Images of cooperation – a methodological exploration in energy networks

Images of cooperation – a methodological exploration in energy networks

PROEFSCHRIFT

ter verkrijging van de graad van doctor
aan de Technische Universiteit Delft,
op gezag van de Rector Magnificus prof. ir. K.C.A.M. Luyben,
voorzitter van het College voor Promoties,
in het openbaar te verdedigen op donderdag 7 februari 2013 om 15:00 uur
door

Andreas LIGTVOET

doctorandus Natuurwetenschappen en Bedrijf & Bestuur
geboren te Leidschendam.

Dit proefschrift is goedgekeurd door de promotoren:

Prof. dr. ir. P.M. Herder
Prof. dr. ir. M.P.C. Weijnen

Samenstelling promotiecommissie:

Rector Magnificus	voorzitter
Prof. dr. ir. P.M. Herder	Technische Universiteit Delft, promotor
Prof. dr. ir. M.P.C. Weijnen	Technische Universiteit Delft, promotor
Prof. dr. C.P. van Beers	Technische Universiteit Delft
Prof. dr. J.M. Cramer	Universiteit Utrecht
Prof. dr. B. Nooteboom	Universiteit van Tilburg
Prof. dr. E. Subrahmanian	Carnegie Mellon University
Prof. dr. ir. W.A.H. Thissen	Technische Universiteit Delft, reservelid

ISBN 978-90-79787-44-9

Published and distributed by: Next Generation Infrastructures Foundation
P.O. Box 5015, 2600 GA Delft, The Netherlands
Phone: +31 15 278 2564
E-mail: info@nextgenerationinfrastructures.eu
Website: http://www.nextgenerationinfrastructures.eu

This research was funded by the Next Generation Infrastructures Foundation and Delft University of Technology.

Keywords: cooperation, energy, networks, socio-technical system, infrastructure, agent-based modelling, serious gaming, case studies, graph theory, methodological choice

Maps used in chapter 3: http://www.openstreetmap.org.
Cover: Hands Holding Jigsaw by Petr Kratochvil http://www.publicdomainpictures.net – Infrastructure pictures http://www.sxc.hu – Cooperative t-shirt design by participants of the Santa Fe Complex Systems Summer School 2010.

Typeset by the author in $\LaTeX\ 2_{\varepsilon}$ in 10pt URW Garamond 8
Printed in the Netherlands by Gildeprint
Available on http://repository.tudelft.nl

Summary

Images of cooperation – a methodological exploration in energy networks

To ensure dependable, affordable, and sustainable use of energy, stakeholders in energy production, distribution, and consumption are increasingly seeking for cooperation. They aim to jointly tackle large energy projects in an environmental context that is changing at an increasing rate, towards increasing complexity. Cooperation is seen as a remedy against the uncertainties of a hyper-competitive society, but the mechanisms of cooperation and the trade-offs are still poorly understood. This thesis provides clarification on *how we can use different methods to understand cooperation activities and how to support cooperative efforts.*

We come to the conclusion that cooperation is a multidimensional issue that can only be understood properly when looking through different research lenses. Each perspective leads to a different image of cooperation and a clarification of why actors take specific steps in a process, what they aim to accomplish, and how they behave. The investigated methods (graph theoretical planning, agent-based modelling, serious gaming, and case studies) are valuable for understanding the decision making process, but no method can *predict* the results of cooperation attempts. We deem this impossible given the complexity of the systems we are interested in. However, graph theoretical planning can quickly provide information on network spatial configurations given certain constraints. Agent-based modelling allows for investigating the diversity of actors and the system consequences of their responses to each other. Serious gaming focuses more on players' behaviour to each other and to the system. Case studies provide a rich description of the systems that we are interested in and allows for extraction of (procedural) lessons.

To show the focus and/or breadth of each method we mapped them in two dimensions. The first dimension that we distinguish is that of world-view. A 'rational' perspective seeks for clear cause and effect relationships, clearly identified goals, and knowable rules and laws. A 'behavioural' perspective acknowledges the idiosyncrasies of individual decision makers and the fact that behaviour is to a great extent determined by social settings and networks of power and influence. A procedural view emphasises the process steps that are necessary for achieving cooperation – the emergent 'rules of the game'.

The second dimension pertains to the level of abstraction. Following general systems theory, we find that a distinction in micro-meso-macro level phenomena helps in classifying the different strands of research and their contribution to systemic understanding

of cooperation phenomena. While we are interested in cooperation among organisations (meso level), we acknowledge that organisations consist of individuals (micro level) and form a part of a larger institutional, cultural, or national setting (macro level). Cooperation in organisations is both influenced from 'above' and from 'below' in interdependent ways.

In scientific research abstraction and simplification are required to come to explanations about system behaviour. However, the necessary abstraction and simplification are performed in different ways for different research methods. Thus not all methods are applicable to all levels of abstraction and may focus on more rational, behavioural, or procedural aspects of cooperation. We find that combining methods with the laudable aim of finding better, more realistic models or descriptions of problems should take the characteristics of the methods into consideration. The different approaches depend on different world-views that may be incommensurate: a rational view that focuses on calculable utility cannot handle procedural steps in a negotiation. However, at the same time different approaches are useful, because they lead researchers to ask different questions highlighting different facets of reality. As Isaiah Berlin stated: every classification throws light on something. For every perspective there are advantages and drawbacks, which we have indicated in this thesis.

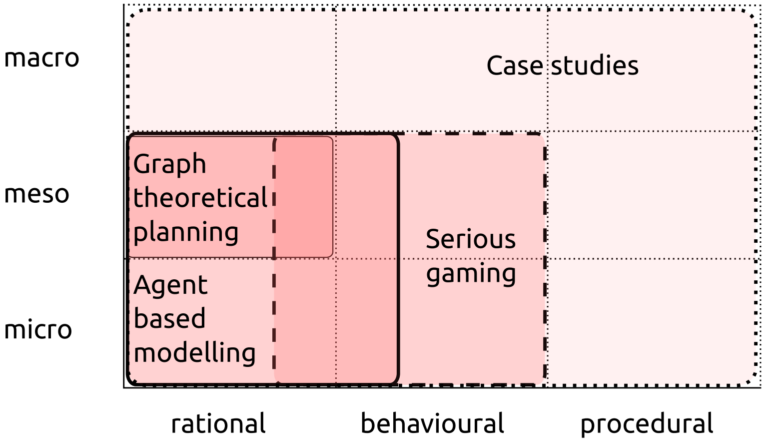


Figure 1 – An overlay of the four research methods in our framework.

What follows is a summary of each of the methods – the ways in which they can be deployed to unveil aspects of cooperation. In terms of the two dimensions we mentioned, figure 1 indicates where the methods can be used. They range from very specific (graph theoretical planning) to very broad (case studies).

Graph theoretical planning

Graph theory mainly focuses on nodes and their linkages. We combined graph theoretical methods and applied them to the planning of physical infrastructures with several participants whose cooperation is not known in advance. No assumptions about behaviour are made and cooperation is treated as a simple probability. Adding an assessment of the likelihood of industries partaking in a joint network, expected infrastructure capacity, and its spatial constraints allows for exploring the solution space of all conceivable network configurations within an industrial or geographic area. This approach allows for different decision makers to decide upon a required risk level and offers a design for a minimal regret network – a configuration that is acceptable under different circumstances.

The advantage of this method is that it is relatively transparent in the assumptions it requires and can be used quickly in the exploratory phase of the cooperation. It calculates the effects on network topology of partners cooperating or not cooperating. As such it supports the decision making process and unveils options, but it cannot handle dynamic situations (the joining of participants at different times). The algorithm allows for quick updating of the minimal regret network as new information becomes available. It provides a substantive contribution to the cooperation process, not an insight in how these processes function.

Agent-based modelling

Agent-based modelling seeks to find a mix between rational and behavioural approaches. Complex and flexible models are possible because each separate agent representing a real-life actor can change behaviour according to different modelled circumstances. Thus, path dependency and co-evolution can be represented in a model and more realistic simulations can be built. These simulations show emergent patterns of macro behaviour that may be surprising and instructive when considering the micro motives that the agents are programmed with, such as positive system outcomes while agents are programmed to be unresponsive. However, models that purport to portray realistic socio-technical systems run the risk of becoming black boxes in which modellers stack layers of assumptions upon layers of assumptions. A certain degree of simplicity is required to enable tractability of the model outcomes.

We developed two agent-based models, building on an existing RePast/JAVA modelling framework developed at the department of Energy and Industry at Delft University of Technology. The first model explores the development of a synthesis gas cluster for the production of fuel, products, and electricity under different assumptions of fossil fuel and biomass prices. By calculating the development of the cluster as compared to a (conventional) fossil fuel cluster in a wide range of scenarios (10,000), we find the fuel price conditions under which a synthesis gas cluster would be profitable. This provides crucial information for a cooperation process. The analysis shows that it would take more than a decade before such a cluster would outperform the conventional cluster (starting with fossil fuel prices in 2008), but that eventually most scenarios will show that synthesis gas has the competitive advantage.

The second simulation model we developed elaborated on behavioural assumptions of the agents. Agents were endowed with a random network of trusted social contacts with whom they could exchange strategic propositions or options. Their stance towards risk, planning horizon, and required financial improvements was altered, as well as the maximum number of options they could handle (mimicking *bounded rationality*). A final factor that we called 'initiative taking' proved the most important for the success of a cluster: only agents willing to engage with other agents were able to build large clusters. From a systems perspective, also a low initiative factor provided interesting results: many permanent 1-to-1 connections were built, eventually lowering transaction costs for the partners. An intermediate setting led to creation and subsequent abandonment of infrastructures.

Serious gaming

Serious games involve human players in a model of reality that aims to elucidate certain aspects of human behaviour and/or the interaction of humans in a certain setting. These games could be seen as behavioural experiments – as performed by e.g. behavioural economists or psychologists – that take a larger parameter space into consideration, therefore representing more life-like situations. The large parameter space, however, allows for totally divergent game play. This lowers the representativeness of the game providing – in the extreme case – a separate case study of human behaviour under certain specified conditions. Furthermore, players may not be representative of the actual decision makers, thus limiting the applicability of conclusions.

We tested the presumed educational value of a serious game on energy markets. By having the participants (103 Masters' and Ph.D. students in a 2011 and 2012 course) answer a questionnaire at three points in the game, we found that the players reported improved understanding of key concepts (bidding procedure, market power, price determinants, and policy influence) as well as understanding main parameters/drivers of the game and being surprised at the outcome.

Questions on cooperative behaviour yielded different responses in the 2011 and 2012 student groups. The 2011 group only reported little communication (certainly not with direct competitors) and only one team attempted to work together but found itself in a Prisoner's Dilemma-like situation. The 2012 group reported much more information exchange amongst teams (generally between friends and room mates) and the all teams of one game tried to form a cartel to influence the CO_2 market – which in the end was thwarted by one team. We concluded that the educational setting in which the game was played, as well as the experience and personal traits of the players, may have led the 2011 group of students to be more cautious while the 2012 group tried to look for the limits of the rules. More repetition of the experiment would be required to find out how often these boundary seeking activities could be expected.

Through their engaging nature, serious games allow players to learn from their experience. This learning may focus on the system under investigation, on the behaviours of co-players, or on their own behaviour under given circumstances. Our experience suggests that games provide researchers with insight on system, network, and actor behaviour. If the players are somewhat free in their game play, this method allows for investigating human creativity and entrepreneurial responses to cooperation options.

Case studies

We provide contextual information on energy networks in the Netherlands by investigating two case studies of district heating (in Delft and The Hague) and one case study of a CO_2 network (connecting the Rotterdam industrial complex to the Westland horticultural complex). The application of case studies provides rich observations that are particular to specific cases, thus embedding the findings in 'real world' issues. By combining the insights from several case studies, we come to generalised findings about the procedural steps that build up to cooperation, as well as substantiation of theoretical notions. However, cause and effect relationships are difficult to identify with certainty, as the craftsmanship of the researcher determines the depth of detail and facts are overlooked or forgotten.

With regard to procedure, we find that cooperation processes do not follow a neat recipe, but iterate through three main steps: *exploration* (in which partners are sought, opportunities and areas of cooperation are identified, and technical and organisational feasibility studies are undertaken), *formalisation* (in which a task force is set up, negotiations are undertaken, and financing and legal structures are agreed upon), and *implementation* (in which contracts are signed, performance is monitored and evaluated, and external communication takes place). Our case studies also show a varying range of reasons why organisations cooperate. Some of these could be captured in a rational framework, but others are more related to social behavioural responses: there is a need for making profit or at least no loss, but at the same time technological enthusiasm, doing something new and unique, keeping up with the competition, hedging risk, fulfilling environmental goals, providing a positive image, sticking to agreements, or circumventing (national) government are mentioned as reasons for working together. These reasons may shift over time and some requirements (such as achieving a minimum return on investment) become less important. In hindsight these arguments are difficult to trace and often path dependent on many contingencies. Trying to predict what will happen within cooperative projects is therefore arduous.

Literature analysis

We have embedded our research in a broad range of research fields that deal with cooperation. Very little integration has taken place although there are ample cross-references between fields of research, which was shown through bibliometric analysis. Such analysis allows us to draw a map of references and to identify clusters of research.

Important research is undertaken in animal behaviour, showing that although short-term benefit can be derived from non-cooperation (sometimes called defection) there are many species who have evolved to be cooperative. This research is considered indicative for the possibility of cooperation in human societies. Evolutionary game theory provides us with hypothetical dilemma's and solutions to these dilemma's that prove the logic of cooperation. Human behavioural experiments in experimental economics and psychology show us that defection takes place in far less cases than we would expect based on classical game theory. Furthermore, cooperation does not follow strict rules of logic: it is influenced by communication, habit, reputation, gender, and a sense of what is right. At the same time social networks (e.g. close cooperation in industrial districts, teamwork, so-called 'gentleman's agreements') influence the willingness of (individuals within) organisations to work together. Finally, national cultures and habits, as well as laws and regulations, determine the response of individuals to opportunities and threats.

Broader research framework

Our energy systems are critical for maintaining a prosperous society. Providing reliable and affordable access to energy, however, faces grand challenges: major sources of fossil fuels are in decline leading to volatility in energy prices and uncertain supply – an undesirable situation in industrial societies; competition for these resources is becoming more intense due to the increasing demand from emerging economies; and energy use is closely linked to CO_2 emissions and climate change – the effects of which need to be mitigated, also at company level. In privatised and liberalised energy markets different players have to act in the face of these uncertainties and their associated risks without clear guidelines from a government that refuses to intervene.

As technology and society are closely intertwined – choices for technological solutions influence markets and societal demands may require adaptations in technology systems – research into cooperation in energy systems is necessarily a multidisciplinary affair. Furthermore, individual, local, national, and international contexts influence each other and the actors involved in this continuous tug-of-war are reflexive and responsive to other actors' behaviours, leading to truly complex system behaviour.

We have chosen to deploy different methods that are considered novel in the engineering systems and management field: agent-based models, serious games, and graph theoretical planning. We contrast these with more 'traditional' approaches of case studies and literature review. The different methodological perspectives focus on different facets of cooperation – each with its own necessary abstractions and simplifications. The combined images, however, should provide a rich and balanced perspective that can help decision makers face an uncertain future.

Samenvatting

Beelden van samenwerking – een methodologische verkenning in energienetwerken

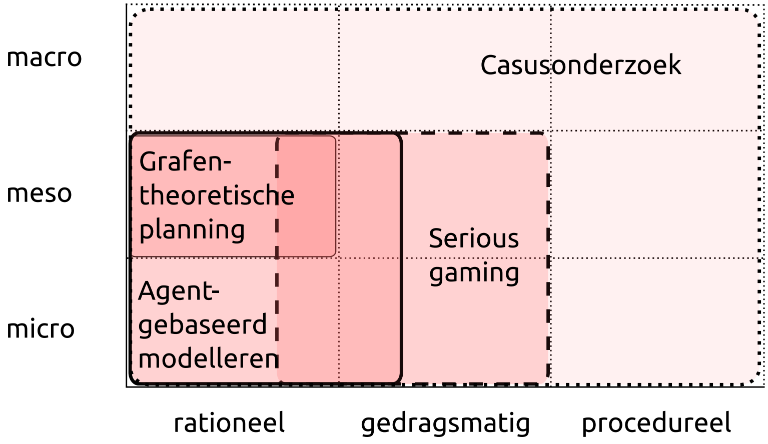
Om betrouwbaar, betaalbaar, en duurzaam energiebruik zeker te stellen, zoeken de belanghebbenden in energieproductie, -distributie en -consumptie steeds vaker naar mogelijkheden om samen te werken. Zij proberen grote energieprojecten tot stand te brengen in een omgeving die steeds sneller verandert en complexer wordt. Samenwerking wordt gezien als een antwoord op de onzekerheden van een hypercompetitieve samenleving. De mechanismes van samenwerking en de daarmee samenhangende voors en tegens zijn echter nog steeds onduidelijk. Dit proefschrift verheldert de vraag *hoe samenwerking met behulp van verschillende onderzoeksmethoden beter begrepen kan worden en hoe samenwerking ondersteund kan worden*. Dit doet het door verschillende methoden te beschrijven en de inzichten die deze methodes genereren te analyseren.

We concluderen dat samenwerking een multidimensionale aangelegenheid is die alleen goed begrepen wordt door verschillende onderzoeksbrillen op te zetten. Elk perspectief levert een ander beeld van samenwerking en een verduidelijking waarom actoren specifieke stappen in een proces nemen, wat zij proberen te bereiken en hoe zij zich gedragen. De methodes die wij toepassen (grafentheoretische planning, agent-gebaseerd modelleren, serious gaming, casusonderzoek en literatuuranalyse) dragen bij aan het beslisproces, maar bieden geen *voorspellingen* van de uitkomsten. Dit is onmogelijk gezien de complexiteit van de systemen waarin we geïnteresseerd zijn. Niettemin kan grafentheorie snel inzicht geven in de ruimtelijke configuraties van netwerken gegeven bepaalde beperkingen. Agent-gebaseerde modellen maken het mogelijk om de effecten van verschillende actoren op elkaar en op het systeem te onderzoeken. Serious gaming richt zich op het gedrag van spelers op elkaar en op het systeem. Casusonderzoek levert een rijke beschrijving van de systemen waarin we geïnteresseerd zijn en levert (procedurele) lessen.

Om de focus en/of breedte van elke methode aan te geven, hebben we ze in twee dimensies beschreven. De eerste dimensie beschrijft de perceptie van de wereld. Een ‘rationeel’ perspectief zoekt naar oorzaak en gevolg relaties, duidelijk omschreven doelen, en kenbare regels en wetten. Een ‘gedragsperspectief’ erkent de eigenaardigheden van individuele beslissers en het feit dat gedrag bepaald wordt door de sociale omgeving en netwerken van macht en invloed. Een procedurele blik benadrukt de processtappen die nodig zijn om samenwerking te bereiken – dit zijn de emergente ‘regels van het spel’.

De tweede dimensie beschrijft het abstractieniveau. Het onderscheid tussen micro, meso, en macro niveau (zoals beschreven in de algemene systeemtheorie) is nuttig om onderzoeksgebieden in te delen en hun contributie aan het begrip van samenwerking te kunnen plaatsen. Hoewel we in eerste instantie benieuwd zijn naar samenwerking op organisatieniveau (meso niveau), moeten we ons rekenschap geven van het feit dat organisaties uit individuen bestaan (micro niveau) en samen onderdeel zijn van een groter institutioneel, cultureel geheel op nationaal niveau (macro niveau). Samenwerking in organisaties wordt zowel van 'boven' als van 'onder' beïnvloed, op onderling afhankelijke wijze.

De wetenschap past abstractie en simplificatie toe om systeemgedrag te begrijpen. Deze abstracties en simplificaties worden echter voor verschillende onderzoeksmethoden op verschillende manieren toegepast. Niet alle methoden zijn dus van toepassing voor alle abstractieniveaus en richten zich op meer rationele, gedragsmatige, of procedurele aspecten van samenwerking. Bij het combineren van verschillende methoden met het lovenswaardige doel om betere, realistische modellen of beschrijvingen van problemen te vinden, moet men rekening houden met deze karakteristieken van de methodes. De verschillende aanpakken zijn afhankelijk van wereldbeelden die mogelijkerwijs niet te combineren zijn: een rationele blik die zich richt op berekeningen van nut kan niet omgaan met procedurele stappen in onderhandelingen. Tegelijkertijd zijn deze verschillende blikken nuttig, omdat ze wetenschappers uitdagen om nieuwe vragen te stellen die verschillende facetten van de werkelijkheid voor het voetlicht brengen. Zoals Isaiah Berlin al stelde: iedere classificatie verduidelijkt iets. Voor elk perspectief zijn er voordelen en nadelen, hetgeen wij hebben aangegeven in dit proefschrift.



Figuur 2 – De nadruk van de vier methoden in dit onderzoek.

Hieronder volgt een samenvatting van elk van de methodes – de manier waarop ze ingezet kunnen worden om aspecten van samenwerking te verhelderen. Figuur 2 laat de nadruk van de methodes in de genoemde dimensies zien. Ze lopen van zeer specifiek (grafentheoretische planning) naar zeer algemeen (casusonderzoek).

Grafentheoretische planning

Grafentheorie richt zich op netwerken van knopen en verbindingen. We hebben methoden uit de grafentheorie gecombineerd en toegepast op de planning van fysieke infrastructuren met meerdere deelnemers, waarvan de samenwerking niet bij voorbaat vaststaat. Er worden geen aannames over gedrag gedaan en samenwerking wordt gezien als een simpele kansverdeling. Door details over de waarschijnlijkheid van deelname toe te voegen, naast de vermoede capaciteit en de ruimtelijke beperkingen, kan een oplossingsruimte van alle mogelijke netwerkconfiguraties binnen een industriegebied verkend worden. Deze aanpak stelt verschillende beslissers in staat om binnen een bepaald risiconiveau hun spijt te minimaliseren – dat is dus een configuratie die onder veel verschillende omstandigheden voldoet.

Het voordeel van deze methode is dat zij relatief transparant is in de benodigde aannames en dat zij snel kan worden toegepast in de exploratieve fase van de samenwerking. De methode berekent de effecten op de netwerktopologie doordat partners wel of niet samenwerken. Op deze manier wordt de besluitvorming ondersteund en nieuwe opties ontdekt. De methode kan echter (nog) niet omgaan met dynamische vraagstukken (het toetreden van deelnemers op verschillende tijdstippen). Het algoritme kan wel worden gebruikt om een nieuw netwerk met minimale spijt te berekenen zodra nieuwe informatie beschikbaar is. De methode draagt bij aan de inhoudelijke discussie van het samenwerkingsproces, niet aan inzicht in de manier waarop dit soort processen verlopen.

Agent-gebaseerde modellen

Agent-gebaseerde modellen zoeken naar een evenwicht tussen een rationele en een gedragsmatige aanpak. Complexe en flexibele modellen zijn mogelijk omdat elke afzonderlijke agent een daadwerkelijke actor voorstelt en individueel gedrag kan vertonen afhankelijk van de gemodelleerde omstandigheden. Zo kan padafhankelijkheid en co-evolutie weergegeven worden in een model, zodat meer realistische simulaties ontstaan. Deze simulaties vertonen emergente patronen van systeemgedrag die zowel onverwacht als instructief kunnen zijn (uitgaande van de micro motieven van agenten). Zo kan een systeem als geheel verandering vertonen terwijl de agenten individueel maar minimale stappen zetten. Modellen die zogenaamd realistisch gedrag van socio-technische systemen vertonen, lopen het risico om zwarte dozen (*black boxes*) te worden waarin onderzoekers lagen van aannames op lagen van aannames stapelen. Een zekere mate van eenvoud is daarom noodzakelijk om de uitkomsten van het model te kunnen traceren.

We hebben twee agent-gebaseerde modellen ontworpen die voortbouwen op bestaande RePast/JAVA modellen van de sectie Energie en Industrie van de Technische Universiteit Delft. Het eerste model verkent de ontwikkeling van een synthesegascluster dat de productie van brandstof, producten en electriciteit verzorgt onder verschillende aannames van brandstofprijzen. Door de ontwikkeling van een industrieel synthesegascluster te vergelijken met de ontwikkeling van een conventioneel fossiel cluster in 10.000 scenario's, kunnen we de omstandigheden verkennen waaronder een dergelijk cluster winstgevend wordt. Deze gegevens zijn van belang voor het samenwerkingsproces. Uit de analyse blijkt dat een dergelijk cluster onder de meest gunstige omstandigheden meer dan 10 jaar nodig heeft om een conventioneel cluster voorbij te streven, maar dat daarna synthesegas in de meeste scenario's een voordeel oplevert.

Het twede model dat we ontwikkeld hebben bouwt verder op de gedragsaannames van de agenten. De agenten werden voorzien van een sociaal netwerk met contacten waarmee ze strategische opties en proposities konden uitwisselen. Er zijn aannames gedaan over hun houding ten opzichte van risico's, hun planningshorizon, en de minimale financiële vooruitgang, net als het maximum aantal opties dat ze mentaal konden verwerken (*bounded rationality*). Een laatste factor die de neiging om initiatief te nemen beschreef, bleek het meest belangrijk voor het succes van het cluster: alleen die agenten die initiatiefrijk genoeg waren konden grote clusters bouwen. Vanuit een systeemperspectief gaf een initiatiefarme instelling ook interessante resultaten: veel 1-op-1 verbindingen werden tot stand gebracht, zodat in ieder geval tussen twee partners de kosten omlaag gingen. Een middelmatig initiatief leidde eerst tot bouw en vervolgens tot verlating van infrastructuren zodra een gunstiger alternatief beschikbaar was.

Serious gaming

Serious games betrekken spelers in een model van de werkelijkheid dat gericht is op het verduidelijken van aspecten van menselijk gedrag en/of de interactie tussen mensen in een bepaalde omgeving. Deze spellen kunnen gezien worden als gedragsexperimenten – zoals uitgevoerd door gedragseconomen of psychologen – die een groot aantal parameters omvatten, zodat meer levensechte situaties worden weergegeven. De grote parameterruimte geeft echter ruimte voor zeer uiteenlopende spelwijzen. Dit verlaagt de representativiteit van het spel, zodat – in het meest extreme geval – elk spel een onafhankelijk casusonderzoek onder verschillende omstandigheden wordt. Daarnaast zijn de spelers vaak niet vergelijkbaar met de daadwerkelijke beslissers, zodat de toepasselijkheid van de conclusies ook beperkt blijft.

We hebben de verwachte educatieve waarde van een serious game voor energiemarkten onderzocht. De deelnemers (103 mastersstudenten en promovendi) hebben een vragenlijst gedurende drie momenten in het spel ingevuld. De spelers rapporteerden toegenomen begrip van de belangrijkste concepten (biedprocedure, marktmacht, prijsbepaling en beleidsinvloed) en de belangrijkste parameters van het spel. Ook werden ze verrast door de uitkomsten.

De vragen die over samenwerking gingen leidden tot verschillende antwoorden in de groep studenten uit 2011 en uit 2012. In 2011 werd er weinig gecommuniceerd tussen de verschillende teams (zeker niet met directe tegenstanders) en slechts één team probeerde samenwerking aan te gaan, maar zag zichzelf in een *Prisoner's Dilemma* situatie. De groep uit 2012 rapporteerde veel meer informatieuitwisseling tussen teams (met name tussen vrienden en huisgenoten) en de gehele gele groep probeerde een kartel te vormen ten aanzien van de CO_2-markt, hetgeen uiteindelijk door één team gedwarsboomd is. We concluderen dat de educatieve omgeving en de ervaring van individuele spelers mogelijk ertoe geleid heeft dat de studenten in 2011 voorzichtiger waren dan de 'ondernemende' groep uit 2012. Verdere herhalingen van dit experiment zijn nodig om uit te vinden hoe vaak 'ondernemend' gedrag van studenten verwacht mag worden.

Vanwege hun uitnodigende aard laten serious games de spelers van hun ervaring leren. Het leren kan zich richten op het onderzochte systeem, het gedrag van medespelers, of hun eigen gedrag onder bepaalde omstandigheden. De ervaring suggereert dat spellen ook onderzoekers inzicht geven in het systeem, netwerken en actorgedrag. Als de spelers meer vrijheid krijgen in hun spelhandelingen kan deze methode ook inzicht bieden in creativiteit en ondernemingszin gegeven samenwerkingsopties.

Casusonderzoek

We hebben meer contextuele informatie over energienetwerken in Nederland onderzocht middels twee casussen over stadsverwarming (in Delft en Den Haag) en een casus over een CO_2-netwerk (dat het Rotterdamse industriële complex koppelt aan de Westlandse kassen). Dit casusonderzoek levert rijke observaties, zodat de bevindingen van dit onderzoek ook op reële problemen van toepassing wordt. Door de inzichten van het casusonderzoek te combineren doen we ook enkele algemene uitspraken over de procedurele stappen van samenwerking en de toepasselijkheid van theoretische inzichten. In de casussen is het echter moeilijk om oorzaak en gevolg met zekerheid vast te stellen – de vaardigheid, ervaring en keuzes van de onderzoeker beïnvloeden de aandacht voor details en feiten.

We constateren dat samenwerkingsprocessen niet netjes een recept volgen, maar door drie stappen itereren: *exploratie* (waarbij partners gezocht worden, kansen en samenwerkingsvelden worden verkend, en technische en organisatorische haalbaarheidsstudies worden uitgevoerd), *formalisatie* (waarbij een 'task force' wordt opgezet, onderhandelingen worden gedaan, en financiële en juridische structuren worden overeengekomen) en *implementatie* (waarbij contracten worden ondertekend, de resultaten worden gemonitord en geëvalueerd, en externe communicatie plaatsvindt). Onze casussen laten ook zien dat er een breed scala aan redenen bestaat om te gaan samenwerken. Enkele daarvan zijn te vatten in een rationeel raamwerk, maar andere hebben meer te maken met sociaal gedrag: naast een behoefte om winstgevend (of tenminste niet verliesgevend) te zijn, worden zaken als technologisch enthousiasme, iets nieuws en unieks tot stand brengen, bijhouden wat de competitie doet, risico's afdekken, milieudoelen bereiken, een positief imago tentoonspreiden, beloftes nakomen, en nationaal beleid omzeilen genoemd als redenen om samen te werken. Al deze redenen kunnen over de tijd veranderen en sommige vereisten (zoals een minimum 'return on investment') worden minder belangrijk. Achteraf gezien zijn al deze factoren moeilijk te traceren en ze zijn padafhankelijk. Voorspellen wat er binnen samenwerkingsprocessen zal gebeuren is daarom moeilijk.

Literatuuranalyse

Dit onderzoek is ingebed in een breed scala van onderzoeksvelden die samenwerking beschrijven. Er heeft zeer weinig integratie tussen deze velden plaatsgevonden, hoewel er veel kruislingse verwijzingen bestaan. Dit hebben wij met een bibliometrische analyse aangetoond. Een dergelijke analyse stelt ons in staat om een overzichtskaart van verwijzingen te maken en zo onderzoeksclusters te identificeren.

Er vindt belangrijk onderzoek plaats in diergedrag, dat aantoont dat hoewel voordelen op korte termijn worden gehaald uit niet-samenwerking (ook wel *defectie* genoemd) er veel soorten zijn die evolutionair samenwerking hebben ontwikkeld. Dit onderzoek wordt gezien als indicatie dat samenwerking in menselijke samenlevingen ook mogelijk is. Evolutionaire speltheorie voorziet ons van hypothetische dilemma's en oplossingen voor deze dilemma's die de logica van samenwerking bewijzen. Gedragsexperimenten met mensen in de experimentele economie en psychologie tonen aan dat defectie veel minder plaatsvindt dan dat we op basis van de klassieke speltheorie zouden verwachten. Bovendien volgt samenwerking niet de stricte wetten van de logica: het wordt beïnvloed door communicatie, gewoontes, reputatie, vertrouwen, geslacht, en een gevoel van rechtvaardigheid. Tegelijkertijd ondersteunen sociale netwerken (bijvoorbeeld in industriewijken, gezamenlijke activiteiten, *gentleman's agreements*) de bereidheid van (individuen binnen) organisaties om samen te werken. Als laatste bepalen ook nationale culturen en wet- en regelgeving de manier waarop personen op kansen en bedreigingen reageren.

Breder onderzoekskader

Energiesystemen zijn van essentieel belang voor het instandhouden van een welvarende samenleving. Om in betrouwbare en betaalbare toegang tot energie te voorzien dienen er grote uitdagingen te worden geslecht: belangrijke bronnen van fossiele brandstoffen raken uitgeput hetgeen leidt tot energieprijsschommelingen en onzekere bevoorrading – een onwenselijke situatie voor een industriële samenleving; de competitie voor toegang tot deze bronnen wordt groter vanwege toenemende behoeften van opkomende economieën; en energiegebruik is nauw gekoppeld aan CO_2-emissies en klimaatverandering – waarvan de effecten voorkomen moeten worden. In een geprivatiseerde en geliberaliseerde markt moeten spelers handelen gegeven deze onzekerheden en de daarmee samenhangende risico's zonder dat de terugtredende overheid duidelijke richtlijnen aanlevert.

Aangezien technologie en de samenleving sterk met elkaar verweven zijn – keuzes voor technische oplossingen beïnvloeden markten en maatschappelijke behoeftes vereisen soms aanpassingen in technische systemen – is onderzoek naar samenwerking in energiesystemen noodzakelijkerwijs een multidisciplinaire aangelegenheid. Daarnaast beïnvloeden individuele, locale, nationale en internationale contexten elkaar. De actoren die betrokken zijn in dit continue krachtenveld zijn reflexief en reageren op de gedragingen van de andere actoren, hetgeen tot complex systeemgedrag leidt.

We hebben ervoor gekozen om verschillende vernieuwende methoden uit het *engineering systems and management* veld toe te passen: agent-gebaseerde modellen, *serious games*, en grafentheoretische planning. Deze plaatsen wij tegenover meer traditionele aanpakken als casusonderzoek en literatuurstudie. De verschillende methodologische perspectieven benadrukken verschillende facetten van samenwerking – elk met zijn eigen noodzakelijke abstracties en vereenvoudigingen. De combinatie van deze beelden zorgen voor een rijk en gebalanceerd totaalbeeld dat besluitvormers kan helpen in een onzekere toekomst.

Contents

Chapter 1

Introduction

This chapter outlines some of the challenges with regard to energy use that face our societies in the coming decades. These challenges are global and unprecedented responses are required. While some solutions are sought in decentralisation, others emphasise a tighter integration that requires large investments and cooperation between stakeholders. How such cooperation emerges is the main focus of this thesis. We place our research within the broader frameworks of socio-technical systems and complex adaptive systems.

1.1 Problem definition

One of the large challenges facing human societies in the next decades is how to sustainably cope with our energy use. It is argued that high energy use over the last 150 years, enabled by a high energy return on energy invested (EROEI), is the main source of prosperity in OECD countries (Hall et al., 2008, 2001). If we want to maintain our high standard of living, we will need fuel to keep the machines of our society running. At the same time, however, we notice that energy production and use come with a number of noteworthy setbacks.

- Energy use is a cause of climate change, notably through CO_2 emissions (IPCC, 2007). To mitigate the effects of climate change, governments at different levels, industries, and citizens have committed themselves to reduce CO_2 emissions: at the global level through the *Kyoto Protocol*, through supra-national (e.g. EU) guidelines, at the national level through programs such as *Nieuwe energie voor het klimaat* in the Netherlands (VROM, 2007), and through numerous private and non-governmental organisations' and citizens' initiatives. Although the science behind climate change is based on rigorous research and broad consensus in academia, there remain sceptics who suggest that money spent on CO_2-reduction is money wasted (e.g. Lomborg (2001)) which keeps on fuelling dissent. Further uncertainty arises from policy responses to these emissions: for example, changing plans for carbon taxation schemes have enormous influence on the business cases of both conventional and alternative power stations.

- Fossil fuels (oil, gas, and coal) are being procured from a limited set of countries, which increases dependence on these countries for keeping the economy running. In the first decade of the 21^{st} century, Russia has shown its political clout by threatening to cut off its neighbours from gas. The military incursions into Iraq have dented the oil production while other large oil suppliers (Iran, Venezuela) have become more assertive. Coal – optimistically judged to provide more than a century of energy – is facing supply bottlenecks (EWG, 2007), which means that energy supply is far from certain. The energy market is heavily influenced by political agendas.
- Large growth in energy demand of the BRIC countries (Brazil, Russia, India, and China) and increased domestic consumption of exporting countries lead to shortages on the world energy market (IEA, 2008; DOE/NETL, 2007). Especially petroleum exploration and production is facing geological, financial, organisational, technological, and political constraints that herald the 'end of cheap oil' (Campbell and Laherrère, 1998; Shell, 2008). As a result, oil prices have become highly volatile. The uncertainty here is whether the invisible hand of economics will lead to innovation and diversification, or whether it will relentlessly herald an era of scarcity and decline.

These challenges are not easily solved, as they are closely interconnected. For example, attempts to increase energy security by relying more on coal has dire consequences for CO_2 emissions. Around the world initiatives are undertaken to curb these problems and to find (sustainable) solutions to our energy needs. In the Netherlands – the country that this thesis focuses on – both politicians and researchers plea for systemic change or a 'transition' towards a more sustainable economy with new, durable, and sustainable energy systems (Rotmans et al., 2001; Loorbach et al., 2008).

We observe that since the liberalisation and privatisation of the energy markets the energy system is being influenced by two seemingly opposite drivers. One is a driver towards decentralisation and self-sufficiency that emphasises solar power, wind power, heat storage, and other technologies that reduce the actors' dependence on centralised energy grids. The other is a driver towards increased ties between heterogeneous actors in the energy system that jointly strive for more efficient use of resources. We see a range of activities at transnational scale: gas and oil pipelines to circumvent traditional suppliers, cross-border high-voltage electrical interconnectors to increase the robustness of the electricity grid, the DESERTEC initiative to harness the solar power in northern Africa to supply European energy needs (Desertec Foundation, 2009). Even more so activities at the regional scale: increased interest in 'waste heat' through district heating networks and closer connection of industrial clusters and networks through *industrial symbiosis* (Chertow, 2000, 2007). There is an increasing emphasis on cooperation as the key to successful energy innovations (see e.g. MINEZ, 2008). However, how this cooperation is to take place and what drives partners to cooperate remains elusive.

For this research we therefore choose to investigate why and how different organisations come together to develop energy infrastructures. This requires balancing the needs and interests of several stakeholders. Whereas for single entrepreneurial firms it is already challenging to take action amidst uncertainty (Meijer et al., 2007a,b), an industrial network faces the additional task of coordinating with other actors that may have different interests or even values. This challenge is described by e.g. Herder et al. (2008a).

- Actors display strategic and opportunistic behaviour. This shouldn't surprise believers in a market economy, but actors generally seem to behave in their own interest, also in networked industries. Furthermore, these interests may not coincide with the general public's interests. On top of that, actors' preferences and values are not always clear, even to themselves (ten Heuvelhof et al., 2009).

- Actors learn how to neutralise interventions by others and are constantly developing new strategies to maximise their interests. De Bruijn and Ten Heuvelhof (2008) describe this as a constant tug-of-war (although they use the metaphor of moving a table). Success is therefore not dependent on optimal technological design, but on balancing interests.

- Actors are reflexive; they interact and learn, while at the same time their information is incomplete, thus leading to decisions that are satisfactory, not perfect (Simon, 2007, 2000). Therefore, the final outcome of a system design cannot be fully understood nor anticipated without knowledge of the interaction process itself.

Coordinating and cooperating with other parties is clearly not an easy task, yet groups of organisations manage to effectively coordinate their activities in building energy networks. This surprises us as traditionally economic literature mainly focused on the coordination of the various activities by means of the competitive market and the price mechanism (the invisible hand) (dei Ottati, 1994; Ginzburg, 2009). Competitive 'survival of the fittest' has been a popular biological and game theoretical analogy that received a lot of attention in management strategy literature: organisations are analysed as similar to individual biological organisms that survive or perish according to how well they compete against each other for the scarce resources needed for survival. However, this model has since been recognised as oversimplified from an evolutionary biology perspective and from a game theoretic perspective (Nielsen, 1988; Desrochers, 2004; Ginzburg, 2009). Humans are simply not fungi or fish.

Based on theoretic models Andras et al. (2007) suggest that under environmental adverse and uncertain conditions, cooperation is the best option to ascertain survival, even for selfish individuals. We take this cue as a starting point for this thesis. Cooperation, although neglected by a large group of (neo)classical economists (dei Ottati, 1994; Granovetter, 1985; Korhonen, 2005; Todeva and Knoke, 2005), is widely practised in the business world. As Nielsen (1988) notes: 'many of today's organizational interactions cannot be explained adequately in terms of competitive warfare…Business policy must pay attention to the institutionalisation of these collective allegiances, for they play an increasingly important role in today's corporate society.' Therefore we aim to address the following research question:

> **How can we use different methods to understand cooperation activities in energy networks and how can these methods support cooperative efforts?**

The proposed research aims to contribute to understanding the different ways in which actors cooperate in complex settings. Part of the research will draw from existing literature and cases in energy networks, in order to understand cooperative behaviour. The other part of the research will be of a more design-oriented nature, which will focus on exploring the options for planning socio-technical systems and how the behaviour of actors influences the design-space. The exploration of the wide range of options in a complex (energy) system will require the use of different analytical tools and we expect that each tool also unveils different facets of cooperation in energy networks (much like different metaphors explain different aspects of organisations or other complex phenomena (Morgan, 1986; Mikulecky, 2001)).

To capture a range of different approaches we look at two extremes in the qualitative versus quantitative spectrum: case studies versus mathematical network models. We differentiate this picture by adding two more hybrid approaches: agent-based modelling and gaming. This leads to the following list of research sub-questions to be investigated.

- What fields of research are investigating cooperation and what can we learn from the literature?
- To what extent has this research on cooperation been applied to complex socio-technical systems?
- To what extent can this knowledge be applied in quantitative or qualitative approaches, including hybrid approaches like agent-based modelling or gaming?
- What types of cooperation responses can be expected under which conditions? What other factors have a large effect on the industries' behaviour?
- Can these responses and factors be described and displayed in a meaningful way to inform decision makers?

As may have become clear from the wording in this section, we place these questions in the context of complex, adaptive, socio-technical systems. In the next section we first describe what we mean by these terms before clarifying the structure of this thesis.

1.2 Complex and adaptive socio-technical systems

We choose to cast the energy systems that we research as *socio-technical* systems, which means that their design, construction, and use is explained and governed by the interplay between social elements (humans, institutions, organisations, rules, laws, and cultures) and technical elements (artefacts, implements, tools, pipes, poles, and other physical infrastructures). The concept of a socio-technical system can be ascribed to Emery and Trist (Emery and Trist, 1965; Trist, 1981) who address the intertwining of technical and human factors, which boils down to the inability to change technology without changing the way that people function. Also Hughes (1987) is credited with regard to the history of large technological systems such as power grids, the internet, and (rail)roads. Emery and Trist combine this notion of socio-technical systems with the notion of complexity, which is closely linked to the 'systems of systems' view in the engineering world (Ryan, 2008). We describe some main characteristics of these notions below.

