. This characteristic of the model comes in handy when one tries to search and screen for a few promising design concepts out of thousands of possibilities.

3.3.2. The contractual structure design model

The objective of the contract model is to structure the allocation of risk between the two actors given the uncertainty in capacity demand from existing and future sources. As shown in Eq. (4) revenue depends on uncertain CO_2 supply/capacity utilization [in units of cubic meters/year] and the constant tariff level [in euros per cubic meter]. When the profitability of the network project is weak, the public actor provides a revenue guarantee to the network operator.

Let P_t be the minimum revenue guaranteed by the public actor in year t. If we assume a constant connection fee (tariff), the actual revenue (R_t) resembles the stochastic process of CO_2 supply, q_i. Taking into account the guarantee, the effective revenue I_t for the network operator in year $t$can be given as:

$$I_t = \max\,(R_t, P_t) \tag{5}$$

Adding discounted values future incomes over the planning period gives the present value of total revenue (PVR). The connection cost or tariff is assumed to be 1 €/t CO_2. It is also assumed that the real discount rate,[3] r, to be 8%.

$$PVR(N) = \sum_{t=0}^{20} \frac{I_t(N)}{(1+r)^t} \tag{6}$$

Eq. (6) is critical in defining the contractual relationship between the network operator and the public actor. From the perspective of the network operator, the performance of a given network design over its lifetime can also be analyzed based on the Net Present Value (NPV) valuation, as shown in Eq. (7).

$$NVP(N) = PVR(N) - C(N) \tag{7}$$

At the conceptual design stage, Eq. (7) can be used by the network operator to explore the economic performance of different network design choices.

On the other hand, the public actor is concerned with the amount of subsidy to be paid to the network operator. The value of the guarantee,

[2] A Steiner minimal tree is a tree connecting points in a plane using lines of shortest possible total length (Gilbert and Pollak, 1968).

[3] Different discount rates are used in different studies: 7.5% (Chrysostomidis and Zakkour, 2008), 10% by (Knoope et al., 2015)

$V(t)$ in year $t$is given as:

$$V(t) = \max(0, P_t - R_t) \tag{8}$$

The total present value of payments over the concession period can be calculated by discounting V(t) over the concession period. The present value of Eq. (8) is the value of the option in each year. The total sum of the option gives total value of guarantee payment, VG_f.

$$VG_f = \sum_{t=1}^{t=T} \frac{V(t)}{(1+r)^t} \tag{9}$$

The expressions in Eqs. (7) and (9) model the objectives of the network operator and the public actors. The network operator's objective is to maximize the NPV or PWR and the public actor is interested in minimizing the amount of VG_f. The conflict arises because the public actor main objective is to provide sufficient capacity for existing and future sources. These design objectives are affected by the way the network designed, i.e. l_e and q_e, and the way the contract is designed, i.e. P_t and α. Therefore, both actors should analyze the value effects of different design concepts in the face of capacity demand uncertainty.

3.3.3. Design concepts

The choice of flexible design concepts should take into account the evolution of capacity demand uncertainty and the effect on the value of the contracting partners. At the conceptual design stage, the network operator and the public actor have two degrees of freedom to integrate flexibility: the layout of the physical network, i.e. capacity and length of the network and the structure of the risk-sharing contract, i.e. the level of the floor and ceiling levels. By playing with these two degrees of freedom, the two actors can find combinations of design strategies that enhance their value under capacity demand uncertainty.

From an engineering design perspective, two network design strategies are considered. The first design strategy is to develop the network by connecting the two existing sources S2 and S3 but without taking into account the future source S1. It is normally considered as the base case design strategy by which the network operator develops the network with the only information available during the conceptual design stage. We name this design strategy as the deterministic design strategy. The expected capacity demands of S2 and S3 are the basis for the deterministic design strategy.

The second design strategy is to develop the network by connecting the two existing sources S2 and S3 and taking into account the possibility that S1 will join the network sometime in the future. We call this design strategy as the flexible design strategy. Moreover, the flexible design strategy takes into account variations in the capacity demands of existing sources (i.e. S2 and S3). Fig. 5 shows the design concepts of the two design strategies.

In the face of capacity demand uncertainty, the network operator can satisfy her/his participation constraint (i.e. expected net present value, ENPV > 0) by carefully selecting the technical and contractual design variables. At the same time, the network operator may also be concerned that capacity shortage will not only reduce revenues but also damages reputation. Therefore, it is assumed that the network operator shares the value of public actor to minimize the capacity shortage for existing and future sources. The network operator can try to accomplish this by finding a suitable combination of the physical design inputs. To summarize, the network operator has to try to find a combination of both physical and contractual design inputs that best accomplishes the stated objectives.