Modern society depends on technology – this is an undeniable fact that can for example be seen in our daily use of electricity and the appliances that make use of it. One could therefore assume that technological development drives societal development. At the same time technological research, development, and application is dependent on societal rules, funding, personal whims, social fancies, and cultural fashions (van der Leeuw et al., 2009; Lane et al., 2009). In the application of technology it is therefore useful to study the technology in combination with the society in which it is developed and implemented, as society steers and shapes technology, and vice versa: they *co-evolve* and are *interdependent*. This means that such systems cannot successfully be analysed by dividing them into separate social and technological subsystems.

Furthermore, the relationship of society and technology is *non-linear* as many positive and negative feedbacks amplify and suppress the effects of decisions (Senge, 1990). As a result, simplistic linear extrapolation of effects is prone to errors, which is what politicians and decision makers find out if they try to combat traffic jams by building more highways (Duranton and Turner, 2009). Moreover, interactions between contributing factors can produce *emergent behaviour*: behaviour that is not readily attributable to one cause, not intuitively anticipatable, or comprehensible in separated chunks (Ligtvoet, 2012b; Pavard and Dugdale, 2006).

Although the myth of a 'steerable society'[1] had its supporters in the last century (Rittel and Webber, 1973), socio-technical systems cannot be governed in a top-down fashion: changes in a technical network can be decided at governmental level, but the success of such a change is determined by the users' willingness to adopt innovations and adapt to change. As technological change at national level requires the cooperation of many different stakeholders, this process may take time and persuasion of many different people. Conversely, changes that occur at a very local level do not immediately alter the state of the larger system, but slowly diffuse (Rogers, 1995).

As indicated above, the fact that different actors interact in setting goals and determining their own stance, makes such systems both *adaptive* and perpetually *innovative* (Astley and Fombrun, 1983; Checkland, 1985; Schelling, 1978). Actors find themselves in networks of interest, constantly negotiating meaning and importance of goals (de Bruijn and ten Heuvelhof, 2008). As a consequence, goalposts are likely to be moved or turn out to be unrealistic; goals that are achieved may turn out to have been the wrong goals. Individuals and groups with complex relationships and shifting allegiances continually arise and new behaviours are tested. Thus, approaches that worked in the past may no longer work, interventions that frustrate the intents of some actors will often simply stimulate them to find new ways to achieve their goals, and opportunities created by vulnerabilities will be rapidly identified and exploited (Grisogono and Radenovic, 2011).

Dealing with complex adaptive socio-technical systems is a daunting task. It is what Rittel and Webber (1973) call a 'wicked problem' and certainly casts doubt upon simplified representations of societal and technological mechanisms. The underlying premise of this research is, however, that by carefully and systematically studying human interaction in such systems, better insight can be gained into patterns of systemic behaviour thus

---

[1] In Dutch: 'de maakbare samenleving'.

opening the door to more effective management of these systems.

1.3 Uncertainty in socio-technical systems

The interplay between social elements and technical elements leads to complex behaviour (Anderson, 1999). Due to uncertain events such as economic crises, political interventions, and natural disasters, in other words environmental change, complexity is only increased (Emery and Trist, 1965). This complexity implies a fundamental uncertainty with regard to the outcome of strategic and operational decisions.

Uncertainty – a state in which information is not defined or determined – can more precisely be subdivided into several causes (Klinke and Renn, 2002; Knight, 1921).

- *Variability:* observed or predicted variation of responses to an identical stimulus among the individual targets. As we will describe in section 2.3.3, humans respond differently to identical stimuli. This response can not always be predicted beforehand. Also technical components' characteristics, such as durability, vary, and technical break-down cannot fully be predicted. The more components in a system interact, the less certain it will be which component will cause the system to malfunction. Finally, environmental circumstances also vary: wind speeds and solar irradiation are only limitedly predictable, market jolts and bubbles even less so.
- *Systematic and random measurement errors:* which is a problem of science; imprecision or imperfection of measurement, problems of drawing inferences from small statistical samples, extrapolation from animal data onto humans, (hidden) uncertainties of modelling, including the choice of functional relationships. In the best cases, these uncertainties are expressed through statistical confidence intervals; in the worst cases, they remain unknown. The advantage of this kind of uncertainty is that it theoretically can be reduced by improving the scientific methods.
- *Indeterminacy:* resulting from a genuine stochastic relationship between cause and effect(s), apparently non-causal or non-cyclical random events, or badly understood non-linear, chaotic relationships. In large multi-component (energy) systems, the sheer amount of interacting components (with multiple feedback and feed-forward loops across different system levels and different time frames) will make changes impossible to predict.
- *Lack of knowledge:* resulting from ignorance, from the deliberate definition of system boundaries and hence exclusion from external influences, and measurement impossibilities.

Next to these there is also ambiguity or ambivalence: the variability of (legitimate) interpretations based on identical observations or data assessments. Ambiguity may come from differences in interpreting factual statements about the world, or from differences in applying normative rules to evaluate a state of the world.

Uncertainty reduces the strength of confidence in the estimated cause and effect chain. Uncertainty is often, implicitly or explicitly, perceived as something that can be eradicated, or at least reduced by research, monitoring, or the passing of time (van Asselt and

Vos, 2006). Decision makers in organisations need to balance between focusing on specific strategic directions (with the chance of being wrong) or maintaining a more flexible stance, hedging their bets. In technology investment decisions, for example, the firm can spread its investment over several technologies; it thus lowers its risk by maintaining flexibility, but may have little chance of becoming a strong competitor (Wernerfelt and Karnani, 1987).

In this rapidly changing world, in which future developments are uncertain, ambiguous, and complex, decision makers turn to experts who can provide information to support the decisions. Traditionally, the expert scientists or consultants would divide the problem into small elements that can be handled more or less confidently with an analytical model (Funtowicz and Ravetz, 1993). However, by transforming the problem into analysable chunks, the analysts and modellers have to compromise between desired functionality, plausibility, and tractability, given the resources at hand (data, time, money, and expertise) (Walker et al., 2003). Although for 'wicked problems' (Rittel and Webber, 1973) clearing all uncertainties is impossible, understanding the various dimensions of uncertainty helps in identifying, articulating, and prioritising critical uncertainties, which is a crucial step to more adequate acknowledgement and treatment of uncertainty in decision support endeavours and more focused research into complex, inherently uncertain, policy issues.

1.4 Approach and reading guide

Turning back to cooperation, we start with the findings of Andras et al. (2007) that environmental adverse and uncertain conditions lead to cooperation. Cooperation is a way to introduce some level of stability in a constantly changing world. As Herbert Simon suggested: you either adapt your organisation to the landscape, or the landscape to your organisation (paraphrased from Langlois, 2003). By doing so the cooperators introduce a new source of uncertainty: dependence on other actors for the smooth operation of their business.

This thesis aims to shed light on this dual nature of cooperation and aims to provide several different approaches to better understand and deal with the non-linear consequences of cooperation. We have therefore both a content oriented and a method oriented task. The logic of this book is displayed in figure 1.1.

After this introduction, we first take a broad look at different scientific fields and their literature on cooperation (chapter 2). By connecting the reviewed literature in a graph, different clusters of research are identified. The review provides a basis of (theoretical) inspiration.

Then we proceed with three case studies of the kinds of energy networks we are interested in: two cases of district heating networks (in Delft and The Hague) and one case of the gradual build-up of a CO_2 network in the Port of Rotterdam industrial area and the Westland horticultural areas (chapter 3). The cases provide us with rich contextual information on the types of issues that the founders of these networks deal with. At the same time the case study approach is seen as the first approach to understanding cooperation.

In chapter 4 we take a mathematical approach, using graph theory, in which the build-

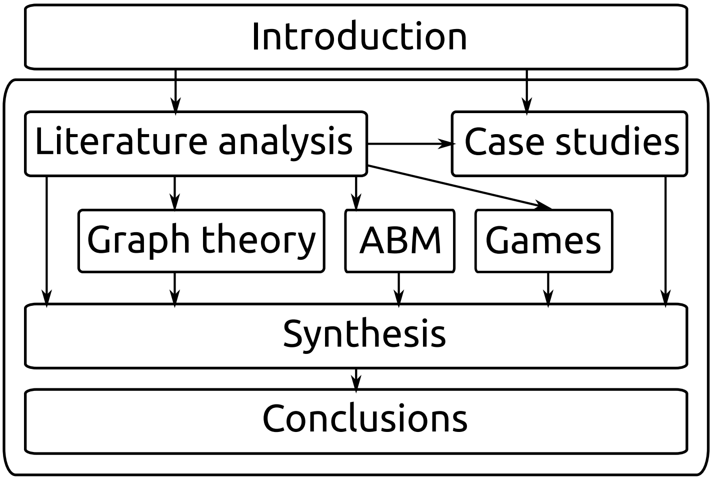


Figure 1.1 – The cohesion of the chapters of this thesis: the introduction serves as a starting point for literature analysis and case studies. The case study chapter serves a dual purpose: it provides both a contextual deepening of cooperation theory as well as an approach to investigating cooperation. The other three approaches are fed by theoretical and practical insights, which leads to a synthesis of methods and conclusions on cooperation research.

ing of energy networks is mainly a planning issue and cooperation (or non-cooperation) is a source of uncertainty for the planner. This uncertainty is dealt with in a simple and transparent way to arrive at low-regret options for cooperation.

The first of the two 'hybrid' approaches tackles the building of energy networks with the help of agent-based models (chapter 5). One could still call this a mathematical approach (since all rules in the models are captured in computer code). However, as compared to the approach in chapter 4, more behavioural components are introduced and different agents are imbued with their own particular behavioural rules.

The other hybrid approach is that of serious gaming (chapter 6). We have observed the cooperative activities of players in an existing energy market game. As this approach builds more on human interaction and (somewhat) less on following the researchers' rules, we see this approach as slightly closer to the case study approach in chapter 3.

In chapter 7 we compare the four different approaches and discuss their merits and shortcomings. Depending on the point of view of the researcher, the framework that is chosen, the different assumptions that are made, and the research goals that are pursued, one approach may be more appropriate for enlightening social and/or technical dynamics than the other.

Finally, we draw the conclusions from all the above in chapter 8, in which we answer the research questions posed in this introductory chapter, reflect on (our) research, and pave the road for further cooperation research.

Chapter 2

Cooperation

This chapter provides a literature analysis of cooperation research in different academic fields. It presents a map of the fields taken into consideration and compares the use and focus of these fields in order to specify which elements can be used in our own research. By choosing those elements that fit within our context of complex adaptive socio-technical systems, we provide a framework for analysing cooperation. Parts of this analysis have been presented in Ligtvoet (2011).

2.1 Introduction

Cooperation is being researched in a range of fields: e.g. in strategic management (Nielsen, 1988; Nooteboom, 2004), (evolutionary) biology (Nowak, 2006; West et al., 2007a), behavioural economics, psychology, and game theory (Axelrod and Hamilton, 1981; Axelrod, 1997). In most fields it is found that contrary to what we understand from the Darwinian idea of 'survival of the fittest' – a vicious dog-eat-dog world – there is a lot of cooperation at all levels in nature, from micro-organisms to macro-societal regimes. It turns out that although non-cooperation (in game theory called 'defection') is a robust and profitable strategy for organisms, it pays to cooperate under certain conditions, e.g. when competing organisations want to pool resources to enable a mutually beneficial project (Nielsen, 1988).

Although some literature does specify what options for cooperation there are, it does not explain why these options are pursued (Roberts and Sherratt, 2007). The *how?* and *why?* of cooperation and how it can be maintained in human societies, construe one of the important unanswered questions of social sciences (Colman, 2006). By analysing a broad range of research fields, we hope to provide a framework that can help understand the role of cooperation in industrial networks.

2.2 Literature analysis

The analysis of available literature is a basic element of scientific enquiry (Creswell, 2009) and a wide range of sources has been used in this thesis. In the current age of Google Scholar, Scopus, Web of Knowledge, arXiv, wikis, and other forms of digital (university) repositories, the issue is not to find literature, but to sift through the thousands of candidates. In the literature search and analysis there are different categories and levels of detail:

- *General literature* provides a general introduction to (well-known) societal issues. The main purpose was to set the stage for this research (chapter 1). Only recent policy and/or research reports are considered.
- *Topical literature* we are interested in focuses on cooperation (this chapter). A range of scientific journals and books in the fields of strategic management, evolutionary biology, game theory, behavioural economics, and related disciplines were reviewed. The aim here was to provide an overview of the different disciplines and their approaches to and understanding of this topic.
- *Case literature* supplies an additional cross-check of facts and dates for the case studies (see chapter 3), which are primarily based on interviews.
- *Methodological literature* encompasses a large set of publications on exploratory modelling, agent-based modelling, graph theory, and serious gaming. The results of the reviews are discussed in the introduction to each of the main chapters (chapters 3, 4, 5, and 6).

By using the data on number of citations, key references were found. Next to this top-down method, we also used the more bottom-up method of ‘snowballing’: following the most interesting references from papers already read. Thus we not only found the most supported literature, but also contrary views or newer developments.

2.2.1 Reference and co-reference analysis

As the snowball method leads to path dependency in the literature analysis, we chose to further analyse the literature we found. For all the literature that was used in the preparation of this thesis[1] we collected the references used in each source, using the Web of Knowledge database and constructed a document graph using the method described in Chappin and Ligtvoet (2012). Due to the fact that not all references are present in the Web of Knowledge database (books and most conference proceedings are excluded), we found 300 articles of the 560 documents, which yielded 10,000 references. When selecting only those references that were referred to by at least two articles, we ended up with 1,300 unique references (figure 2.1 explains the method). We then identified clusters of research fields based on 1) direct reference of one source by another source and 2) co-reference of a third source by two sources. By drawing the (co-)reference links in a graph, a visual overview can be created (see figure 2.2).

---

[1] See http://www.citeulike.org/user/ligtvoet for a complete overview.

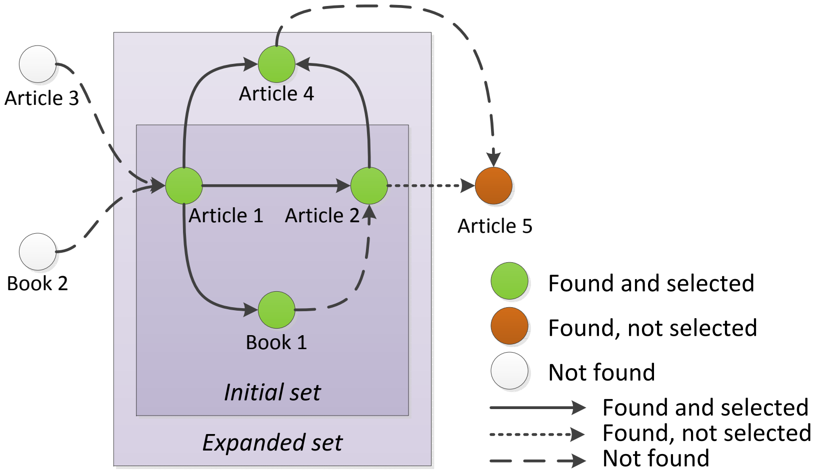


Figure 2.1 – This graph shows the method for our analysis: of all literature read (the 'initial set') we collected the references and only selected those that are co-referenced by two or more of the articles we read, which forms the 'expanded set'. Article 4 is included in the analysis, whereas article 5 is not. Article 3 and Book 2 were not found using this method.

Figure 2.2 shows clusters of research fields. Those clusters with a high density are the ones that received most attention in our literature review. The clusters for a large part form the basis for section 2.3 that elaborates on cooperation in different disciplines: animal behaviour, game theory, social interaction and rationality, behavioural sciences, as well as organisational behaviour and management. Other notable clusters relate to the methodology (agent-based modelling, gaming) and to broader research themes that lie close to this research (systems theory and systems thinking, judgement under uncertainty, transition management, industrial ecology). By analysing the (co-)references of this literature we expect to identify the most important sources that can be considered the basis on which our research builds.

2.2.2 Standing on shoulders

In order to identify key literature resources, we used basic graph metrics (we explain more about graph theory in chapter 4). The *degree* of a node (in our case a node is a literature reference) is the number of connections (edges) it has to other nodes. One can differentiate between in-degree (other nodes pointing towards this node) and out-degree (other nodes to which this node points). Those sources that have a high in-degree is the *key* literature that many others build upon, the proverbial 'shoulders of giants'. Sources with a high out-degree are sources that provide an overview, so-called overview articles. Since we only display those sources that are referenced by at least two separate sources, we can assume that these high out-degree articles are embedded in our selection of the field of research.

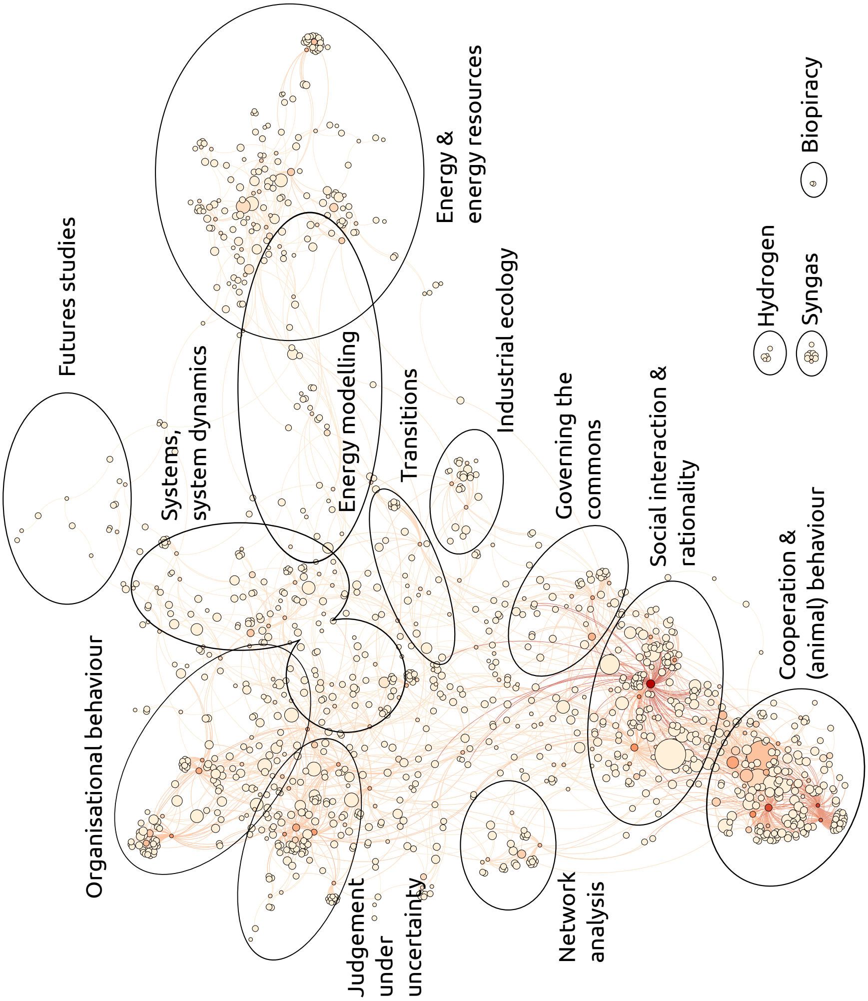


Figure 2.2 – The clusters of references and co-references based on the literature that formed the basis of this thesis, see http://www.citeulike.org/user/ligtvoet.

High out-degree

Articles with a high out-degree refer to many other literature sources (e.g. in figure 2.1, article 1 has an out-degree of 3). They are generally overview articles that attempt to draw together a whole field of research. When performing a (snowballing) literature review, they provide many connections to other articles and often provide the reader with the context in which the research is performed, thus providing many new starting points but also acting as a filter.

Since we did not perform a second degree analysis (the references of the references – article 4 referring to article 5 in figure 2.1), the articles listed in table 2.1 are all articles that we read (as we only found the out-degree for articles that we read). They form the kernels of the clusters that we identified in figure 2.2. Note that we only counted those references that are also mentioned by at least one other paper (thus checking that the papers mentioned here do not 'randomly' refer to a large list of unrelated literature sources – article 4 in figure 2.1 is taken into consideration, whereas article 5 is not).

High in-degree

References with a high in-degree are the literature sources (including books) that the articles read refer to (in figure 2.1, article 4 has an in-degree of 2). They can be seen as the basis that others build upon. Looking at table 2.2, Axelrod is clearly important to our research, as his research combines game theory, computer science, and behaviour (as well as political science and other fields). Closely related are the evolutionary biologists Hamilton and Trivers for their ground breaking work on cooperation, along with their more mathematically inclined colleagues Nowak and Sigmund. Organisational behaviour is covered by March, Simon, and Cyert, while the institutional economics are represented by Ostrom and Williamson. The seminal *Tragedy of the commons* by Hardin 1968 also plays an important role, as this text relates to challenges of resource use facing communities, providing an exemplary case of defection trumping cooperation.

2.3 Disciplinary and cross-disciplinary approaches

Out of this plethora of theory on cooperation (and energy related research), we highlight several disciplines along the same categories as Nielsen (1988). In the overview presented below, it should be noted that the research in these fields tends to overlap and that a clear distinction between disciplines cannot always be made (Roberts and Sherratt, 2007; Lazarus, 2003). This holds for many fields of research: the field of *Industrial Ecology*, for example, in which the behaviour of individual industries is compared to the behaviour of plant or animal species in their natural environment, is a discipline that is approached from engineering traditions as well as economic and social researchers (Garner and Keoleian, 1995; Duchin and Hertwich, 2003). Likewise, *Evolutionary Psychology* builds psychological insights on the basis of biology and paleo-anthropology (Barkow et al., 1992), whereas *Transaction Cost Economics* is a cross-disciplinary mix of economics, organisational theory, and law (Williamson, 1998). By approaching a problem in a cross-disciplinary fashion, the researchers hope to learn from insights developed in different

Table 2.1 – Ten articles with the highest out-degree

Title	Author	Out-degree
A behavioral approach to the rational choice theory of collective action	Ostrom (1998)	101
Social semantics: altruism, cooperation, mutualism, strong reciprocity and group selection	West et al. (2007b)	77
Models of cooperation based on the Prisoner's Dilemma and the Snowdrift game	Doebeli and Hauer (2005)	73
Evolutionary explanations for cooperation	West et al. (2007a)	64
Social dilemmas: the anatomy of cooperation	Kollock (1998)	52
Five rules for the evolution of cooperation	Nowak (2006)	48
Cooperation, psychological game theory, and limitations of rationality in social interaction	Colman (2003a)	47
What do interlocks do? An analysis, critique, and assessment of research on interlocking	Mizruchi (1996)	43
Collective action and the evolution of social norms	Ostrom (2000)	43
Dynamic capabilities and strategic management	Teece et al. (1997)	41

Table 2.2 – Ten literature sources with the highest in-degree

Title	Author	In-degree
The evolution of cooperation	Axelrod and Hamilton (1981)	24
The evolution of cooperation	Axelrod (1984)	24
The evolution of reciprocal altruism	Trivers (1971)	16
The tragedy of the commons	Hardin (1968)	14
Evolution of indirect reciprocity by image scoring	Nowak and Sigmund (1998)	11
Governing the commons: The evolution of institutions for collective action	Ostrom (1990)	10
The genetical evolution of social behaviour	Hamilton (1964)	10
A behavioral theory of the firm	Cyert and March (1963)	9
Organizations	March and Simon (1958)	9
Markets and Hierarchies: Analysis and Antitrust Implications	Williamson (1975)	9

fields. In the same way this chapter will combine different academic fields in order to reach insights into the mechanisms of cooperation (as is suggested by Lazarus, 2003).

2.3.1 Biology and animal behaviour

Cooperation in organisms, whether bacteria or primates, has been a difficulty for evolutionary theory since Darwin (Axelrod and Hamilton, 1981): when analysing situations in which social behaviour takes place (those behaviours which have fitness consequences for both the individual that performs the behaviour and another individual), non-cooperative or defective behaviour appears to be the strategy required for greatest fitness (West et al., 2007b). In many biological systems, however, cooperation emerges as a successful strategy. It turns out that a population of only cooperators has the highest average fitness, whereas a population of only defectors has the lowest. For some reason, cooperation among presumed 'selfish' individuals succeeds. What happens next is that either cooperation remains in place, providing perpetual advantages, or is outcompeted by defection that provides individual success in the short term. Nowak (2006) has summarised five different modes of cooperation that can be found in biology and related literature:

- *Kin selection:* this form of cooperation favours relatives, based on the distance to the individual under research (the amount of DNA they share) (Hamilton, 1964). This means that parents are most likely to help or cooperate with their children, whereas cousins are less likely to be helped, and non-relatives not at all. In human societies this behaviour also takes place; we refer to it as *nepotism*. Although this type of cooperation does not seem directly applicable to industrial relations, one could imagine that firms are more likely to cooperate with 'daughter' or 'mother' companies, than with totally unrelated industries.

- *Direct reciprocity:* cooperation between unrelated individuals or even between members of different species can also take place. Trivers (1971) suggests that the reason for this type of cooperation is that both individuals involved in a transaction gain from that activity, possibly over time (Connor, 1986; West et al., 2007a). Direct reciprocity can lead to the evolution of cooperation only if the probability of another encounter between the same two individuals exceeds the cost-to-benefit ratio of the act. Using a competition of algorithms, Axelrod and Hamilton (1981) discovered that an effective strategy in such encounters is one of the simplest of all, tit-for-tat (do onto others as they do onto you; see section 2.3.2 on evolutionary game theory).

- *Indirect reciprocity:* particularly for humans, reputation allows evolution of cooperation by indirect reciprocity. People benefit by cooperating, even in one-off encounters with strangers, because cooperation enhances one's reputation for cooperativeness and elicits reciprocal cooperation from others (Colman, 2006; Fehr and Fischbacher, 2003; Milinski et al., 2002). An example of this mechanism is a donation to a charity, so that that charity on its turn may support a particular goal. Indirect reciprocity can only promote cooperation if the probability of knowing someone's reputation exceeds the cost-to-benefit ratio of the act. For this to work, some way of identifying cooperators would increase the chance of cooperation taking place (Jansen and van Baalen, 2006; Riolo et al., 2001).

- *Group selection:* members of the same group may choose to support each other when the survival of the group rather than the individual is at stake. One could see this as an extension of kin selection, but the incentive for cooperation comes from other advantages that individuals may derive from groups too, such as protection (which would be a combination of direct and indirect reciprocity). Group selection is a complex process in which selection on the lower level (between individuals) favours defectors, whereas selection on the higher level (between groups) favours within-group cooperators (Knudsen, 2003).

- *Network reciprocity:* networks consist of individuals that are linked to other individuals and thus form a web of relationships. Spatial structure as well as different network memberships imply that some individuals interact more often than others. Thus the benefit of the reciprocal behaviour depends on the individual's neighbours: benefits of local exchanges between neighbours diffuse through 'weak ties' to outsiders (Macy and Skvoretz, 1998; Granovetter, 1985).

Whereas the drive to understand the emergence of cooperation in selfish individuals has generated a large body of theoretical and empirical research, much of the research focuses on the dynamics of interactions between individuals and pays relatively little attention to the effects of the environment. As the adversity (harshness) and uncertainty of the environment increase cooperation is enhanced (Andras et al., 2007). Also, it can be argued that cooperation has some larger systemic advantages, such as specialisation, which also lead to selection of cooperative strategies.

In animal cooperation research often comparisons with human examples are given, as it is reasoned that human social life is likely to be similar to biological life (Astley and Fombrun, 1983; Milinski, 1987). However, people frequently cooperate with genetically unrelated strangers, often in large groups, with people they will never meet again, and when reputation gains are small or absent. Human patterns of cooperation therefore cannot only be explained by the nepotistic motives associated with kin selection and the selfish motives associated with direct reciprocity.

This points towards the importance of both theories of cultural evolution as well as biology-culture co-evolution (Fehr and Fischbacher, 2003). Cooperative behaviour can be learned and maintained even when immediate and tangible pay-offs are absent, insufficient, or sub-optimal (so-called *intrinsic reinforcement:* Schuster and Perelberg, 2004). We therefore must look beyond biological explanations for more insights in human psychology and behaviour.

2.3.2 Game theory

Game theory offers a mathematical description of behaviour in strategic situations, in which an individual's success depends on the choices of others. Game theory allows the study of 'emergence, transformation, and stabilisation of behaviour' and has been used to analyse various social, ecological, and political tensions (Grimes-Casey et al., 2007). In game theory it is assumed that the involved actors have common knowledge and that they are rational (abbreviated as the CKR-assumption) (Colman, 2003a):

- The specification of the game, including the players' strategy sets and pay-off functions, is common knowledge in the game, together with everything that can be deduced logically from it.
- The players are rational in the sense of expected utility (EU) theory, hence they always choose strategies that maximize their individual expected utilities, relative to their knowledge and beliefs at the time of acting.

Based on their pay-off or individual utility, players rationally choose in a way to maximise their profit. The different situations, or games, that the players face are chosen in such a way that they represent different types of dilemmas (see box 1 for the most salient examples). Game theorists of the strict school believe that their prescriptions for rational play in games can be deduced, in principle, from one-person rationality considerations without the need to invent collective rationality criteria – provided that sufficient information is assumed to be common knowledge (Colman, 2003a).

Of course, the validity or representativeness of the dilemmas and their game theoretic solutions can be discussed: whereas considerable efforts have been made to use the *Prisoner's dilemma* as a key example for (the evolution of) cooperation, Doebeli and Hauer (2005) put forward that the *Snowdrift game* may be more relevant to describe a situation where the cooperating individual is rewarded.

Many of the classical examples as described in box 1 are games among two players that have to make a single decision. Human interaction, however, is often characterised by multiple interactions instead of one-shot games. Therefore, some game theorists have taken an evolutionary stance in the sense that strategies can 'emerge' if the games are iterated within a certain population – the strategies that remain in place are called Evolutionary Stable Strategies (ESS). Axelrod and Hamilton (1981), for example, ask what types of strategies are the most effective in an iterative game in which a player can choose either a cooperative strategy or a competitive strategy. The authors showed that certain strategies can lead to continued strategical success. The so-called *(generous) tit-for-tat* strategy (start with cooperation, but defect when the other player does so, and cooperate when the other player does so) entails a combination of being nice, retaliatory, forgiving, and clear. Its niceness prevents it from getting into unnecessary trouble. Its retaliation discourages the other side from persisting whenever defection is tried. Its forgiveness helps restore mutual cooperation. And its clarity makes it intelligible to the other player, thereby eliciting long-term cooperation.

However, evolutionary game theory cannot solve all the problems of orthodox game theory, because it is only relevant to large populations and repeated interactions. It cannot solve the problems that arise in isolated interactions such as single negotiations. Human decision makers can, and do, anticipate the future consequences of their actions, whereas genetic and other evolutionary algorithms are backward-looking, their actions being determined exclusively by past pay-offs (plus a little randomness in stochastic models) (Colman, 2003b).

Game theory in general has received ample criticism with regard to its assumptions and its representation of 'reality'. Kollock (1998), for instance, complains that the meta-

One of the most salient elements of game theory are the exemplary dilemmas. A situation is described in which two (or more) players face a problem for which they receive a certain known pay-off. The question is which solution each player would pick, assuming they are rational decision makers (with no further considerations).

Prisoner's dilemma Two suspects are arrested by the police. The police have insufficient evidence for a conviction, and, having separated both prisoners, visit each of them to offer the same deal. If one testifies ('defects') for the prosecution against the other and the other remains silent, the betrayer goes free and the silent accomplice receives the full 10-year sentence. If both remain silent, both prisoners are sentenced to only six months in jail for a minor charge. If each betrays the other, each receives a five-year sentence. Each prisoner must choose to betray the other or to remain silent. Each one is assured that the other would not know about the betrayal before the end of the investigation.

Snowdrift game (or hawk-dove game, chicken game) Two drivers are trapped on either side of a snowdrift and have the options of staying in the car or removing the snowdrift. Letting the opponent do all the work is the best option but if the other player stays in the car it is better to shovel. In this game, cooperation yields a benefit that is accessible to both players (i.e. free passage to go home), whereas the cost (i.e. removing the snowdrift) is shared between cooperators. Defection is favoured when the other player cooperates, which occurs at the cost of the overall group pay-off. Situations similar to the snowdrift game are ubiquitous in human working life. For example, two scientists accomplishing a research project would each benefit if the other invests more time than oneself in the writing of the paper reporting the collaborative work. But if one of the collaborators does not contribute at all, the best option probably remains to do all the work on one's own (Kümmerli et al., 2007).

Stag hunt (or assurance game, coordination game, trust dilemma) Two hunters go out on a hunt. Each individually can choose to hunt a stag or hunt a hare and chooses an action without knowing the choice of the other. If an individual hunts a stag, he must have the cooperation of his partner in order to succeed. An individual can get a hare by himself, but a hare is worth less than a stag. This situation describes the conflict between social cooperation and the safety of a known return.

Ultimatum game Two players decide how to divide a sum of money that is given to them. The first player proposes how to divide the sum between the two players, and the second player can either accept or reject this proposal ('take it or leave it'). If the second player rejects, neither player receives anything. If the second player accepts, the money is split according to the proposal. The game is played only once so that reciprocation is not an issue.

Box 1 – Archetypical dilemmas in game theory phorical stories have reached such mythical proportions that both researchers and even policy makers have been led to believe that all social dilemmas could be represented by them (or could be redefined to be represented by them). West et al. (2007a) state that theoretical analyses of games contort real systems into the form of an artificial game, and that other methods are available that allow biology (i.e. observed behaviour) to lead mathematics (i.e. hypothesised behaviour).

More fundamentally, the assumption of rational decision makers is attacked by Colman (2003a), amongst others:

> Rational choice theory enjoys unprecedented popularity and influence, but it generates intractable problems when applied to socially interactive decisions. In individual decisions, instrumental rationality is defined in terms of expected utility maximization. This becomes problematic in interactive decisions, when individuals have only partial control over the outcomes, because expected utility maximization is undefined in the absence of assumptions about how the other participants will behave. Game theory therefore incorporates not only rationality but also common knowledge assumptions, enabling players to anticipate their co-players' strategies.

Not only is it highly debatable whether players are capable of including all costs – internal to their decisions and the externalities of their impacts – in their pay-off functions (Grimes-Casey et al., 2007), behavioural tests of game theoretic situations show that the outcomes of games played by humans differ significantly from the predictions of the theoretical models. In team sports, military situations, joint business ventures, and even family outings, people sometimes choose to do what is best for the group, even when this collective interest does not coincide with their individual preferences (Colman, 2003a). Assuming the presence of a utility function, which assigns pay-offs to possible outcomes, is simply not practicable for many real-world problems. In this sense, game-theoretic models – even though they are strong formalisms – are simply too coarse-grained for direct implementation in real systems (Wooldridge and Jennings, 1999).

2.3.3 Behavioural science

As indicated in the section above, the assumption that human actors are rational decision makers does not hold in most test settings. Behavioural sciences, like psychology and behavioural economics, attempt to find out what factors do play a role in cooperative activities. The willingness to cooperate does not only depend on the type of social dilemma, but also on the surroundings and the class of individuals involved. Women, for example, cooperate significantly more often than male subjects and apply tit-for-tat-like strategies more often than do male players, thereby achieving significantly higher pay-offs (Kümmerli et al., 2007). From a behavioural perspective, the choice between cooperation and non-cooperation is also determined by social dimensions, such as the presence and behaviours of familiar partners, working in groups, and experiencing positive emotions linked to both coordinated ceremonial behaviours and simpler acts of 'behaviour matching' (Schuster and Perelberg, 2004).

The ultimatum game (see box 1), for example, clearly illustrates that rather than rationally accepting a pay-off that requires little more than saying 'yes' or 'no', people from a wide variety of cultures are willing to punish others at a cost to themselves to prevent inequitable outcomes or to sanction unfair behaviour. Furthermore, the belief that all or most members of the group will cooperate is decisive. Any mechanism that generates such a belief has to provide cooperation incentives for the selfish individuals.

According to Simon (2007), the essence of organisations is communication and thus by definition a multi-actor issue. From a rational point of view, communication is purely functional, a means to convey information. Talking about one's intention to perform a certain action is considered 'cheap talk'. Bicchieri (2005), however, points out that cheap talk is more than data exchange. Discussion focuses subjects on socially desirable behaviour. By sharing information, participants start to think they are members of a group and their motives and behaviour change. It has been shown that individuals are more likely to cooperate when everyone in the group promises to cooperate. Basically, communication allows for the emergence of cooperation (Miller et al., 2002).

Another powerful mechanism for the enforcement of cooperation in public goods situations is a reputation for behaving altruistically. Humans exhibit a sizeable baseline level of altruistic rewarding, and when given the opportunity to gain a reputation for being generous, helping rates increase strongly (Fehr and Fischbacher, 2003).

From an evolutionary perspective, human information-processing mechanisms are still adapted to ancestral hunter-gatherer environments. In these circumstances, humans were dependent on each other for mutual protection, sharing food, and providing for the young. Survival did not only depend on aggressively seeking individual returns but also on solving many day-to-day collective action problems. Those of our ancestors who solved these problems most effectively, and learned how to recognize who was deceitful and who was a trustworthy reciprocator, had a selective advantage over those who did not (Barkow et al., 1992).

Recent empirical research provides strong support for the assumption that modern humans have inherited a propensity to learn social norms – shared understandings about actions that are obligatory, permitted, or forbidden. Which norms are learned, however, varies from one culture to another, across families, and with exposure to diverse social norms expressed within various types of situations (Knudsen, 2003; Ostrom, 2000). Therefore, understanding the context in which these social norms play a role is crucial for understanding the norms themselves.

2.3.4 Strategic and organisational management

The literature on strategy and organisational management could be seen as a more specific field with regard to cooperation, limited to the context of firms and corporations. Although the focus of strategy-oriented researchers on cooperation is not new, the focus remained strongly on market-based competition (Hernández-Martínez, 2007; Nielsen, 1988; Astley, 1984; Mariti and Smiley, 1983) possibly because cooperation can take many shapes between the extremes of market control and hierarchical steering (Todeva and Knoke, 2005; de Bruijn and ten Heuvelhof, 2008). Several authors refer to one or more fields mentioned in the previous sections to embed their work in a broader scientific context. The focus of their own contributions, however, also differs: some focus on the different (legal, institutional) forms for organisations to cooperate in, some describe the process of cooperation, the requirements for cooperation to work, whereas others focus on the reasons for cooperation (the benefit for the individual participants). In recent years, quite an extensive literature has developed on the issue of cooperation specifically for research and development, and joint innovation (Belderbos et al., 2006; Miotti and Sachwald, 2003; Kleinknecht and Reijnen, 1992).

Reasons for cooperation The rationale for collective strategies as a means to cope with the variation of interdependent environments, is to minimize decision making uncertainty by reducing movement among environmental elements. Environmental movement and the resulting decision making uncertainty can be reduced if a collective strategy decreases the frequency or increases the predictability of change (Astley and Fombrun, 1983). Furthermore, strategic alliances can be aimed at: time advantages, know-how advantages, access to markets, cost advantages, and system competence (Bronder and Pritzl, 1992), transfer or complementarity of technologies, marketing agreements, economies of scale, and risk reduction (Mariti and Smiley, 1983).

Nielsen (1988) makes the following observations:

1. internal coordination and cooperative strategies within large organisations can be more efficient than relying on external market mechanisms;

2. network arrangements can be more efficient than relying on strictly internal hierarchy or external market competitive mechanisms;

3. while some cases of inter-organisational cooperation considered suggest reduction of efficiency caused by cooperation, most cases revealed the opposite: cooperation can increase efficiency;

4. cooperative strategies can improve efficiency in a wide range of market environments.

At the same time, however, interdependence can create problems of decision making uncertainty because the success of input acquisition, transformation, and output disposal activities of any interdependent organisation is contingent upon the activities chosen by other organisations (Bresser and Harl, 1986). Thus while cooperation can lead to benefits, it also incorporates risks.

Forms of cooperation According to Astley and Fombrun (1983), structures of collective action are emerging, ranging from informal arrangements and discussions to formal devices such as interlocking directorates, joint ventures, and mergers. Increasingly, interindustry relationships are being managed through cooperative ventures rather than left to the forces of supply and demand. Strategic alliances emerge from an evolutionary process of mutual learning and continuous adaptation. Moreover, a company is no longer an integrated unit with clearly defined borders: it is a network consisting of strategic alliances, operative cooperation and value chain activities of its own within its respective environment (Bronder and Pritzl, 1992; Astley, 1984).

Collective strategies can be reactive, absorbing variation within an environment, or they can be proactive, forestalling unpredictable behaviour by other organisations. In an analysis of different types of firm behaviour or strategy, Nielsen (1988) comes up with four types of cooperation strategy.

- The *pool strategy* is focused on reducing duplication and redundancy. It can help accumulate the resources needed for reaching a threshold where economies of scale can be achieved. Examples are the *Keidanren* (associations of Japanese manufacturers), who agree to pool production resources through joint ownership of production facilities and Intelsat (an international satellite communication corporation) that was set up by international telecommunication companies that wanted to pool resources for building, launching and managing communication satellites.

- The *exchange strategy* is the opposite: if one organisation is not able to perform all operations, then two or more organisations – each performing a part of these operations – can be an effective and efficient strategy. This strategy can be seen in General Motor's promise not to lobby for auto quotas against Japanese cars while Toyota agreed to share its small car manufacturing technology, and also in the agreement between the United States and Mexico, where the USA agreed to long-term purchases of Mexican oil in exchange for large-scale loans.

- The *de-escalation strategy* aims to reduce or eliminate attacks on each other can increase the welfare of both organisations. An example for this strategy is the Council of European Federations of Industrial Chemicals' decision to have member companies de-escalate competition by mutually reducing production and production capacity.

- In the *contingency strategy*, organisations agree to cooperate in specific ways now and in the future conditionally upon how future events occur. Organisations are able to make agreements and benefit even though they are unsure of future events by agreeing to cooperate and compensate each other in different ways according to how future events might occur. This happened e.g. when the Organisation of Petroleum Exporting Countries (OPEC) agreed to maintain petroleum prices even if the market declined.

It may be clear that while these strategies may have a positive effect on the organisations partaking, some may actually curb access to markets and competition. In these cases, competition law determines whether these 'trusts' or 'cartels' are legal.

Requirements for cooperation Although price is a very strong information carrier (as Austrian economists like Hayek (1945) emphasise), the coordination of activities sometimes calls for greater information than can be conveyed by price alone. Not only should their operations be aligned (synergy or strategic overlap, leading to lower costs or higher profit), but the organisations should also have the same strategic views and expectations and be culturally compatible (Bronder and Pritzl, 1992; Teece, 1992).

Of particular importance are reputation and trust, which to some extent are mutually reinforcing (Ostrom, 1998). Especially in an industrial district, i.e. a limited geographical area, actors live close to each other, they have shared vested interests, and their behaviours are observable and remembered (Gibbs, 2003; dei Ottati, 1994). Sometimes the intervention of a brokering organisation to bring parties together is required, although whether a 'facilitated emergence' can lead to cooperation depends to a great degree on the nature of the broker, the dynamics of the network, and the robustness of the system that evolves as a result (Paquin and Howard-Grenville, 2009).

2.3.5 Theory and practice

In her analysis of teamwork and cooperation, Gold (2005) identifies a number of dimensions in which theory and practice differ (see table 2.3). In most theories, team size is focused on *dyads* (1-on-1 relationships), whereas in many practical problems others play either a direct or indirect role. Furthermore, much economic theory focuses on pay-off or utility maximisation, whereas in 'real life' actors must weigh heterogeneous motives that are difficult to express in a common denominator (social pressure versus euros, for example). The types and competences of actors are generally assumed equal; often, however, networks are built up with actors of different sizes, powers, and skills. When looking at the way such networks operate (which Gold calls architecture), theory assumes no communication and independent decision making whereas in practice communication takes place and different kinds of hierarchical relationships exist. In theory, cooperation is voluntary, whereas in intra-organisational settings actors can be assigned to teams and in inter-organisational settings certain actors (such as governments, large neighbours, monopsonistic buyers, or monopolistic providers) cannot be avoided. Finally, in theory actors are often allowed a limited set of activities they can pursue, whereas in practice actors are constantly attempting to improve their options by not playing games that have been defined by others.

If we aim to support decision making, this discussion teaches us that there are major differences in which theorists approach cooperation and the practical examples that are encountered in empirical examples.

Table 2.3 – Dimensions of cooperation research as used in theory and in practice

Dimension	In theory	In practice
Team size	Small - 2 players	Variable - may be large
Motivations	Payoff maximising (though what payoffs consist of may vary)	Heterogeneous motives
Competences	Symmetrical agents	Heterogeneous agents, different types with different skills
Architecture	No communication, No hierarchy	Communication, leaders
Activity	Limited strategy space, strategies given	Many nuanced strategies, creativity
Formation	Voluntary team formation	Assignment to team

2.4 A layered approach

We find that socio-technical systems can be analysed as containing layers of elements at different levels of aggregation. In the field of *Transition Management* (see e.g. Rotmans et al., 2001; Geels, 2002; Kemp and Loorbach, 2005; Chiong Meza, 2012), societal changes are described as taking place in three distinct levels: the micro level (single organisations, people, innovations, and technologies within these organisations), the meso level (groups of organisations, such as sectors of industry, governmental organisations), and the macro level (laws and regulations, society and culture at large). In short, the theory states that at the micro (niche or actor) level a multitude of experiments or changes take place that, under the right circumstances, are picked up in the meso (network or regime) level. When these regimes incorporate innovations, they turn into ‘the way we do things’, and eventually become part of the socio-cultural phenomena at macro (system) level. Conversely, the way that our culture is shaped determines the types of organisational regimes that exist, which provide the framework for individual elements at the micro-level. This is at the same time a top-down and bottom-up influence relationship.

A similar way of analysing societal systems can be found in *Transaction Cost Economics*, that itself is a cross-disciplinary mix of economics, organisational theory, and law (Williamson, 1998). In this field of research, a distinction is made in four layers (Bauer and Herder, 2009):

- *Embeddedness:* the highest level of analysis, where customs, traditions, norms, and religion reside. Often this layer is treated as a ‘given’, as changes here take very long to materialise (in the order of centuries).

- *Institutional environment:* here, the formal ‘rules of the game’, such as laws and regulations, are codified. Changes in this realm take decades to a century.

- *Governance:* where the interplay between organisations takes place. Important elements are contracts, the alignment of governance structures with transactions, and networks of organisations. Here, changes occur yearly up to several times per decade.

- *Resource allocation and employment:* the level at which firms make daily decisions on prices and quantities of goods produced, which is basically a continuous process. Individual firms, or even individual people, are the main element of analysis.

The point of mentioning these fields of research is that layered analysis can help in the analysis of complex social phenomena that take place in socio-technical systems. Each layer is described in terms of the level above and below it, and layers influence each other mutually (Laszlo and Laszlo, 1997; Rousseau, 1985). For instance, the nature of organisations’ behaviour influences their relationships, but these relationships also in turn affect the organisations’ behaviour (Kohler, 2000). In observing how individual firms behave, we have to acknowledge that this behaviour is conditioned by the social networks and cultural traditions that actors operate in. It is therefore important to take heed of contextual information.

We propose that research into the complex phenomenon of cooperation should also consider several layers of analysis. As we have seen in the game theory and biology, *individual fitness* or *gain* is an important factor in deciding what strategy (the choice between cooperate or defect) to follow. Behavioural science teaches us that such simple and mathematically elegant approaches often do not help us in predicting and understanding human behaviour. Cultural norms, acquired over centuries, and institutions like government and law, determine the 'degrees of freedom' that individuals or organisations have. At the same time, the importance of formal and informal social networks allow for the dissemination of ideas, the influence of peers, and the opportunity to find partners. These are the micro, macro, and meso layers that play an important role in cooperation between organisations.

2.4.1 Macro layer

The macro layer encompasses institutional and cultural embeddedness. This layer emerges as centuries of individual and group decision making becomes codified in written or unwritten rules. As Cosmides and Tooby (1994) point out, cooperation has been a survival strategy for humans for several millennia. The only way for hunter-gatherers to effectively live and survive, was to work together in small bands: large game could only be caught by several hunters working together, settlements could only be defended against wild animals and opposing tribes by living close.

At the macro level historical, political, economic, and social factors determine the fate of whole populations of organisations, so that the actions of single organisations count for little in the long run (Astley and Fombrun, 1983; Williamson, 1998). At this level, differences can be seen when we compare countries (Kollock, 1998).

One example of these comparisons is the emphasis on the Rhineland model versus the Anglo-Saxon model (Brookes et al., 2005): whereas organisations in the United Kingdom and United States focus more on market forces and liberalisation, organisations in mainland Europe focus more on government coordination and cross-sectoral consensus. Even further on the axis of market versus coordination are Asian countries, of which Japan is often taken as an example. The highly coordinated industrial organisation in Japan, with complex interfirm relationships, has led Teece (1992) to comment that '...the appropriate Western image is perhaps neither that of the 'visible hand' nor the 'invisible hand', but of the continuous handshake'.

Hofstede and Hofstede (2005), in their analysis of cultures and organisations, show that even in identical organisational settings the cultural background of individuals plays a very strong role. Especially in cross-cultural cooperation mutual expectations may differ: whereas one party may decide to cut to the chase, the other party may still require a closer introduction to strengthen bonds of trust. A failure to acknowledge these cultural differences may lead to a failure to strike a deal.

As Williamson (1998) admits, the macro layer is often overlooked in (transaction cost) economics, as it is deemed unalterable, a process spanning decades or even centuries. Also in our work we will not dwell too much on cultural aspects. However, we do acknowledge the influence of culture on cooperation procedures and outcomes.

2.4.2 Meso layer

According to Simon (2007), organisations only exist by the grace of communication between individuals. That, however, does not mean that one could suffice to describe organisations by describing individual motives (in the micro layer). It is the collective patterns of cooperation and coordination that emerge from interorganisational networks as a 'superstructure of sentiments and interactions' (Astley and Fombrun, 1983). This superstructure is one of the explanations that Riolo et al. (2001) give for cooperation between non-kin: a context-preserving network. Networks facilitate continuing interactions that provide a shadow of the future (the expectation of an ongoing relationship) that can sustain reciprocity.

The shape of networks, its participants, and the strength of the ties within a network therefore to a large extent determine whether cooperation will succeed. In the context of our work, these networks can be of many different types: formal or informal, pleasure or work related, religious or secular. It is important to understand that several networks are at play, often at the same time, in which individuals inform, influence, and conform to each other.

2.4.3 Micro layer

At the micro layer individuals' behaviour and decisions are at play. Most of the literature on animal and human behaviour, as well as game theory, describe the suggested mechanisms of this level of analysis.

One of the critical elements in this layer is the notion of rationality. More than relating to, based on, or agreeable to reason (according to the Merriam-Webster dictionary), this sometimes refers to rational actor theory which claims that actors know their preferences, and will seek them out fully and accordingly. As already discussed in section 2.3.2 on game theory, this notion is often too simplistic in real-life situations.

In disaccord with institutional economists like Williamson (1998) or Ostrom et al. (1994) we set aside the strong assumption of rational actors and assume that actors in the micro layer are satisficing and bounded in their rationality (Simon, 2007, 2000; March, 1978). This means that decisions are not made with full knowledge, but that the actors make the best decisions which are possible to them given their time, information, and resources. Actors are limited in their choices because they do not have full understanding of alternatives.

2.5 Investigating cooperation

The literature on cooperation spans many research fields that focus on micro, meso, and macro aspects of the topic. Yet before we proceed there is still a distinction to be made in the way that cooperation is addressed in research and that can also be seen in the fields of research that we mentioned in this chapter. Several authors have suggested a split between rational and behavioural approaches (e.g. Brewer, 1978).

Astley and Zajac (1991), for example, argue that some authors view organisations (and we would argue nascent cooperation between organisations) as 'coalitions' of diverse stakeholders – a behavioural view of the system. The involved political dynamics are typically viewed as leading to 'loosely coupled' organisational structures in which participants strive to avoid dependence on others. Quite a different model of organisational design is implied by the analysis of interdependence as a system of workflow linkages created by the division of labour. This conceptualisation of interdependence could be described as the 'rational model' of organisation, in which subunits are regarded as components of a 'machine' and contribute in a directly instrumental way to the realisation of collective goals. Taking one view or the other would mean defining organisations in a different, limited way. A third way of looking at organisations, which they dub 'procedural', is a rational adaptive way that implements 'flexible coupling' to different circumstances. This is in line with de Bruijn and ten Heuvelhof (2008) who suggest that in a networked society, process is the penultimate focus of analysis: activities are irregular, actors join and withdraw from the process, actors behave strategically in several different arenas, with no clear start or end, continuously shifting the content of the problem.

Extending Astley and Zajac (1991) beyond their original field of interest, we see that a similar distinction can be made for different research approaches that focus on cooperation: it can emphasise rationally describing mechanisms of actors or systems, it can emphasise behavioural (coalitional) aspects, or it can emphasise the procedural contingencies that life throws at cooperative efforts. We argue that the emphasis of the approach colours the outcomes of the research. Therefore, we will compare the approaches referring to these distinctions (see figure 2.3).

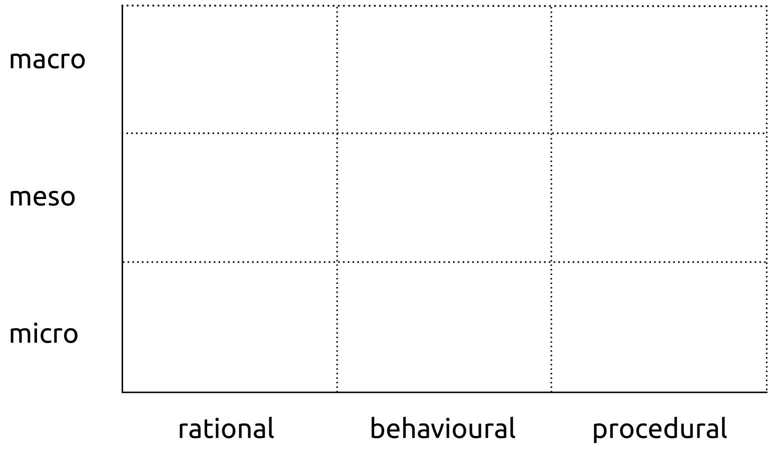


Figure 2.3 – The emphasis of the different approaches that we investigate can lie in the micro-meso-macro dimension and the rational-behavioural-procedural dimension. We use this grid to denote the emphasis of the methods described in chapters 3 (case studies), 4 (graph theory), 5 (ABM), and 6 (serious gaming).

In the following chapters (3 for case studies, 4 for graph theory, 5 for ABM, and 6 for serious gaming) we will use figure 2.3 to map the reseach approaches – to see to what extent they overlap and cover the different dimensions we identified. Not only will this provide a way to compare and contrast the different approaches, but also to identify gaps that were not covered by our research.

Chapter 3

Energy networks case studies

This chapter describes case studies of several energy grids in the Netherlands. We investigated two district heat cases (in the municipalities of Delft and Den Haag) and the OCAP CO_2 *network within the larger frame of Rotterdam's Climate Initiative (RCI) ambitions. As we have seen in the previous chapter, context matters. This chapter provides further contextual information for our analyses. The thermal grid case studies in this chapter appear in Ligtvoet (2012a).*

3.1 Case studies

Research into socio-technical systems aims to contribute understanding to practical, real-life issues. Thus, it moves into the realm of post-normal research (Funtowicz and Ravetz, 1993) in an attempt to avoid a 'reductionist, analytical world view which divides systems into ever smaller elements, studied by ever more esoteric specialisms'. What is favoured is a 'systemic, synthetic, and humanistic approach' that blurs the dividing line between science, applied science, and professional consultancy.

The use of case studies fits this purpose: it provides both context in which theories can be tested as well as a data source for developing new theories (Eisenhardt and Graebner, 2007; Eisenhardt, 1989b). For 'traditional' sciences, the use of case studies is deemed somewhat problematic as it cannot definitively lead to generalised knowledge. However, as Flyvbjerg (2006a) argues, a scientific discipline without a large number of thoroughly executed case studies is a discipline without systematic production of exemplars, and a discipline without exemplars is an ineffective one. Or as Herbert Simon suggested: research that includes aspects of motivation should begin with empirical observations of real people in real organisations (Knudsen, 2003). The proposed research requires a level of detail that is only feasible if we focus on specific industrial networks. As behaviour in different industries can be expected to differ, the selected case studies are characterised by the need for cooperation between different (types of) actors and by the need to respond to the challenges mentioned in the introductory chapter.

We have chosen to focus on two types of networks: thermal grids that have recently received a renewed interest and carbon capture and storage that is closely tied to industrial complexes and the associated CO_2 emissions. The selection criteria for the cases were:

- a regional energy network in the Netherlands that involves several suppliers and/or several clients with differing interests;
- a balance between recent activities so that key informants can be traced and sufficient 'history' to trace the cooperation process of the network all the way to implementation (this means approximately 10 years);
- access to key informants.

For each case we spoke to a minimum of three informants (see appendix B for the list), using the quasi-structured interview protocol in appendix C. We presented the interviewees with the summary of the interview and cross-referenced the remarks using case literature.

3.2 Thermal grids in the Netherlands

District heating in the Netherlands started in the city of Utrecht in 1923 (de Jong, 2011). The waste heat from a power plant was connected to the academic hospital (AZU) and later the headquarters of the Dutch Railways were connected. Thus, using waste heat, the primary energy demand for these organisations was reduced. Although in the ensuing decades the Utrecht network was expanded and similar initiatives were started, the boost for thermal grid development was given by the energy crises in the 1970s (Schepers and van Valkengoed, 2009). Aiming to reduce energy dependence and increasing fuel diversification, the government supported and subsidised heat projects around the country.

Many projects ran into financial problems when gas prices subsided and government provided additional subsidies, loans, and contributions to energy companies for reorganising the heat projects. The liberalised energy market in the Netherlands added issues: whereas electricity and gas consumers were able to change providers, the heat consumers were bound to their local provider. Privatised energy companies indicated that it became more difficult to cover the losses of heat projects with the income from production and delivery of electricity. Furthermore, it became unclear which gas price should serve as a reference for the price of heat delivered (Schepers and van Valkengoed, 2009). Thus, uncertainties increased and heat delivery became more risky for the energy companies (Tweede Kamer, 2003).

In the last decade, heat grids have gained more interest due to increasing gas prices and attempts to curb CO_2 emissions. Local initiatives have successfully acquired funding from national arrangements such as the Environmental Quality of Energy Production subsidy (*Milieukwaliteit Elektriciteitsproductie* – MEP), its follow-up Sustainable Energy Production Stimulation scheme (*Stimuleringsregeling Duurzame Energieproductie* – SDE), and the Unique Chances Agreement (*Unieke Kansen Regeling* – UKR) for stimulating cooperation between market and non-market parties. A 'heat law' (*Warmtewet*) was proposed to ensure the not-more-than-other (*niet-meer-dan-anders* – NMDA) principle, which ensures transparent coupling of heat prices to the costs of domestic heating using gas.

3.3 Warmtebedrijf Delft

3.3.1 History

Approximately 10 years ago, the Delft Alderman for environment Rik Grashoff and the municipal department for the environment were investigating ways to reduce energy use and CO_2 emissions, which resulted in the Climate Plan 2003-2012 (Municipality of Delft, 2009). One of the elements of the climate plan was investment in district heating. The main example was that of the proposed heat company in Rotterdam and a similar approach was considered for Delft. The original idea was that excess heat from the Rijnmond industrial area would be distributed throughout the region – possibly as a part of the Warmtebedrijf (heat company) Rotterdam. This plan proved too expensive and more local solutions were sought (Timár, 2010a).

As environmental policy generally follows building plans, the large scale renewal of the Poptahof area (highrise buildings from the 1960s, see figure 3.1) was taken as an opportunity to implement heat pipes – the heat was to be delivered by the DSM Gist factories located north of the center. It had been calculated that the heat produced by DSM would satisfy the heat demands of the whole of Delft. The housing corporations, as owners of 60% of the Delft housing stock, were natural partners as (representatives of the) end-users. However, the plan had no real problem owner and the required investments were large, long-term, and potentially with low returns on investment. Furthermore, DSM Gist was not willing to enter into long-term contracts for heat delivery as the company required flexibility to move activities around the world to most cost-effective locations. (Indeed, the main intended DSM Gist heat source was later relocated to China).

Delft controlled some funds from the (partial) sale of electricity company PZH that were earmarked as a funding for energy saving activities (*Reserve Energiebesparende Maatregelen* – REM). For Delft's ambitions, however, more funds were required. The Dutch national environmental policy was perceived as whimsical so that other sources of financial support had to be sought: the European Union was seen as a more stable source of funding. Moreover, through cooperation in European networks access to other municipalities' knowledge would be possible.

To investigate the options for energy and CO_2 savings the Delft Energy Agency (DEA) was established with support from the European SAVE II programme. Right from the beginning DEA was set up in cooperation with housing corporations, the Chamber of Commerce, Eneco Energy, the Delft wind association, and the Technical University Delft (as a large employer, asset manager, and operator of a power station). The municipality of Midden-Delfland was added to reach more than 100,000 inhabitants. Later, DEA merged with the Energy Agency Zoetermeer (EAZ) to form the regional energy agency EREA. Furthermore, an EU project with the cities of Grenoble (France) and Växjö (Sweden) called SESAC was formulated that provided for funds for a pilot study and the necessary continuity in the process.

Since the DSM option had not been successful, a new partner was sought and found in the Delfland water authority (Hoogheemraadschap Delfland) who were developing a waste water treatment plant (AWZI) in the Harnaschpolder area. It was found that utilities had the same frame of community-serving investments for long term (50+ years) and

Figure 3.1 – Map of Delft, with the location of different actors and relevant areas in the case study.

thus AWZI and a district heat network would be based on the same values. The AWZI, however, was built with a public-private partnership concession (Design, Build, Finance, Operate) for 30 years, so it was not always clear who the counterpart was: the authority or the operator of the plant (Municipality of Delft, 2006).

As per the example in Rotterdam, the heat company was seen as the intermediate between the heat source and the local distribution networks. In 2007 the distribution network was tendered and the initial plan was to serve 20,000 households. Eneco was historically already the energy provider in Delft and had just lost from Nuon in the Rotterdam area, thus they were eager to win the bid. The business cases for the production and distribution were developed separately and it turned out that the business case was unfavourable (e.g. because of the not-more-than-other principle, in which collective heating should not be more expensive than the gas alternative). The municipality had set requirements for end-user costs, but given the chosen ownership construction, there was no possibility for sufficient returns to all parties involved. It was therefore suggested that instead of splitting production and distribution, these two parts would be operated as a whole (Municipality of Delft, 2009).

The plan was presented in the municipal council, where a split into separate 'islands' was proposed: the northern Harnaschpolder area with new building activities and the southern area with the Poptahof renovation. Also, it was proposed that the risk for the 120 M€investment would be mainly borne by Eneco (as it was reasoned that municipalities should not be involved in too large financing activities). Furthermore, the clients should also be included in the company, in the shape of the housing corporations. However, the uncertainties with regard to the spark spread (difference in electricity and gas price, making district heating an attractive proposal), the European Emissions Trading Scheme

(ETS-III), and the speed of connection required the partners to review the business case again. The municipality would have to invest more than initially planned. Furthermore, the heat company would have to search for other means to reach CO_2 reduction targets, including geothermal energy and solar cells (Municipality of Delft, 2011b,c).

The chosen legal construction in 2009 is a limited company (Warmtebedrijf Eneco Delft BV), owned for 97% by Eneco, with 1% of preferential stock owned by the municipalities of Delft and Midden-Delfland, 1% owned by the housing corporations Woonbron (previously Delft Wonen), DuWo, and Vidomes, and the final 1% by Eneco. The preferential stock allows for shared control with regard to environmental decisions, tariffs, service level (which was considered important by the housing corporations), and the distribution of additional profits. From the point of view of the municipality, the two main concerns were acceptable living expenses and environmental sustainability, thus the chosen construction allowed for a large influence on those matters that mattered most, with a relatively small financial involvement. From the point of view of the housing corporations, they were becoming more dependent on a monopolist. However, the heat company, as a partial daughter of Eneco, has more access to technical knowledge and is able to optimise the whole heat system. In such a project, entering each others' terrain is inevitable and a shift of responsibilities and thus mentality is also required (Timár, 2010a; Municipality of Delft, 2011a).

3.3.2 Partnership

The partners in the limited company each brought in their own expertise and interest. Eneco had a policy to remain closely involved with its shareholders (of which Delft is one). Although Delft was the first mover from its environmental policy, Eneco picked up the project and brought in a more financial focus. The housing cooperatives were interested in participating to keep the living expenses for their tenants acceptable and delivery of heat reliable. They were also the most logical party to communicate with the tenants and wanted to increase the energy efficiency of their houses; connecting to a larger heat grid would allow them to do so for lower costs per housing unit. Moreover, joining the heat company would allow them to have specialists take care of their district heating network.

It is important that a municipality is involved as the digging activities are most costly (approximately 70-80% of total costs). If through efficient planning and efficient permitting several percent can be saved, this represents a large share in the total costs. For municipalities it is important to plan in a smart way so that roads need not be dug up more (e.g. by coordinating works). Furthermore, municipalities are deemed to be more experienced in organising permits and communication with the general public.

It is important to also consider the stakeholders of the different partners. Commercial companies such as Eneco have shareholders and their own board to consider when participating in projects. Municipalities have councils and political processes to consider. For this kind of long-term projects the involvement of a municipality is needed. Setting up a heat network is a lengthy process, one has to endure many set-backs and try to solve different problems that pop up.

During the build-up phase some other shareholders in the project were also considered. The water authority (Hoogheemraadschap Delfland) was one of the candidates. However, their interest in building heat networks was not large enough. Neither was the interest of the Technical University Delft with its power station, which would have been an interesting partner for generative capacity. A fourth housing corporation in Delft deemed itself too small to participate. Now they are being pressured by the other corporations to connect to the proposed heat network. Also, the municipality is starting cooperation with the university on a geothermal project.

3.3.3 Opportunities and threats

Several interviewees commented that not the institutional networks but the personal networks are most important in such projects. Certain personal affinities were important: the Alderman and the director of Woonbron teamed up and jointly supported the project. It is said that the success lies less in the institutions and more in people. Political will and enthusiasm are required, certainly in the initial phase. In the beginning there need to be enthusiastic 'free spirits' who keep their interest during the long planning and negotiating phase. In the next phase there need to be feasibility assessments, for which financial calculators and legal counsels are required. Currently Vidomes' financial director keeps the focus of Warmtebedrijf Delft on the business case.

As the implementation phase lasts for 20 years, continuity is required. The European SESAC project not only provided the necessary funds for the demonstration of the Poptahof and Harnaschpolder project, but also was important for keeping the activities going as it provided external deadlines, commitments, and pressure to perform. Furthermore, the EU network provided a lobby channel to the European Commission and Parliament. Now that SESAC finished the continuation of the activities requires other incentives.

For Delft the political process was very important. Alderman Rik Grashof (of green party GroenLinks) had created a lot of support for sustainability. Later on his successors Lian Merkx and Saskia Bolt picked up the responsibility. The project fitted in the ideological ideas at the time and the Hague region (Stadsgewest Haaglanden) was also thinking of similar activities. A lot of intellectual investment was made in the shape of hiring experts for planning and designing (approximately 1.8 M€).

The scale of a municipality such as Delft makes it easier to get things done: people meet each other at the baker's and are open and willing to help each other. Delft prides itself in having a cooperative mode. At the same time, however, the municipality has strictly separated departments: if sustainability and heat networks are deemed important, it could be more pro-active in requiring building activities to be connected to the grid. This is currently not the case.

The different partners in the cooperation each have their own expertise and specialities. Housing corporations focus on security of supply, costs to tenants, and are better at communicating with the end-users. They can make tenants think about energy reduction options, for example by organising competitions ('Energiedereen'). Also, housing corporations are able to borrow money at cheaper rates than energy companies can. Thus there is a search for combining the advantages of one partner with those of the others. This obviously depends on the focus of the organisation: whereas Woonbron wants other (specialised) parties to take care of the heat and cold installations, Vestia has chosen to keep control over that part of its operations.

One of the risks of long planning periods is that external circumstances change. Major events such as financial crises also lead to different assessments on returns on investment. During the project several risk analyses with regard to gas price (which was conceived as the major risk) and the housing market had been made. It was clear from the beginning that the project would have a relatively low rate of return. As the bearer of highest risk, Eneco accepted this. However, in the process they had to accept even lower rates.

Changes in regulations are a likely candidate for such extensive projects. Heat network activities have become a part of the European CO_2 trading scheme ETS-III, which had not been clear from the start of the project. Whereas Warmtebedrijf Delft was set up as a CO_2 reduction programme and thus a source of income, the heat production now needed to compensate its CO_2 production by buying emission rights. At the same time the EU seems to be moving towards a stricter definition of the competencies of housing corporations: the move toward co-ownership of heat networks is an opposite direction.

Several risk analyses regarding gas price and the housing market had been made during the process, but an important one was for the final plan of Warmtebedrijf Delft with Eneco as 98% shareholder. A financial consultancy performed a second opinion and deemed the plans feasible. Eneco was willing to accept a lower return on investment so that they would be able to fulfil the concession.

3.3.4 Future developments

Due to financial restrictions, the scale of the project is not as large as it was originally projected. Therefore, the municipality and heat company need to look for other additional projects to reach the CO_2 reduction targets. Warmtebedrijf Delft is transforming itself into an energy broker that identifies new opportunities, such as the Reinier de Graaff hospital with its newly planned heat and cold storage and the fact that new tunnels and highway infrastructure allow the easy placement of heat pipes. In its role as energy broker Warmtebedrijf Delft is again trying to involve large organisations such as the hospital, the university, and DSM. Of course, this requires some adjustments on the part of each potential candidate. Also, Warmtebedrijf Delft is looking beyond heat: solar energy is one of the options being investigated.

What currently is going on with Woonbron (and other corporations) is a search for cooperation with energy (network) companies such as Eneco, both at strategic and operational level. For example, the operations and maintenance of collective kettles in high rise buildings was tendered to Eneco (who had bid low in order to win the contract) (Municipality of Delft, 2011d).

As a spin-off of the heat company, similar studies were done by DEA in the Hague region (Stadsgewest Haaglanden). A larger view for a regional network was constructed, but this grand scheme was deemed too interdependent and thus subnets are developed separately (Timár, 2010a).

3.4 Aardwarmte Den Haag

3.4.1 History

The anecdote that several interviewees repeated was that the 'Aardwarmte Den Haag (ADH – *Geothermal Heat The Hague*)' project was started by accident: a civil servant of The Hague department of Building Physics and Building Ecology partook in a congress that was organised by Stichting Platform Geothermie (Geothermal Foundation) in March 2004. Instead of learning about heat and cold storage, he was informed about deep geothermal layers and thought that this might be an opportunity for promoting sustainable heating in The Hague. A window of opportunity presented itself as E.On Benelux – that was already generating district heating in the area – had to invest in new equipment. Eneco, as the distributor, was a logical candidate to join (Timár, 2010b; de Zwart and Heijboer, 2010).

Soon thereafter the first preparations for (technical) feasibility studies were made in which several consultants were involved: IF Technology (geothermal and heat/cold storage), DWA (heat installations), and TNO Bouw en Ondergrond (underground heat layers). This combination of expertise was required as no single organisation had the knowledge of both surface and underground installations. It was found that the earth layers did not contain sufficient water of 90°C. An alternative was a novel technological approach using the heat of a deeper layer (at approximately 60°C) for heating newly built houses. At that same time housing corporations Vestia, Staedion, and Haagwonen were restructuring their buildings in the Southwest of The Hague and they were asked to join the consortium. The cost estimate rose from 6-10 to 45-50 M€, but the project seemed promising and several preparatory interviews and discussions were held.

In 2005 the plans were presented to a wider group of stakeholders. The municipality and the housing corporations freed funds for further investigations. Although a declaration of intent to provide 4000-6000 households with geothermal energy was signed in June 2006, the project had slowed down: discussions were still held, but progress was not being made. A new ambassador/project leader was appointed and some financial requirements were clarified: the participants agreed to open their books and be frank about cost estimates. Due to the opportunity of a subsidy from the national Unique Chances Agreement (UKR – for stimulating cooperation between market and non-market parties) a business case was quickly drawn up and several working groups were installed to work out details. Furthermore, a benchmark comparison with other energy sources was made by DWA that showed that the geothermal project could achieve CO_2 reductions at relatively low costs (ADH, 2008).

When the UKR subsidy was granted in April 2007 the parties started to believe the business case was feasible, although there still had to be a discussion on the required return on investment. A press conference was held and, although major technical details still had to be clarified, ADH was presented as a feasible project. According to some interviewees this proved to be a point of no return. Within the participating parties the project was promoted and a risk analysis was made. Study visits were made to France and Germany.

The financial crisis that started in 2008 proved a large risk for the project. The calculated returns sank and the commercial participants were discussing culling the project.

The building activities were slower than expected, thus not providing enough clients for the pumped up heat. Also, the legal form of the partnership had to be decided upon – allowing for the municipality to participate as an equal partner with E.On, Eneco, and the three housing corporations. Furthermore, several permits had to be obtained for drilling and building a heat station and a heat network. Again, the combination of permits required the expertise of different legal advisers as no single party had all knowledge required. The permits were granted, but groups of concerned citizens close to the foreseen well objected to the permits. The legal fight was pursued until the highest court (*Raad van State*) where all objections were dismissed.

By that time it was clear that the planned building activities would lag behind and that yet again another technical solution had to be sought. Review of the new heat technologies showed that it would be feasible to connect existing households to a lower temperature heat source. From a commercial perspective this also made more sense as existing buildings have a higher heat requirement than new houses (30-40 GJ as opposed to 20 GJ per household). The partners again reconsidered the returns, but finally decided that they had passed the go/no-go point and that they would have to accept the project, even with a lower return. The drilling could finally commence in March 2010 and by November it was clear that the wells would produce sufficient heat. However, the extracted water contained gas which has to be extracted (at additional cost) before the warm water can be distributed through the network.

At the end of 2011, ADH was in operation[1] albeit using an auxiliary kettle. Clients received invoices, the wells had been drilled (and were expected to be operational in 2012), and the heat station (for emergency generation capacity) was operational. Although the start had been slower than expected, the amount of connected households was moving up towards 4000. When that goal is reached, further (large) expansion makes little sense since the geothermal source has a limited capacity that can only be expanded by also investing in non-sustainable excess capacity.

3.4.2 Partnership

ADH is an example of a successful partnership with six different partners and a range of support parties. The original partners were the obvious partners for the project: the biggest players in the region with regard to their own speciality. The short history above already indicates that the actors had their differences. However, several factors contributed to the success.

By joining forces, the different parties would be able to fulfil some of their policy goals: CO_2 reduction, fuel reduction, cost reduction, and innovation. Right from the beginning there was a ‘click’ between some of the participants, some of which are still actively involved in the project. The idea for using geothermal energy as the first Dutch city at this scale – especially the technological challenges – provided a binding factor. Even to the legal counsel the ADH construction was an interesting case that had never been tried before.

Eneco did not want to do the project alone and E.On had an incentive to keep energy production under its own control. Housing corporations (Vestia, Haagwonen, and

---

[1] See http://www.aardwarmtedenhaag.nl

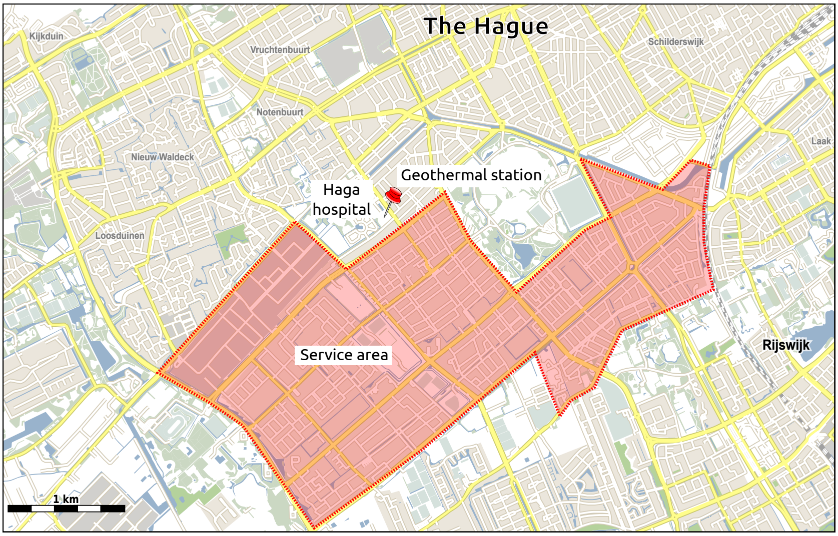


Figure 3.2 – Map of The Hague

Staedion) wanted to participate so that they would not solely depend on energy monopolists. The Alderman wanted to show that public-private partnership constructions could be done and wanted the municipality to play an important role.

From the end of 2005 onward the partners exchanged a lot of information in an open way, sharing visions of risks and experiences of what *(not)* to do. Eneco, for example, shared its energy price prognoses and the housing corporations shared detailed plans of their renovation and restructuring process. This trust factor was important – as well as the fact that the partners could call each other at any time to check facts or ask additional questions.

The fact that the partners were in it as equal shareholders is seen as an important factor for success. Although problems could be attributed to the different parties, they were picked up as shared problems. Furthermore, the 1/6 division was logical given the depreciation rules for energy investments. By treating the project as a commercial project, the municipality could treat it as a regular investment and it would not be seen as state support (ELI, 2011).

Working together with the different parties allowed for insight in the operations and activities of other players in the value chain. This chain is changing (e.g. housing corporations becoming energy producers) and cooperating in the project allows for exploring new activities and strategies. In the worst case they would loose their investment, in the better cases they would have initialised the first geothermal heating project in the Netherlands.

Apart from the business partners there had to be several relationships with neighbourhood committees, the fire department, public relations, and press relations. There were 6-weekly meetings with the neighbourhood around the well in which all issues concerning noise, risks, ground collapse, and technology were discussed.

Some potential partnerships that were not pursued were with the proposed Rotterdam heat network and the nearby Haga-hospital. The Rotterdam solution proved to be too far away for cost-effective transmission of heat. The Haga-hospital required its own solution because they wanted to be in full control of their primary heat needs. Also, one housing corporation in the area was so small that it was not involved. Since the subsidies and the financial position of the partners meant that the activities could be internally financed by the consortium, there was no need to talk to banks. This averted 'partnership' was seen as a way to speed up the process.

3.4.3 Opportunities and threats

Since the liberalisation of the energy market utilities, like any other commercial party, require a minimum return on investment and a certain risk profile for their projects. This makes experimenting more difficult as E.On does not accept additional risk. The return on investment was going to be relatively low, but this was accepted by the partners, partially to show their green image. Moreover, the involved investments are relatively small compared to other large E.On investments. As E.On operates large coal plants, it has some PR advantage taking part in a novel district heat project like ADH. Although the project is financially not yet risk-free, it is seen as a basis for further activities and cooperation with Eneco in The Hague area.

Originally the idea was to have a return on investment of around 6% when taking into consideration the uncertainties with regard to housing prices and gas prices. When the project would exceed this return, the excess profit would be shared: 1/3 for the clients, 1/3 for ADH itself, and 1/3 for the shareholders. Due to recession, the returns were projected to be lower. At a certain point E.On warned that if the returns would dive below 3,5%, the whole project would have to be reconsidered. However, more negotiations with contractors and some fortunate developments concerning the building costs make the expected returns now in the range of 4-5%.

Interviewees indicated the importance of the willingness to cooperate: allowing colleagues a closer look at internal operations of each partner. This requires trust, but does not necessarily mean following each other's opinions. Also, it means accepting the fact that situations change, for example the phasing in building activities due to the financial crisis.

One of the interviewees commented on the Dutch culture allowing for segmenting problems: one can be enemies on one issue whereas one could be friends on another issue. This relationship between two companies can even be seen in cases in which the same people are involved. At the company level culture is also important. Large commercial companies may be bureaucratic, but every employee is aware of the need to make a profit. In the utilities sector the first concern is security of supply: people are happy when things are stable and secure. By cooperating with other organisations, one sees the advantages and disadvantages of such a culture. This can lead to a learning experience.

For the building phase a risk and safety plan was devised and insurances were acquired to cover the risks. For the financial calculation worst and best case scenarios were drafted, with factors such as oil and gas price, energy coefficients of houses, and the temperature of the well (which would allow for connecting more houses). The slow-down in the building sector due to the financial crisis was not foreseen -- given this fact, maybe more guarantees by the corporations would have been useful to keep the speed of the project going. Also it was not foreseen that the well would actually produce some gas. An unforeseen advantage was the dip in the steel price, which made some of the construction activities cheaper.

There were 10 potential locations for drilling, but none was really satisfactory. For example, political interests, distance to apartment buildings and a day-care centre, or the ecological function of locations proved difficult. The chosen location was on top of a water storage location, so that alternatives had to be negotiated with the water council Delfland.

There is a substantial risk (still) that the well will not yield the required heat. However, the project is a basis for heat and cold storage and other low temperature sources and thus a source of learning. Initial tests did show that the operating temperature would probably be around 75 degrees, higher than expected, and thus more profitable.

Also, laws and regulations have been changed. This means that changing from a research and drilling permit to an operating permit requires the owners to have sufficient capital (in case of an accident) as well as sufficient knowledge in-house.

District heating may actually turn out to be an unfavourable activity. First of all, the new heating norms for houses lower the annual energy consumption considerably which means that energy losses due to transportation will be a larger percentage (from 10% moving up to 40%). Secondly, because of the lowering price effect of solar and wind on the e-price, the spark-spread (difference between the electricity and gas price) is diminishing, which makes combined heat and power more expensive.

3.5 CCS activity in the Rotterdam area

Through international agreements such as the Kyoto Protocol, European legislation (e.g. on emission trading), and national policy, Dutch organisations are trying to curb CO_2 emissions and thus avoid the devastating consequences of climate change. One of the technical solutions proposed is carbon capture and storage (CCS). CCS is seen as an intermediate solution, a way to avoid release of CO_2 into the atmosphere until the transition towards and environmentally friendly way of industrial production has taken place (Vosbeek and Warmenhoven, 2007).

At the end of 2006, the Rotterdam Mayor and Aldermen were pointed to the economic opportunities of clean energy and CO_2 reduction in the Rotterdam area. Following the Large Cities Climate Leadership Group formed by the mayor of London and the Clinton Climate Initiative formed by former US president Bill Clinton, the Rotterdam Climate Initiative (RCI) was set up in 2007 as a joint activity between the municipality of Rotterdam, the Port of Rotterdam, environmental protection agency DCMR, and the association of businesses in the Rotterdam area Deltalinqs. RCI's ambitious goal is the reduction of Rotterdam's CO_2 emissions by 50% as compared to the 1990 levels. CCS is considered an essential part of the initiative without which Rotterdam can not fulfil its goals. The advantage of the Rotterdam area is that it has a high concentration of industrial emissions in the Port of Rotterdam area and it lies close to storage capacity, both offshore (on the Dutch continental shelf) and onshore (RCI, 2009).

Two EU decisions at the end of 2008 created new conditions for the further development of CCS: it reserved 300 million CO_2 allowances from the New Entrants Reserve

(NER300) of the Emissions Trading Scheme. Auctioning these allowances is supposed to generate the funding required for large-scale demonstration projects (European Commission, 2010). Also, the European Energy Programme for Recovery (EEPR) was instated including a tender for seven CCS demonstration projects. Supported by these financial incentives, several multi-actor initiatives are being developed under the aegis of RCI (2011):

- ROAD (Rotterdam Opslag en Afvang Demonstratieproject) – a joint venture between E.On Benelux and Electrabel Nederland/GDF-Suez group to build and develop a demonstration of a carbon capture unit on a coal-fired plant by 2015. The project is developed in close cooperation with TAQA who will store the CO_2 in its offshore gas fields close to Rotterdam and GDF Suez who will develop and operate the pipeline. This project received an EEPR grant.

- CINTRA – a combination of Vopak (storage), Anthony Veder (shipping), Air Liquide (gas production), and Gasunie (the Dutch national gas company) to create a gas hub in the port area. The pipeline would be connected to Maersk offshore fields for Enhanced Oil Recovery (EOR).

- Pegasus Project – building an combined cycle gas turbine (CCGT) oxyfuel power plant with storage in gas reservoirs. This is an initiative by SEQ International (engineers) and AES Transpower (power plant developer), with cooperation from Linde Gas (gas production), Siemens (CCGT manufacturer), and CES (technology developers). The project is developing a pilot with Tata Steel in the port of Ijmuiden and is awaiting NER300 subsidy.

RCI functions as a catalyst, bringing different parties with different interests together. One project that is also captured under the RCI flag has a somewhat longer history: the OCAP project that uses carbon dioxide from industry and delivers it to greenhouses. As this project covers a longer period, we have chosen to describe it in detail below.

3.6 Carbon dioxide capture and use – OCAP

3.6.1 History

In 1965 a 83 km long pipeline was built by the Ministry of Economic Affairs and the municipality of Amsterdam from the Botlek area in Rotterdam to the Westhaven in Amsterdam. This pipeline was operated by the government-owned Nederlandse Pijpleidingmaatschappij (NPM) and delivered 400.000 barrels/day of crude oil to a refinery complex owned by Mobil. In 1982 Mobil closed down this complex and since then this pipeline has lain idle (Tweede Kamer, 2004).