One the other hand, the public actor's primary interest is ensuring the availability of sufficient capacity for current and future CO_2 emitters. The public actor can try to accomplish this objective by finding a suitable combination of the physical and contractual designs. However, the public actor faces a trade-off between providing sufficient capacity and contractual payments that must be made to the network operator. Since revenue to the network operator depends on the capacity utilization which is uncertain, if it falls below MRG, the public actor will have to pay a subsidy to the network operator to bring its revenue back to the MRG level.

The value of guarantee payment not only depends on the level of P_t but also on the design configurations. Some design configurations could cost more than others. Moreover, the way the network is designed closes or opens options for cost-effective expansion of the network over its lifespan. Therefore, the public actor has to find the combination of both physical and contractual design inputs that will help to accomplish the stated objective, i.e. reduce capacity shortage and minimize subsidy payment.

To deal with the risk of excessive subsidy payments, the public actor may include a revenue ceiling (Engel et al., 2013). The joint modeling of the MRG and ceiling can be seen as a compound options by which the two options are mutually exclusive and can be modeled by assuming that the actual revenue will fall in either of the three positions: below the revenue floor (i.e. MRG level), between the revenue floor and the revenue ceiling or above the revenue ceiling. The inclusion of the floor and ceiling in the contract provides flexibility for both actors and impose bounds on the risk associated with unpredictable revenue streams. (Quiggin, 1996) suggested the use of options concept in PPP contracts to provide flexibility and mitigate exposure to risk associated with unpredictable revenue streams.

Similar to work by Brandao and Saraiva (2008), in this paper, the risk-sharing contract model is structured as a composition of a minimum revenue guarantee and a maximum revenue ceiling. The minimum revenue guarantee can make the CCS project more attractive financially to the network operator since it ensures a minimum level of income. On the other hand, the maximum revenue ceiling works like a cap for total revenue on the upper side, allowing the public actor to control for higher-than-expected returns by the network operator.

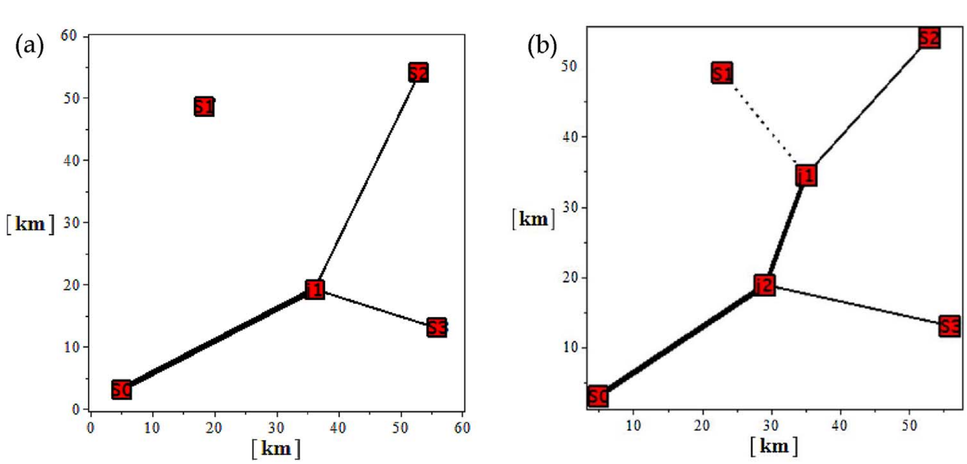

Fig. 5. Network design concepts based on the determinstic design stratgey (a), and the flexible design strategy (b).

However, the ceiling does not restrict the direct revenue amount obtained from CO_2 sources. Therefore, the contract model has an option like characteristics; it is exercised when the actual revenue falls below the minimum level of revenue or above the maximum revenue ceiling (Jun 2010).

In the case of revenue floor and ceiling contractual structure, the effective revenues IG_t received by the network operator (i.e. observed from tariff and subsidy) in each period t are given by:

$$IG_t = \min\{\max\,(R_t, P_t),\, Q_t\} \tag{10}$$

where Qt is the revenue ceiling level

The public actor can limit exposure opportunistic behavior by using the revenue ceilings, where payments terminate once a ceiling is reached. With revenue ceiling, the value of the option in each year is determined as shown in Eq. (10), but the cumulative sum of all payments made by the public actor is limited to the cap. Then, under the revenue floor and ceiling arrangement, the total value of guarantee payment, VG_{fc} such as shown in Eq. (11).

$$VG_{fc} = \min\{VG_f,\, Cap\} \tag{11}$$

VG_{fc} depends on the choice of the cap. In practice, the cap will take into account the type and size of the investment and the maximum risk exposure the public actor is willing to have on the CCS project, and its impact on the effectiveness of the MRG (Tan and Yang, 2012). In reality, the effect of the cap is limited because it affects only the total outlays of at the highest end of the revenue, which are the ones that have the lowest probability of occurring. On the other hand, including a cap on the amount of revenue can help to eliminate the uncertainty over the maximum exposure by the public actor in the project.

3.4. Step 3 – Monte Carlo simulation and design analysis

This step involves evaluating, analyzing and comparing the performance of different combinations of physical and contractual design strategies. In Section 3.4.1, the performances of the two physical design strategies are compared in a situation where the network operator invests without a risk sharing arrangement. Profit (i.e. NPV) and capacity shortage are used to compare the two physical design strategies. The network operator is mainly concerned about profit but still considers reducing capacity shortage as a secondary objective. Then, in Section 3.4.2, the outcomes of two physical design strategies are compared under a risk-sharing contract arrangement. Profit, capacity shortage, and subsidy payment are evaluated at different revenue guarantee level, and their implications for the network operator and the public actor are analyzed and compared.

3.4.1. Comparing physical design strategies without risk sharing arrangement

The performances of the two physical design strategies are evaluated for different uncertainty realizations defined in step 1. The analysis is carried out for the scenarios on which the new source (S1) joins the network in years 4, 8, and 12. The connection fee/tariff level paid by the sources is set at 0.6 €/ton of CO_2. Monte Carlo simulation is carried out resulting in distributions of NPVs and capacity shortage values for each design strategy. Then, NPVs are sorted and plotted as cumulative distribution function, otherwise known as value-at-risk-gain (VARG) curve (de Neufville and Scholtes, 2011). Fig. 6 shows cumulative probability distribution curve of the two design strategies.

From Fig. 6a it can be seen that both physical design strategies present, in varying degree, a major risk for the network operator. However, comparing the two design strategies the flexible design strategy performs better than the rigid design strategy if S1 joins at year 4 or earlier. The flexible design strategy enables the network operator to capitalize from future CO_2 flow increases from existing sources S2 and S3, and the new source S1. The redundant pipe capacities in edge S0-J1 and edge J1–J2 and the proximity of the connection node J1 to source S1 enable cheaper expansion of the network. In contrary, the rigid design strategy cannot allow accommodation of S1 and potential flow increases from existing sources. Under the given problem definition, if the network developed based on rigid design strategy, S1 may have to build in individual connection directly to sink (i.e. a line from S1 to S0), which would be much more expensive than building a line from S1 to J1.

However, the performance of the flexible design strategy decreases when S1 joins later, as seen in year 8 and year 12 scenarios. Moreover, when S1 joins the network at year 8 and year 12, the flexible design strategy performance lower than the rigid design strategy. The decrease in the performance of the flexible design strategy suggests that the economic value of having oversized capacity diminishes with time. Therefore, the economic viability of designing the network with oversized capacity is contingent on the timing of the future sources joining the network. Unused capacity locks capital and imposes a great risk for the network operator. In commercial CO_2 pipeline investment, the term 'no-regret-period' is used to indicate anticipatory extra capacity investment decisions. At tariff level of 0.65€/ton, the 'no-regret-period' for the flexible design strategy is around 4 years. Currently, in commercial CO_2 pipeline investments 'a no-regrets-period' is around 10 years (Austell et al., 2011).

Another, perhaps, less interesting, performance evaluation measure for the network operator is the capacity shortage. From Fig. 6b it is clear to see that the flexible design strategy minimizes capacity shortage compared to the rigid design strategy. It shows that including oversized pipelines in critical links of the network enables cost effective accommodation of future CO_2 flow increases from existing sources and new sources. Moreover, since the flexible design strategy allows anticipatory capacity availability, it may encourage other emitters (i.e. CO_2 sources) to invest in CO_2 capture technologies. Therefore, the flexible design strategy could be interesting for potential future participants and the public actor as it allows realization of integrated CCS network. However, such a design strategy could have a negative economic incentive for the network operator as shown in Fig. 6b.