By the mid-1990s the business development department of energy company Energiebedrijf Delfland, in cooperation with Energie Westland, and Eneco, started to develop the idea of using the pipe to deliver carbon dioxide to the large concentration of greenhouses in the Westland area north-west of Rotterdam (see figure 3.3). The logic behind the plan (called OKEP) was that greenhouses burn natural gas to generate CO_2, but that this gas consumption could be mitigated by using CO_2 created by industrial processes in the Botlek area. The Shell refinery in the Botlek area and its planned hydrogen plant (PER+) were the primary candidate for delivering the carbon dioxide. Thus, industry could reduce emissions to the air and greenhouses could reduce their emissions from energy consumption (van Leenders and Baidenmann, 2010).

When Energiebedrijf Delfland was bought by ENECO, the OKEP project was terminated in the need to focus on core business. Former Delfland employees Hans Tiemeijer and Jacob Limbeek continued with their own energy consultancy Syens and attempted to get new parties interested in OKEP and combined and power (CHP) projects. After discussing their plans with several investors, they came into contact with construction company Visser & Smit Hanab (a daughter of the VolkerWessels group) which had recently decided to become a more entrepreneurial builder instead of just a contractor. To be able to realise the project, a partner was sought that both had the technical knowledge of compressed gasses as well as the organisational size to set up a sales team and the financial backing for the project. Gas provider HoekLoos (currently Linde Gas Benelux) turned out to be the right candidate.

The two companies were no direct competitors and thus were less hesitant to cooperate. Both companies were also sufficiently large to bear (some of) the investment costs for such a project. VolkerWessels was a suitable construction company as the local distribution network still needed to be designed and built. Linde Gas harboured much of the marketing knowledge for developing this type of project. A general partnership (an unincorporated company, in Dutch: *Vennotschap onder Firma*) called OCAP (Organic Carbon dioxide for Assimilation of Plants) was created between VolkerWessels and Linde Gas, allowing for transparent cooperation among stakeholders in which each partner remains liable. Shell was interested in the project since the OKEP phase, but since their core business is oil it decided that this project would remain on their periphery. Therefore they would only engage with OCAP as a supplier of CO_2.

In 2004 the ownership of the pipeline was transferred from NPM to OCAP through a bidding procedure to which only one party responded. The transfer sum was a negative amount (6 M€) to cover feasibility studies and overdue maintenance (Tweede Kamer, 2004). The OCAP project received subsidies through the energy investment deduction (*energie-investeringsaftrek* – EIA) tax benefits and the Unique Chances Agreement (UKR – also mentioned in sections 3.2 and 3.4). Furthermore, the firm received a declaration of general benefit, which meant that permit procedures would be made easier (van Leenders and Baidenmann, 2010; Stafford, 2006). Economic risk was partially mitigated by ING bank providing 70 of the 100 million euro funding. Nevertheless, to make the project work OCAP had to find at least 500 customers.

After frantic activities to reach this minimum amount of customers September 2005 heralded the opening of the OCAP pipeline and the delivery of CO_2 to greenhouses. Since then the project has increased to include the area between Bleiswijk, Berkel-Rodenrijs and Bergschenhoek (the B-triangle), and the Zuidplaspolder (see figure 3.3). Also, after several years of exploratory talks it was agreed to connect the Abengoa bio-ethanol factory to the network, which became operational in 2011.

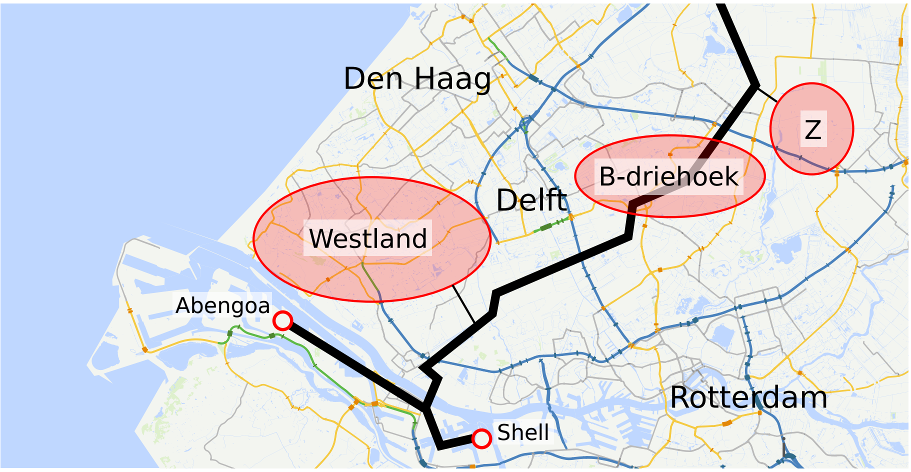


Figure 3.3 – Map of OCAP in Rotterdam and the Westland area, the B-triangle, and the Zuidplaspolder (Z).

3.6.2 Partnership

The idea of OCAP has been adopted and passed on between several parties before ending up as OCAP VoF. The binding factor in these stages was the leadership of Hans Tiemeijer and Jacob Limbeek, who were able to combine industry with horticulturists, to convince government in supporting the project, and to bring together two organisations that had not worked together before. Much of the original business development had already been prepared under the OKEP project flag. The initial development phases were therefore largely led by Syens whose founders even continued after the consultancy's bankruptcy. Once the agreements had been made and OCAP moved to operational level, leadership was in the hands of the director of OCAP. It required a specific set of expertise in the construction phase and a different set of skills in the operational phase.

OCAP VoF has a supervisory board of 2 VolkerWessels and 2 Linde Gas members. The joint venture of the two companies ran into issues of compatibility of business culture. Linde Gas is a large international, hierarchical organisation that requires many layers of approval. VolkerWessels on the other hand is more local, less formal, and also more entrepreneurial. As the core business and strategic goals are different, this adds a layer of complexity in combining a shared vision. Cultural differences are also visible in the economic calculation for investment decisions: Linde Gas bases its decisions on Internal Rate of Return (before taxes) while VolkerWessels focuses on profitability (after taxes). Each organisation has different internal disciplines and networks that require alignment and approval to move ahead (economic, legal, commercial, technical), with Linde's requirements being slightly more stringent or detailed. Since Linde Gas has grown significantly in the last years, the decision making is considered more complex.

3.6.3 Opportunities and Risks

In the beginning phase, the risk was considered mostly from an economic point of view: would there be enough clients to cover the operating costs. In the early operational years OCAP had an inherent risk of CO_2 supplier failure: Shell could not always produce the agreed 105 ton/h – for example due to scheduled outings and repairs (which was the case in 2009) – this created a risk to the operations of the greenhouses. Several times Linde Gas had to supply the carbon dioxide to continue operations (OCAP, 2009). Therefore, OCAP needed to look for additional sources of CO_2 to ensure reliability and enable expansion. The connection of Abengoa greatly increased reliability and the future expansion with liquid storage facilities will be an additional improvement.

As indicated above, the project benefited from legal support and subsidies from the Dutch government. The success created some opportunities for further CO_2-related activities. As OCAP has experience with carbon dioxide handling in a piped infrastructure, it was involved in the CO_2 storage plan under the municipality of Barendrecht. This project failed due to fear among the citizens and resulting political pressure to stop the pilot. Now OCAP is involved in the Rotterdam Climate Initiative for storing CO_2 in abandoned gas fields in the North Sea. Basically, a CO_2 infrastructure would increase the number of OCAP's potential suppliers and allow for a flexible switch between underground storage and horticultural use.

Discussions about CO_2 emissions trading also threatened to undermine OCAP. For some time it was unclear who could claim CO_2 reduction: Shell or the horticulturists. The national horticultural organisation LTO had already agreed to reduce its emissions and did not want to receive the additional carbon dioxide on its balance. The ministry of the environment (VROM) decided that Shell could claim the reduction and the glasshouses were responsible, which led some horticulturists to threaten to stop the project. The issue was solved by Shell and OCAP offering to compensate for possible excess emission fines (van Leenders and Baidenmann, 2010; OCAP, 2005).

3.6.4 Future developments

OCAP is still working on expanding its network between Rotterdam and Amsterdam. Originally VolkerWessels wanted to build OCAP together with Linde and then sell their share of the project. However, since OCAP generated several spin-off activities, it decided to keep playing a role. The OCAP success has led to follow-up business opportunities for both partners: VolkerWessels and Linde Gas are cooperating in separate CO_2 projects in the province of North-Holland, among others 80+ hectare greenhouses in Wieringermeer. A similar project called WarmCO2 is set up with Visser & Smit Hanab, artificial fertiliser company Yara (one of the original contenders for the partnership), the Zeeland Seaports authority, and greenhouses in Sluiskil near the Belgian border.

3.7 Analysis

We have summarised some key characteristics of the cases in table 3.1. We find that all three cases are driven by the desire to curb emissions through pooled infrastructural re-

Table 3.1 – Characteristics of the case studies

Characteristic	ADH	WD	OCAP
Number of partners	6 (1 municipality, 2 energy companies, 3 housing corporations)	6 (2 municipalities, 1 energy company, 3 housing corporations)	2+1 (1 industrial gas company, 1 construction company, plus the initiators)
Risk sharing	equal	private company bears risk	equal
Infrastructure	new	new	existing pipeline, repurposed
Source	geothermal source, auxiliary kettle	waste water plant (not controlled by cooperation)	industry (not controlled by cooperation)
Novelty	geothermal source, end-user technology		CO_2 distribution through existing pipeline
Initiator	municipality	municipality	energy company, entrepreneurs
Clients	within consortium	within consortium	individual horticulturists

sources and economies of scale. Throughout these cases we see that more considerations than standard economic analysis (net present value or return on investment) play a role, although a 'business case' is always required (several times during the process). Moreover, the considerations are not fully apparent at the beginning of a project and also shift in importance as the project progresses and is influenced by (external) political and economic changes. Some of the considerations mentioned are:

- technological enthusiasm and the belief that a certain solution is worth pursuing (even though the technology has not fully proven itself) (ADH, OCAP);
- doing something new and unique creates a drive to keep on going, even in hard times (ADH, OCAP);
- keeping up with the competition, to find out what businesses they are in and to keep in touch with new developments (ADH);
- hedging risk by cooperating on projects with uncertain outcomes (WD);
- fulfilling environmental goals the organisation has set itself (ADH, WD);
- providing a positive image by contributing to an environmentally friendly project (ADH);
- sticking to a 'gentleman's agreement' (avoid loosing face in public press) (ADH);
- participation in other projects to create a sense of urgency (WD);

- circumventing (national) government (WD);
- expanding focus beyond original plan (AHD, WD, OCAP).

3.7.1 Comparison with literature analysis

These considerations are somewhat different and more detailed than the ones we saw in the literature analysis. They do support the notion that animal behaviour comparisons and game theoretical concepts are somewhat simplistic. We argue that because of these different motivations and considerations, decision making about energy networks is complex. Other characteristics that add to this complexity are:

- many different players (citizens, organisations, pressure groups, industry, government) with financial and non-financial interests;
- different organisational levels involved (local, municipal, regional, provincial, national, European);
- different (policy) initiatives in different organisations that are not coordinated;
- uncertainty with regard to legislation, technical developments, procedural steps;
- dependence on other organisations for knowledge, finance, or as a source of heat or CO_2;
- constantly changing environments, leading to different assessments of risks and profits.

One can imagine that given these uncertainties the need to cooperate increases so as to ascertain some kind of stability in the environment of the decision makers. As the case studies show, the durability of cooperations is tested throughout the whole process of planning and building the energy networks.

In section 2.3.5 we already suggested that how cooperation is depicted in theory differs distinctly from the way that cooperation takes place in practice. Following the distinctions made by Gold (2005) we see in each of these cases that the number of directly involved players is larger than 2, that the players are the ‘usual suspects’ due to path dependency and lack of alternatives, that the players are to a large extent heterogeneous (which was the reason to cooperate in the first place), and that oftentimes the players (especially the public organisations) have to take into consideration the interests of several stakeholders (citizens, tenants, shareholders). This means that priorities may shift over time and that periodical updating of the stakeholders is required. The idea that players are one-dimensional (financial) payoff maximisers can also be refuted: sustainability ambitions are the prime driver for the municipalities and housing corporations aim for affordability and security of supply for their tenants. Even the commercial parties with a more financial focus may be willing to lower their required rate of return in order to achieve innovation, strengthen relationships, promote goodwill, be involved, learn from others, and show a green face (all of which are hard to express as financial propositions). It is not maximising behaviour, but satisficing (‘good enough’, given the circumstances) behaviour the each player displays (see Simon, 2000). The parties are not the same in terms of knowledge, expertise, and financial resources. The individuals working on such projects also differ in style and amount of effort, enthusiasm, and leadership displayed.

3.7.2 Cooperation process

We see that the cooperation process progresses at different speeds due to delays and setbacks with times of frequent communication and times of individual reassessment. This also means that the strategy space is virtually limitless: new features can be added (such as solar panels for a heat company) and old ones dropped. There is no 'game' with fixed rules, but a constant search for changing the rules, for new games to play, for ways of making the pie bigger. (Excellent case studies of such behaviour are popular books like *Barbarians at the gate* (Burrough and Helyar, 2009) about the hostile takeover of tobacco/cookie giant RJR Nabisco and *The Prey* (Smit, 2008) about the demise of ABNAmro bank.) These game changes are not only due to strategic behaviour, but also due to constantly reappraising interests as risks are time-bound. We find that in all cases new insights have led to changes in the contract proposals, as is common in negotiation processes (Waterhouse et al., 2011). Thus, there is not clearly one decision moment: even after having signed contracts there is always a way to address unforeseen issues by appealing to reason and shared interests.

One can therefore hardly define process steps that sufficiently describe the process of cooperation. In very rough terms we distinguish three phases that contain several iterative steps that flow into each other (following UNDP (2010), see figure 3.4):

- *Exploratory phase*: in this phase all options are open. One of the members of the (future) cooperation has an idea and identifies possibilities and needs. Possible partners are identified and contacted. An analysis is made of the (legal) environment and first feasibility studies are made. Areas of cooperation are further defined and awareness and support is created.

- *Formalisation phase*: here, a joint task force further explores the options, possibly splitting out into different working groups. Further business case calculations are performed, as well as risk analyses, financing options, and legal forms of the partnership. Negotiations take place about contracts, statutes, and legal status.

- *Implementation phase*: management and representative structures are established. Monitoring, self-assessment, and communication takes place, as well as regular evaluations by the cooperating parties. This, however, does not preclude the option to renegotiate.

3.7.3 Cooperation at different layers

Referring back to our literature findings that cooperation takes place through the interaction of different layers (see chapter 2.4), we can analyse the cases in a similar fashion.

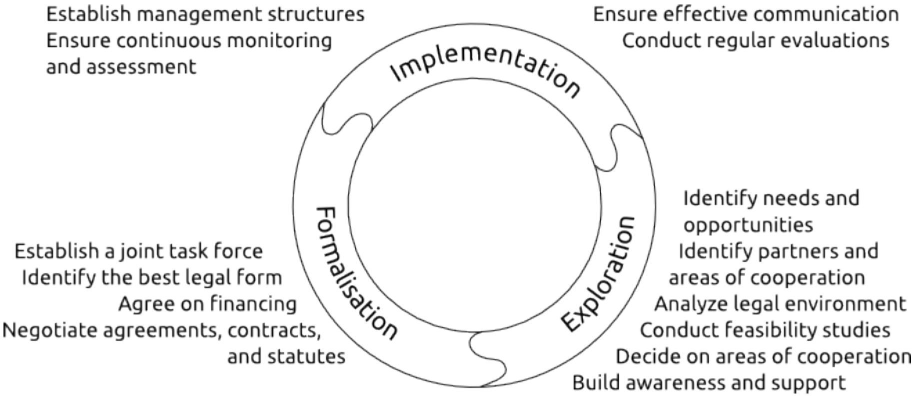


Figure 3.4 – The stages of exploration, formalisation, and implementation follow each other in the longer term, but go back and forth in the short term (following UNDP (2010)).

micro - behaviour

Ultimately decisions are made by politicians, directors, or boards of organisations, but a lot of the groundwork is being prepared by employees who need to be motivated to keep projects running. Of course this is a part of their job description, but principal-agent theory tells us that the alignment of managers and workers is difficult and that often other motivations than contract obligations play a role (Eisenhardt, 1989a). Some other source of inspiration is therefore needed, which can be a consideration for the environment or the thrill of novel technological solutions. We have seen that (re)negotiations are a common feature in the cases, so that we may safely assume that negotiation skills of the different actors influence outcomes. There is the need for trust, which may be based on (perceived) skills, network or legal cooptation, reputation, and previous working relationships. Furthermore, we see Herbert Simon's concept of bounded rationality when individuals make decisions based on incomplete information and the multitude of cognitive biases that occur when decisions are made (Tversky and Kahneman, 1974).

meso - networks

In cases such as the ones we describe, networks have two meanings: the social and the physical networks. Parties are bound by existing hardware, by paths taken in the past, which makes them obvious candidates for further expansion and experimentation. Of course, multiple cooperation activities breed familiarity and trust, but there is also a need not to fall behind the competitor that may sometimes act as a colleague. As the players generally act in a restricted geographical area (which may be as big as a city or harbour) they are bound to come into regular contact and be linked through different projects, possibly at different levels of the organisations. The small size of the city of Delft, for example, is mentioned as a binding factor as the different actors meet each other 'at the baker's'. Also, the presence and linking activities of networking organisations such as Deltalinqs ensures that parties are more likely to sit together and discuss cooperation possibilities. We agree with Keeney (1994) that the processes typically used to arrive at decisions are often not as logical or systematic as we would like them to be.

When we see organisational culture as a higher order of individual behaviour, we also find that organisations or industries have cultures, that can either match or clash. Large organisations, for example, tend to foster more bureaucratic approaches even though they purport to be led by commercial motives. Energy companies still have a legacy of thoroughness, of finding the optimal technical solution, which is seen as an advantage from the point of view of housing corporations, but hampers the profitability.

macro - culture

The case studies were specifically selected to be Dutch and thus were not a good ground for investigating the influence of (national) culture on cooperation efforts. One interviewee commented that the ability of the Dutch to compartmentalise problems (distinguishing the items on which they wholeheartedly disagree from the ones on which they concur) makes it easier to hold negotiations on principles instead of positions. Furthermore, the Dutch culture is characterised by a pragmatic approach whereas for example the German culture has a more hierarchical and formal approach, which led to some communication issues in the OCAP case.

As a part of the macro layer we also defined rules and regulations that may influence partnerships. Some governmental programs are specifically designed to promote the cooperation between profit and non-profit organisations; European projects are often set up to foster cross-national learning through partnerships. Antitrust law may obviously hinder certain kinds of cooperation, although such examples were not found in the cases.

3.8 Using the case study method for investigating cooperation

The case study method is characterised by highly detailed information that is case specific and thus hard to generalise beyond what we present in section 3.7.2. The focus of the case study strongly depends on the interest of the researcher, but generally tends towards a mixed focus of social and technical elements. Rules, dynamics, and uncertainties are described as they occur, with the main aim of learning form the descriptions rather than taking a normative approach. Information is presented as openly as possible, seen through the lenses of the problem definition. The goals of such an exercise is to learn from examples in practice, mainly focusing on learning and extracting ‘lessons’. The pitfall of this approach lies in believing that the lessons learnt are directly applicable to other organisations. Often, the lessons are case specific and can be generalised only with a loss of specificity.

To investigate cooperation, the case study method provides a rich insight into process, choices, changes, and contingencies. Although a case study can focus on technical details, we have chosen to focus mainly on the different decisions and the institutional background. The behaviour of actors and the dynamics of the case are registered as they occurred in the interviewees’ recollection and the literature supporting these recollections. It is clear that the uncertainty in the cases stems from many different sources:

individuals, (immediate) surroundings, and even national and European (legislatory and subsidy) contexts.

The wealth of information is somewhat structured by the use of the interview protocol. The conclusions drawn from the cases studies (as presented in the previous section) should follow clearly and logically from the case description, although in writing the case descriptions details were left out for reasons of readability. By choosing to frame the research in a certain way (e.g. by emphasising cooperation) the researchers do colour the information that they receive.

Case studies do not provide direct input into the assessments of new cooperation proposals. They do, however, give insight in different process steps, the mistakes that can be made, and the patterns that such cooperation takes place in. In a sense they provide reference material to inform the decision makers. Depending on the case study, any layer in the micro-meso-macro range may be described and focus can lie on behaviour, procedure, and even rational elements (see figure 3.5).

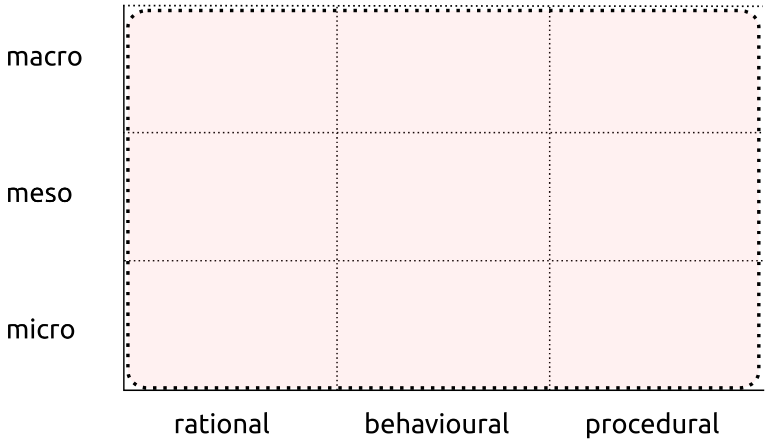


Figure 3.5 – The emphasis of case studies in the framework presented in section 2.5. Depending on the precise research questions, case studies can provide information on every cell of the grid.

3.9 Using the case study insights for other methods

The case studies do not yield clear hypotheses that could be implemented or tested in the following chapters. They do provide a rich list of success factors in these cases. Furthermore, the description of the cooperation process can be used to assess at what point in the process the methods be best applied. Finally, the rich stories and different considerations for cooperating act as a contextual framework and provide points of reflection when attempting abstraction.

Chapter 4

Graph theory and uncertainty

This chapter investigates a mathematical approach to cooperation in networks. The optimal network infrastructure between several cooperating organisations is determined by minimal spanning trees and Steiner minimal trees. When capacities also play a role in the cost function, a minimal Gilbert network gives the cheapest network structure. When participating organisations are not yet determined, a probabilistic extension to these networks minimises planners' regret. Cooperation is thus treated as a possible outcome. Parts of this chapter have appeared in Heijnen et al. (2011).

4.1 Introduction

The evolution of networked infrastructures (gas pipes, water pipes, electricity cables, glass fibre, (rail) roads) can often be described as a situation of organic growth: local initiatives are scaled up or main lines branch out over time. The eventual outcomes of these processes are often bounded by historical choices – existing infrastructures influence the choices that decision makers have – a situation we call path-dependency. Sometimes the outcome of these choices seem suboptimal or even illogical, in hindsight. One could imagine decision-makers regretting the choices they made at earlier development phases. By taking some of the uncertainties of a cooperation process into consideration, the initial design choice could be made more flexible to anticipate future developments and to reduce later regret.

In densely populated areas the 'greenfield' roll-out of a new network is a rare phenomenon. However, when completely new industrial areas are built it is important to design the network in such a way that it is robust against future contingencies. That is: nascent networks can be designed to be able to accommodate a varying set of cooperating partners (nodes in a network) at different capacities and at different points in time. The network design should consider uncertainty and complexity (Herder et al., 2008a), while minimising regret. This follows recent developments in thinking about dealing with uncertainty in project planning (de Neufville et al., 2009; Herder et al., 2011), policy making (Walker et al., 2001, 2003) and risk (Klinke and Renn, 2002): not the optimal solution is sought, but a robust one that stands the test of time and its many unanticipated developments.

One of these unanticipated events is the participation (cooperation) of different actors in an infrastructure project in an industrial area, such as a CO_2 or heat pipeline (see chapter 3). With regard to the uncertainty that we face concerning cooperation we follow an exploratory approach (Bankes, 2002; Lempert et al., 2003).

Given an uncertain set of participants in a bounded area, we not only focus on the choice of network topology and location of partners, but also on the combination of the network capacities while attempting to minimise cost. For this we apply graph theory concepts of minimal spanning trees, Steiner minimal trees and minimal Gilbert networks. We develop a case of a planned gas pipe infrastructure in a new industrial port area (a relatively coordinated setting) to demonstrate the features and limitations of this approach. Finally, we spend some thought on the further use of this approach in similar settings.

4.2 Graph theoretical planning

4.2.1 Mathematical background

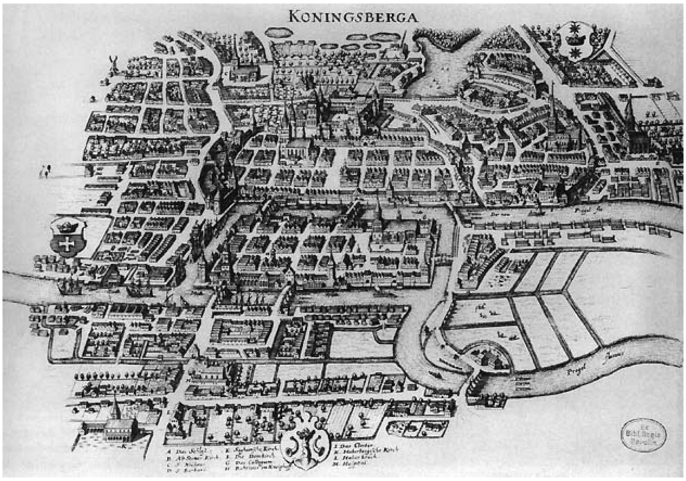
The study of networks or graphs dates back to the mathematician Leonard Euler, who tried to solve the famous Königsberg Bridge Problem (see Box 2) by describing the problem as a graph (Newman et al., 2006; Jamaković, 2008). The abstraction of a problem in graph terms has been applied to a range of topics: computers and communication lines, airport hubs and airline connections, chemicals and reactions, papers and citations (see section 2.2), and people and friendships (Omić, 2010).

Although pure graph theory is an elegant and well-established field of mathematics, the ‘new’ science of networks is characterised by a focus on existing, evolving networks like physical infrastructures, or social and biological networks (Newman et al., 2006). In this chapter we focus on physical infrastructures in which the edges are pipelines and the nodes are factories or support stations that are controlled by decision makers, of whom we do not know whether they are inclined to cooperate in building a new network.

The first step is to find a minimal cost network that connects several nodes with fixed coordinates. When the assumption is made that the costs for building the network solely depend on the length of the connections between the nodes, which is the Euclidean distance between nodes, the minimum spanning tree (MST – the network that connects all nodes with the shortest path) is generally determined by algorithms suggested by Kruskal (1956) or Prim (1957) (Graham and Hell, 1985).

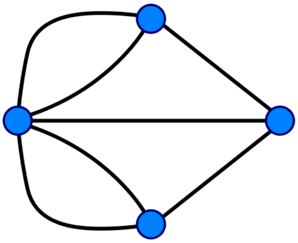
It is possible that cheaper networks can be found if connections can be made at other locations than at the initial nodes. In that case virtual nodes are added to the network. If only the length of the edges determines the costs, finding the location and connections of these virtual nodes is a well-known problem: the Euclidean Steiner minimal tree problem (Gilbert and Pollak, 1968, see appendix A.2). For an arbitrary number of terminals, finding the Euclidean Steiner minimal tree is computationally hard (*NP-hard*) and hence it is not known whether an optimal solution can be found. Melzak (1961) presented an algorithm by which a Steiner minimal tree can be found. For this algorithm a large number of different topologies should be searched, which makes the algorithm infeasible for large sets of terminals, although many improvements on the method of Melzak have been made since then (Zachariasen, 1997, 1999).

The mathematician Leonard Euler attempted to tackle the Königsberg Bridge Problem in 1736. The city of Königsberg in Prussia (present day Kaliningrad, Russia), set on both sides of the Pregel River, included two islands that were connected to each other and the mainland by seven bridges (see figure below).



The city of Königsberg in the 17th century.

The problem was to find a path that would cross each bridge exactly once each. The islands could not be reached by any route other than the bridges and every bridge must be crossed completely. Using a simple *graph* – a mathematical object consisting of points (also: vertices, nodes) and lines (also: edges, links) (see figure below) – Euler proved that the problem has no solution. There could be no non-retracing continuous curve that passed through all seven of the bridges.



The Königsberg Bridge Problem represented as a graph.

Box 2 – Königsberg Bridge Problem

Gilbert defined a flow-dependent model in which flow demands are assigned between each pair of terminals (see appendix A.3). Like the Steiner tree problem, a Gilbert network allows for the addition of extra points to reduce the cost of the network. These points are still called Steiner points. The topology of a minimal cost Gilbert network stands between two extremes (Thomas and Weng, 2006): the complete network $G(A)$ on A (if the capacity of a connection has a large influence on the costs) and the edge-weighted Steiner minimal tree $W(A)$ on A (if the capacity of a connection has only little influence on the costs).

For our problem, we focus on the required capacities of the connections between terminals as these will be literally cast in concrete. The capacities of the connections should be large enough to satisfy the expected flow demands. By that, our problem is defined as finding a minimum cost Gilbert network. The cost function a network N with edges E is defined by:

$$C(N) = \sum_{e \in E} l_e q_e^{\beta}, 0 \leq \beta \leq 1. \tag{4.1}$$

where l denotes the length of edge e, q is the capacity of edge e, and β is the cost component factor.

We choose for β the value of 0.6. This reasonable value (Rui et al., 2011) indicates that the capacity of a connection adds to the costs, but that a connection with a capacity twice as much as another connection of the same length is not twice as expensive. If the exponent β of the capacity in the cost function $C(N)$ is not too large, it can be proved that the minimal cost Gilbert network is an edge-weighted Steiner minimal tree. Moreover, since we assume that the network is fed by only one source node and all the other terminals are consumption nodes, the minimal cost Gilbert network can only be an edge-weighted Steiner minimal tree.

We adapted the generalized Melzak method (Melzak, 1961) to find the optimum location of possible Steiner points within a subset of terminals. This specific problem has not been addressed in literature. Capacity (or flow) costs are taken into account in Gouveia and João Lopes (2000), Bousba and Wolsey (1991), and Balakrishnan et al. (1992), but they do not assume any economies of scale as we do. In their cost function, a pipeline of capacity two is twice as expensive as a pipeline of capacity one.

Figure 4.1 shows an example with eight terminals on fixed locations of which terminal 1 is the source node. The required capacities for all consumption nodes, terminals 2 to 8, are chosen to be equal to 1. The minimal cost spanning tree for these eight terminals is the spanning tree for which the total costs, defined by equation 4.1 are minimal, which is different from a normal minimum spanning tree found by Kruskal's algorithm. With the adapted Melzak method, three Steiner points (nodes 9, 10 and 11) are added to find a minimal cost Gilbert network. A short description of the adapted Melzak method can be found in appendix A.4.

4.2.2 Extension: network within a bounded region

The method described above could only deal with a greenfield situation in which no environmental obstacles hinder a new pipeline or node at the optimal location. Since we intend to use the case of a new network in an existing port area, we will have to deal with

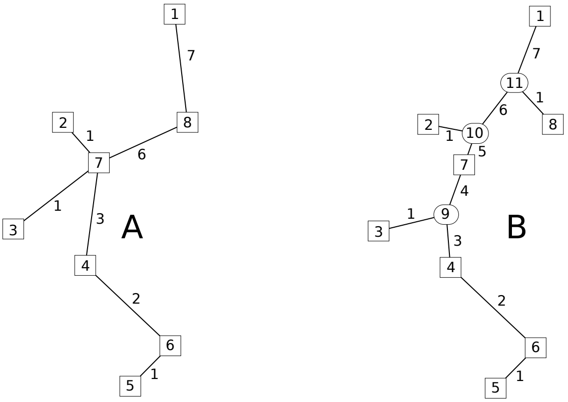


Figure 4.1 – An example of an 8-terminal network {1… 8}. The left figure (A) shows the minimal cost spanning tree. The right figure (B) shows the (sub)minimal cost Gilbert network with 3 added Steiner points {9… 11}. The numbers next to the edges are the capacities. If the Steiner points can be added at no additional cost, cost reductions are around 5%.

the topographical restrictions that such an area poses: the presence of existing buildings, infrastructure, and land boundaries, most importantly the difference between land and water. It is obvious that constructing (pipeline) infrastructure on land has significantly lower costs than building it under water.

If we represent a harbour industrial area as a closed region, meaning that the costs for building under water are prohibitively high and that we are not interested in the world outside this industrial area, we can describe the area as a simple polygon in which the networks found by the method in section 4.2.1 will be adapted to fit into this region. To find a shortest path between one node and another one, a triangulation is made of the simple polygon (Lee and Preparata, 1984; Eberly, 2008) (see figure 4.2). Then a tree is constructed based on these triangulations, connecting the middle points of the triangles in case the triangles have one side in common.

Winter (1993), Winter et al. (2002), and Asadi and Razzazi (2007) define exact algo-

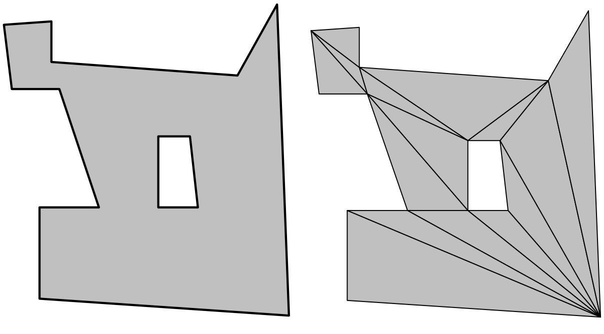


Figure 4.2 – Triangulating a simple polygon using the ear-clipping triangulation method by Eberly (2008).

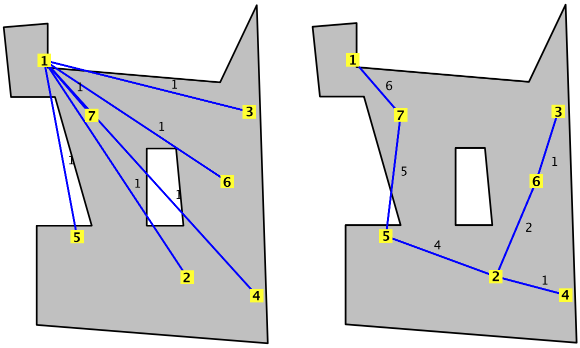


Figure 4.3 – Two initial steps towards a solution given one source {1} and six sinks {2…7}: a star and a minimal spanning tree.

rithms for a small number of nodes and heuristic ones for larger instances to find a Euclidean Steiner minimal tree within a simple polygon. Moreover, the heuristics of Asadi and Razzazi (2007) can solve the problem in a simple polygon with some obstacles inside. Also Weng and Smith (2001) discuss Steiner minimal trees with one polygonal obstacle. The problem of finding an *edge weighted* Steiner minimal tree (EWSMT) inside a simple polygon has not been discussed in the literature (which we further discuss in Heijnen et al. (submitted)).

The edge-weighted Steiner minimal tree from the previous algorithm will serve as the input for the next steps to determine a EWSMT within the allowed region. The new algorithm will be an iterative process that consists of the following steps:

1. Solve angles that do not satisfy the angle condition;
2. Relocate nodes and edges to the allowed region;
3. Remove obsolete Steiner points and corner points.

The first step in which angles that do not satisfy the angle condition are solved by adding extra Steiner points or finding a better sub spanning tree, is exactly the same and the heuristic algorithm discussed in section 4.2.1. The other two steps will be discussed in more detail below.

We replace Steiner points outside the polygon to the nearest point on the boundary of the simple polygon. After that, each edge in the network will be relocated to the shortest path within the simple polygon connecting both its endpoints. The shortest path within a simple polygon is determined using the method from Guibas and Hershberger (1989). Possibly, two edges are redirected such that their shortest paths partly overlap. In that case the original weights of the edges are taken together, considering the appropriate direction of the flow (from source to consumption node).

When the network is redirected to the simple polygon, the topology of the optimal network will still be a tree. However, redirected edges may cause loops in the network, which is not acceptable. These loops are removed from the network, again by allocating the weight of the removed edge to the other edges of the loop, taking into account the appropriate direction of the flow.

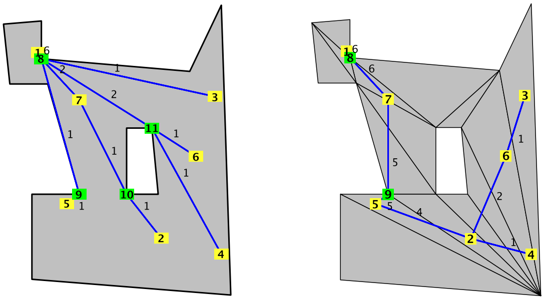


Figure 4.4 – Using the triangulated simple polygon to relocate the nodes and edges within the allowed region. For this example, the star shape is 1% more cost effective.

4.2.3 Application to a planned syngas network

We have chosen to apply this approach to a planned (but not yet realised) case (PoR, 2011): the roll-out of a syngas network in the harbour of Rotterdam, reminiscent of the cases described in chapter 3. The Netherlands, and especially the Rotterdam Port area, create economic value by distribution, transport, and processing of fossil fuels with a strong focus on petroleum. As indicated in the introduction to this thesis, current use of fossil fuels and feedstocks increasingly faces uncertainty of supply due to geological, financial, organisational, and environmental constraints. In the last years, the price of oil has sky-rocketed and dropped (McKinsey, 2011), and gas supplies are threatened due to geopolitical interventions (Correljé and van der Linde, 2006). At the same time, industries willing to use coal as a substitute for natural gas need to prepare for carbon capture and storage (CCS) technologies becoming mandatory in the future (EWG, 2007).

Industries that are heavily dependent on fossil fuels will increasingly have to look for alternative fuel sources to be able to continue their business. A possible solution to cope with these challenges is the creation of synthesis gas (syngas) clusters. Syngas is produced by gasifying any carbon-containing feedstock (both fossil fuels and biofuels). It is a mixture of carbon monoxide (CO) and hydrogen (H_2) and is widely used for methanol and ammonia synthesis as well as in the production of their derivatives (Andrews, 2007; Rostrup-Nielsen, 2002, 2000). Furthermore, syngas feeds into the Fischer-Tropsch process to produce liquid transport fuels (Wilhelm et al., 2001). Carbon monoxide and hydrogen also have other applications, for example in the direct reduction of iron. Finally, synthesis gas may also be used in electric power generation. These processes are already taking place in different sites around the world and thus constitute proven technology (Asadullah et al., 2002). However, connecting such plants to a shared syngas grid would offer the participating firms flexibility in the use of their feedstocks. Furthermore, during the process of gasification, CO_2 can be separated in a more efficient manner as compared with other technologies for capturing carbon dioxide (Herder et al., 2008b; Stikkelman et al., 2006).

The recent expansion of the Port of Rotterdam into the North Sea – the Maasvlakte II area – has created a greenfield situation that is yet to be filled with port-related industries. As Rotterdam already has a strong position as an energy port, it is a logical option to capitalise on this fact and build networks of highly energy-dependent industries (PoR, 2011; Herder et al., 2009b). By building a shared energy infrastructure a reduction in costs due to economies of scale could be achieved. There are several plans for linking syngas pipes to supply to different users. Here we will describe one of the possible options.

If we assume one source of gas – in the case of Rotterdam this would be a multifuel gasifier (terminal 1 in figure 4.5) – a whole host of industries could feed off the supplied syngas that is transported through pipelines. Likely clients are the chemical industry. However, it is unclear what parties would be willing to participate in such a set-up, since they are facing a chicken-and-egg conundrum: the users want certainty of supply, the producers want certainty of demand. To make things worse, the actual location of the potential clients is not yet known (it is a greenfield situation), although the options are somewhat bounded by the shape of the harbour and zoning plans.

Applying the approach described in the previous section, we define a source position with eight locations for candidate clients. As the participation of these clients is uncertain, we calculate the relevant minimal cost Gilbert networks for each possible combination of clients. While figure 4.1 was based on a network in which *all* clients participate, figure 4.5 (right) shows the aggregate of all networks for each combination of clients. Thus, the graph shows the most likely location for the pipelines given complete uncertainty on the participation of the different clients. Should the participation of one of the candidates be more certain, an appropriate weighting factor can be applied.

Four types of actors may use this algorithm: the designer, the infrastructure provider, the landlord (port authority), and clients. During the exploratory phase (as we defined in chapter 3, see figure 4.6), most of the future clients of the area are not settled or even known. The designer may use the algorithm several times to reduce the amount of space for infrastructural needs by varying the location of several types of plausible clients. This effort will result in geographical cluster areas for specific types of clients that are interested connecting to the infrastructure.

In the implementation phase, each time clients present themselves, runs of the algorithm offer the landlord the location that results in a minimal loss of value of capital. Clients with a high clustering potential may be located in an area with a high likelihood for the connecting infrastructure. In due time the area will develop from a greenfield into an area with strategically located clients, all having options to exchange goods via an

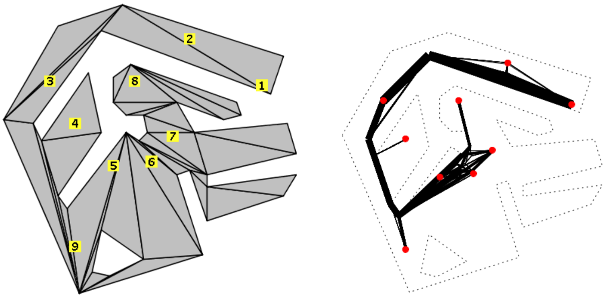


Figure 4.5 – A triangulated simple polygon of the Tweede Maasvlakte with one source {1} and eight potential sinks {2…9} (left) and a density graph based on a hypothetical syngas network (right).

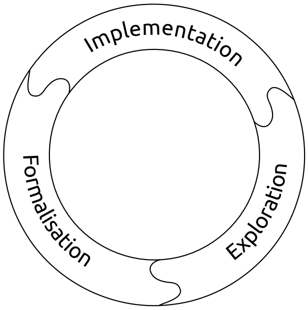


Figure 4.6 – The stages of exploration, formalisation, and implementation follow each other in the longer term, but go back and forth in the short term.

infrastructure. However, the infrastructure still may not be there.

When two or more clients show serious interest in using the infrastructure, the algorithm assists the infrastructure provider and the landlord in selecting the most strategic lay out of the infrastructure, continually taking into account the actual situation and the future expectations. A pipeline in the dense areas of figure 4.5 would minimise regret given future unknown developments. An exemplary outcome could be a hooked connection between two clients instead of a straight connection that is financially attractive from a narrow perspective. We see this for example in the density graph in figure 4.5, where a likely candidate (3) is connected directly, whereas an unlikely candidate (2) is served by a separate pipeline.

After (a part of) the infrastructure has materialised, new clients may be attracted to join the cluster. The algorithm assists the company, the infrastructure provider, and the landlord in assessing locations for new infrastructure investments.