However, from the network operator's perspective, the economic performance the flexible design strategy can be improved by increasing tariff paid by CO_2 sources. Fig. 7 shows the expected net present value (ENPV) of the two design strategies at different tariff level. It can be seen that when the tariff level is increased from 0.65€/ton to 1.5€/ton, the flexible design strategy provides better economic performance than the rigid design strategy. The improvement in ENPV also provides a valuable insight with regard to 'no-regret' anticipatory capacity investments. The 'no-regrets-period' increases from 4 years to 8 and 12 years depending on the tariff level. For example, at tariff level of 0.65€/ton, the flexible design strategy performs better for scenarios that S1 joins the network at year 4 or earlier. When the tariff level is increased to 1 €/ton, the flexible design strategy performs better than the rigid design strategy for a scenario that S1 joins the network at year 8. As the tariff level is increased to 1.5 €/ton, the no-regrets period for the flexible design strategy increases to 12 years. However, the result shown in Fig. 7 is only based on uncertainty in future capacity demand. Other factors (e.g. discounting rate, tax) could increase the cost of investment and, therefore, reduce the no-regrets period. The no-regrets period could increase if policies that encourage CCS investment and reduce the capital cost of CCS are in place.

Tariff level could also have an effect on capacity shortage. A higher tariff level means that the flexible design strategy becomes economically viable than the rigid design strategy. In such cases, the network operator could be willing to invest in extra capacity, and that will reduce capacity shortage. However, a higher tariff level may discourage emitters from engaging in CO_2 reduction investments. In such situations, government support in the form of a risk sharing could be necessary.

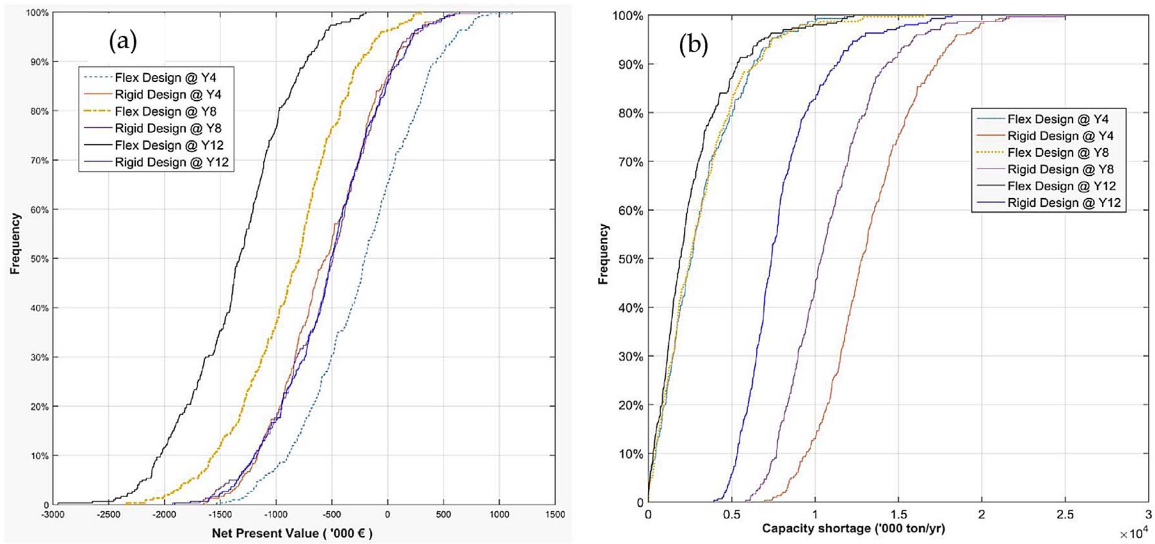

Fig. 6. Cumulative probability distribution curve of NPVs (a) and capacity shortage (b).

3.4.2. Comparing physical design strategies with a risk sharing arrangement

Similar to the preceding section, the performances of the two physical design strategies are evaluated for different uncertainty realizations: i.e. the new source (S1) joins the network in years 4, 8, and 12. The connection fee/tariff level is set at 0.6 €/ton of CO_2. However, unlike the previous case, the public actor shares revenue risk in the form of minimum revenue guarantee (MRG). If revenue falls below MRG (which is set based on the expected CO_2 flow rate), the public actor will have to pay a subsidy to the network operator to improve revenue risk. We analyze how the values of each actor are affected under such situations.