4.3 Discussion

This approach does not provide answers at the push of a button. Although a large part of the work can be performed as desk research, there will always be a need for expert feedback that Kirkwood (1997) calls 'casual empiricism'. For one, in any realistic setting there will be limitations posed by other infrastructures or (regulatory) requirements that are ill documented. For example, the solution space may still contain certain no-go areas that can immediately be recognised by the experienced planner or by a person with intimate knowledge of the area. On the other hand, not immediately discarding options may lead to a discussion on hidden assumptions and thus expand previously unsought options.

The relative simplicity of this approach makes it an excellent tool for quickly analysing dynamic developments and a further range of 'what-if?' analyses. It should be used to engage in strategic discussions regarding decision options and decision making in the exploration phase.

When dealing with the development of networks that are not fully locked-in with regard to their lay-out, the approach presented here allows for quick (re)assessment of network connections. By attributing probabilities to the participating nodes, a range of scenarios can be generated that comprise a multitude of Gilbert networks. The trick is not to optimise for one scenario, but to choose the most robust option for the whole range in order to minimise regret.

We have applied this approach to one case of piped infrastructure in an industrial harbour setting. Similar problems also occur in other infrastructure-bound fields. One could think of the planning of new urban development. The application is somewhat geographically bound: this approach is most useful for areas that are planned and controlled by one authority that has at least some say on the location and admittance of new players. If the uncertainties become too large, other less quantitative approaches should be pursued.

Future work will need to deal with other extensions to the method to make it more realistic and to make it better applicable in real-world problem situations. Probable extensions might be multiple sources or sinks, cost differentiation for different regions, and dynamic re-planning of the network when part of it is already built.

4.4 Investigating cooperation with graph theoretical planning

Graph theory can be applied to both social and technical problems. However, the approach we have taken in this chapter is related to the technical dimension of socio-technical systems. The main focus was hardware: pipes, poles, relay stations, although the boundaries of a physical network are determined by social and legal requirements. Behaviour is not investigated *per se*, but treated as a source of uncertainty that determines the willingness to cooperate in a piped infrastructure. Depending on the (un)certainty with regard to this buy-in, a probability distribution function may be estimated or chosen. In other words, cooperation is treated as an outcome, not as a process. Although a normal distribution is a regular choice for uncertain decisions (Marshall, 1988), one could argue that true ignorance may be better represented by a uniform distribution.

The beauty of this approach is its relative abstractness, which means that apart from some understanding of graph theory the underlying assumptions need not be hidden in a 'black box'. The method can produce insightful charts that contain a large part of the required information (especially when overlaid on maps). This approach could be seen as the extreme opposite of the case study descriptions in chapter 3. Most detail is factored out, decisions are binary, and the accompanying uncertainty is represented in a distribution function. It is a relatively simple and straightforward approach. Dynamics are not directly represented, but the method allows for calculating different starting points and adding or removing vertices allows for a scenario-like approach. The most prominent application of this method would be to roughly explore physical planning options and sketch possible outcomes therewith supporting actors in their decision whether or not to cooperate.

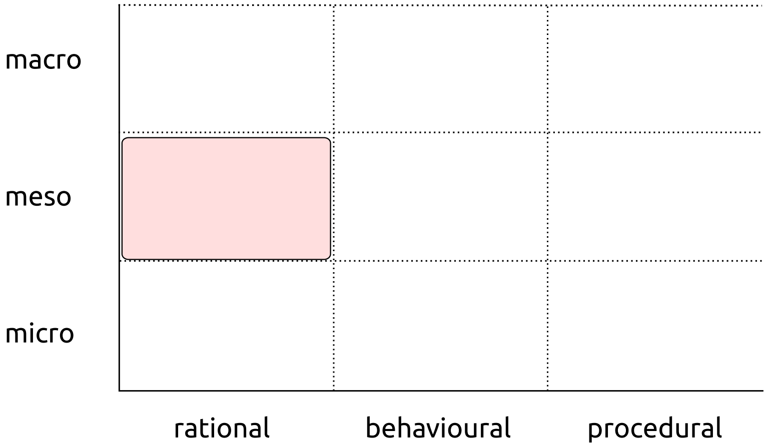


Figure 4.7 – The emphasis of graph theory in our framework is mainly concentrated in one cell.

Chapter 5

Agent-based models of a syngas cluster

This chapter applies agent-based modelling to the case of a synthesis gas cluster in the Port of Rotterdam industrial complex. Such a planned cluster will only be realised if key stakeholders cooperate in the design, planning, and investment in combined gasifiers and pipeline networks. We have used two different agent-based models for analysing the cluster, which we compare and use to analyse the effectiveness of agent-based models as a tool for investigating cooperation. These findings were reported in Ligtvoet et al. (2010) and Ligtvoet (2010).

5.1 The use of models

No substantial part of the universe is so simple that it can be grasped and controlled without abstraction (Rosenblueth and Wiener, 1945). If we want to understand and control some part of the universe, we will have to replace the part of the universe under consideration by a model of similar but simpler structure. One could also say that a model is an analytically focused metaphor: a tool for reasoning about reality. Models encompass a wide range of tools for description and analysis: maps, scaled replicas, blueprints, flow charts, causal diagrams, organisational charts, formulae, graphs, games, simulations. A conceptual model may be as simple as a line and box diagram of the structure of the system, with lines representing more or less well known relationships, varying from facts to beliefs (Walker et al., 2003). Depending on the question asked, any of the models mentioned could provide an answer, but not all are equally scientifically fruitful.

The types of model we focus on here, are of the computational kind; by capturing (part of) reality in rules and formulae we attempt to correctly describe dynamic phenomena that we deem interesting. Doing so, we clarify our assumptions of the internal workings of the system and may test the outcomes by comparing them to expectations or possibly (historical) observations. Whereas understanding is the first goal, ultimately models are made to exercise some form of control (influence) over the system (although for Ryan (2008) this signifies the difference between complexity theory and systems theory).

The modelling approach falls within a large corpus of research that stems from and builds on General Systems Theory (François, 1999). As Boulding (1956) explains, General Systems Theory is based on theoretical model-building which lies somewhere between the highly generalised constructions of pure mathematics and the specific theories of specialised disciplines. The formal model may be a heterogeneous assembly of elements, some treated specifically or structurally, and some treated generically or functionally.

By using such formal models in combination with computers, five important qualities to human understanding can be added beyond what can be achieved by the mind alone (Meadows and Robinson, 2002):

1. *Explicitness:* for models to be calculated with the aid of computers, the important variables will need to be defined and described. The modellers need to be unambiguous about the meaning of these variables.

2. *Precision:* computer models allow for accurate definition of variables and this accuracy is preserved in all calculations.

3. *Comprehensiveness:* for models to be run, all elements that are of importance need to be present and can be taken along in any runs.

4. *Logic:* the modelling exercise follows certain formalisms and the interrelation or sequence of facts and events is repeatable.

5. *Flexibility:* if elements are considered wrong or superfluous, they can be replaced, and calculations can be rerun using the same setup.

Models can thus reveal trade-offs, uncertainties, and sensitivities in our ways of reasoning. They can discipline the dialogue about options and make unavoidable judgements more considered (Epstein, 2008). However, we have to acknowledge that the way models are built and understood is fundamentally pluralist: 'human activity systems can never be described (or 'modelled') in a single account which will be either generally acceptable or sufficient' (Checkland, 1981).

5.1.1 Modelling paradigms

As we already indicated above, modelling is a formalisation of thought. When applying these formalisations to computers, we gain in precision and speed. Furthermore, computer models not only allow for analytical solutions, but for dynamic description of the system: its development over time. Such approaches are called 'computer simulations' (Borshchev and Filippov, 2004). Because of the complexity of the systems described, mathematical solutions are often impossible and simulation becomes the primary tool to describe the behaviour of the systems (Axelrod, 1997). One could make many distinctions between modelling paradigms, often stemming from different 'parent' disciplines (such as management, control engineering, and industrial engineering), but the most fundamental distinction is the one between a top-down (as exemplified by System Dynamics) and a bottom-up (various types of Agent-Based Modelling) approach.

Top-down

The top-down approach is characterised by a description of a system as a whole. Groups of individual components are aggregated and their aggregate behaviour is described. Real-world processes are represented in terms of stocks (for example stocks of fuel or knowledge), flows between the stocks, and information that determines the value of the flows (Schieritz and Milling, 2003). The internal causal structure of a system determines its dynamic tendencies (Meadows and Robinson, 2002) and the overarching structure is responsible for decisions made, via information-feedback loops.

What the researcher looks for is macroscopic dynamics. However, macro level models have been critiqued for their lack of realism, the use of micro level behaviour at aggregated levels of society, and the narrow concept of welfare used. These models assume, for example, ideal or perfectly rational behaviour by economic agents, on the basis of perfect information, and they lack consideration of technology dynamics. Business decision making is assumed to be driven exclusively by the desire to maximise profit (Beck et al., 2008).

Bottom-up

The agent-based modelling (ABM) method aims to analyse the actions of individual stakeholders (agents) and the effects of different agents on their environment and on each other. The approach is based on the thought that in order to understand systemic behaviour, the behaviour of individual components should be understood ('Seeing the trees, instead of the forest' (Schieritz and Milling, 2003)).

According to Beck et al. (2008), ABM is particularly useful to study system behaviour that is a function of the interaction of agents and their dynamic environment, and which cannot be deduced by aggregating the properties of agents. In general, an agent is a model for any entity in reality that acts according to a set of rules, depending on input from the outside world. Agent-based modelling theory uses agents (computer algorithms) that act and interact according to a given set of rules to get a better insight into system behaviour. The emergent (system) behaviour follows from the behaviour of the agents at the lower level.

An agent-based simulation is a dynamic computerised model of a number of decision makers (agents) and institutions, that interact through prescribed rules. The agents can be as diverse as needed – from consumers, to policy makers, and wall street professionals – and the institutional structure can include anything from banks, to the government, to countries as a whole (Farmer and Foley, 2009).

Creating a carefully crafted agent-based model of the economy is, like climate modelling, a huge (if not impossible) undertaking. It requires close feedback between simulation, testing, data collection, and the development of theory. This demands serious computing power and multi-disciplinary collaboration among economists, computer scientists, psychologists, biologists, and physical scientists, some of which should have experience in large-scale modelling (Farmer and Foley, 2009).

Choosing the paradigm

The choice of paradigm is determined by the research question and the level of detail at which data is available. Chappin (2011) gives an overview of different modelling paradigms and scores them according to requirements and nice-to-haves (see table 5.1). He concludes that for the analysis of socio-technical systems with interacting heterogeneous actors and emergent system structures agent-based models are most suited and are easily extendible. A similar exercise was done by Behdani (2012) for the use of models in supply-chain simulations, which led to similar conclusions. Using the bottom-up approach, proponents claim that more real life phenomena can be captured than with the top-down approach. However, there are applications where top-down can efficiently solve the problem, being more efficient, easier to develop, and matching the nature of the problem (Borshchev and Filippov, 2004; van Dam, 2009). In our research that focuses on individual companies' behaviour, a bottom-up method is more relevant as unique individuals' behaviour is expected to influence the outcome of the system. In some decision support systems this may not be necessary as models are used to describe physical phenomena while the actual decisions are made by the decision makers using the tool.

5.1.2 Models as an exploratory tool

With complex systems the issue is not to predict – as this is by definition impossible – but to understand system behaviour. Thus, decision making under uncertainty requires a different approach than calculating probability and effect. Issues of indeterminacy, stochastic effects, and non-linear relationships cannot be handled by deterministic approaches. We believe that agent-based modelling and simulation can be a useful tool to deal with uncertainty in complex systems.

According to Fioretti (2005), agent-based models of industrial networks have largely explored the space of abstract concepts; the next frontier is in getting closer to reality. The strength of agent-based models of real organisations is that decision makers end up saying 'I would have never thought that this could happen!'. The practical value of agent-based modelling is its ability to produce emergent properties that lead to these reactions.

In the following sections we will apply ABM on a planned industrial cluster (PoR, 2011). First we will focus on exploring technological feasibility under uncertain fuel price scenarios. Second we elaborate on the social or behavioural aspects of the agents.

5.2 Syngas cluster

Currently, the Port of Rotterdam has a large petrochemical cluster that processes crude oil into numerous end products, which provides a large flow of income to the region. Rotterdam's heavy reliance on crude oil as a feedstock may threaten the operations of all cluster partners. Therefore it is deemed prudent to reduce the dependency on certain fossil fuels by increasing feedstock flexibility by introducing a syngas infrastructure (PoR, 2011).

As introduced in section 4.2.3, the design and implementation of a syngas infrastructure is a complicated task that needs to consider multiple (and possibly conflicting) inter-

Table 5.1 – Score on requirements for modelling paradigms (ABM=agent-based model, SD=system dynamics, DS=dynamic systems, DES=discreet event simulation, CGE=computational general equilibrium).

Requirement	ABM	SD	DS	DES	CGE
Need to have					
Physical components	+	?	+	+	+
Social components	+	?	–	+	?
Interactions	+	?	+	+	?
Emergent system structure	+	–	–	–	–
Evaluation of policy design	?	?	–	?	?
Specific new insight	+	+	+	+	+
Nice to have					
Existing models	+	+	–	+	+
Modularity	+	–	–	?	+

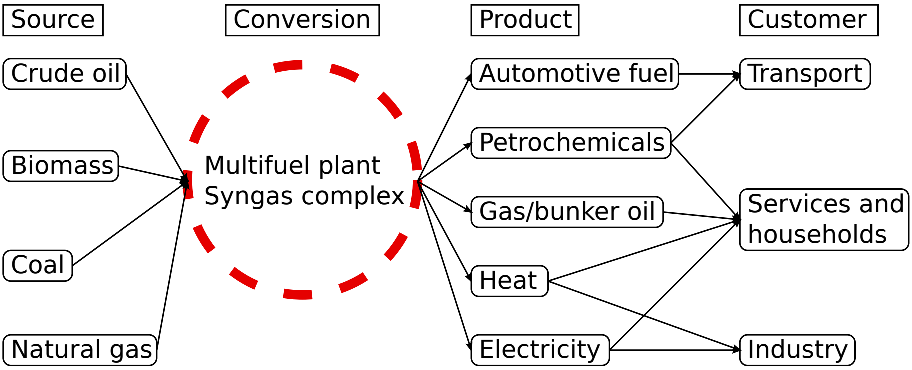


Figure 5.1 – Schematic of a 'syngas' infrastructure in which syngas is used for electricity production, fuel production and the production of generic products.

ests. A multi-fuel syngas cluster and infrastructure consists of a distribution network (see figure 5.1):

- large, but flexible multi-fuel gasifiers that produce syngas of various qualities from various feedstock;
- units to refine syngas to set specifications;
- industrial processes that convert syngas into usable products, electric power, and heat.

In case several gasifiers are connected to the network, each may produce syngas within a given quality range, which provides leeway to cope with temporary maintenance shutdowns of individual gasifiers. However, the robustness of such plants is not investigated here.

Our case focuses on the use of agent-based models to investigate the social and technical aspects of cooperation of firms in such a large technical network. A combined approach is deemed essential, because socio-technical complex systems cannot be understood or designed without knowledge of both the physical system and the constellation of actors (Herder et al., 2008a). We present a range of possible scenarios in which clusters are formed and conditions that determine success or failure. As we explain below, agent-based models allow for exploring the design options in a socio-technical system. Based on the outcomes of our two models (sections 5.3 and 5.4) we discuss the applicability of this approach (section 5.5).

5.2.1 The need for cooperation

As we have seen in chapters 2 and 3, cooperation has several benefits. As the design and commercialisation of infrastructures are often high cost activities, the scale and scope of assets needed lie beyond the financial capabilities of a single firm. The different partners can provide their specific expertise and view of the market, and risks are shared. Thus, cooperation – horizontal and/or vertical – may be the only viable means for moving forward.

While successful innovation and its financial rewards are often highly visible, behind the scenes there are usually many failed efforts and unproductive paths. 'Dry holes' and 'blind alleys' are commonplace. Risk can be diversified and spread through cooperation. Indeed, when risk is particularly high because the technology being pursued is both expensive and undeveloped, cooperation may be the only way that firms will undertake the needed effort. There is no arena in which uncertainty is higher and the need to coordinate greater than in the development and commercialisation of new technology (Teece, 1992).

5.2.2 Model implementation

The use of agent-based models for analysing industrial processes is described in the work of Nikolić (2009), van Dam (2009), and Chappin (2011). Nikolić describes the evolutionary process of building, testing and improving agent-based models (ABMs), while Van

Dam focuses on the requirements of the ABM as a tool in 'what if?' analyses. Chappin applied and extended the models in his research on *energy transitions*. This research further builds upon their methodological framework and toolkit. A large part of the possible interactions between agents in an industrial cluster (e.g. exchange of physical and financial flows, contracts, ownership of technologies) is described in an ontology (a structured set of definitions and relationships) that at the same time functions as a repository of facts on existing industrial installations (such as cost, size, operational configuration, and efficiency). The ontology is directly read into the model, which is developed in the Java programming language, using the basic features of the agent-based modelling toolkit Repast 3. Data analysis of the outcomes of the scenario runs is performed with statistical software packages Matlab and R.

We test the use of ABM as a strategic tool. For the technical design of (energy) clusters, the methods described by Chappin, Van Dam and Nikolić have already shown a wide range of applications and perform favourably when compared to other modelling approaches (van Dam, 2009). Agents' behaviour, however, is mainly based on rational cost/benefit assessments. By implementing more social aspects of the agents, such as co-operation, trust, and different risk attitudes, other dynamics may emerge in clusters of agents. This will clearly impact the assessment of the feasibility of certain projects.

5.3 A model for analysing the syngas cluster

A first step to test the use of ABM in strategic decisions concerning infrastructures is the implementation of a simplified model of two clusters of industries that could exist in the Rotterdam Port area. Each cluster consists of an electricity plant, a petrochemical complex (making transport fuels), and a generic products factory. In the first cluster, the companies buy their feedstocks or fuels from a world market, and deliver their products (electricity, fuel, and generic products) to three distinct customers. In the second cluster, a multi-fuel syngas plant procures the cheapest fuel from the world market and turns this into syngas. The syngas is then distributed to the different companies to be made into products. These products are bought by the customers. All agents procure the cheapest source of the feedstock or product they need. The main question that needs to be answered is if, and under which conditions, a syngas cluster would be more profitable.

Each agent goes through a number of steps in each time frame:

1. observe the status of the world and own state (the agents are fully able to do so);
2. evaluate options with regard to feedstocks purchase, product sales, and technology acquisition (based on net present value calculation and financial status);
3. execute options (buy feedstocks, produce and sell products, invest in technology);
4. review options list (eliminate options);
5. materials flow analysis, financial accounting, and possibly bankruptcy.

In this model setup, the main determinant of uncertainty is the availability and price development of the different feedstocks. The traditional way of approaching this uncertainty would be to calculate the probability of a certain price at a certain time. This has been done extensively for petroleum (and to a lesser extent natural gas and coal; see e.g. Greene et al. (2006) and Kerr (2008)), but these findings have been refuted by as many researchers (e.g. Brätland (2008) and Watkins (2006)). The exploratory approach that we took is not to 'solve' the uncertainty in fossil fuel prices, but to run a 'parameter sweep' over a range of price developments. This way, we do not add (and hide) more uncertainty in the model, but treat all the possible combinations of parameters as scenarios.

For the parameter sweep we took as initial values the average price for each of the four feedstocks (oil, coal, gas, and biomass) in 2008 and allowed for an *annual* price change for each separate feedstock in the range of -5% to +4% (with steps of 1 percent), thus creating a 4-dimensional scenario space with 10,000 scenarios. Our basic setup involved agents who only decide on the basis of demand and supply and choose for the cheapest option available to them. We assumed that the agents in the simulated port area do not influence world prices and that no supply shocks take place. In the discussion below we explain how the setup may be expanded in later versions.

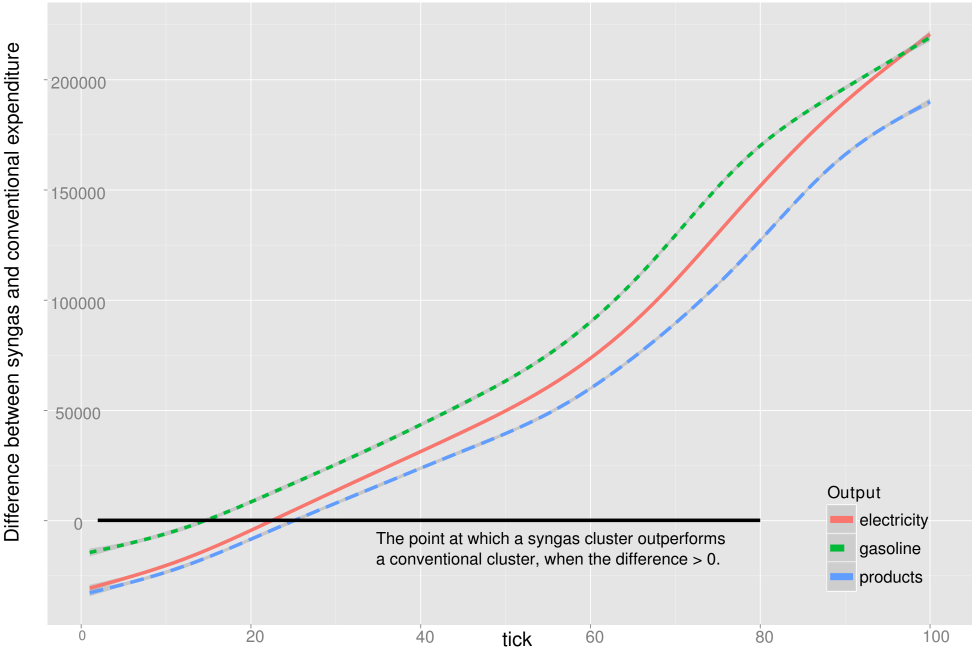


Figure 5.2 – The mean difference (for 10,000 scenarios) between the expenditure for the conventional cluster and the syngas cluster, for fuel, electricity, and generic products. In this simulation each time step or 'tick' represents one year.

In our analysis of the syngas cluster we are interested in whether, and under what conditions, the syngas cluster would lead to lower costs for the production of several generic goods. Given that the investment in the syngas infrastructure would involve several billions of euros over a number of years, it is important to know within which time-frame and under what conditions such an investment could be worthwhile. In other words: is the decision to invest in a syngas infrastructure *robust* over a wide range of scenarios?

Figure 5.2 shows that for the three different product types considered the point in time at which a syngas cluster could become less expensive than a standard cluster is different, but that on average this would take between 14 (gasoline) and 23 (products) years. Furthermore, the figure indicates that on average the difference between conventional costs and syngas costs increases over time. Under the conditions assumed for the starting year, none of the processes immediately show the syngas cluster to be advantageous. However, as time progresses, the syngas cluster will become cheaper in comparison to the conventional processes. After 50 years, lower expenses are achieved for more than 70 percent of the scenarios for electricity production through syngas, and more than 84 percent of the scenarios for fuel production.

The reason that fuel production through syngas is less expensive, can be shown when looking at the correlation between the fuel price and the expenditure in different firms (see table 5.2): both the expenditure on conventional products and conventional fuel production are heavily dependent on the oil price, whereas the expenditure of conventional electricity production is mainly determined by coal price. By choosing for a syngas solution, the processes become less dependent on one particular fuel price.

This relationship can also be explored graphically, which provides more intuitive insight into the effects of price changes on the comparative advantage of a syngas cluster (Wierzbicki, 1997). Figure 5.3, for example, shows a summary of 10*x*1,000 scenarios in which the development in coal price differs. We see that only electricity production is heavily influenced when the coal price rises sharply – the other two products remain relatively stable. What the results show is that under a wide range of scenario assumptions the syngas option is cheaper, but only in the long term. If we are indiscriminate about the likeliness of a certain scenario, there is only a limited set of scenarios that would lead to early payback of the investment. In other words: short-term considerations would lead cooperating organisations to reject such a proposal. Also, using syngas for fuel production will become more profitable in an earlier phase than the processes for electricity and products. This indicates that the monetary argument for building a syngas cluster should be most appealing to those industries that operate on the fuel market. Stability and flexibility, which are harder to capitalise, are other reasons for investing in a syngas cluster.

Table 5.2 – Correlation of fuel prices and expenditure

Fuel	Syngas	Conv. products	Conv. electricity	Conv. fuel
Biomass	0.20	0.05	0.12	0.04
Coal	0.16	0.00	0.86	0.00
Gas	0.34	0.05	0.02	0.03
Oil	0.13	0.87	0.04	0.87

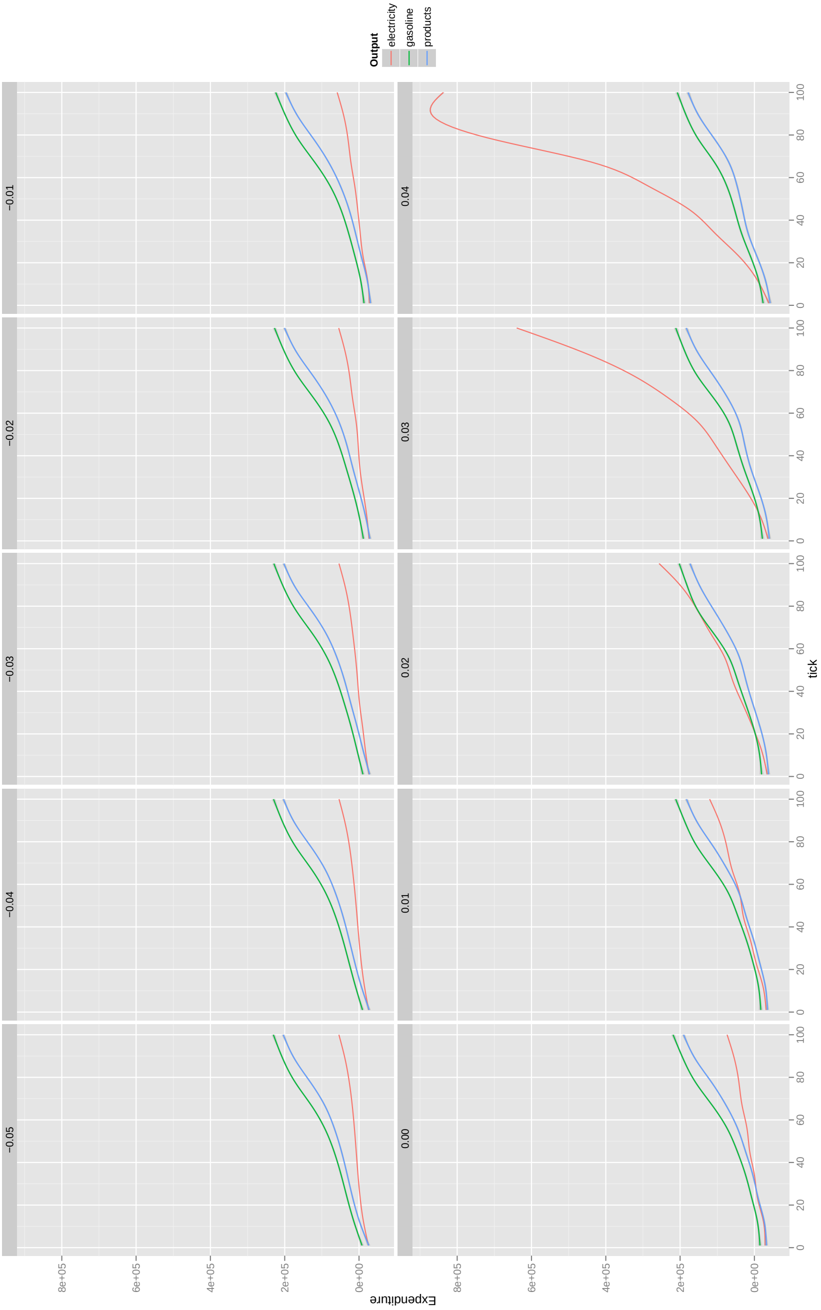


Figure 5.3 – The parameter sweep allows us to investigate the effects of coal price on the comparative advantage of the syngas cluster. Each facet in the graph represents 1,000 scenarios with equal assumptions about coal price development.

5.4 A model for cooperation in syngas agents

In a further test of the agent-based modelling toolkit we focused more on the cooperative behaviour of the agents. We applied our model with additional cooperation settings to a test case: a cluster of n identical agents representing industries that trade a particular good (e.g. petroleum). For reasons of simplicity and tractability, the agents are placed with equal distances on a circle (see figure 5.4). The issue at hand is the transportation of the good: the agents can either decide to choose for the flexible option (i.e. truck transport) or to cooperatively build a piped infrastructure to transport the good.

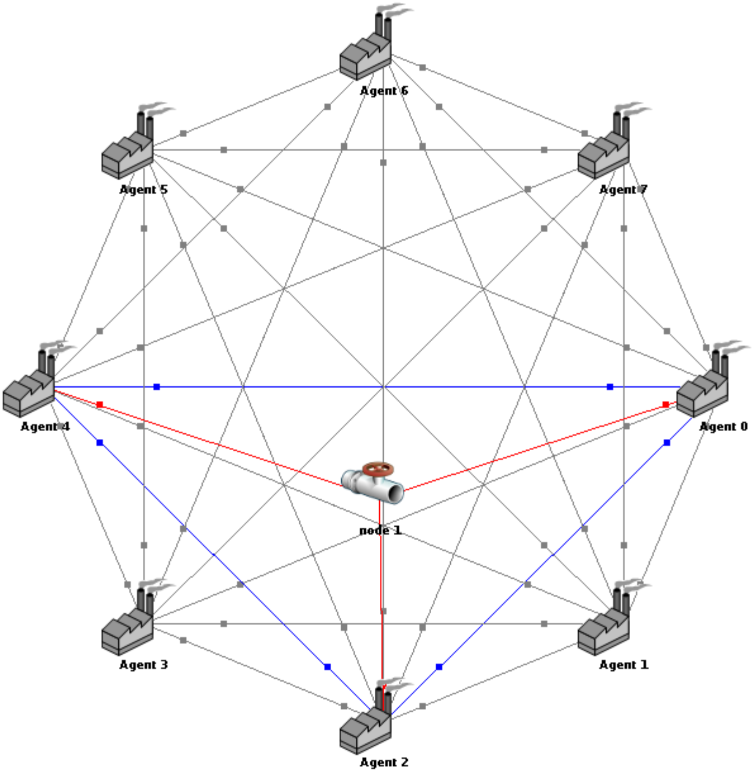


Figure 5.4 – A cluster of 8 trading agents in which 3 agents have cooperated to build a pipeline.

Flexible commitments are contracted for a yearly period only. They are agreements between two agents with as the main cost component variable costs as a function of distance. The permanent transportation infrastructure is built by two or more agents (sharing costs equally) and is characterised by high initial capital costs and relatively low variable costs per distance. The more agents participate in the building of the infrastructure, the lower the capital costs per agent.

Costs minimisation will be a dominating factor in the selection of the optimal infrastructure. Depending on the distance and the number of agents involved, a flexible solution may be cheaper than building a fixed infrastructure. By varying the behavioural assumptions mentioned in the section above, we investigate to what extent cooperation takes place and what the (financial) consequences are for the agents.

We modified the agent behaviour to examine specific cooperation-related behaviour, based on the findings in chapters 2 and 3. The following list of behavioural assumptions were added to the already existing rule base:

- agents create a **list of (strategic) options** they wish to pursue: an option contains a set of agents that agent wants to cooperate with and the net present value of that cooperation. For the agent it becomes a list of prioritisation: the option with the highest net present value is investigated first. In the communication with other agents, the option is presented as a suggestion that the other agents can consider (i.e. perform their own calculations on);
- the agents have a **maximum number of options** they can consider, to reflect the limited time and attention decision makers can spend on investigating leads and to prevent a combinatorial explosion when the number of agents is above ≈10. When more profitable options are presented to the agent, the least profitable option disappears from the list that each agent has made;
- the agents select the agents they want to cooperate with on the basis of predetermined **trust relationships**: these are the initial options that the agents will determine the value of. This does not mean that other combinations with agents are impossible, but these options are hampered due to the *initiative taking* setting (see below);
- agents can have a short term (<5 years) or long term (>5 years) **planning horizon**, which determines the time within which payback of investments should be achieved. Agents with a longer term perspective have the possibility to agree with options with a longer pay-back time;
- agents can be **risk-averse** or risk-seeking by adjusting discount factor in the discounted cash flow. Like with the planning horizon agents may accept a project that is slightly riskier;
- agents want a minimum percentage of cost reduction before they consider an alternative options, a **minimum required improvement**: cooperating in a joint project entails some inconvenience, which means that a project that only yields little profit is not truly interesting;
- agents can be **initiative taking** or entrepreneurial, which means that they initiate suggestions to other agents and respond to inter-agent communication. This means that they actively search for more options.

Part of these assumptions are to provide the agents with ‘bounded rationality’: Herbert Simon’s idea that true rational decision making is impossible due to the time constraints and incomplete access to information of decision makers (Simon, 2000). We assume that agents do not have the time nor the resources to completely analyse all possible combinations of teams in their network. They will have to make do with heuristics to select and analyse possible partnerships. This is completely in line with the heuristics approach of agent-based modelling.

5.4.1 Options

One of the key problems is how to decide with whom to cooperate. In the completely homogeneous setting that we describe, any combination of agents is possible. However, with a large number of agents we quickly run into a combinatorial explosion of options to consider. Therefore, the sets of colleagues to cooperate with that each agent considers are randomly determined (mimicking an initial 'social network'); the full set (n agents) as well as each individual connection are always considered. This way all agents have access to the optimal solution (one infrastructure in which all agents are connected) as well as the minimal solution (a connection between all pairs).

Furthermore, agents may accept a cooperation proposal from any agent if they are open to such communication (the *initiative taking* setting). They will assess this proposal on the basis of net present value (which is determined by risk factor, required improvement, and planning horizon) and may add this new option to their list. When the list of options exceeds a predetermined number (in the settings we used 25), the options with the lowest value are discarded.

5.4.2 Varying the behaviour of agents

With the case as described above, we performed a parameter sweep in which we varied the following variables: number of agents, initiative taking, risk aversion, and planning horizon, to see what the effects were on the outcome of the model. The outcome of the model can be measured in infrastructure usage (number of pipelines built versus used) and expenditure or income of the agents.

An analysis of the different variables' influence shows that the initiative taking factor is of crucial importance. An example of the variation of this factor for five agents is shown in figure 5.5. We see that with a low initiative setting, a number of pipelines are built and a near equal number of pipelines are used. These pipelines are mainly built in pairs, thus only slightly more efficient than driving trucks. With a medium initiative setting, we see that more pipes are built, but at a later stage abandoned for more efficient pipelines with more than two agents connected. At the end, in all cases for the medium setting, the optimal solution of a pipeline for all five agents is chosen. The highest level of initiative displayed shows that some pipes are built that are used by more than two agents, but they are immediately abandoned when a more optimal solution is presented.

This first variation already shows that the effect of varying initiative in agents does not have a linear response in the model. Although the agents choose the optimal solution more often with higher initiative settings, they also create unused infrastructure in the process (in the medium initiative setting more so than in the high). From the viewpoint of efficient use of built infrastructure, a low initiative setting is preferable.

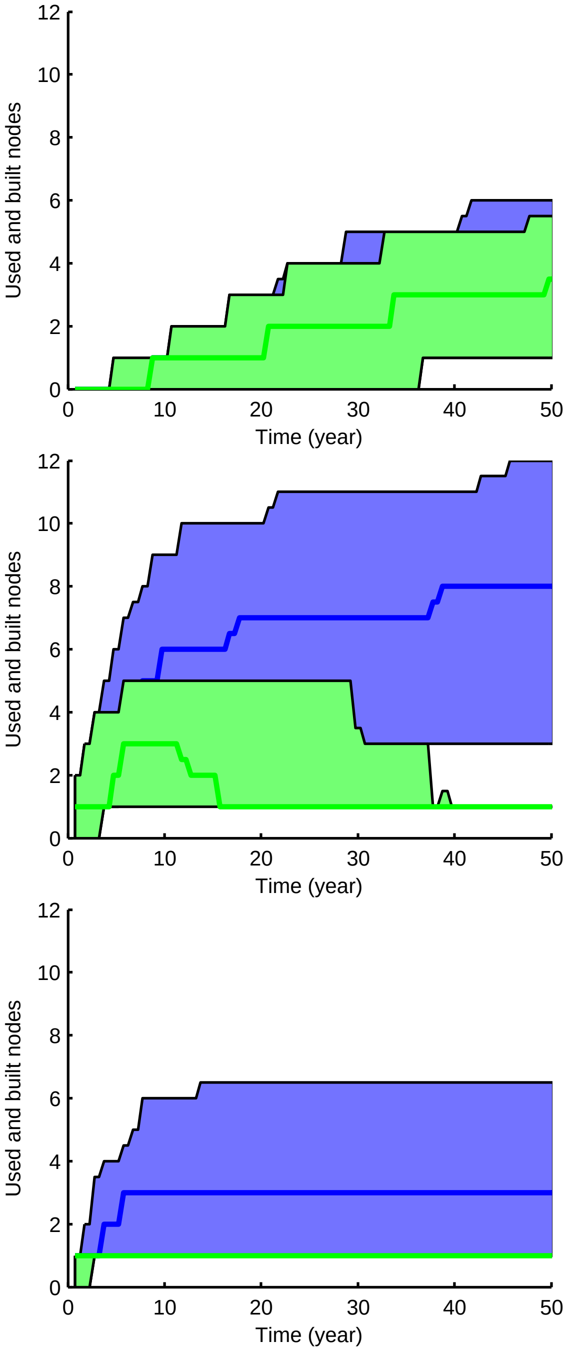


Figure 5.5 – A cluster of five agents with initiative setting of 10%, 50% and 90% (dark/blue = nodes built, light/green = nodes used)

5.5 Discussion on model outcomes

Using the agent-based model as described above allows for the quick appraisal of different endogenous and exogenous effects on the profitability of infrastructure investments. The main question is not: 'what is the optimal or most likely outcome?', but: 'under what conditions will the proposed design of a syngas cluster be more valuable?' It turns out that in the long run, most scenarios applied will favour a syngas cluster. Thus, the choice for building a syngas cluster is deemed robust.

Now the question arises whether a decision maker would indeed claim that she could never have imagined these outcomes, as we suggested in section 5.1.2. In the model described here, the added value of implementing an agent-based model is already apparent. Although commercial software exists that allows for parameter sweeps and risk analysis on top of a spreadsheet model, the ABM is more extensible when the described problem lies at the agent level. By describing behaviour from the agents' point of view, new decision rules (such as preferences based on geographic or social proximity) can be added that would be hard to implement in equation-based modelling systems.

This brings us to discuss some of the potential additions to this setup that would improve the realism:

- In the current setup agents are not 'punished' for bad performance: they do not change their strategy under different circumstances (although they can go bankrupt). In corporations, active shareholders will probably fire the board of directors and insist on a new strategy when performance is consistently bad. Long before *creative destruction* of underperforming industries would take place, we expect firms to adapt their behaviour.

- This punishment would also occur in terms of reputation and/or trust: if existing projects are cancelled because one of the partners has a better lead, that would severely jeopardise the existing relationships.

- Agents could determine the moment to invest in the infrastructure, instead of it being implemented from the moment that a decision is made. This could involve *real options* strategies (Herder et al., 2011), such as waiting until the right moment, building in phases, or even abandoning already initialised projects.

- When introducing more volatility in the price developments or even supply shortages, agents with a certain notion of risk and a risk-taking attitude may expedite or delay their investments. Furthermore, this attitude may be influenced by interaction with other agents: as we have seen in chapter 2, communication influences behaviour.

- Agents should be able to pool their resources by forming different legal structures (such as joint ventures; for an overview see Todeva and Knoke (2005)) to cooperatively build the required infrastructure. This would require social networks, trust relationships, provisional agreements, possibly even penalties, and a host of legal and institutional rules that are currently not available in the toolkit.

- Agents are by definition limited in the amount of strategies they can handle. We would expect that in a social setting actors that suggest unsuccessful propositions will be penalised in terms of lower 'trust'. Currently, each proposal is neutrally assessed.

- Although they have some additional behavioural characteristics and social networks, the agents remain to a large extent rational. We would expect more realistic agents to care about sunk costs (Bresser and Harl, 1986).

It is clear that such efforts to add 'realism' (thus complexity) to agent behaviour may in the end be detrimental to the goal of explaining the model to decision makers. There remains ample room for research to further develop the notion of exploratory ABM and to determine what the required level of detail is to provide useful analyses. The more detail is added, the more difficult the explanation will have to be.

For the social sciences, explaining and understanding cooperation is one of the grand challenges (Colman, 2006). As pointed out in Fioretti (2005), for researchers of industrial clusters, the space of abstract concepts has been largely explored; the challenge is to get closer to realistic models. It is important to find the appropriate balance between detail or 'richness' of the model and general applicability or 'simpleness'. We attempted to do this in the presented models.

In our models a crucial parameter is the 'initiative taking' factor or the willingness to cooperate. Especially in large groups of agents just one agent unwilling to cooperate can halt the process. More so if the agent is a key player. Clearly, the chances of all agents reaching an agreement is small when the initiative taking factor is small. The lower the initiative factor, the less optimal solutions (including fewer agents) are pursued by the remaining cluster of agents and the more money is spent on infrastructure building. One could see here the difficulty of reaching consensus with a large group and the subsequent build-up of infrastructures in small steps. We also see that before reaching the optimal solution from the agents' point of view, some form of inefficiency cannot be avoided.

When agents attempt to compute all possible cooperation strategies with more than approximately 10 agents, one quickly runs into the problem of combinatorial explosions. As with 'real' actors, the agents require a heuristic to limit the number of options they consider. Each agent starts with his own (randomised) set of preferred cooperation candidates. The agents have a maximum number of strategies they consider each round. When they cooperate, they may exchange new suggestions for strategies, of which only the most profitable are kept. In this way computational time is limited. However, successful options may be barred from the beginning.

Although agents are pay-off maximising, their decisions are influenced by several factors, and therefore more heterogeneous. Their strategies are combinatorial and not binary, although not very creative or entrepreneurial (e.g. they do not start a totally different type of business, which we would consider truly strategic decision making). Different agents have different strategies that they need to communicate to achieve cooperation. And finally, the model allows for any number of agents involved although adding agents will increase computing time exponentially. For the sake of tractability we have kept the agents symmetrical, although introducing asymmetrical agents (both from the viewpoint of location and behavioural characteristics) is possible in the model.

5.6 ABM for modelling cooperation

Our experiments show that agent-based models can be used for an exploratory analysis of strategic options in industrial clusters. The modular logic of ABMs fits the idea of the gradual evolution of these industrial areas. The fact that industrial networks are not pre-determined, but are free to form and dissolve over time makes it possible to test the robustness of network designs and behavioural assumptions. The first attempts to embed cooperative behaviour with bounded rationality in our agents has yielded interesting and unexpected results. Further investigation of factors that play a role in cooperation decisions seems appropriate as well as further development on an (agent-based) behavioural theory of the firm (for example building on Dew et al. (2008); Cyert and March (1963) or taking organisational 'scripts' (Nooteboom, 1999) into consideration). It is, however, questionable whether detailed technical *and* social aspects should be combined in *one* model.