The network operator requires MRG rate that can satisfy her/his participation constraint (i.e. NPV > 0). Fig. 8 shows the effect of MRG rate on the expected profit (ENPV) of the flexible design strategy. It indicates that the MRG rate that is required to satisfy the participation constraint of the network operator depends on the timing of the new source S1. The required MRG rate increases approximately from 9% to 43% when the participation time of S1 increase from 4 years to 12 years. One other hand, the required guarantee rate for the rigid design is between 25% and 30%. With the rigid designs strategy, the network operator enjoys surplus profit above 30% MRG rate.

Although a higher MRG rate implies increased profit for the network operator, it has negative implications for the public actor, specifically, regarding subsidy payments. Fig. 9 shows the effect of different MRG rate on the expected subsidy payments for both physical design strategies. It can be seen that subsidy payment depends on the physical design strategies and the level of MRG. Up to 25% MRG rate, there is no government guarantee payment implying that the network operator direct revenue from tariff is higher than the guarantee level. However, above 25% MRG rate, the guarantee level exceeds the direct revenue from the tariff resulting in subsidy payments by the public actor. For the flexible design strategy, the amount of subsidy payment over the concession period depends on the timing of the new source. For example, for 50% MRG rate, the subsidy payment doubles when connection time of the S1 changes from year 4 to year 12. On the other hand, subsidy payment for the rigid design strategy does not vary with the timing of the new source because the revenue of such design strategy depends only on the flow from the existing two sources. However, by comparison, the government pays more for the rigid design strategy than the flexible design strategy for the same MRG rate. Although a higher MRG rate increases the network operator's profit, it presents a huge risk for the public actor. Therefore, intuitively one can say that, if the network operator chooses the rigid design strategy, the MRG rate that would be

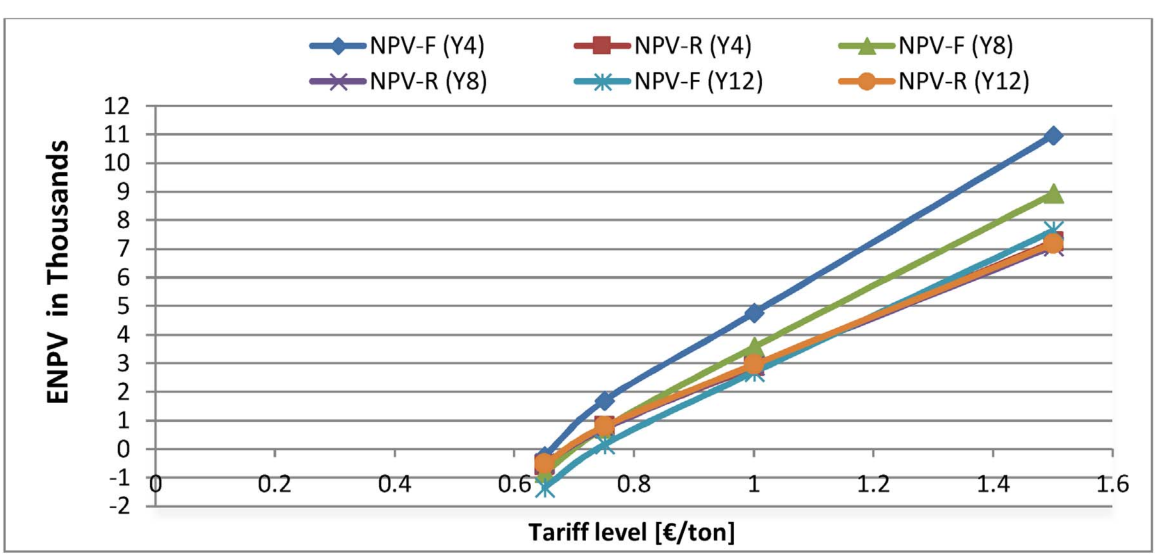

Fig. 7. Expected net present value of the two design strategies at different tariff level.

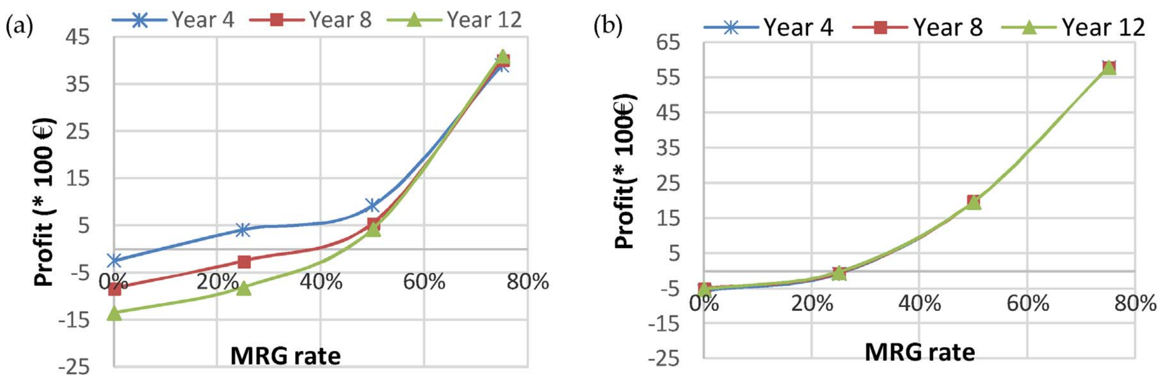

Fig. 8. Effect of MRG rate on the expected profit (ENPV): (a) the flexible design strategy, (b) rigid design strategy.

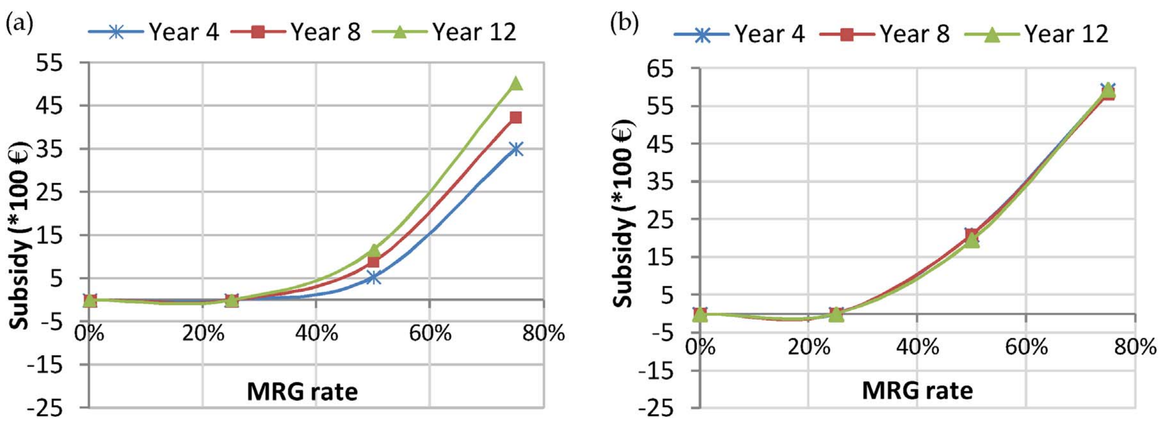

Fig. 9. The effect of different MRG rate on the expected subsidy payments: (a) flexible design strategy, (b) rigid design strategy.

acceptable by the public actor is expected to be lower than what it would be for the flexible design strategy.

As shown in Eq. (11), the public actor can guard itself against excessive subsidy payments using revenue cap. For example, in the case of the rigid design strategy, the public actor could negotiate a fixed revenue cap level that will limit the cumulative sum of all government outlays. Therefore, using the real options pricing method provides a realistic valuation of the guarantee payments than the tradition discounted cash flow method. The valuation of revenue guarantee using options pricing method allows the public actor to determine the value of future contingent liabilities. It also enables the public actor to define guarantees that are high enough to allow economically feasible CCS deployment by network operator but low enough not to burden public funds.

The public actor's main objective is to provide sufficient capacity for existing and future sources at reasonable subsidy payments. So, far we have seen the effect of design choices on profit and subsidy payments, but not on capacity shortage. A better impression of the value space can be seen by drawing all the three performance measures in a three-dimensional axis. The value space can reveal physical and contractual design combinations that provide high outcomes(i.e. low capacity shortage, high profit, low subsidy payments) and provide an indication of the feasible solution region that satisfies both actors. It can also provide value insight regarding value trade-offs for different contractual and physical design strategies. Depending on the realization of flow and participation uncertainty some design combinations provide low performances on all measures. Although these designs are not likely choices for the actors, they are feasible designs and represent a part of the trade-off surface in the value space. Many physical and contractual design combinations deliver intermediate as well as high outcomes, i.e. [high profit, low subsidy payments, and low capacity shortage]. Likely design choices for the actors are those who resulted in a low capacity shortage and positive NPV.