Given the outcomes of the two separate models, we expect a combination of constraints to lead to a more narrowly defined range of outcomes. However, we did not combine the models as, firstly, this would not yield more insight into the possibilities of modelling cooperative behaviour. Secondly, and more importantly, piling new elements into a model – possibly in order to make it more 'realistic' – runs the risk of creating obscure (if not black) boxes that may provide an answer, but do not help in understanding how this answer was obtained. Only considering the technical dynamics of diverse, interlinked companies already provides a large solution space that is difficult to analyse and interpret. Adding too many behavioural dimensions would make such models truly intractable, which would defeat the purpose of modelling in the first place.

The question remains where the boundary lies between the need for more detail (and thus, often, complexity) of the model and the general usability of it. Although they are elegant in their simplicity, the $2x2$ pay-off matrices of game theory do not adequately capture the issue of cooperation in a real-world setting. Conversely, introducing a plethora of factors and heuristics to enrich agent behaviour will lead to intractable outcomes and (too) long computation time. A limited set of factors (we suggest less than 10) is adequate. This would be in line with the 'keep it simple' principle advocated, amongst others, by Axelrod (1997).

Agent-based models have been presented as a truly bottom-up representation of systems, thus a way of modelling the forest without forgetting the trees. This is especially handy if behaviour at the lower scale is better known or easier to identify and validate. For example, reasoning from the point of view of a driver comes generally more natural than reasoning from the point of view of a traffic jam; or the buying and selling behaviour of a trader can be easier described than the movements of the market. On the other hand, the law of large numbers would allow for describing the aggregate behaviour of whole populations, as the science of demographics shows. Nevertheless, some of the cautions of Meadows and Robinson (2002) need to be taken into consideration. Modellers tend to:

- concentrate on easily-quantifiable parts of the system, not the important parts. In our models, the technical aspects seem to be easier described than the social aspects;
- devote tremendous labour, both in data-gathering and computation, to achieving

small increases in precision, meanwhile doing little effective testing for general accuracy. Of course, this depends on the goal of the model. This is why we have chosen for an exploratory approach;

- assume and reinforce the social structures and institutions that are the cause of unwanted behaviours, rather than raising questions of long-term goals, meaningful social indicators, or system redesign. It is highly questionable whether *energy transitions* and the required entrepreneurial stance (Dew et al., 2008) can be modelled when basing an ABM on existing actors and institutions;
- produce complicated black boxes that outsiders must take on faith – modelling does not share its learning effectively with users;
- proceed from the paradigm that the future happens and at best can be foreseen, rather than from the paradigm that the future can be chosen and designed. Once again this touches the discussion on optimising versus effectuating, of continuing existing business versus setting up new ventures (Dew et al., 2008);
- forget to underpin their models so that efforts are not credible, not used, and not even documented so that others can learn from mistakes. We suggest using frameworks from institutional economics for designing models, so that outcomes can at least be shared and understood by researchers from other disciplines (see an explanation in appendix D).

This critique sounds harsh, but it is the flip side of the arguments mentioned in section 5.1: explicitness, precision, comprehensiveness, logic, and flexibility. Sharp scientific tools are like knives: they should be handled with care.

We conclude that ABMs are powerful tools for observing the effects of (assumed) individual behaviour on the larger system: they focus on micro level behaviour that adds up to meso level network behaviour and possibly macro level societal change – although the latter seems to be more difficult as it necessarily encompasses many more factors. The rational aspect of the models is strongly emphasised – as these elements are most easily quantified – and some behavioural aspects are added to capture some of the complexity of socio-technical systems (see figure 5.6).

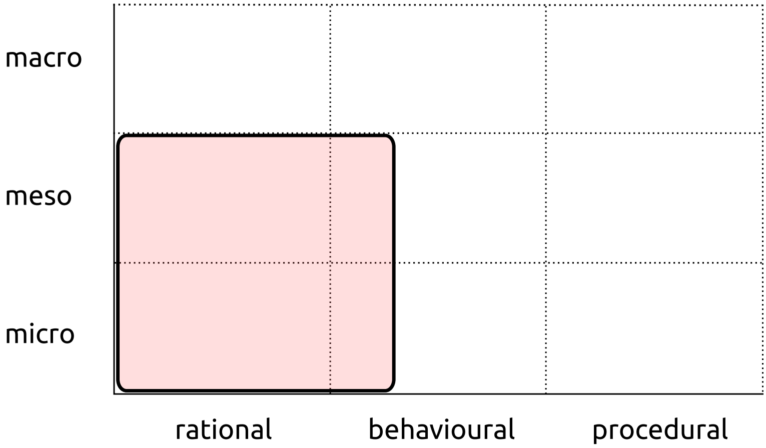


Figure 5.6 – The emphasis of agent-based modelling in our framework lies in the micro and meso levels with an emphasis on a rational world-view, although some behavioural elements are touched upon.

Chapter 6

Cooperation in an energy game

In this chapter we investigate the study of cooperative behaviour in serious games. We build on an existing energy market game and use repetitive questionnaires to understand player behaviour. We contrast the outcomes of the energy market game – which restricts the players' freedom – with a more free-form game on road maintenance. Parts of this chapter have appeared in Ligtvoet and Chappin (2012a) and Ligtvoet and Chappin (2012b).

6.1 Introduction

Computer simulations, formal game-theory models, and other formal structures, many of which can be computer programmed or mathematically studied, depend primarily on numerical data and the logic of mathematics and statistics (Brewer, 1978). However, in many relevant policy issues there is often a lack of data, disagreement on the cause and effect relationships, and complex system behaviour that makes a straightforward appraisal of the situation difficult (as we introduced in chapter 1 and illustrated in chapter 3). When (inter-)human behaviour is an uncertain factor, which we argue is the case in cooperation attempts, serious games may help clarify actor and social system response to different strategies.

We used questionnaires to capture players' response to and cooperative behaviour in an existing game that was developed for teaching students about electricity markets. Before describing the use of gaming as a tool for investigating cooperation (section 6.7), we first describe the history and applications of serious games (section 6.2), the used Electricity Market Game (section 6.3), the players and how we gauged their response (section 6.4), and the outcomes of the questionnaire (section 6.5). We contrast the findings with those of a more free-form game on road maintenance (section 6.6).

6.2 Serious gaming

Stemming from applied mathematics, operations research and systems analysis, the field of *(serious)* gaming aims to understand the counter-intuitive behaviour of social systems

(Forrester, 1971). Whereas increased computing power has enabled ever more complicated representations of reality, studies in policy sciences showed that decision making was far from rational and comprehensive, but rather political and incremental, and even highly erratic and volatile (Mayer, 2009). The toolbox used by system and policy analysts needed to become more human-centred and responsive to socio-political complexity. By allowing for more freedom to the human players, games lend themselves particularly to transmitting the character of complex, confusing reality (Duke, 1980).

Far more than analytical understanding, gaming allows for acquiring social or teamwork skills, gaining strategic and decision making experience, training in and learning from stressful situations. As an educational tool, business simulation games have grown considerably in use during the past 40 years and have moved from being a supplemental exercise in business courses to a central mode of business instruction (Faria et al., 2009). In broad lines, Stahl (1988) mentions five purposes of games.

1. *Entertainment games* have the diversionary purpose suggested by their name. All the positive results of the games are obtained during its play. Card games, board games, and computer (console) games are most known in this category, but more elaborate role-playing games can be also played purely for fun.

2. *Educational games* have teaching, learning, and attitude-changing goals. All direct benefits of the game are obtained by the players. These benefits are usually fairly general and intended to endure over some period of time.

3. *Experimental games* are aimed at investigating hypotheses or theories. They are without specific situational content or context and without any direct intent to apply the results to a practical situation. Game theoretical games described in section 2.3.2 fall under this heading. The main planned benefit of the game lies in reporting its findings to an outside audience of persons interested in the hypotheses or theories examined by the game. Often, these are contrary to what game theory predicts (see e.g. Janssen et al., 2010).

4. *Research games* are played to obtain empirical findings concerning fairly broad areas; the practical application of these results to immediate decision and policy problems is not usually apparent. For example, games are played for finding parameters to add to models (Dubois et al., 2010).

5. *Operational games* are played to aid decision making, planning, and implementation in specific and fairly immediate situations (e.g. by demonstrating principles; generating ideas; changing attitudes (for example, by motivating people); testing models; forecasting; answering ‘what if?’ questions; providing dress rehearsals for future new operations and policies; establishing communication; testing personnel during recruitment.). The findings are reported to the decision makers concerned, and the main benefits accrue shortly after the play of the game is over.

In general, games can be defined as experience-focused, experimental, rule-based, interactive environments, where players learn by taking actions and by experiencing their effects through feedback mechanisms that are deliberately built into and around the game

(Mayer, 2009). Gaming is based on the assumption that the individual learning and social learning that emerges in the game can be transferred to the world outside the game. Games can take many different forms, from fully oral, including role-playing, to dice-, card- and board-based, to computer supported (Duke, 1974). They can be designed to require strict adherence to rules or allowing for more freedom of action. In terms of usability for complex policy making, variants such as free-form gaming gaming seem to perform much better, especially in terms of usability, client satisfaction, communication and learning and, not unimportantly, cost effectiveness. On one hand there is a need to keep games simple and playable (Meadows, 1999a), on the other hand there is a positive relationship between realism and the degree of learning from the simulation.

With the advent of more powerful computers, with high graphic capabilities and network connectivity, the transition to computer supported games allowed for the development of more complex games. By using the graphics engine from first-person shooters, a more realistic world can be displayed on the screen, which allows the players to immerse more fully into their role. Also, computer connectivity has increased tremendously so that several hundreds to thousands of players can interact online in real time (these are the MMPO(R)Gs: massive multi-player online (role-playing) games) (McGonigal, 2006).

The question remains whether technological improvements resulted in games that are better teaching and learning tools. Critics state that gaming has progressed far more in a hardware technological sense than it has progressed either as a teaching method or as a field of research (Faria et al., 2009). Furthermore, the distinction with games for amusement is becoming increasingly blurred by advances in computer modelling power. This permits the development of simulations and games that are ambiguous in both their degree of representational fidelity and their intent (Bogost, 2008). Such simulations, particularly when widely distributed, are liable to charges of perpetrating misunderstanding, analogous to the excessive confidence with which formal models have long been changed in regular policy processes (Mayer, 2009).

6.3 Energy market game

The game we have chosen to investigate was developed in the context of a course on energy market design (de Vries et al., 2009; de Vries and Chappin, 2010). We chose an existing game as it had over three years of development time (meaning it had been thoroughly tested) and other games representing energy systems were not available. Although this game emphasises a social rather than a physical network, we believe it still represents problems of investment that are contingent upon other organisations' decisions and other uncertain factors (as we describe below) and thus provides insight in the use of serious gaming for investigating cooperation.

Since the liberalisation of the European energy markets in the late 1990s, energy production and transmission were decentralised. This implied a whole new dynamic in the planning of energy generation: power generators would have to compete in a market. The mechanisms of this market are based on basic economic notions of marginal prices. Although this could be explained in a rather abstract and dry fashion, the instructors deemed it more insightful to let students play the role of electricity companies that have to compete on the electricity market. The game has been revised several times between 2008 and 2011 (e.g. to introduce an impending CO_2 market) and has been played with students and energy company professionals. In several instances of the game, players have been observed to attempt to manipulate the outcome of the game by exchanging information and devising joint strategies. Also, players have been observed to exploit the software to confuse and misinform the 'opposition'. We therefore argued that the game was engaging enough to test the occurrence of cooperative and/or competitive behaviour.

6.3.1 Rules and game play

The players (usually forming teams of 2–3) represent the directors of five competing electricity companies that manage a portfolio of power plants and have to make electricity pricing and investment decisions. They face uncertainties such as future electricity demand, fuel prices, outages, and a possible CO_2 tax (that embodies the main characteristics of the European emissions trading scheme) (de Vries et al., 2009). Each round represents a year, and a period of approximately two decades is simulated in order to give the players insight in long-term consequences of their actions. The company with the highest bank balance at the end of the game wins the game, because it achieved the highest return on investment.

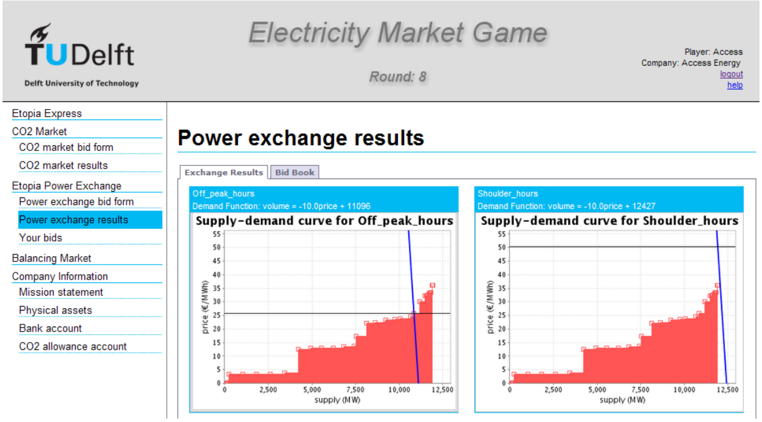
The game is played and operated through the internet on a dedicated server[1]. Each company has its own website (a screenshot is shown in figure 6.1), part of which provides public information, such as news and market prices, and part of which contains private information, such as the company's assets and its bank account. Players do not have to be physically together to play the game. This has the advantage that only a limited amount of contact time needs to be spent on the introduction and the final evaluation of the game, and the length of game rounds can be chosen to fit the players' schedule (de Vries and Chappin, 2010). As the game is played on a normal web browser interface, no special software or hardware (other than a computer with internet connection) is required. The interface is set up in such a way that bids (a list of price/power combinations) can be copy-pasted from spreadsheet software to facilitate calculations.

Each round, companies have to perform a set of tasks. First, they have to offer electricity to the power exchange. The essence of the offer is a list of power generated (in megawatts) and the price for which this power is offered. Theory stipulates that in a competitive market the price should be at or close to the marginal cost of a power plant (but players are free to set any price for any amount of power – if they can't deliver they are forced to buy from their competitors to fulfil their offer). Second, the companies decide whether to build new power plants and to dismantle old ones. Third, after the CO_2 market has been turned on (which is usually around round seven) they have to acquire a limited amount of CO_2 credits. Without CO_2 credits the companies amass CO_2 'debt' over which they have to pay a fine.

To be able to perform these tasks, information is available through the web pages. The main information sources include a history of prices of fuels, CO_2 prices, and electricity prices. News items, written by the game operator, provide some degree of insight into future energy price developments and a partial analysis (based on public data available to

---

[1] See http://emg.tudelft.nl.



Electricity Market Game

Round: 8

Player: Access
Company: Access Energy

Power exchange results

Off_peak_hours
Demand Function: volume = -10.0price + 11096

Shoulder_hours
Demand Function: volume = -10.0price + 12427

Figure 6.1 – Snapshot of the Electricity Market Game: Player/team 'Access' observes the power prices in round 8 (Chappin et al., 2010).

all participants) of what is happening in the market. The news items (like news papers in real life) are generally only an indication of what might be going on and are therefore a source of uncertainty, although no deliberate false information is fed to the players (for example, the impending CO_2 market, or an increase in coal prices are announced). In addition, detailed characteristics are available on the power plants in their portfolio and the availability of new generators. All revenues and expenses of the companies appear in their bank account: revenues from selling electricity and the costs of each power plant, including fuel costs. The net values of the companies are plotted in the game's news bulletin, so the players can see how well they are doing as compared to their opponents.

When the game operator starts a new round, the power market is cleared. The clearing procedure is modelled after European power exchanges: the price/power combinations from all bids are lined up and – starting from the lowest price – are accepted until the power needs are met. This is the so-called 'bid ladder' of which two examples can be seen in figure 6.1. The price from the last bid that gets accepted becomes the clearing price for *all* accepted bids. CO_2 credits are auctioned off in reverse order: the highest bids are accepted first until all credits are sold off. The clearing price for CO_2 credits is also the last bid that is accepted.

The power companies all start with a comparable set of generators, including coal, gas, wind, and nuclear stations, so that market shares are equal. However, power plants differ with respect to load cost, age, size, capacity, fuel efficiency, and reliability. Existing plants deteriorate with respect to reliability: the chance they fail during a particular round increases over time. New technologies become more fuel-efficient and cheaper over time according to a simple multiplication factor.

Although the power exchange is modelled after European power exchanges, there are two main differences with reality. First, there are no contracts outside the exchange, so the price on the market is uniform for all players. Second, within one round, representing one year, the market is split up in three segments, one containing 5000 hours with base demand, one containing 3600 hours with shoulder demand, and one containing 160 hours with peak demand. This means that there are three electricity prices each year: a base, a shoulder, and a peak price.

Power producers place bids for all their available power plants in each of the market segments. To calculate their bids, players use information on the cost structure of the power plants, the fuel prices, and the wind factor. Bids can be different in the three segments, so the players can try to manipulate the market. Sources for uncertainty are the availability of competitors' generators and the exact levels of demand, while historical data and news given to the players provide only an indication.

As the simulation package performs all administrative tasks for the game operator (which plants were deployed and which ones remained idle, how much power was sold, and accounting all revenues and costs), he can concentrate on analysing the game while it is played, on coaching the participants, and on checking for any irregularities (such as collusion).

6.3.2 Premises of the game

Following Stahl's list of purposes (section 6.2), the Electricity Market Game is mainly focused on teaching. According to the developers, playing the game will help participants in understanding: the effects of competition, investments in an uncertain environment, the need for policies and evaluating policy designs, and learning to deal with conflicting assumptions (Chappin, 2011). We wanted to validate this assessment by questioning the students involved. Furthermore, this provided a context for investigating the cooperative activities of the players without which the purpose of cooperation related questions would have been too obvious to the participants. Earlier runs of the game led us to believe that players display a range of strategic behaviours, some of which we describe below.

6.4 Questioning the students

The students that were enquired about the Electricity Market Game were two classes following the 2011 and 2012 fall course *Energy and gas market design and policy issues (SPM4520)* at Delft University of Technology, consisting mainly of Masters' students System Engineering, Policy Analysis and Management (SEPAM), other Masters' programmes at Delft, and Ph.D. candidates from Delft and Eindhoven technical universities. In total 103 students participated in the course and game, of which 52 (50%) answered all the questionnaires during the game. Given the size of the groups, each year three games were played simultaneously (called the red (yellow in 2012), blue, and green game) that included the standard five teams with three or four players per team.

A limited set of questions was asked at the beginning of the game (round 1), halfway through the game (round 7), and just before the end of the game (round 18). Partially, these questions were aimed at evaluating players' response (this goal was communicated to the students), but they were also focused at the cooperative behaviour of the students (see appendix E for an overview of the questions). All students received a personalised email that linked to an online survey (using LimeSurvey software[2]); this also allowed for

---

[2] See http://www.limesurvey.org.

sending reminders to students who did not respond promptly.

As collusion is not allowed in markets like the electricity market, and consequently also not allowed in the game, the questions about cooperation were nested in such a way that they only appeared after players admitted communicating with other teams. This way the questionnaire would not lead players towards the behaviour we intended to observe. Having played the game before, we did observe cooperation quite profusely in earlier instances. The players were informed that because of the evaluative nature of the questionnaire, none of their answers would be shared with the course professors.

6.5 Outcomes and discussion

As indicated above, 52 students (32 in 2011 and 20 in 2012) answered all questionnaires. Given that they were not obligated to participate we can consider this a good response. We chose not to make answering obligatory (as a requirement for passing the course) as we wanted the students to not feel pressured into giving politically correct answers. Since the students made remarks about the high number of game rounds and the associated time pressure to bid, they may have chosen not to answer the questionnaire to save some time. Making the questionnaire obligatory would probably have boosted the response rate close to 100%, but might have invited some quick and easy responses.

First of all, we investigated the (self-reported) understanding of key concepts by the players. Figure 6.2 displays the answers that were given in the three rounds in 2011 (the outcomes of 2012 are added in appendix F). We see that for all four topics (bidding procedure, market power, price determinants, and influence of policy) the understanding increased throughout the game, which is what we expect: playing the game actually teaches the concepts. After round 18, 84% of the students claimed to understand all topics reasonably well or fully; close to 100% understood the bidding procedure.

What is interesting to see is that more students report understanding the relatively easy concept of the bidding procedure than they do with regard to the other topics. This can be explained by the fact that the mechanics of the game and bidding are explained in class, whereas market power and price determinants are more difficult concepts that are partially left to be experienced by the game play. Policy effects can be considered the most complex topic and therefore understanding lags behind the other learning effects.

The greater understanding also follows from the average time spent per round: while in the first round the students spent close to four hours preparing their bids, in round seven they went down to slightly more than two hours, and in round 18 less than an hour and a quarter. We have reasons to believe that these numbers are still overestimated, as a well-prepared spreadsheet could offer a quick calculation tool (as stated 63% of students in response to the question about tools and strategies used: ‘copy paste old bids’, ‘re-adjust Excel spreadsheet’).

When looking at the statements (figure 6.3), we see that the students find both the main parameters of the game and the concepts of the game increasingly clear as the game progresses. We highlight some of the remarks below that could shed some light on the items that were less clear. From the game developers’ perspective it was good to see that 95% of the players agreed (somewhat) about the excitement of the game. According to the literature on designing games, the 'fun' or 'excitement' component is important (Harteveld, 2011). However, some remarks were made about the repetitive character of the bidding after 18 rounds. It is also interesting to see that although a large portion of the students found little surprise to the game in the beginning (65% disagreed (somewhat)), the unanticipated events, the market response, and the influence of the CO_2 market did surprise the players further along the game. We find that the students have to appreciate the complexity of the interactions in the game, even though the premises are rather simple and easy to convey.

Sifting through to comments and remarks, the picture that arose from the questions about understanding concepts and agreeing with statements is underlined – thus confirming the educational purpose of the game. Whereas in the first rounds the comments about uncertainties are long and winding, in round 18 they become more precise. It is clear that some teams took a more reserved stance, observing market behaviour, while other teams immediately started off with choosing to be low-price, or low on carbon, or cheap base load providers. 'The game really gets interesting while the game is developing and gets more challenging, making you think on investment strategies that can make you win other teams or just to have a higher company values per round. At the same time, economic terms are easier to understand while playing and discussing them with your team mates.' A number of players anticipated the arrival of the CO_2 market, while at least one team expected a Fukushima-like massive failure of nuclear installations (and subsequently did not invest in nuclear plants).

The general line of comments supported the notion of fun and excitement. There were some remarks about the game taking too long, the time pressure being too high, and the bidding procedure getting tedious, but in general we find that this part of the questionnaire supported the premises about the game that were suggested by the developers.

The second part of the questionnaire, pertaining to cooperative behaviour, yielded fewer responses in 2011 than expected. Of the 32 students that answered all questionnaires, only one admitted communicating with other teams in the first round. Of the 48 questionnaires that were filled in the first round, only five $\approx$ 10% reported communication. In round seven for both sets the number was also approximately 10%, and in round 18, this number was even lower: about 7%. The communications in the first round mainly took place with teams from the other gaming instances, to compare prices and tactics. In the seventh round the players admitted to talking to other teams in their own game, to see how they responded to the CO_2 market. One player admitted strategising how to work together for 'ruining others', but this didn't work out because they were stuck in a Prisoner's Dilemma (no further explanation offered, but we assume they meant that they couldn't trust the other keeping their bargain). In round 18 other teams were contacted to discuss the uncertainties and the course of the game.

In 2012, however, the students showed more cooperative and boundary seeking behaviour. Already in the first round 10 of the 44 students who answered ($\approx$ 23%) reported exchange of information, discussing the benefits of different investments, and one report of price agreements was made. The teams that were cooperated with were either friends, room mates, or lab partners for different courses. In round seven fewer communication efforts were reported ($\approx$ 19%) – the main topic was the choice for different generation capacities. Finally, in round 18 more than half of the students ($\approx$ 58%) admitted to co-

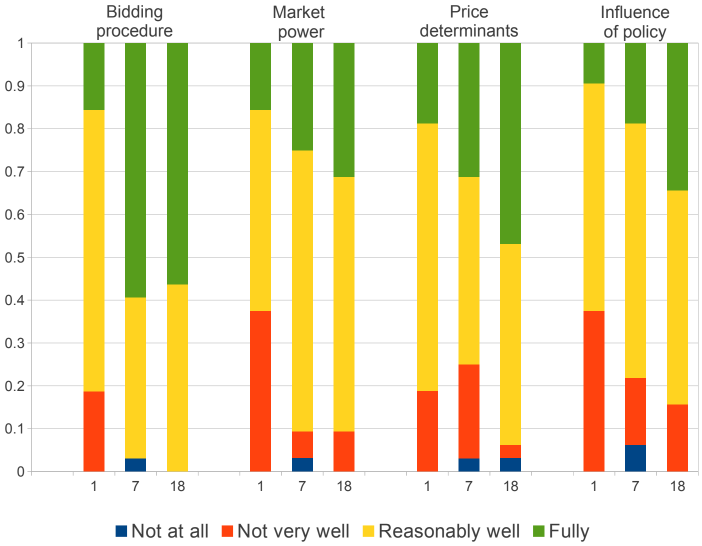


Figure 6.2 – Reported understanding of a) bidding procedure, b) the concept of market power, c) price determinants, and d) policy effects in rounds 1, 7, and 18 – 2011 group.

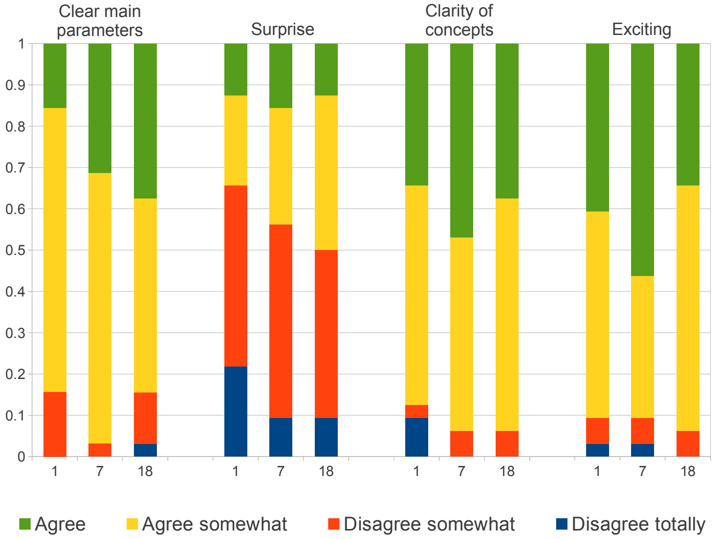


Figure 6.3 – Agreement with statements a) the main parameters in the game are clear, b) the outcome of (one of) the last rounds has surprised me, c) playing the game has led me to better understand the concepts, and d) the game is exciting, in rounds 1, 7, and 18 – 2011 group.

operative behaviour. Especially the teams in the yellow game tried to influence the CO_2 market by making price agreements. In the end, one yellow team did not stick their promises so the attempt to form a cartel failed. Again, the students noticed that they were stuck in a dilemma that resembled the Prisoner's Dilemma. Also, some teams admitted that they wanted to beat their close competitors instead of cooperating with them.

6.6 Free-form gaming for innovative contracting

We contrast the energy market game, which follows a rather prescriptive format, with a game that provided more leeway for the players to experiment. We once again used an existing game for the same reasons as mentioned in section 6.3.

The game 'Road Roles', developed by Altamirano (2009), does not address energy networks, but contracting maintenance activities for a road network. It also deals with a physical network in which multiple actors compete and/or cooperate to achieve their goals. In the 14 instances that this game was played, the researchers encountered cooperation and defection, cartel formation, principal-agent problems, lawsuits, and the trial of different 'sticks' and 'carrots' that could be a part of contract negotiations. As such, the issues addressed by the game relate to the overall theme of our research.

6.6.1 Background

Like the liberalisation and privatisation of energy networks, the public road infrastructure has also seen more private sector involvement over the last decades. Under the banner of public-private partnerships (PPP) there have been scores of infrastructure projects (worth more than a trillion dollars since 1985) in which a balanced and acceptable sharing of responsibilities, risks, and rewards between governments and corporations has been attempted. In the road sector salient trends are more long-term contracts, involving private financing, allowing contractors more freedom to design and operate the roads during their life cycle. This means a more distant role for traditionally hands-on road authorities, that try to figure out how much steering is required while allowing 'the market' to come up with cost-effective measures to maintain availability and quality of the road network.

6.6.2 Road roles

To shed light on the complex question of incentives for positive contracting arrangements, while minimising the negative effects of opportunistic behaviour, Altamirano (2009) designed, built, and operated a game on innovative contracting in the road sector. Based on literature research, system models, and case studies in Finland, Spain, and the Netherlands, a free-form game was developed in which the essence of the problem was captured. Several contractors compete for a maintenance contract with the road authority. The long-term performance-based contract allows the contractor to decide which road section, when, and what kind of work he will perform, with the only condition of keeping a certain level of performance for the whole road network for a certain number of years.

6.6.3 Rules and game play

Two types of players play an active role in the game: the contractors (played by 4 ± 1 teams) and the road authority (played by one team). Other roles, like the bank, central government, and all other external factors are played by the facilitators.

The game play goes through the following phases. First, the road authority issues an invitation to tender for the maintenance of a road network consisting of five road sections – the initial tender specifies the minimal road quality after the contracting period. Second, contractors present an offer consisting of a work plan for each of the sections (consisting of heavy actions, light actions, or no actions) and compete for the contract. They can also invest in additional research and development to increase their competitive edge. Next, the contract is awarded to the best offer and the maintenance activities are performed according to the work plan. After the work plan of the winning contractor has been simulated using a spreadsheet model, the road condition at the end of the contracting period is reported, financial consequences are calculated and administered by the bank, and a new tendering cycle begins.

The simulation evolves as contractors learn to manipulate the selection criteria and payment mechanisms – bonuses and penalties – to maximise their profits and specialise through investments in research and development. Also, the road authority learns from the response of the contractors and refines the rules and selection criteria. The game ends with a debriefing session to discuss the results of all players: the contractors with regard to their financial status and the road authority with regard to the final network condition.

6.6.4 Premises of the game

When looking at the list of purposes in section 6.2, Road Roles is typically a research game with some experimental elements. It is used to corroborate findings in literature and in case studies. Since it addresses the same problem in slightly different game settings (e.g. with differences in contractor numbers and finances), the outcomes of the games provide additional support to the trends that were already found in the accompanying research.

According to the researchers (Altamirano and de Jong, 2009; Altamirano, 2009), the game is built on game theoretic concepts and helps the players to understand and cope with opportunistic behaviour in road maintenance markets. As the different instances of the game were thoroughly documented, we refrain from using questionnaires but instead use the existing descriptions of the rounds.

6.6.5 Outcomes and discussion

A verified and fine-tuned version has been played 14 times, in the Netherlands, Finland, and Spain. Eight of these sessions involved professionals and experts in the area of innovative contracting, while six involved engineering students. Although students and professionals did not behave fundamentally differently, students tended to make more radical choices. As is suggested by Doerner (1980, 1990), life experiences influence game play and thus we should expect different behaviour in games that involve 'seasoned' experts as opposed to those that involve freshmen.

In all the experiments, a process of market concentration was observed; road authorities seldom succeeded in keeping the condition of the roads under control or effectively implementing other selection criteria than price. Contractors' opportunistic behaviour played a substantial role during the tendering process.

Some authorities were more creative than others in creating incentives for contractor cooperation and investment in research and development. It was observed that while high penalties create incentives for collusive behaviour, a combination of moderate penalties with significant bonuses proved effective in making contractors pursue more cooperative and proactive strategies.

Some contractors proved more successful than others. Depending on the incentives introduced by road authorities, the best approach generally was not to cooperate or defect, but to read the invitation to tender literally and find weak points in it. Finally, there was evidence that the financial situation of contractors had a strong impact on their strategy: they made riskier choices as their financial resources dwindled.

When playing a free-form game, a strong framework of analysis is necessary to be able to conclude anything that pertains to the modelled system. If not, the exercise runs the risk of becoming a set of case studies of one instance of a game each. Road roles was analysed according to the following set of indicators:

- determinant selection criteria;
- contract incentives;
- monitoring;
- authority financial performance;
- network condition;
- sector financial performance;
- sector innovation;
- sector satisfaction;
- market development.

This framework made comparison between the cases easier and allowed for some generalised observations. However, these observations can only serve as a source of hypotheses that need to be further tested – either in more observations of practices or in more tightly controlled tests. Indeed, without asking the players about their exact motives and reasoning[3] the absence of behaviour *in a game* cannot automatically lead to the conclusion that this behaviour is also absent in 'real life'. Conversely, the presence of (strategic) behaviour may be an artefact of the game (e.g. by the game leader suggesting certain outcomes) rather than being an indication of realistic behaviour. We believe that games provide an excellent way for testing out new strategies (of cooperation or competition) to test how other players react to that strategy. However, the bankruptcy of an *imagined*

---

[3] This runs into the discussion whether one can trust the interviewee's word as it will reflect socially desirable answers.

company surely weighs less than that of a real company with employees, stakeholders, and several years of personal involvement.

6.7 Gaming as a tool for investigating cooperation

When looking at the two examples of successful games, there are several cautions with regard to the use of games for studying cooperation behaviour:

- Game play is strongly influenced by the rules of the game. Players are encouraged to remain within the bounds of what is allowed and do not step 'out of the box'. When there are few rules, (the absence of) behaviour could still be influenced by unmentioned ideas about politically correct play. It is hard to find out what other implicit rules play a role and conclusions should not be made too quickly.
- Each game is different, not only in terms of measured outcome but also in terms of the approach of each team – the host of mentioned calculations and important uncertainties in the first round of the electricity market game suggests this, as well as the diverse outcomes of Road Roles. In Road Roles students displayed more risky behaviour and the earlier instances of the electricity market game in which Delft staff members competed, had a totally different dynamic that may have resulted from a lack of teacher-student relationship and a whole host of additional life experiences that influence game play (as is suggested by Doerner (1980, 1990)).
- Individuals play a large role: aggressive or taunting behaviour may trigger a totally different outcome. We noticed differences with regard to bidding strategy, but this could equally hold for dealing with the 'competition'.

Serious games can be used for testing behaviour under uncertain circumstances. It does, however, give rise to caution about the definitive conclusions that can be drawn from such experiments: either cooperation is too strongly suggested by the game set-up and rules, or, the options for cooperation are hidden and unclear to the players. Artefacts of the (rules of the) game do not necessarily reflect reality, even though there may be conspicuous anchors that suggest a clear match. Therefore sharp conclusions may only be drawn after many repetitions of the game.

Although serious games like the ones we described are built using (computer) models and abstracted notions of market mechanisms, the behaviour of players and teams plays an important role. One could argue that the players are free to choose their moves within a framework of options. In the electricity market game, this framework is restricted and an optimal solution can be played when factoring in a bandwidth for wind and fuel uncertainties (in fact the game operator has a console which shows what the optimal bid would be for each team). Thus, the game is somewhat prescriptive with regard to the winning strategy, which is to be expected of an educational game that aims to convey knowledge. However, as we have seen in chapter 2, humans are limited in their ability to calculate the optimal strategy and have a host of other non-rational (as in: the rationality of the game) reasons for making different choices (e.g. talking to teams friends are in). In Road Roles there are very few rules and sometimes one can only guess as to the motives of the players.

The technical uncertainties in the energy market game are of the predictable kind (with a probability distribution function); no nuclear meltdowns are planned, nor could they be handled in a meaningful way given the options the players have – still, some players expect such extreme events. The behaviour of the other players is somewhat more unpredictable, although the rules of the game do channel the range of options. In Road Roles technical unpredictability is portrayed by Research and Development cards and unforeseen events. Experienced players seem to base their decisions on the certainties of the game rather than hoping for a change of luck.

The ultimate question that remains is whether the games accurately capture the uncertainties and the decision space that is experienced in the 'real situation' that is simulated. More than the proof of the pudding being in the eating, researchers should remain vigilant in asking the question whether the certainties and uncertainties in the model reflect reality, and to what extent the assumptions of the researchers are biasing the analysis or the behaviour of the players.

In our framework we place serious gaming somewhat stronger in the behavioural corner, although the design of the game is generally based on rational models of reality. The focus is strong on individual learning and the effects of the combination of individual activities (which we call the meso level). Although Altamirano (2009) did observe some cultural differences and other examples exist of games being used for cultural measurements, the macro (time)scale is generally not the focus of gaming exercises.

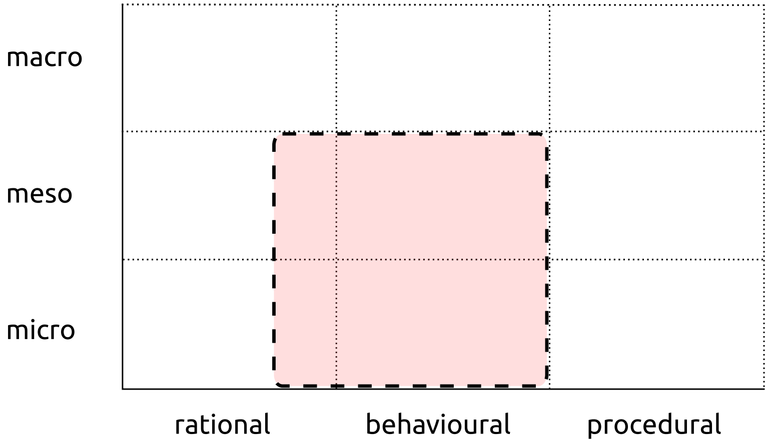


Figure 6.4 – The emphasis of serious games in our framework lies in the behavioural dimension, with a focus on micro and meso levels.

Chapter 7

Synthesis

This chapter combines and contrasts the approaches to understanding cooperation. It provides an overview of the four methods investigated in this research and compares them with regard to the axis micro-meso-macro and the axis rational-behavioural-procedural. The analysis builds on earlier versions in Ligtvoet and Chappin (2012a) and Ligtvoet and Herder (2012).

7.1 What we know about cooperation

The literature overview in chapter 2 already indicated that human or organisational cooperation is a phenomenon that can be and should be explained as a multi-dimensional issue, using game theoretic, behavioural, economic, and organisational viewpoints. When taken on their own, these fields represent an unnecessary reduction of what cooperation encompasses (which was summarised by Gold (2005) in table 2.3). At the same time, however, there seems to be no single formalism that can capture all elements that play a role (which, according to Mikulecky (2001), is one of the definitions of complexity, and according to Funtowicz and Ravetz (1993) is the essence of the wicked societal problems we try to solve). By definition, this requires a multi-(time)scale and multi-level appreciation of cooperation phenomena: personal motivations, interpersonal dynamics, and organisational, institutional, or cultural pressures. It also requires the willingness to address several formalisms at the same time. In this thesis we did so by looking at cooperation through what Astley and Zajac (1991) would call a rational frame of reference – strongly present in graph theory and also in agent-based modelling – and a behavioural and procedural frame of reference – which in this thesis is exemplified by serious gaming and case studies. In the following sections we assess to what extent we were successful in bringing these frames closer together.

7.1.1 Case studies

We started off by using a case study approach in chapter 3. This approach provides a wealth of contextual information that needs to be structured and ordered within a research framework. If we apply the distinction between micro-meso-macro level, we gain the following insights from our case studies.

Micro In terms of behavioural aspects, the case studies provide quite some information that would be hard to capture in a purely analytical model. The cooperation in each case is achieved through a lengthy process of identifying opportunities, getting to know the prospective partners, perseverance in the light of setbacks, maintaining momentum (stamina), and a (shared) enthusiasm for the collective task. These are all individual traits for each of the participants, but should also be shared at the group level.

The cases furthermore show that individual goals are being defined, but given the circumstances are readjusted. For example, minimal requirements for return on investment turn out to be flexible after all. Sometimes the 'usual suspects' for cooperation, such as large industries that provide a steady flow of heat or CO_2, are not willing to commit themselves in order to maintain some degree of flexibility. In a sense, the more connections an actor has, the more they tie him down. De Bruijn and Ten Heuvelhof (2008) call this the law of the spider and the fly.

On the other hand, the connections also offer opportunities that (seem to) outweigh the setbacks: access to expertise, capital, simplified procedures, gaining reputation, innovative ideas, and closer relationships with other stakeholders (such as citizens).

Meso At the network level groups of cooperators form and sometimes endure, even beyond the initial project. There seems to be a need for a shared problem or a challenge, that kindles shared commitment. Through frequent interaction the actors get to know each other and build trust. This can also generate a reputation for being trustworthy. Ostrom (1998) shows this to be a self-reinforcing loop. When successful, the project and the built trust can lead to further ventures in similar projects. The OCAP case is illustrative of such ongoing ventures. From the other two cases we learn that keeping up with the competition also is an important driver.

Macro Although we chose cases that lie close to each other in terms of geographic position and type of network involved, there are some remarks to be made on the influence of society and culture. First of all, the national and international policy context plays an important role as the projects are either defined to support certain policy goals, or are designed to circumvent some of the inefficiencies that take place at the national level. Secondly, the cultural context even plays a role in seemingly Dutch examples: the difference of reporting style and entrepreneurial stance was underlined in the OCAP example, where one of the partners is a subsidiary of a foreign company. This provided some additional effort to convince the participating parties to cooperate on their own terms.

Rational-behavioural-procedural The case studies allow for a closer investigation of behavioural and procedural aspects of cooperation. Case studies can be used to hypothesise about cause-and-effect relationships (the rational mode); more so, they provide insight in procedural steps that each project seems to go through as well as some behavioural aspects that are important.

One of the dangers of this method is that the experiences of a few well researched organisations is presented as 'best practice' for all; a substantial proportion of the management literature is characterised by a high degree of prescriptiveness that cannot be proven to hold for all organisations (Vickers and Cordey-Hayes, 1999; Huxham and Vangen, 2005). Thus, there is a need to be more precise about the specific conditions under which the observations hold.

7.1.2 Graph theoretical planning

In chapter 4, cooperation is treated as an outcome, not as a process (following the advice of Stephens and Anderson (1997)). By being agnostic about unknown behaviours, a simple probabilistic approach can be followed that does not rely on a range of (unspecified) assumptions but only only clear one: a probability function. This keeps the model tractable and allows for an exploratory approach that scans a wide array of options.

Micro At the micro level of the actors, this means that this method provides little information. The implementation that we used distinguishes between nodes with regard to size and likelihood of cooperation, nothing else. This is a very transparent way of using the approach. If, however, more information about the behaviour of certain actors is available, the details could be added to the algorithm. The flip-side of this is that the model will become less tractable.

Meso The interesting element of this approach is the use at the meso level. By analysing the different types of networks that can occur by calculating all possible sets of participants, we can provide insight in the likelihood of a network edge or Steiner point being needed. Thus not cooperation itself, but the possible permutations that cooperation can contribute to are identified.