Fig. 10 shows all the three value combinations (profit, capacity shortage, and subsidy payment) for both physical design strategies. It can be seen that it is impossible to recommend a single Pareto-optimal solution that is best for both actors. Instead, it is possible to identify a set of design combinations (physical and contractual design strategies) that could be acceptable for both actors. For example, a flexible design strategy with 50% MRG rate risk sharing contract would improve profit for the network operator while providing extra capacity for future new sources. MRG rate higher than 50% could expose the public actor to huge subsidy payment for a small increase in capacity availability (or slight decrease in capacity shortage). On the other hand, MRG rate much less than 50% would expose to the network operator to revenue risk. Moreover, it could make the extra capacity investment unattractive and could force the network operator to choose the rigid design strategy. Such a situation would be far more likely if the new source joins the network far in the future (e.g. > 12 years). In general, it can be said that a risk sharing arrangement with MRG rates higher than 25% but less than 75% with a flexible physical design strategy constitute a set of design choices that could be selected by both actors. Within this set, actors have the opportunity to make value trade-offs and find synergies. However, the set of design combinations could vary depending on the tariff level. Intuitively, one can expect the level of MRG to decrease when the tariff level increases. Higher tariff level increases real revenue for the network operator keeping it above the MRG floor for most of the time, and vice-versa.

4. Conclusions

This paper discusses the use of flexible design concept for deployment of large-scale CCS infrastructures via PPP arrangement under CO_2 supply uncertainty. A framework for a flexible design approach is presented for design and value analysis different physical and contractual design strategies. The approach employs probabilistic and

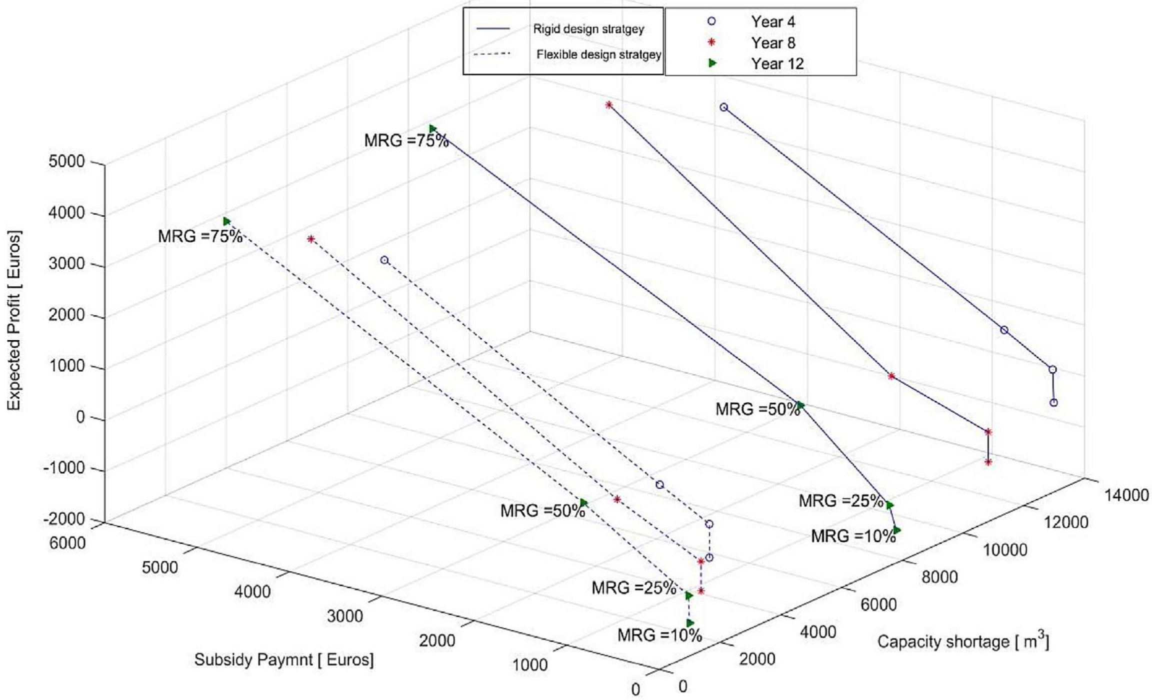

Fig. 10. Performance measures for different risk sharing and physical design strategies.

simulation methods to anticipate a range of future CO_2 supply scenarios. Then, Monte Carlo simulation is employed to compare the value effects of design strategies under different CO_2 supply scenarios.