What becomes apparent is that the combinatorial explosion quickly gets out of hand. Even a relatively straightforward mathematical model will not be able to handle large sets of actors (more than ≈ 20).

Macro At the macro level this method remains very modest. The only influence that is taken into consideration is the geographic zoning that might be the effect of policy decisions. All further assumptions are avoided and considered captured by the probability function.

Rational-behavioural-procedural Of the methods investigated this is the most rational in its approach. Behavioural and procedural elements are not at all taken into consideration. We see a clear place for this method in an exploratory phase of a project: it can provide a quick analysis of path options for new networks. The decision on risk appetite is left to the decision makers themselves.

7.1.3 Agent-based modelling

In chapter 5 we applied agent-based modelling as a hybrid approach in which we integrate both technical and social aspects. We found that such an approach can be valuable in exploring scenarios, calculating the feasibility of proposed networks, and investigating under what conditions such a proposition would make economic sense. Like the graph theoretic approach, this is in line with the idea of *exploratory modelling*. The aim is not to provide an exact answer, but to display an array of possible outcomes and to learn from the modelling process.

Micro The two agent-based models we built differ somewhat in terms of behaviour of agents. Whereas the first was based on rational and solely economic reasoning, the second model was based on different settings of bounded rationality, planning horizon, required improvement, initiative, risk-aversion, and social trust networks. Depending on these different settings, the agents displayed more or less cooperative behaviour which led to the agents building energy infrastructures. This does not provide insights into the behaviour itself, but into the effects of *assumptions about* agent behaviour. We find that there is a risk of providing more detail in one area of the model (e.g. the technology), thus suggesting more predictive power, whereas other areas of the model (e.g. (economic) behaviour) remain sketchy.

Meso At the meso level we find that the individual behaviours do lead to the types of networks we are interested in. Some elements actually surprised us, which is exactly what Fioretti (2005) thinks agent-based models should be used for (see section 5.1.2).

We found that high levels of initiative-taking and low levels of risk-aversion lead to more willingness to cooperate – this is hardly surprising. Furthermore, the number of options the agents were willing to entertain, the required pay-back time, the minimum required gain for a new project and the number of connections, all influenced cooperation in a predictable fashion. From an exploratory stance a more interesting outcome was that a cluster of highly cooperative agents produces a low number of highly connected networks and that a cluster of uncooperative agents produces a large number of 1-to-1 connections. Both situations lead to a high level of use of the built infrastructures.

The intermediate situation, in which the agents have mixed incentives for cooperation, leads to a tremendous amount of trial-and-error: 1-to-1 networks are built, but abandoned once a slightly better alternative with more than one counterpart is offered. From an economic perspective this may make sense as the net present value of the investments is positive. In firms we would expect the behaviour to be different: decisions are often not quickly abandoned as decision makers' reputation plays an important role (dei Ottati, 1994) and the sunk costs fallacy holds. Nevertheless, it was interesting to observe that the 'intermediate' settings did not lead to 'intermediate' results, but to large wastage of materials and effort. This underlines the risk of partaking in a project in which not all partners are equally committed.

Macro In the model we built the macro elements of society, such as culture and policy, did not play a role: we assumed that they were similar for each agent and thus did not provide a parameter that could be changed and analysed. As such we did not gain any insight in macro processes of interest.

However, modellers should be aware that any model about agents that represent humans or human institutions also encompasses assumptions about the environment the agents 'live' in. The laws of physics – and thus the way that technology works – may be universal, the laws of human interaction are certainly not: buying and selling technologies implies markets, ownership rules, the rule of law in general (see appendix D for some suggestions).

ABMs that do include the macro level can provide information on the effectiveness of policies changing the rules of the market (see e.g. Ligtvoet et al., 2011), the way in which company culture is aligned with the dominant societal culture (March, 1991), or how social influences impact on opinion (Axelrod, 1997).

Rational-behavioural-procedural First and foremost ABM is a rational approach, that blends in behavioural and procedural elements. These behavioural and procedural elements are, however, bound by rules and descriptions of social processes or procedures. As such, they restrict the behaviour of agents to what programmers deem 'normal and expected' behaviour which may, of course, be grounded in existing research. As we saw in chapter 5, very little can be said about expected behaviour, as parties shift and re-evaluate their options repetitively.

7.1.4 Serious gaming

The second hybrid approach, in chapter 6, we find more geared towards (unpredictable) actor behaviour. Although serious gaming requires a model of reality with certain rules and boundaries, it is the players that add spice to this method. The players each bring their own implicit set of skills, knowledge, and assumptions, which allows for emergent behaviour of the system that is being simulated.

Micro For the players their own personal response to a certain situation is part of the learning process. Depending on the number of rules regarding play, the range of options for the players is large or small. With a small amount of options the choices remain tractable and the comparison of games can be performed in an structured way. With a large amount of options each individual game turns more into a case study with a wide range of activities and responses.

In the particular Electricity Market Game instances that we observed, the width of micro behaviour was restricted by the rules and the educational setting in which the game took place. As the game progressed the players better understood the explicit and implicit rules of the game. They were hardly tempted to 'step out of the box' and challenge the modellers' assumptions. The Road Roles game allowed for more 'colourful' outcomes in terms of actor behaviour. The analysis, however, was harder and less conclusive.

Meso We consider the meso level as the focal point of serious games as it is the response to multiple players' behaviours that makes these games interesting. Again depending on the rules set, the range of outcomes can vary widely or minimally.

In terms of the games played in the Energy Market Game we saw that some groups were better at collectively servicing the needs of the market whereas others entered a boom and bust cycle. Although collectively lessons were learnt by the joint debriefing, individual lessons may have been different as the situations the players were in differed.

Macro The Energy Market Game was not specifically focused at learning macro-societal effects, although the influence of policy changes was being simulated (creating more uncertainty after the game had just settled down). By playing the same game in different countries, lessons may be learnt about cultural differences between these countries (see e.g. Meijer (2009); Altamirano (2009)). This was the case for Road Roles, although it was not played often enough to provide solid evidence for the cultural differences that were suggested by the different gaming instances.

Rational-behavioural-procedural Serious gaming needs a rational component to be able to design the game with its boundaries, rules, and game play, to look like the system that is being simulated. At the same time some procedural choices have to be made with regard to the rules. Depending on the rules, the procedures are to be chosen by the candidates or bindingly set by the game designers. The heart of the matter is the social interaction between the players, be it directly through negotiation or facilitated by computer screens.

7.2 Contrasting the approaches

We have chosen graph theoretical planning and case studies as two outliers on the continuum between quantitative and qualitative approaches. The 'hybrid' approaches of agent-based models and serious games stem from the same mathematical and operations research origins. We therefore suggest they are not two (fully) distinct methods, but freely flow into each other: computer models are used to support and enhance gaming exercises, whereas games can provide the empirical basis for the stylised behaviour of agents as well as a validation of the observed outcomes. Even for the farther extremes of graph theoretical planning and case studies the inclusion of elements of one approach is possible in the other. On the other hand, as we already emphasised above, there are some elements that clash. To make distinctions clear, we have to caricaturise the approaches somewhat. We therefore use the 'archetypical' forms of these four approaches to distinguish and contrast several basic characteristics of a model building process (see table 7.1 for a summary). These characteristics represent salient elements of each of the methods and have emerged from the method descriptions in the earlier chapters, as well as the evaluation literature for the different methods (Mayer, 2009; Meadows and Robinson, 2002; Stahl, 1988; Checkland, 1985, among others).

7.2.1 Goals of the exercise

In section 6.2 we have seen that methods can have different purposes or goals. Although formally the goals may be stated differently, we suggest that case studies are most geared to-

Table 7.1 – Characteristics of archetypes of graph theory, ABM, gaming, and case studies

Characteristics	Graph theory	ABM	Gaming	Case studies
goal	outcomes	outcomes	learning and understanding	point of reference, learning and understanding
logic	rational, optimisation	rational, incremental	behavioural, effectuation	rational, behavioural, procedural
abstraction	abstract, but tractable	black box, in practice	explicit for players	as explicit as possible
model openness	simple enough to be open	closed, in practice	open for players	analysis framework is model
main elements	technical or social	technical	social	technical or social
learning	researchers and clients	researchers and clients	participants and researchers	researchers and clients
dynamics	through iteration	shown by repeated simulation	revealed or exposed by game play	described
rules	fixed	fixed, possibly evolutionary	fixed or negotiable	described
level of detail	simplicity desired	inclination to detail	simplicity required for players	inclination to detail
treatment of uncertainties	captured in probabilities	captured in probabilities, but also emergent behaviour	cannot be captured, interaction and emergent behaviour	are described afterwards

wards understanding or at least revealing social intricacies, richness, and contextual complexity. ABM simulations and other quantitative models are often expected to produce quantitative outcomes as this is deemed more valuable to the intended users. Games are aimed at providing value to the player by offering learning experiences.

7.2.2 Logic or framework

We strongly underline that different approaches adhere to different 'world views' and that thus the answers that are sought and found are based on different premises. As we introduced in chapter 2, Astley and Zajac (1991) suggest that there is a distinction between rational approaches and behavioural approaches. They offer a third way, which they dub the procedural approach. Graph theory is strongly rational and ABM is also grounded in that tradition, although behavioural aspects do get attention and are being captured. Case studies are multifaceted in the sense that they can address all three views at once, depending on the research interest. Serious games focus primarily on behaviour, but are based on a rational analysis of the system.

An additional distinction can be made, based on Dew et al. (2008). In their view, there is a difference between optimisation and effectuation. The former being geared towards understanding and improving existing situations; the latter towards creating and designing new situations, opening new paths, innovating, exploring. It is about stepping 'out of the box', it is about choosing the game to play rather than playing according to rules made up by others. Bringing in human creativity allows for an effectuation mode.

Especially where creativity or entrepreneurship is involved, a rational approach will lead to blind spots. We argue that this limitation can also be found in implementing laws and regulations: humans, using their boundless creativity to achieve a certain goal, will always find a loophole. Thus, serious games allow for this additional dimension, whereas the other approaches only can provide input to it.

7.2.3 Abstraction

Likewise, the abstractions of the model remains more hidden in a simulation, because understanding them requires time and effort to dig into the code and assumptions that were made in the programming process. The tendency we identified above of adding more complexity and/or detail to computer models would suggest that a lower level of abstraction is chosen. However, this cannot be checked easily and therefore the abstraction remains obscured. In games, the abstractions need to be more explicit for the players to understand the model and therefore are also contestable for the players. As we have seen in chapter 6, the setting of the game may prevent the participants from actually challenging the game assumptions.

The graph theoretical approach is obviously an abstraction, which is its strength: simplicity. In case studies abstractions may lie in the treatment of the elements of the case, but generally the sought information is as explicit as possible.

7.2.4 Openness of the model

Agent-based models tend to hide many of the assumptions and abstractions that underlie the calculations – this is frequently necessary as the parameter space is very large and the details are many. Although gaming, as indicated, can also rely on such mathematical models, the abstractions are more explicit, as participants are in closer contact with the representation of the world: it is potentially easier to trace outcomes of activities (and then either accept or reject the abstractions).

The simplicity of the graph approach allows for easier inspection of the assumptions, although the way that these are represented in formulae maybe more daunting than the algorithms of ABMs. Case studies should be open in the sense that all the deductions that are made from the cases should be traceable to the case descriptions or supportive material.

7.2.5 Main elements concerned

Whereas all of the investigated approaches can be used for investigating cooperation in socio-technical systems, the main elements or main determinants are different. We suggest that graph theory and agent-based models are more appropriate for studying the (shape, robustness, costs of) emergent physical structures, thus necessarily focusing more on the physical characteristics of the system under study. Although both types of approaches are also used for simulating the development of social networks and social behaviour (e.g. Axelrod (1997) and Heath et al. (2009)), the level of specificity remains lower than for the technical elements.

Whereas physical realities (pipes, poles, machines) can be confidently captured by a limited set of equations, social phenomena (trust, friendship, bargaining) are dependent on a wide range of inputs that can hardly be specified in detail. Of course, they can be represented by variables and serve as input to models, which then either become one-dimensional or quickly become intractable. We suggest that serious games lend themselves to investigating behavioural components as well as case studies that allow for intricate description of the phases that cooperative ventures go through.

7.2.6 Learning parties

The learning aspects of models and simulations (graphs and ABMs) lie predominantly with the researchers themselves (although the models are often made for policy makers or other clients). In designing a valid model, many details need to be considered and researched which constitutes a learning process ('modelling as a way of organising knowledge' (Wierzbicki, 2007)). For outsiders, the simulation quickly turns into a black box that simply provides an outcome.

Gaming potentially allows for the same learning experiences for researchers or designers (Stahl (1988) suggests that most knowledge is gained from constructing games), but is also often specifically focused on a learning experience for the participants. In general we would say that the latter goal is deemed more important.

Case studies obviously aim to inform interested parties, but we would argue that the main learning is with the researchers. Like with models, the case study is highly influenced by the analysis framework that the researchers chose.

7.2.7 Dynamics

Three approaches allow for the observation of dynamics. In ABM simulations this can often be shown by displaying a time line of the variables of interest. In games the participants experience the different time steps and the different choices that can be made: thus, the dynamics of the game are slowly revealed to them. Possibly this leads to surprises. Case studies of business examples are generally described as a sequence of events, thus including the dynamic aspects.

Only graph theory does not automatically include a dynamic analysis of events (although dynamic analyses could be made). Depending on changing circumstances the calculations would be redone to arrive at new insights.

7.2.8 Rules present

One could say that modelling in general and agent-based modelling in particular is about codification or formalisation of behavioural rules. In describing an agent, we specify what steps the agent goes through in each time frame. Once this order of steps is fixed, it is assumed they remain so during the execution of the ABM simulation. There are a lot of hidden assumptions about institutions present (and non-present) and the rules that these institutions encompass. For example, the fact that agents trade goods assumes the presence of a market, an accepted way of trading goods (via a monetary system), and laws regarding ownership. Often, these rules are not made explicit and assumed to be commonly known and accepted.

Because of its focus on one specific type of relationship there is a limited set of rules in graphs, mainly about what node can connect to another node. We could also see the boundaries as representing rules, such as zoning laws.

In games, the rules are also mostly fixed at the beginning. As players are supposed to actively engage with the rules, they are to a large extent made explicit. Given what we have already said about level of detail, the rules need to be comprehensible and clear. There are, however, also games of a more ‘free-form’ nature, in which the participants can challenge the assumptions of the game developers. Some of the rules may then be adjusted to better fit the views and expectations of the players. This makes the outcomes of the individual games somewhat harder (or impossible) to compare, but it adds to acceptance and participation of the players and possibly also to new insights of the game facilitators. It may also help in uncovering players’ tacit assumptions.

Case studies allow for focusing on many types of rules if these are deemed important for the research question. Depending on the aim of the case study, they can be described extensively. However, a lack of focus on rules may also constitute a blind spot.

7.2.9 Level of detail

As computers are patient and Moore’s Law (Mollick, 2006) still holds, all rational analytical model developers are hardly hampered in their desire to capture detail and enhance the complexity of their models (Meadows and Robinson, 2002; Wooldridge and Jennings, 1998; Lee, 1973). This arguably leads to larger models that become increasingly difficult to verify (Galán et al., 2009). Although there are guidelines for better, more transparent presentation of models and their outcomes, some modellers continually need to be reminded of the KISS (keep it simple and straightforward/stupid) principle (Axelrod, 1997) – there is a tendency to what one could dub 'detail-creep'.

For designers of games, on the other hand, the limited cognitive load that participants can handle is an important given. The design needs to embody simplicity to a certain extent (as suggested by Meadows (1999b)), unless, of course, the aim of the game is to handle complex situations (as tested by e.g. Doerner (1980, 1990)). We would argue that successful engagement of players requires a certain level of simplicity, thus a built-in incentive for the researcher to limit the amount of detail. This tendency is somewhat offset by the knowledge that the higher the level of *relevant* details, the more trustworthy a game becomes for the players (Grisogono and Radenovic, 2011).

At the same time, we run the risk of simplification as a delusion (Brewer, 1978): treating a simply structured model as if it were reality itself rather than a perspective of reality and selecting a narrow range of topics from the array that could reasonably be included in the analysis.

Case studies are somewhat flexible: they can range from one-page descriptions that highlight the main elements to whole books that describe every relevant detail. We argue that case studies are often chosen to provide additional detail even though the knowledge of what details are relevant is not known beforehand.

7.2.10 Treatment of uncertainties

When a graph is calculated or an ABM is run, all elements of the model are specified: rules are explicitly stated and uncertainties have to be captured in a certain way to allow for quantification and calculation. The world the model represents is necessarily closed, even the uncertainties are known (which according to Knight (1921) turns them into mere risks). As the world that models try to emulate is ripe with uncertainties (van Asselt and Vos, 2006; Klinke and Renn, 2002; Walker et al., 2003), models quickly run the risk of being 'precisely wrong'.

Gaming is more geared towards allowing the knowledge and experience of the participants to directly influence the process of the game. First of all, the outcome of the game is strongly dependent on the will of participants to 'play along'. Often, details of the rules are still negotiable while gaming, allowing for a more realistic setting. Thus, behaviour-related uncertainties are not captured in the set-up of the game. This implies that the model should be open to 'irregularities' taking place. Once these irregularities do take place, the individual games immediately become less comparable.

Case studies are supposed to capture the salient uncertainties, although the reader cannot know whether this task has been performed sufficiently. It is said that the process of discovery is often different from the *ex post* justification (Hoyningen-Huene, 1987). Even though the case study may be drawn up by a skilful historian, the story-telling it entails also focuses on some details and ignores others (Brewer, 1978).

7.3 Three pitfalls

When using any of the mentioned approaches we see that researchers could easily fall into several traps. First of all they may be tempted to add *detail* to the analysis under the assumption that more detail leads to more information. For example, a more detailed description of all the installations of a plant may not lead to better insight in the energy flows. For exploratory purposes often a rough estimate is sufficient and – given all uncertainties involved – providing more detail is pretending that there is precision while it cannot be substantiated. It is important to understand what layer of analysis the investigation addresses and that not all layers need to be addressed equally.

Secondly, the researchers may be tempted to add to the *scope* of the investigation, which is the number of different factors that are included in the explanation. A scope that encompasses different types of industries, a range of behaviours, and that includes a description of the institutional and environmental surroundings of the system that we are interested in, may distract from the matters that matter. In statistics, if enough variables are taken into consideration, something is bound to correlate with something else.

Finally, researchers may be tempted to deploy their approach for purposes for which it has not been designed (*overstretch*). Generally, this entails giving advice based on an investigation where only hypotheses could be made. For example, we found that in animal behaviour studies the translation to human behaviour is made all too easily. In modelling agents, conclusions are drawn about the world that is modelled, instead of about the model itself. A model that is based on rational assumptions will provide limited procedural or behavioural insights.

7.4 Multi-perspective

Whether using graph theory, gaming, agent-based simulation, case study analysis, or a hybrid of these four, it is important to be aware of the dimensions in which these methods can be applied. Figure 7.1 displays all four methods in the framework that we presented in chapter 2. Especially the stark contrast between graph theory and case studies is noticeable. This suggests that researchers need to find the appropriate balance between detail or ‘richness’ and general applicability or ‘simpleness’.

All approaches allow for understanding different aspects of complex, adaptive, socio-technical systems. We argue that prediction should not be the main goal as predicting a complex system is impossible, but that patterns emerge that teach us something about the systems we investigate. However, the methods actually emphasise different aspects of reality, that may not be fully in line with each other. Therefore Nooteboom (2004) talks about the incommensurability of approaches: by framing a problem in one particular way the details required for another frame of reference are necessarily lost. Also Astley and Zajac (1991) suggest that there are different types of logic that are required for understanding organisations: rational, procedural, or behavioural. An important implication of this argument for organisation designers and analysts is that viewing organisations exclusively from either world-view may lead to inappropriate design choices.

According to Ryan (2008), the deepest divide between systems approaches occurs be-

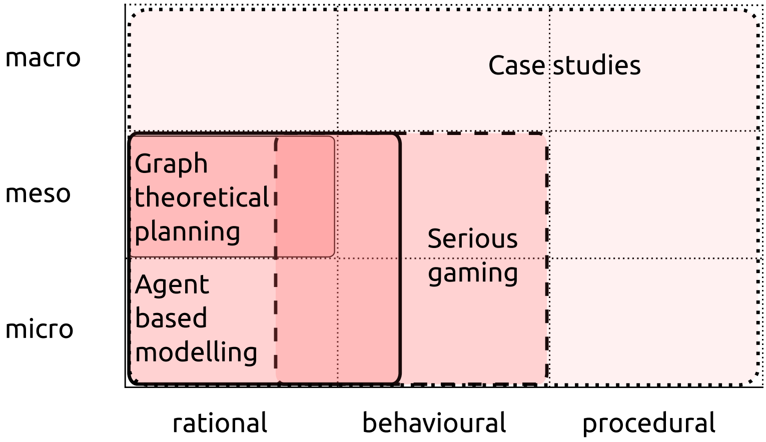


Figure 7.1 – An overlay of the four research methods in our framework shows differences in focus.

tween hard and soft methods. Soft systems methods take a pluralist stance: a systems model is taken to say more about the modeller and their assumptions than the system of interest itself. Advocates of soft systems approaches claim that hard approaches to social systems can be dangerous, because they do not account for the special nature of self-conscious and free-willed humans. Another way of approaching the dichotomy is to ask whether the goal of enquiry is objective knowledge or inter-subjective discourse. By using different approaches beside each other, we can give due attention to the dualistic nature of socio-technical systems. The following sections elaborate on possible combinations.

7.4.1 Case studies as a general approach

In terms of combining methods, we already indicated that case studies can be broadly applied as the researcher can focus on particular elements (analytical, social, or procedural) that suit his interest. We would argue that case studies is an excellent companion method for any of the other approaches. It can ground the more abstract, theoretical models in real life facts, it can provide input to games and models, it can be used to justify approaches and validate findings. As Flyvbjerg (2006b) states, concrete, context-dependent knowledge is extremely valuable.

7.4.2 Graph theory and agent-based models

We would argue that the two rational analytical approaches can also be easily combined. Although we kept our own agent-based model reasonably simple, the implementation of Steiner trees and minimal cost Gilbert networks would have been possible. The attribution of nodes/agents with reasoning power would most likely limit the options available as the decision rules would automatically prune some of the outcomes.

7.4.3 Bringing together simulation and gaming

Although in our overview we see an overlap between agent-based simulation and gaming, we see limitations in bringing them closer together (as opposed to e.g. Chappin, 2011) since their focus lies in different world-views. Some researchers say that rational and behavioural approaches are erroneously regarded as opposing (Brewer, 1978). This does not mean that they are equal and can be integrated. We rather would see them as juxtaposed, like eyes, to see depth. These approaches should not be brought together with the goal to integrate them, but as separate parts of a research process, to provide understanding and meaning to outcomes. This means accepting that not all behaviour is rational, or that certain types of behaviour can only be approached probabilistically.

One can use the creativity of humans to design better adgent representations. However, agents that rely on the improved, but fixed, behavioural rules will remain trapped in the framework that the programmers created. Conversely, students playing a serious game may also be constrained by social convention in a classroom setting and also the framework of the game designers.

7.4.4 Graph theory and gaming

The combination of graph theory and gaming would be a combination of two very different worlds. Of course the applied graph algorithms could generate networks that serve as an input to certain games and the outcome of games could lead to an improved assessment of chances of nodes joining a network. However, a combination is not likely to add new insights.

7.5 Using research for policy making

When policies are made, the policy makers rely on some type of model or idea of reality. Sometimes this is a very basic one, such as: competition leads to wealth creation. However, as our social systems are bewilderingly complex, (computational) models are employed to provide clarity. The whole idea of modelling is that in complex environments, individuals are not fully able to analyse the situation and calculate their optimal strategy (Axelrod, 1997).

Even experts may find it difficult to predict the outcomes of a relatively simple system. Given the complexity of our environments, modelling is deemed a necessity (Conant and Ashby, 1970; Epstein, 2008). Models legitimise, publicise, oppose, or make concrete some major old or new ways of thinking about the systems we live in (Meadows and Robinson, 2002) and open these ways of thinking up for discussion, be it not in a broad public setting, then at least in the scientific community.

Most policy problems involve complex and adaptive systems. For those systems the classical approaches of predictive modelling and optimisation that have been used in decision support software are not appropriate. Given the uncertainties we mentioned above, optimal policies for best estimate models may not be robust across the range of possible behaviours of the complex adaptive social system they represent.

Even more so, policy problems often present communities of stakeholders with values that are sometimes incompatible and group knowledge that is very difficult to elicit and capture in a single probabilistic structure. For complex adaptive systems – thus, for cooperation in energy networks – no modelling exercise can be viewed as final and definitive. The goal is to discover recommendations that hold for a large range of plausible models of the problem.

Chapter 8

Discussion and Conclusion

This chapter provides the conclusions and discussion of the thesis. To better understand cooperation we need a range of research methods that provide us with different images of cooperation. By understanding the advantages and shortcomings of the research methods we employed, we can better value the insights they provide. Our framework not only allows for mapping the micro-meso-macro and rational-behavioural-procedural dimensions of the research methods we used, but also allows for mapping future research directions in complex adaptive socio-technical systems.

8.1 Insights from the applied methods

The main goal of this research was to apply different research methods to increase our understanding of cooperation activities in energy networks. In the following sections we reiterate the contribution of the methods we investigated, and how and in what phase of the cooperation activities (see section 3.7.2) they can support decision makers.

8.1.1 Cooperation in case studies

Case studies provide appealing examples of 'real world' situations in which cooperation succeeded (or failed). Moreover, they provide the contextual information without which theories remain abstract and barren. Therefore, in tackling any realistic problem, some form of case study will be required.

Our case studies have shown that in planning and building energy networks the following factors can contribute to successful cooperation (section 3.7):

- technological enthusiasm and the belief that a certain solution is worth pursuing (even though the technology has not fully proven itself);
- doing something new and unique creates a drive to keep going, even in hard times;
- keeping up with the competition, to find out what businesses they are in and to keep in touch with new developments;

- hedging risk in projects with uncertain outcomes;
- fulfilling environmental goals the organisation has set itself;
- providing a positive image by contributing to an environmentally friendly project;
- sticking to a 'gentleman's agreement' (or loosing face in public press);
- participation in other projects to create a sense of urgency;
- circumventing (national) government;
- expanding focus beyond the original plan.

Whereas some of the factors provide rational arguments, social behaviour and unforeseen contingencies also provide part of the puzzle. The partners influence each other in their hopes and expectations, ambitions, requirements, and will to carry on – even when no-go decisions and ultimata are transgressed. There is no clear stopping rule, boundaries continuously shift, values are adjusted in a constant 'tug-of-war'.

Next to rational arguments and behavioural factors, understanding of cooperation can also be found in procedures. We have identified three procedural steps in cooperation practice (exploration, formalisation, and implementation). These may be expanded by adding more detail on what is to be done (e.g. sharing values, making procedural arrangements, shaping technological and organisational choices). The more details are given in a 'cook-book' approach, the less likely the actual process will look like it. A procedural approach should therefore be used as a rough guideline.

Because key elements in a given context may never reappear in exactly the same form, there is uncertainty that any given phenomenon will ever reappear (for example, the illustrious *Kalundborg* example in industrial ecology (Ehrenfeld and Gertler, 1997)). While the skillful historian may tell a story that is plausible and consequently widely accepted, we must not lose sight of the fact that it is just a story and may be a happy coincidence. Nevertheless, these phenomenological descriptions lead to plausible hypotheses about cooperation and rules of thumb that help in setting up cooperative efforts.

8.1.2 Cooperation in graph theoretical planning

The research on graph theory and planning has taught us that there are relatively simple and transparent tools that support spatial and infrastructural planning. Graph theory does not provide direct information on additional reasons for cooperation, but it does allow analysis and visualisation of options for cooperatively building infrastructures. Thus its role would be of informing decision makers in the *exploratory phase* of cooperation. It provides a contribution to the cooperation process, not an insight in how these processes function.

Although it may be uncertain which potential cooperators take part in the joint building of a pipeline network, or what their reasons for cooperation might be, an exploratory approach can yield information on likely and unlikely locations of such an infrastructure. However, we learn that the application of this method to a relatively small group of participants (≈ 20) already leads to combinatorial explosion of options therefore limiting this approach to small groups of actors. Furthermore, dynamic developments can not (yet) be captured.

8.1.3 Cooperation in agent-based models

Agent-based models can be applied to a wide range of problems in which (assumptions about) individual behaviour has an effect on collective system behaviour. They can also be used to explore vast scenario spaces of parameters and their effect on system behaviour. Often the systems that are simulated display complex behaviour that would be intractable without the help of formal computer models.

ABMs can simulate patterns of development and success paths of industrial clusters, identifying factors that may hinder the desired outcome – as we have seen in the syngas case. They may also show whether assumed cooperative behaviour makes operational sense. One of the premises, however, is that there is sufficient knowledge to model individual decision making. It can be argued that for daily routine decisions there is sufficient information available to approach actual human behaviour. Strategic decisions on large infrastructures are not of that kind: as we have seen they generally involve prolonged interaction of different stakeholder firms and within those firms different planners, strategists, operational personnel, and executives who operate in a network of influence.

We found that ideas of exploratory modelling can be applied to agent-based models. In exploring the scenario space of a relatively simple agent-based model of an industrial cluster we found areas of failure and success. This approach provides an analysis of the feasibility of the cluster operation, especially under the dynamic conditions of the *implementation phase*.

One of the pitfalls of this method is in thinking that detail leads to better insights. Often the model needs to remain somewhat abstract to render it tractable. The abstraction, unfortunately, hinders the communicative power of this method.

8.1.4 Cooperation in serious gaming

Serious gaming probes more into behavioural aspects than the previous two methods. It should therefore be used in situations in which stakeholders' response to environmental conditions or each other is unclear. More importantly, the involvement of human actors allows for an effectuative element, the emergence of new ideas, and responses that may even surprise the researcher. This means that more emphasis is given to personal and interpersonal motivations and creation of new options, less to technological details. It would therefore be more suitable for simulating and tackling problems in the *formalisation phase*.

Although the experiment we did with the Energy Market Game concerned a social network instead of a physical one, the game and the questionnaire we used to probe the players' response still provide insights in cooperation (cartel formation). First steps towards cooperation seem to build on existing social structures, whereas players would like to know about competitors' strategies in investing in power stations. The competitive factor remains important, which may be due to the game boundaries. A more free-form game like Road Roles leads to wider ranging behaviour, which is more difficult to analyse in terms of rules and dynamics.

This method can lead to lessons and personal insights for the players, the information gained by gaming is not necessarily generalisable as some of the implicit rules remain hidden. Also, personal traits and group dynamics may differ as we saw in the 2011 and 2012 student groups. Manifold repetition of the experiment is required to identify what to expect as 'normal' behaviour of players given the boundaries of the game. Otherwise, serious games turn into singular case studies of how one game is played.

8.2 Learning from previous research

We have built our research on a wide range of literature that investigates cooperation: some fields address it from an explanatory stance (how does it work? what are the underlying reasons?), a phenomenological stance (what examples of cooperation are there? how does it progress?), and a normative stance (what is the best cooperative behaviour? what should be done?). As we indicated in chapter 2, the level of analysis differs from micro level behavioural or game theoretic approaches, through meso level network and actor influence analysis, to macro level evolutionary and cultural analyses.

Although game theory prescribes the optimal outcomes of games between rational players, experimental economics and psychology show us that defection takes place in far less cases than we would expect based on classical game theory. Furthermore, both individual (e.g. gender), interpersonal (e.g. communication, negotiation), as well as cultural traits all play a role in decision making. This means that any answer is contingent upon a vast array of – often unknown – factors. Research performed to provide practical advice can only offer rules of thumb and broad guidelines.

Animal behaviour provides us a wealth of examples of (non-)cooperation in nature, some of which is very mechanical or unintended, but scarcely addresses the reflexive nature of humans. We can safely assume that humans do not respond the same way that slime moulds do, although some scientists would have you believe it. The similarity of the outcome, however, does not prove the reasoning behind it. Even primates do not share the reflexive nature of humans (as far as we currently know). In human societies, not only micro motives determine macro behaviours, but accumulated culture also shapes the degrees of freedom that individuals and organisations have.

In order to unravel the workings of cooperation, we have to understand what influence the different layers of cooperation have. Path dependency – the fact that history matters – plays an important role as historical choices curtail decision makers' freedom to act. Society has become more 'turbulent' as its networks and institutions have become more densely interconnected and interdependent. Just as Darwin saw the biological world as a 'web of life', so the organisational world is endowed with relations that connect its elements in a sophisticated way. In this organisational world single organisations belong to multiple collectives because of the multiplicity of actions they engage in and the relationships they (necessarily) have.

Cooperation therefore is not a simple matter of cost and benefit (although this balance may greatly determine the choice), but a learning process that is influenced by history and tradition, laws and regulations, networks and alliances, goals and aspirations, and, quite simply, chance: a complex adaptive phenomenon. In our opinion, failing to understand this is failing to understand cooperation. We have to conclude that not one of these disciplines explains cooperation phenomena sufficiently on its own. We have to combine knowledge derived from different fields to obtain a more complete picture; one that at least challenges simple solutions.

8.3 Cooperation in complex socio-technical systems

From a descriptive point of view, there is ample information from the management sciences on the successes (unfortunately less often on the failures) of cooperative ventures in the business world. Implicitly and sometimes explicitly (e.g. by Emery and Trist, 1965; Ligtvoet, 2012b), this business world has been described as a complex socio-technical system. This complexity makes it hard to describe a meaningful formal model. A phenomenological approach can provide rules of thumb and heuristics.

Learn and adapt As we have seen in our case studies, cooperation emerges from an evolutionary process of mutual learning and continuous adaptation in which confidence, trust, and excitement are a positive basis for starting the cooperation. Based on the participants' experience in working together, they are more likely to engage in new ventures. Although thorough calculation of benefits and costs and optimisation of available resources is a stated goal, learning to cooperate often takes place in incremental steps, by tweaking the available resources, one step at a time, adjusting to contingencies. Although it is easier for modelling purposes to portray an organisation as one actor, these organisations are in fact collections of communicating individuals. These individuals sometimes influence each other to collectively fit the environment and sometimes create a collective that is not aligned with the outside world. Therefore, opportunities for cooperation do not only depend on organisations' profiles, but also on the individuals that constitute the organisation.

Explore and try out The willingness to learn and adapt also entails trial and error. In a complex system, creative exploration and diversity of strategies may be more effective than selfish short-term stratagems. The effectiveness of such cooperative strategies can be demonstrated in agent-based models in which the agents have the option to choose for conventional, solitary operation (see section 5.3). As the future is erratic and hard to predict (if not unpredictable), choosing a fixed optimal strategy is intellectual hubris. Cooperation is often undertaken with the idea of taking limited shared risk, going beyond what is known, jointly exploring future options. This explorative attitude is by definition entrepreneurial, as participants venture into the unknown. Free-form games allow for simulating and testing the effects of entrepreneurial or boundary seeking behaviour. Whereas in reality explorers who perish in unknown lands are never heard of again and successful scouts are hailed as shining examples of best practices although they might have just been very lucky, serious games may actually be used to capture some of the mistakes that decision makers make.

Social behaviour builds up to relationships From literature we learned that in cooperation a range of human phenomena play a role: cheating, trust, reciprocity, fairness, sanction, retribution, punishment, guilt, forgiveness, and reconciliation. Repeated interactions, reputation-formation, and reciprocity are powerful determinants of human behaviour. In commerce, the great enforcer of morality is the continuing relationship: the belief that one will have to do business again with this customer, or this supplier. In setting up energy networks one is assured of long-term interaction through physical networks that form a permanent dependency. Our case studies show us that this building of relationship takes place long before the actual physical infrastructures are a fact, through teamwork and joint experiences.

Building social capital Cooperations are more than simple instrumental means for achieving collective goals directly benefiting the collaborators. They also constitute each partner firms' corporate social capital, providing potential access to various assets controlled by other strategic alliance network members. Alliances provide opportunities for participants to tap into the resources, knowledge, and skills of their immediate partners in a portfolio of inter-firm agreements. Even though some cooperative effort may not yield direct returns, it opens up options. The options may or may not lead to concrete opportunities.

Rules emerge from long-term interactions Where rational self-interest falters, social norms can come to the rescue. Cooperation is underpinned by rules, norms, and conventions established and maintained to varying degrees, dependent on the location of the industrial district by trade associations, trade unions, the state, political parties, religious affiliations, and more informal community-based institutions. This institutional web not only creates an environment for cooperation, it eventually provides procedures to resolve disputes, to impose sanctions on transgressors, and to adjust to external environmental changes. At the same time cooperating partners form modi of operation that fulfill dynamic needs.

The level of cooperation between businesses is much less influenced by costs and benefits than by the history of the partnering firms' relationships, the current market positions of each firm, their joint resource capabilities, and informational asymmetries. In other words, forming business networks and contractual or relational alliances is driven by their strategic intentions: two or more autonomous organisations decide to form an alliance for an emerging joint purpose. This emerging joint purpose is extremely difficult to capture in formal models.

Conditions of cooperation and countervailing forces It is found in several studies – both theoretical and empirical – that uncertainty leads to cooperative efforts: a varying environment compels actors to join forces and face the unknown together. An advantage of joining forces is that it reduces network or relational uncertainty. That is, if the cognitive distance between the actors is not too large (Nooteboom, 2004).

However, there are also risks and disadvantages of cooperation. Some dysfunctional outcomes of collective strategies include a reduction of strategic flexibility due to contractual obligations, an increased impact of external disturbances, false illusions of strength, and lower organisational adaptability. In industrial networks we do not see as much symbiosis as we would expect based on rational analysis of cooperation benefits. This may be because the fear of mistake is bigger than the lure of profit or corporate responsible reputation. Literature on group dynamics suggests that groups, more readily than individuals, may create illusions of invulnerability, censor information, suppress dissent, or become locked into a decision making impasse ('group-think') if conflicting interests appear irreconcilable (Bresser and Harl, 1986).

Contractual interconnectedness – especially if it entails hard-wired connections in energy networks – tends to reduce strategic flexibility. By creating or tightening interconnections between organisations channels open up through which the impact of external forces can reverberate throughout a collective. Abstaining from competitive behaviour, economics tells us, attracts new entrants because reductions in competition usually result in prices fixed at monopolistic levels and in limited innovations.

8.4 Informing decision makers

The approach we have taken throughout the research is one of understanding the uncertainties of cooperation, not of solving them. The modest goal of the methods described in this thesis is to *inform* decision makers, to *help* them make up their mind and reason through different options. As Keeney (1994) and Wierzbicki (1997) write, we perform research to lend *some insight* about a complex situation to *complement* intuitive thinking of decision makers.

Case studies do so by providing good (and sometimes bad) examples of organisations that have attempted similar cooperative projects. They are appealing as they present holistic stories that create 'mental hooks' for decision makers; these stories can be related to and are open for decision makers' own interpretation and analysis. This openness is at the same time its major flaw: salient details are chosen by the researcher and possibly highlight the conclusions that the researcher is working towards.

Graph theory, in the way that we used it, can help find low-regret cooperation decisions with regard to network location in an uncertain environment. Its strength lies in not hypothesising about particular behaviour, but in treating it as a simple probability. In an exploratory phase of a cooperation process, the generated graphs create rough sketches that aid decision makers with suggestions of low regret pipeline routes.

Agent-based models are able to combine the strength of rational analytical approaches with the notion that surprises can emerge due to individual, path- and context-dependent behaviour of agents. This should convey the notion that the future cannot be predicted, but emergent patterns can be unveiled. The question is not whether cooperation emerges, but what the shape and dynamics of the socio-technical system could look like if it does. The outcomes may actually surprise the decision makers.

Serious games as a research tool remain as distant from decision makers as do other methods. The strength of serious games is that they allow for closer interaction of participants with the researchers' model. For decision makers the true value comes from participating in the game, from experiencing the uncertainties, and responding to other players' interpretations and actions. Even though the model that the game is based on may be flawed, the participants gain from the exchange with other players (possibly building trust and reputation), or – if the game is constructed well – at least they will have had some fun. One might even be tempted to conclude that if cooperation with other parties is considered, the prospective partners should begin by playing a game.

The four methods we investigated thus each contribute to rational, behavioural, and procedural insights in cooperation. Without technical, financial, legal, underpinning – a rational analysis of the situation – proposals will loose credibility in the face of shareholders, financiers, constituents, and the wider public. We argue that this rational analysis should not aim for predicting the *one true* value, but offer a range of possibilities that do justice to the uncertainties that play a role. However, behavioural and coalitional tendencies of actors might steer away from rational optimal solutions towards social solutions that follow a different logic. We have suggested a number of factors that seem to play a role, but acknowledge that this list is not complete and dependent on external circumstances. Furthermore, by understanding procedures – the way things go – decision makers receive some guidelines as to what might happen in the course of a cooperation process. We argue that these procedures are the patterns that emerge under the influence of the institutional context and the interplay of rational and behavioural factors. Therefore, small changes at the micro level may actually cascade through to the meso and even to the macro level. Finally, it should be realised that in new ventures actors operate in effectuation mode – they each have their own goals that continuously shift and are updated according to the options available.

8.5 Reflection

8.5.1 Energy networks are like other cooperation efforts

We started this thesis with a focus on energy challenges and cooperative responses to these challenges. Our initial argument was that energy networks are different from other cooperative efforts as they require large investments that physically tie together the participants for a long period. In the end, however, we come to the conclusion that this does not fundamentally differ from other cooperation activities. The type of projects we describe in our case studies do tend to be more complex because of the multiple stakeholders involved, the dependence on political decisions and shifting regulations, the geographic scope transversing public and private terrain, and the connection of different *types* of partners in one project which requires different forms of justification for the projects they engage in.

8.5.2 Choosing your game is no routine

The type of decisions we write about are no daily activities, they are not done on autopilot, and generally involve a lot of thought of the actors involved. Whereas the idea of an organisational ‘script’ (e.g. mentioned in Nooteboom, 1999) is appealing, the strategic choices we are interested in are hard to capture in scripts (other than a very general, procedural one). This is unfortunate, because the notion of a script lies very close to the decision making algorithms in agent-based models. The more an activity becomes a routine, the more likely it is to be captured with such scripts.

Furthermore, our research has led us to ponder on the definition of strategy. Is strategy about the scale of the project involved? About the amount of time one looks ahead or the scope of the influences considered? Whether a prime minister or a CEO is involved? We would like to give a short answer as follows: strategy involves the decision *which game to play*. Therefore it is difficult to have simulated agents make true strategic decisions: they only do what they are programmed to do and generally do not seek for better games with more chances of winning. Therefore it is also difficult to behave truly strategically in a serious game, as many options have been closed down by the framing of the game. Although some games are specifically designed to challenge the players' frame of reference, participating in a game generally involves accepting someone else's model of reality.