The analysis revealed some valuable insights. It is found that the choice of the physical configuration of the physical network and the contract structure affects values of the two actors differently. For example, oversizing the capacity of critical links of the network favors the public actors objective but comes at the expense of exposing the network operator to high revenue risk. However, the two actors can find design solutions that not only able to change the risk exposure of the network operator but also enable value-creation and value-exchange with the public actor. For example, by designing the network with flexibility options, i.e. extra capacity, and length, and using option based revenue guarantee mechanism, the two actors not only able to reduce risk but also enhance value, in the face of uncertainty. More broadly, the framework enables to two actors to iteratively explore different design solutions in the face of CO_2 supply uncertainty and converge on a design that is acceptable to both of them.

It must be pointed out that practical deployment of CCS networks depends on other uncertainty factors in addition to CO_2 supply uncertainty. For example, the kind of incentive offered for reducing CO_2 emissions will likely influence the progressive deployment of individual CCS projects and the final layout of the CCS network. An improved cost function (including, for example, pumping cost, the thickness of the material, the terrain of the landscape, and operation and maintenance cost) for the network model would provide better insight regarding design and investment decisions. Future research should take into account these issues.

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Curriculum Vitae

Yeshambel Melese was born on February 24th, 1983 in Lay Birr, Ethiopia. He attended high school at Damot Senior Secondary School from 1998-2001 (1990-1993 Ethiopian Calendar), which he concluded with the matriculation exam.

Subsequently, Yeshambel joined The College of Natural Sciences (4-kilo campus) at Addis Ababa University to study his Bachelor Degree. After a year he decided to focus his study on Chemical Engineering and joined The school of Chemical Engineering at The Addis Ababa Institute of Technology. In 2006, he graduated with a Bachelor Science degree in Chemical Engineering. Right after that, he started working at the school of chemical engineering as a Graduate Assistant until June 2010, during which time, he conducted research, lectured multiple courses and counseled undergraduate students.

In September 2010, Yeshambel started an Erasmus Mundus Joint Masters program in Environomical Pathways for Sustainable Energy Systems at the Royal Institute of Technology (KTH) in Stockholm, Sweden. After two semesters, he decided to specialize in solar energy technology and joined the Technical University of Eindhoven (Eindhoven, The Netherlands), where he obtained a Masters in Sustainable Energy Technologies.

In January 2011, he began an Erasmus Mundus Joint Doctorate in Sustainable Energy Technologies and Strategies (SETS) at the Delft University of Technology in Delft, The Netherlands. As part of the SETS program, he spent a year at Comillas Pontifical University in Madrid, Spain. His research was focused on the design of multi-actor nascent energy and industrial infrastructure networks under uncertainty. During his research, Yeshambel published three journal articles, presented at international conferences and collaborated with researchers.

Strategic design of multi-actor nascent energy and industrial infrastructure networks under uncertainty

Yeshambel Girma Melese

Society is increasingly challenged with dwindling energy reserves for electricity generation and adverse effects from the emission of carbon dioxide from energy use. As a result, new strategies are being adopted to provide alternatives to fossil fuel and reduce carbon dioxide emissions. A critical element of these strategies is the availability of a reliable infrastructure network to transport energy carriers such as electricity, gas and hot/cold water and carbon dioxide.

This thesis focuses on the design of nascent energy and industrial infrastructure networks: networks that still needed to be built and for which neither scope, size, nor participants were certain. It develops systematic design analysis approaches to help improve design under uncertainty by means of flexibility. There are four parts to the thesis. The first part focuses on understanding the concept of flexible design and its application to the design of engineering systems and energy infrastructure networks. The second part focuses on flexibility analysis with the objective of improving their lifetime performance in the face of uncertain design requirements. A systematic engineering design approach combining graph theory network modelling, exploratory modelling and real options is proposed to explore candidate designs, identify valuable flexibility enablers and appreciate the value of flexible design strategies. The third part considers the role of risk sharing when actors co-invest in infrastructure networks under uncertain environment. Contractual arrangements are modelled between actors as a cooperative game and analyses the effects of uncertainty. The fourth part focuses on how private and public actors may enhance desired performances when developing new energy and industrial infrastructure networks under uncertainty.

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