8.5.3 Networks old and new

Throughout this thesis we have (implicitly) focused on nascent networks: networks that still needed to be built and for which neither scope, size, nor participants were certain. In our case studies we had one existing network, the OCAP main pipeline, but that was being used for novel purposes by new parties. So in fact we chose to focus on processes that emphasise the entrepreneurial, effectuation mode of the different actors involved.

Had we chosen for already existing networks, the focus may have been different as a large part of the design uncertainties would have already been decided on. Micro motives would still play an important role for choosing with what parties to cooperate; however, the actors maintaining the existing network would have an existing power position and supposedly a stronger bargaining position. There would be an existing base of formal and informal institutional arrangements, that might be changed, but would most likely limit the degrees of freedom available. In short, the mode that Dew et al. (2008) call optimisation would be more appropriate, allowing both agent-based models and serious games to capture the issues at stake more decidedly. Also for case studies, there would be more available material in terms of actual physical networks and presumably a range of agreements. For graph theory, connecting to existing networks would provide an additional expansion to our work, as we argue in Heijnen et al. (submitted).

8.5.4 Muddling through – a pessimistic view?

In our attempt to tackle 'wicked problems' (Rittel and Webber, 1973), we (scientists, consultants, decision makers, humans) often end up 'muddling through' (Lindblom, 1959). Or even more cheerfully: 'for most adaptive or humanly defined problems the islands of success are infinitesimal next to the illimitable seascapes of failure' (Tooby and Cosmides, 1992, p.103). This is either a cry of despair or proof that we miraculously must be doing something right. However, the fact that we have done something right in earlier examples of cooperation, does not necessarily mean that the path we took is conducive to cooperation success in other cases. Thus, we must continuously and critically review our ideas and hypotheses about cooperation.

The debate about strategising versus economising comes to mind (Astley and Fombrun, 1983; Williamson, 1991): one can try to predict the unpredictable future with sophisticated methods (strategising), or one can try to improve the daily routines and thus improve the overall cash flow and profitability of the enterprise (economising). At this boundary it is possibly where academia and practice meet: one providing new projections and vistas, the other providing the hard facts of life that practitioners have to deal with. We may be muddling, but as long as we are muddling together, we can make progress and learn from each other.

8.5.5 Macro myopia

In this thesis we have steered away from macro level influences: we specifically chose examples of the Netherlands for which we can safely assume that there is a similar political, institutional, and cultural environment. Even though we limited our scope, cultural elements do come into play as foreign organisations acquire subsidiaries in the Netherlands (see the OCAP case in chapter 3). We agree with Chiong Meza (2012) who argues the importance of considering macro level influences and suggests that there needs to be more thorough research on the influence of culture in socio-technical systems. Even though – as Williamson (1998) argues – the cultural change processes take decades and are therefore often ignored by (institutional) economics and research domains that build on this theory, the macro level plays a consistent role and should not be overlooked. For serious games, Meijer (2009) and Altamirano (2009) provide interesting starting points.

Dignum et al. (2008) suggest that culture manifests itself in a number of ways. First, culture filters observation and sets norms for what constitutes an appropriate partner or offer. It determines the salience of clues about the acceptability of these trade partners and their proposals. Furthermore, it sets expectations for the context of the transactions, for example, the enforceability of regulations and the possible sanctions in case of breach of the rules. Finally, it sets norms for the kind of action that is appropriate given the difference between the actual situation and the desired situation. Given the importance of culture and the increasing globalisation that we face, we had better acknowledge macro level influence lest we make the mistake of transplanting solutions without knowing the context in which these solutions are used (as extensively described by Rogers (1995)).

8.5.6 Procedures as emergent property

When looking at the four methods and their focus, we notice that only case studies address procedures. The other three approaches *assume* procedures to be present and implicitly or explicitly codify these assumed procedures in their model of reality. In complexity terms, we can see procedures as the emergent property of actors' rationality and behaviour. In a sense, procedures constitute higher order patterns that are described as 'rules of the game' (Astley, 1984; de Bruijn and ten Heuvelhof, 2008; Howard-Grenville and Paquin, 2009), 'scripts' (Nooteboom, 1999; Dignum et al., 2008), or just 'the way things work'. The problem is that the origins of these procedures are not explained by merely describing them and thus further research on how procedures emerge is warranted.

8.5.7 Testing and validating

Any modeller wrestling with the representation of a social system in the demanding language of the computer must come to terms with uncertainty, with the inadequacy of social data, and with the annoying tendency of interconnected elements not to behave in the way he or she thought they would (Meadows and Robinson, 2002). The goal of testing and validating a model therefore becomes a rather modest enterprise. For, if one accepts the tenets of complex systems in which small changes make big differences and local disturbances can modify the outcome of whole systems, the only test is whether the elements of the model behave in some predictable way from one time step to the next. This means not focusing on the macro outcomes and certainly not pretending to reproduce historical events. It does mean looking at micro behaviour under certain conditions. The more elaborate the model, the more elaborate this testing will need to be.

One could always present the outcomes of the models to decision makers and experts in the relevant sector. They could be asked to provide comments and suggestions regarding the model runs, thus providing a rough 'test' whether the outcomes can be considered realistic and practical. However, in a dynamic, changing world the plausibility test may again be biased by expert expectations that may have been valid in the past, but do not reflect future reality.

8.5.8 Simple versus complex

The ideal formal model would be one that could cover the entire universe, that would agree with it in complexity, and that would have a one to one correspondence with it. Anyone capable of elaborating and comprehending such a model in its entirety, would find the model unnecessary, because he could then grasp the universe directly as a whole (Rosenblueth and Wiener, 1945). Somewhere, however, between the specific that has no meaning and the general that has no content there must be, for each purpose and at each level of abstraction, an optimum degree of generality (Boulding, 1956).

An important question that any modelling effort must address is what the correct balance is between detail or 'richness' of the model and general applicability or 'simpleness' (following the KISS-principle advocated by Axelrod (1997), amongst others). We already indicated that researchers adhere to rational choice models, whereas their explanatory power is limited. As Fioretti (2005) points out, the space of abstract concepts has been largely explored and the paucity of empirical and applied models is criticised; the next frontier is in getting closer to reality. The way to achieve this is not by building increasingly complex models, but by selecting a range of representative simple models that – by definition and explicitly stated by the researcher – only capture a limited set of system behaviours.

8.5.9 On researching and modelling cooperation

The beauty of building mental models is that – in principle – there is an explicit logic that can be traced, analysed and falsified, where necessary. As these mental models require testing, the modellers go through a process of 'modelling as learning', where the process is as important as any predictive answer (Wolstenholme, 1999). Axelrod and Tesfatsion (2006), however, specify a number of goals pursued by researchers: empirical, normative, heuristic, and methodological understanding.

When the goal of a researcher is *empirical understanding*, he asks the question why particular large-scale regularities have evolved and persisted, despite (the lack of) top-down control. The idea is that micro-level rules lead to these macro-level regularities and thus form the basis for the observed phenomenon. Research on complex adaptive systems has proven helpful in exploring issues of path dependency, the consequences of heterogeneity among actors, the design of institutional mechanisms to achieve specific goals in a population of autonomous actors, and the effects of network structure. This understanding remains on a conceptual level.

Another goal of the researcher may be *normative understanding*: using models as laboratories for good designs. For designing energy networks under conditions of uncertainty, this may be one of the ways of testing different topologies as well as the effects of introducing new actors to the network. The added value is, however, mainly in the technical design as we are not confident enough that our understanding of human behaviour is sufficient for the type of problems that we try to tackle. If we assume that actors are reflexive and respond strategically to differing situations, claiming that a limited set of rules could capture this behaviour would be too bold a statement.

A third goal is *heuristic understanding*. It is closely linked to the empirical understanding mentioned above. The focus is more on investigating the fundamental causal mechanisms in social systems: what steps and rules of thumb produce what types of outcomes? Hypothesising about and modelling the different heuristics for actors leads to insight into the stability of the system. We could say that a simulation agents' script is always considered a behavioural rule of thumb. As indicated above, the explicit description of the heuristics allows for inspection and falsification. One can question whether in practice this will take place. However, models quickly become too large, oversight is easily lost and costly to obtain.

Finally, one tries to achieve *methodological advancement*: how best to provide researchers with the methods and tools they need to undertake the rigorous study of social systems through controlled experiments? With regard to tools, this thesis has mainly built upon earlier developments and existing platforms. We have contributed to methodological thinking about the boundaries of new research methods such as serious games and agent-based models. By making their assumptions more explicit, by recognising that the choice for a paradigm limits the outcomes of a model, researchers can better communicate the caveats of their work.

8.5.10 Postnormal

By framing our research within complexity science *as well as* postnormal science, we run into the difficulty of drifting far away from what is 'traditional' science. Uncertainty is not banished but is managed, values are made explicit, complexity is embraced, and location and process become an important element of the explanation of the problem. Once you accept this, science can never be quite the same. Conversely, the search for single solutions and 'the ultimate answer' becomes a futile quest. Scientists are no neutral observers and equally shape (or even distort) the systems that they study. We find out that the best numbers available may simply be guesses collected from experts, and by presenting outcomes in a scientific style (formulas, diagrams, and system models) researchers convey greater confidence than they should, based on their methods.

As Funtowicz and Ravetz (1993) state in their seminal paper on postnormal science, computers could in principle be used to enhance human skill and creativity by doing all the routine work swiftly and effortlessly, but have instead become substitutes for disciplined thought and scientific rigour. More is not always better (although it *is* different (Anderson, 1972)). This leads us to the final point of reflection.

8.5.11 Complexity and modesty

Even though it is tempting – and in certain settings required – to present outcomes of scientific research as breakthroughs, guidelines, and cook-book recipes for success, the fact that we have framed our problem as one that falls within the domain of complexity science must lead us to conclude that what we know about the dynamics in socio-technical systems is rather limited. We have to admit that we cannot predict, we have limited data, much of which is flawed, and there are many unknown unknowns. This, however, is no reason to dismay.

First of all we have gained a stronger basis for dismissing general and simplistic answers. Furthermore, we have clarified the fact that different facets play a role in cooperative efforts and that understanding cooperation requires a multidisciplinary effort. Cooperation is an interplay of utility – often expressed as financial gain – and other personal motives, trust and reputation in existing and newly forming networks, and the influence of business cultures, national cultures, and laws. It is sometimes an entrepreneurial and sometimes an optimisation process, depending on the frame of reference. Heisenberg for the social sciences.

8.6 Further research

The framework we have used to qualify the research methods in this thesis may also be used for identifying research opportunities (see figure 8.1).

An upcoming field of research is that of social networks. The opportunities that our electronic media have given us in terms of available data (via e.g. Facebook, Twitter, and LinkedIn) open up vistas of better understanding the dynamics of corporate social networks. By investigating connections and interlocks between boards (Mizruchi, 1996; Moliterno and Mahony, 2011), one could start investigating whether (semi-)formal social networks influence organisational decision making. In terms of our current research that would be a deepening of understanding the way that the meso level of cooperation works. One of the challenges of such an approach would be in finding the necessary network data, which is currently not publicly available in the Netherlands. Further pursuing this line of research would eventually touch upon ethical questions of privacy and commercial questions that relate to the competitiveness of firms.

One of the most interesting challenges in research is to achieve truly interdisciplinary understanding by tying together different scientific streams. This thesis has been an exercise in finding the difficulties of such an approach, but at the same time it has shown that bringing together diverse points of view can actually lead to insight. The crux is being aware that core assumptions (one could say: *paradigms*) determine the way in which

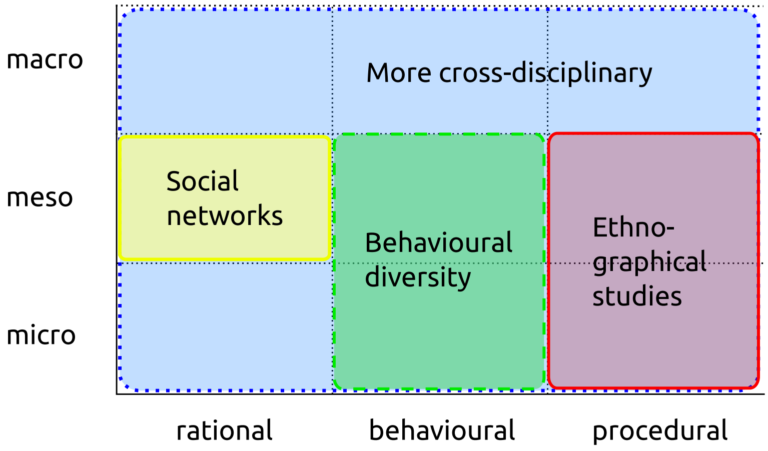


Figure 8.1 – Future research directions in our two-dimensional framework.

methods are employed. Astley and Zajac (1991), for example, talk about the difference between a coalition and politics oriented view of an organisation versus a rational goals-oriented view. Looking at an organisation from different points of view leads to different conclusions as to what course to take in the future. Dew et al. (2008) clearly distinguish between a predictive position and an effectual position: the former focuses on solving problems whereas the latter focuses on finding (new and unthought of) solutions. If we are interested in supporting decision making, we would have to get a better grip of the question *what it means to employ a predictive tool in an environment that is more design-oriented (or vice-versa).*

Supporting Brewer (1978), we find that (still) far too little is known about differences that experience, gender, culture, risk level, and uncertainty make for game play and outcomes. Like pharmaceutical testing is based on healthy males between the ages of 18 and 65, much of the behavioural research is biased towards highly educated adults between the ages of 18 and 23. These matters should be explored more systematically and made more explicit. This would, however, require critically observing the tools that we design for teaching purposes. Even in an academic environment this is hard to achieve given operational requirements and shrinking budgets. As with modelling, more focus can and should be given to systematic improvements of the basis and assumptions of existing tools and solutions rather than building whole new artefacts.

Finally, there is still room for studying the process of cooperation in more detail. Instead of *ex post* case studies, ethnographical studies allow for more participative observation. The researcher may even perform 'action research': positive intervention that supports the desired organisational change and lowers feelings of anxiety or suspicion towards the researcher (Coughlan and Coghlan, 2002; Checkland and Holwell, 1998). Such an approach would certainly cross the borders of 'normal science' but – provided that scientific rigour is pursued – offers exciting vistas for socially relevant research.

Appendices

Appendix A

Graph theory

A.1 Minimum cost spanning tree

Given a set A of n terminals, $a_1, a_2, \ldots, a_n$, in the Euclidean plane, from which a_1 is the source node and the terminals $a_2, a_3, \ldots$, an are the consumption nodes and given the required capacities $q_{1,i}, i \in 2, 3, \ldots, n$ of the connections between the source node a_1 and the consumption nodes a_i , and the cost 0.6 function (equation 4.1), $C(N) = \sum_{e \in E} l_e q_e^{0.6}$. Starting from the source node a_1 , add one of the nodes $a_i, i \in 2, 3, \ldots, n$ to the tree that yields the smallest increase in costs and that is not yet included. Additionally, it is ensured that all intermediate trees do satisfy the capacity requirements of the nodes that had already entered the tree.

A.2 Euclidean Steiner minimal tree problem

Gilbert and Pollak (1968) define the Euclidean Steiner minimal tree problem as follows: a Steiner minimal tree for given points $a_1, a_2, \ldots, a_n$, the terminals, in the Euclidean plane is a tree which interconnects these points using lines of shortest possible total length. In order to achieve minimum length the Steiner minimal tree may contain other vertices (Steiner points) beside $a_1, a_2, \ldots, a_n$. They also define some useful properties of a Steiner minimal tree:

- No two edges meet at an angle less than 120°.
- Edges incident to a Steiner point meet at exactly 120°.
- The degree of a terminal point is at most three.
- Each Steiner point has exactly degree three.

A.3 Minimal cost Gilbert network

Given a set A of n points (nodes) $a_1, a_2, \ldots, a_n$, in the Euclidean plane and given a flow set Q of bilateral non-negative flow demands q_i, j between a_i and a_j $(i \neq j)$, let $N = N(A, Q, f(Q))$ be a network connecting the given points with a cost function $f(q)$ which represents the cost per unit length of an edge in N to which a flow $q (q \geq 0)$ is assigned. Hence, the cost of an edge e is $C_e = l_e f(q_e)$, where l_e is the length of e and q_e is the total flow assigned to edge e. The total cost $C(N)$ of the network N is the sum of all edge costs:

$$C(N) = \sum_{e \in E} l_e f(q_e) \tag{A.1}$$

where E is the set of edges of N. The cost function $f(q)$ can be naturally assumed:

- (non-negative) $f(0) \geq 0$ and $f(q) > 0$ if $q > 0$;
- (non-decreasing) $f(q + r) \geq f(q)$ for any $r > 0$;
- (triangular) $f(q + r) \leq f(q) + f(r)$ for any $q, r > 0$.

A network N satisfying the above conditions is a Gilbert network and the given points in A are the terminals (Gilbert and Pollak, 1968; Thomas and Weng, 2006). A Gilbert network N is a (global) minimum cost Gilbert network if N has the minimum cost of all Gilbert networks spanning the same terminal set A, with the same flow demand q_i, j and the same cost function $f(q)$. Also finding the minimum cost Gilbert network is NP-hard.

A.4 Adapted Melzak method

In the classical Steiner tree problem, if a Steiner tree is locally minimal then every angle in the tree is greater than or equal to 120° (Hwang et al., 1992). Thomas and Weng (2006) also define an angle condition for locally minimal Gilbert networks. Let

$$\phi(w_1, w_2, w_3) = \arccos\left(\frac{w_3^2 - w_1^2 - w_2^2}{2 w_1 w_2}\right) \tag{A.2}$$

Then a Gilbert network N is locally minimal when every angle in N formed by two edges $e_1 = p_1 p$ and $e_2 = p p_2$ satisfies the following angle condition:

$$\angle p_1 p p_2 \geq \phi(f(q_1), f(q_2), f(q_1 + q_2 - 2q^*)) \tag{A.3}$$

where q_1 and q_2 are the capacities of e_1 (from p_1 to p) and e_2 (from p_2 to p) respectively, and q^* is the flow from p_1 to p_2.

Given a set A of n terminals $a_1, a_2, \ldots, a_n$, in the Euclidean plane, from which a_1 is the source node and the terminals $a_2, a_3, \ldots, a_n$ are the consumption nodes and given the required capacities $\mathrm{q}_{1,i}$ of the connections between the source node a_1 and the consumption nodes $a_2, a_3, \ldots, a_n$, and the cost function (equation 4.1), we define the following algorithm to find a (local) minimum Gilbert network (based on the first heuristic of Thomas and Weng (2006)). By that our algorithm is also heuristic by nature. The algorithm starts from a minimal cost spanning tree satisfying the required capacities $q_{1,i}, i \in 2, 3, \ldots, n$ for all consumption nodes.

If the number of Steiner points is maximal, i.e. $k-2$ when k terminals are involved, the tree is called a full Steiner tree (FST). Each Steiner minimal tree is a union of full Steiner trees.

1. Find the minimal cost spanning tree GT with nodes $a_1, a_2, \ldots, a_n$ and with the weights on the edges satisfying the required capacities $q_{1,i}, i \in 2, 3, \ldots, n$.
2. Find all angles $\angle p_1 p p_2$ of edges $e_{p_1 p}$ and $e_{p p_2}$ in GT that do not satisfy the angle condition (eq. A.3).
3. Let $e_{p_i p_j}$ and $e_{p_j p_k}$ of which the angle $\angle p_i p_j p_k$ has the minimum ratio between the left hand side and the right hand side of the angle condition (eq. A.3).
4. Use the adapted Melzak method, to find the weighted Steiner minimal subtree for the nodes p_i , p_j and p_k , in which the nodes can be directly connected or can be connected by a new Steiner point.
5. Replace the subtree formed by the nodes p_i , p_j and p_k in the tree GT by the newly found weighted Steiner minimal subtree.
6. If one of the nodes p_i , p_j or p_k is itself a Steiner point, apply the adapted Melzak method again to find the weighted Steiner minimal subtree for the terminals connected to the involved Steiner points. And replace the relevant part of GT by the newly found weighted Steiner minimal subtree.
7. Repeat from step 2 until all angles in the tree GT satisfy the angle condition (eq. A.3).

In step 4 and 6 of the algorithm, the location of one or more Steiner points between three or more nodes (terminals or other Steiner points) is found using the adapted Melzak method. The subtrees involved are FSTs. When the topology of an FST is known, the required capacities of the edges can easily be determined. Possible topologies of FSTs of k nodes are listed in e.g. Gilbert and Pollak (1968).

A.4.1 Determine angles of edges incident to Steiner points

If capacities of the edges incident to a Steiner point are known, the angles that these edges make in the Steiner point can be calculated. The capacities of the edges can be considered as forces that pull the Steiner point. When the capacity of all connections is the same, their pull force is equal and equilibrium is found when all angles are equal to 120°.

When the capacity of the connections is different, the edge with the highest capacity should be shortened to minimize the total costs of the network. The force of this edge on the Steiner point is larger than that of the other edges. And the equilibrium is nearer to the terminal (or other Steiner point) incident to this higher capacity edge.

Let C_i be the capacity of edge $i, i \in 1, 2, 3$ connected to the Steiner point. Then the force from this edge working on the Steiner point equals C_e^β, with β the capacity exponent, as defined before. Let $\alpha_{i,j}$ be the angle between edge i and edge j connected to the Steiner point. See figure A.1.

The Steiner point is found in the equilibrium of these forces, both in two arbitrary chosen orthogonal directions, which gives e.g. the following equations:

$$C_1^\beta + C_2^\beta \cos\alpha_{1,2} + C_3^\beta \cos\alpha_{1,3} = 0 \tag{A.4}$$

$$C_2^\beta \sin\alpha_{1,2} - C_3^\beta \sin\alpha_{1,3} = 0 \tag{A.5}$$

The following equation guarantees that the sum of all angles equal 360°:

$$\alpha_{1,2} + \alpha_{1,3} + \alpha_{2,3} = 360^\circ \tag{A.6}$$

By solving the equations A.4, A.5 and A.6, the angles of the edges incident to each Steiner point can uniquely be found. It is evident that when $C_1 = C_2 = C_3$, the solution is found in $\alpha_{1,2} = \alpha_{1,3} = \alpha_{2,3} = 120^\circ$. If the FST contains more than one Steiner point, the angles at each Steiner point can be determined in the same way as long as all capacities of the edges in the FST are known.

A.4.2 Determine location of Steiner points

Now the topology, the coordinates of the terminals and the angles of the edges incident to all Steiner points are known, the exact location of the Steiner points can be found. To determine the exact location of the Steiner points, the following observations are useful:

1. Terminals can only form an FST if they all lie on their convex hull.
2. All Steiner points of an FST are within the convex hull of the terminals of that FST.
3. If the locations of two points A and B are known, the circle C_{AB} through A and B can be found, such that an arbitrary point P on one arc of C_{AB} makes a constant angle $\angle APB = \alpha$. If P is the Steiner point connected with A and B then $\angle APB = \alpha$ is known from equations A.4, A.5 and A.6.

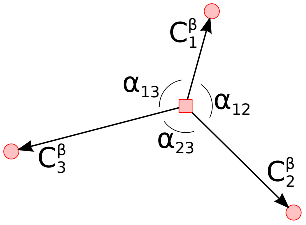


Figure A.1 – Calculation of the angles between the edges incident to one Steiner point.

4. Also the other angles between the edges incident to the Steiner point P are known. For all possible locations of the Steiner point P on the arc of the circle C_{AB}, the lines that make the required angles in point P will cross in one point M on the other arc of the circle, as shown in figure A.2.

These observations are enough to determine the exact location of the Steiner points in an FST. Note that for a clear picture of the used geometry, figures A.3, A.4, and A.5 show the situation in which all terminals are equally spread on a circle and all capacities are equal. However, for all other situations the geometric procedure to find the location of the Steiner points is exactly the same.

- For $k = 2$, there is no Steiner point.
- For $k \geq 2$, define the k terminals $A_i, i \in 1,2,...,k$. Without loss of generalization, assume that the pair of terminals $[A_{2i-1}, A_{2i}]$ is connected by the Steiner point $SP_i, i \in 1,2,\ldots,\frac{k}{2}$. Define the circles $C_{A_{2i-1},A_{2i}}, i \in 1,2,\ldots,\frac{k}{2}$, using observation 2 above. Define the point $P_i, i \in 1,2,\ldots,\frac{k}{2}$, using observation 3 above.
- For $k = 3$, the line M_1A_3 intersects the circle $C_{A_1A_2}$ in SP_1 , see figure A.3.
- For $k = 4$, the Steiner point SP_2 lies on the line M_1SP_1 and the Steiner point SP_1 lies on the line M_2SP_2. Therefore, the Steiner point SP_1 is the intersection between the line M_1M_2 and the circle $C_{A_1A_2}$ and the Steiner point SP_2 is the intersection between the line M_1M_2 and the circle $C_{A_1A_2}$.
- For $k = 5$, an extra circle $C_{M_1M_2}$ is needed that contains on one circle arc the third Steiner point SP_3. Knowing the angles of SP_3 , also the point M_3 on the circle $C_{M_1M_2}$ can be determined with observation 3 above. The line M_3SP_3 should also go through the last terminal A_5. So, SP_3 is the intersection between the circle $C_{M_1M_2}$ and the line M_3A_5 . When the location of SP_3 is known, SP_2 is the intersection between the circle $C_{A_3A_4}$ and the line M_2SP_3 and SP_1 is the intersection between the circle $C_{A_1A_2}$ and the line M_1SP_3 .

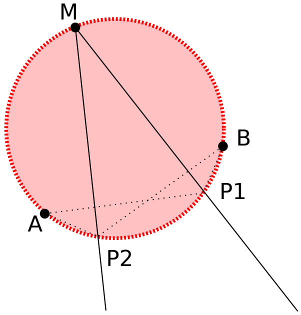


Figure A.2 – Circle with constant angle.

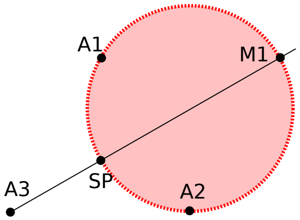


Figure A.3 – Geometric procedure to find Steiner point in FST with 3 terminals.

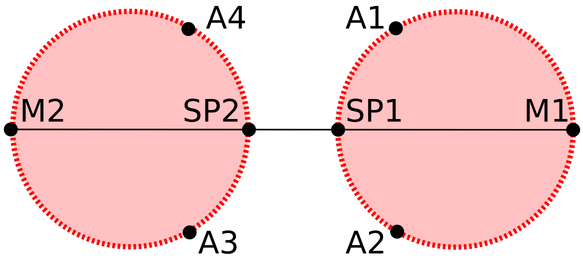


Figure A.4 – Geometric procedure to find Steiner point in FST with 4 terminals.

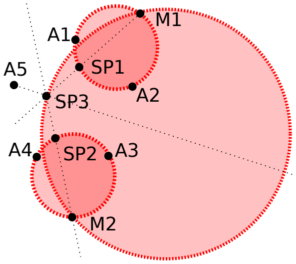


Figure A.5 – Geometric procedure to find Steiner point in FST with 5 terminals.

- For $k = 6$ or higher, the locations of the Steiner points in the FST can be found following more or less the same argumentation. However, FSTs of $k \geq 6$ hardly occur in practice.

Appendix B

Interviewees

The contents of chapter 3 build on the cooperation of the following interviewees:

- Henk Bakker – manager building physics and ecology The Hague – 20 October 2011
- Hans Knippels and Barend van Engelenburg – project managers DCMR/RCI – 01 February 2012
- Kees Kruijff – project leader SESAC project Delft – 13 October 2011
- Jacob Limbeek – director OCAP – 10 July 2012
- Anne van der Marel – product manager heat E.On – 21 November 2011
- Eric Muller – director ADH/Staedion – 01 November 2011
- Peter Ripson – commercial director Linde Gas – 14 February 2012
- Peter Rommens – energy and sustainable building specialist Delft – 18 August 2011
- Frank Schoof – director ADH and WD – 10 October 2011
- Karin Schrederhof – director Woonbron – 23 January 2012
- Gerrit van Tongeren – chairman Deltalinqs Energy Forum – 24 January 2012
- Hendrik de Wit – general manager OCAP – 17 June 2009

B. Interviewees

Appendix C

Questionnaire for cases

These are the questions that were asked for the case studies of cooperation energy networks. The method followed was that of a semi-structured interview, which means that the interviewees were allowed to elaborate on their answer and choose their own order in answering the questions, as long as in the end all the topics are covered. The overall question we want to answer is:

> What are the enabling factors or disabling factors that drive actors to cooperate and what makes a successful partnership?

Initial planning stage – history

- Who initialised the idea for cooperation?
- When was the idea conceived? At what kind of meeting?
- Were several options considered?
- How many meetings were required to specify requirements/detailed plans?

Team members/partners

- Who were involved?
- Were all stakeholders involved from the beginning?
- Were stakeholder interests taken into consideration? How?
- Were there specific networks/groups from which cooperators were sought?
- Had they cooperated before?
- How did trust evolve?
- Did all parties stay involved? What caused them to abandon the project?

- Is the size of cooperating partners relevant?
- Are specific types of partners required?

Process

- Was there a clear project leader? Was it the same person throughout the project?
- How was communication dealt with?
- Were there investment coordination issues?
- Was a risk analysis done? Were there risks that came up during the project that were not taken into consideration?
- How did the organisations deal with these risks?
- Was a cost-benefit analysis done?
- What were the decisive factors for choosing to go ahead?

Current status

- What is the current status of the project?
- What are current risks, barriers, and opportunities?

Appendix D

Unveiling models

Several authors have commented on the risk of over-enthusiastic use of models in decision support (e.g. Lee, 1973; Meadows and Robinson, 2002). Setting aside any possibilities of using wrong data and making programming mistakes, a model quickly becomes so large and complex that it is nearly impossible to trace all assumptions that were made in building it. To remedy that shortcoming, protocols have been designed to ensure better communication of the ideas and variables behind the modelling effort (e.g. the ODD protocol proposed by Grimm et al. (2006)). What we propose, goes even one step further: there needs to be an analysis of those elements that are *left out* of the model. However, such a potentially limitless effort should be bounded.

The boundary we suggest is given by the Institutional Analysis and Development framework as worked on by Elinor Ostrom and colleagues (Ostrom et al., 1994). Although her focus is on *socio-ecological* systems and common-pool resources, we believe the basic categorisation of the IAD-framework is equally valid for socio-technical systems in an industrial network setting (see figure D.1).

The central concept is the 'action arena', in which individuals (or organisations) interact, exchange goods and services, engage in appropriation and provision activities, solve problems, or fight. The action arena is described by the participants (who have a set of resources, preferences, information, and selection criteria for action) and the action situa-

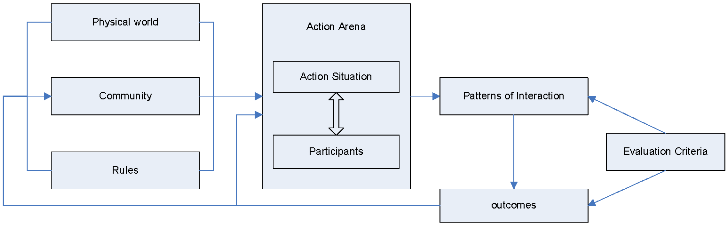


Figure D.1 – The Institutional Analysis and Development (IAD) framework.

tion: the actual activity (or 'game') that is to be understood. What happens in the action arena leads to patterns of interaction and outcomes that can be judged on the basis of evaluative criteria. The action arena itself is influenced by attributes of the physical world (e.g. climate, present technological artefacts), the attributes of the community in which the actors/actions are embedded (e.g. cultural norms regarding cooperation, demographics or education levels), and the set of rules that the individuals involved use to guide and govern their behaviour.

Although physical world and community influence the action arena, it is the rules of the game that actually define it. Therefore, in IAD quite some attention is given to these rules. Rules are statements about what actions are required, prohibited, or permitted and the sanctions authorized if the rules are not followed. Seven distinct types of rules are distinguished:

- *Boundary*. Specify who is eligible to play a role: who is in and who is out of the game?
- *Position*. Determine to what extent a distinction is made regarding the position of the different participants. For example, a buyer or seller on a market have a different role than an auctioneer (and thus different access to information, and different choices).
- *Choice*. Specify what a participant must, must not, or may do at a specific point of the process.
- *Pay-off*. Assign external rewards or sanctions to particular actions that have been taken.
- *Information*. Describe what information may or may not be shared by participants and whether they have a set of common, shared information.
- *Scope*. Define what outcome variables should or should not be affected by the actions undertaken.
- *Aggregation*. Specify who has responsibility for an action: for example, whether a single participant or multiple participants should come to a decision.

These rules can be analysed within three distinct layers: the operational, the collective choice and the constitutional choice levels. The different levels relate to different time-frames: day-to-day activities fall within the operation level, the collective choices determine what operational activities take place and these are reviewed over a 5–10 year time frame, whereas the constitutional level determines how the process of collective choice is organised (which is a long-term process).

We have suggested using institutional economics for designing models and have applied it as described in Ghorbani et al. (2010) and Ligtvoet (2011). Whereas we initially only described it as a guideline for designing and building models, we could equally use the framework for analysing models and their assumptions. It should be clear that such a time-consuming effort should only be made for models that purport to actually simulate our complex socio-technical world.

Appendix E

Questionnaire for the Energy Market Game

The following questions were presented to the students playing the *Energy Market Game*. The answers were recorded using *LimeSurvey* software and exported to *LibreOffice* for further spreadsheet analysis.

- How many hours did your team spend per round on discussing/preparing your investment strategy and bid? This is an estimate. Use the average over the last rounds. If the discussions were short, you may also use decimals (15 minutes = 0.25 hour).
- What did you do to prepare your bid? We are interested in the tools you used and the calculations you did. Describe them in short (1 line per tool/calculation).
- I fully understand the following concepts. Please note: this does not influence your mark for this course. We only want to measure whether the concepts are clear. (not at all, not very well, reasonably well, fully)
    - bidding procedure
    - market power
    - price determinants
    - influence of policy
- Statement: the main parameters in the game are clear. Respond to the statement and add in the comment field what are the main parameters according to you. What is your response to this statement and what are the important parameters? (disagree totally, disagree somewhat, agree somewhat, agree totally)
- Statement: the outcome of (one of) the last rounds has surprised me. Respond to the statement and, if so, clarify what has surprised you. (disagree totally, disagree somewhat, agree somewhat, agree totally)

- Explain what investment strategy you have used in the last rounds (invest or not, choice of type of plant, etc.). Please describe with a few key words/terms.
- Did you read the news messages?
  - **Nested** Statement: the information in the news bulletins was useful for or influenced our choices. Respond to the statement and explain if necessary. (disagree totally, disagree somewhat, agree somewhat, agree totally)
- Did you communicate / cooperate with other players?
  - **Nested** What teams did you talk to? Was/is there a specific reason to cooperate with (members of) these teams? For example: you know them, they are the largest/smallest competitor, ... (Use the team letters A,B,C,D,E to refer to teams) (describe)
  - **Nested** What topics did you address in your communication with the other teams? You may choose several options. (capacity, price, game play, investment decisions, bid strategy)
  - **Nested** Did you make any agreements? What were they? Were they effective? (describe)
- Statement: playing the game has led me to better understand the concepts. Provide your opinion and explain if necessary. (disagree totally, disagree somewhat, agree somewhat, agree totally)
- Statement: the game is exciting. Provide your opinion and explain if necessary (synonyms for exciting could also be: fun, enticing, enthralling, …) (disagree totally, disagree somewhat, agree somewhat, agree totally)
- Do you have other remarks about the game, the survey, interesting conclusions or observations? (describe)

Appendix F

Outcome of the 2012 questionnaire

In 2012 the questionnaire was again deployed at the *Energy and gas market design and policy issues (SPM4520)* course. Of the 50 students who answered some of the questionnaires, 20 answered all three questionnaires. Figures F.1 and F.2 summarise the outcome of the questionnaire in the 2012 student group.

The wording of the questions was slighly altered on request of the teaching staff. Instead of asking 'I fully understand the following concepts' (bidding procedure, market power, price determinants, influence of policy — see appendix E) we asked 'I understand the following concepts':

- How to develop a bid strategy
- How the electricity price is determined
- How I can exert market power
- How public policy influences the electricity market.

Three concepts were added:

- How to determine the cost of generating electricity
- How to decide about investing in new power plants
- How to win this game.

Also the statement 'The main parameters in the game are clear' was changed into 'I understand the main drivers of the dynamics of the game' and instead of 'Playing the game has led me to better understand the concepts' we asked about the separate concepts listed above. We believe this has not significantly altered the questionnaire and thus results remain comparable.

F. Outcome of the 2012 questionnaire

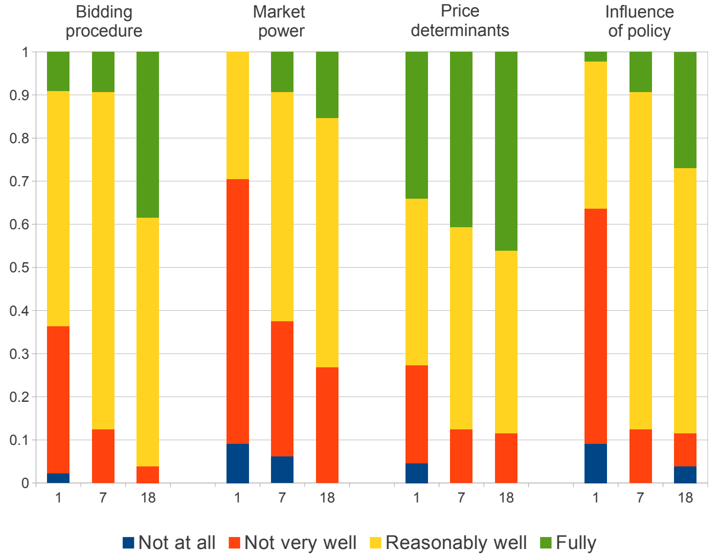


Figure F.1 – Reported understanding of a) bidding procedure, b) the concept of market power, c) price determinants, and d) policy effects in rounds 1, 7, and 18 – 2012 group.

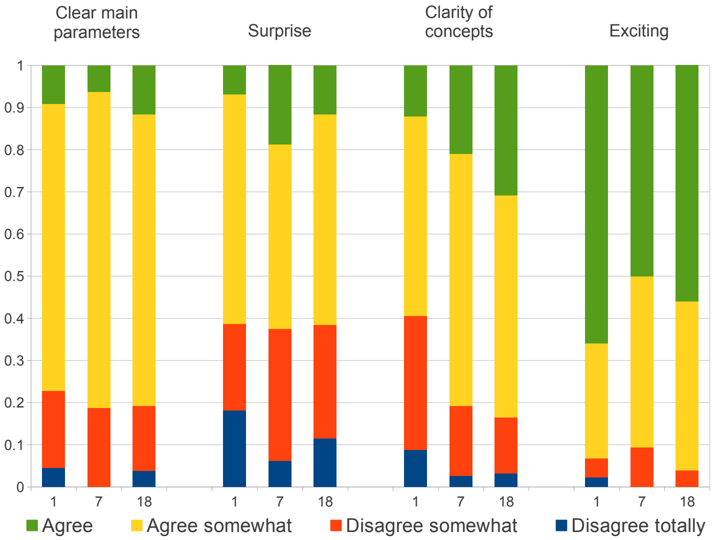


Figure F.2 – Agreement with statements a) the main parameters in the game are clear, b) the outcome of (one of) the last rounds has surprised me, c) playing the game has led me to better understand the concepts, and d) the game is exciting, in rounds 1, 7, and 18 – 2012 group.

Bibliography

ADH. Aardwarmte Den Haag – energie uit de aarde. Technical report, Aardwarmte Den Haag, 2008. 36

Mónica Altamirano. *Innovative contracting practices in the road sector – Cross-national lessons in dealing with opportunistic behaviour*. PhD thesis, Delft University of Technology, Delft, the Netherlands, 2009. 92, 93, 96, 102, 122

Mónica A. Altamirano and W. Martin de Jong. Opportunistic behavior in road maintenance markets: Exploring the consequences through gaming simulation. *Transportation Research Record: Journal of the Transportation Research Board*, (2108):13–22, 2009. 93

Philip Anderson. Complexity theory and organization science. *Organization Science*, 10(3):216–232, May-June 1999. 6

Philip W. Anderson. More is different. *Science*, 177(4047):393–396, 1972. 125

Peter Andras, John Lazarus, and Gilbert Roberts. Environmental adversity and uncertainty favour cooperation. *BMC Evolutionary Biology*, 7:240, 2007. 3, 7, 16

Anthony Andrews. Liquid fuels from coal, natural gas, and biomass: Background and policy. report RL34133, Congresional Research Service, 2007. 57

Ali Asadi and Mohammad Reza Razzazi. Euclidean Steiner minimal tree inside simple polygon avoiding obstacles. In *Computational Science and its Applications, The International Conference Computational Science and its Applications (ICCSA)*, pages 200–207, 2007. 55, 56

Mohammad Asadullah, Shin-Ichi Ito, Kimio Kunimori, Muneyoshi Yamada, and Keiichi Tomishige. Energy efficient production of hydrogen and syngas from biomass: Development of low-temperature catalytic process for cellulose gasification. *Environmental science technology*, 36: 4476–4481, 2002. 57

W. Graham Astley. Toward an appreciation of collective strategy. *Academy of Management Review*, 9(3):526–535, 1984. 20, 21, 122

W. Graham Astley and Charles J. Fombrun. Collective strategy: Social ecology of organizational environments. *Academy of Management Review*, 8(4):576–587, 1983. 5, 16, 21, 25, 26, 121

W. Graham Astley and Edward J. Zajac. Intraorganizational power and organizational design: Reconciling rational and coalitional models of organization. *Organization Science*, 2(4):399–411, November 1991. 26, 27, 97, 104, 108, 126

Robert Axelrod. *The complexity of cooperation*. Princeton University Press, Princeton, NJ, 1997. 9, 64, 79, 101, 105, 107, 110, 123

Robert Axelrod and William D. Hamilton. The evolution of cooperation. *Science*, 211:1390–1396, 1981. 9, 14, 15, 17

Robert Axelrod and Leigh Tesfatsion. *A guide for newcomers to agent-based modelling in the social sciences*, volume 2, chapter in: Handbook of Computational Economics, pages 1647–1659. Elsevier, 2006. 123

Anantaram Balakrishnan, Thomas L. Magnanti, and Richard T. Wong. A decomposition algorithm for local access telecommunications network expansion planning. Technical report, Sloan School of Management, Cambridge, MA, USA, September 1992. 54

Steve Bankes. Tools and techniques for developing policies for complex and uncertain systems. *PNAS*, 99:7263–7266, 2002. 52

Jerome H. Barkow, Leda Cosmides, and John Tooby, editors. *The adapted mind - evolutionary psychology and the generation of culture*. Oxford University Press, New York, 1992. 13, 20

Johannes M. Bauer and Paulien M. Herder. *Designing Socio-Technical Systems*, volume 9, chapter in: Philosophy of technology and engineering sciences, pages 601–630. North-Holland, Elsevier, 2009. 24

Jessica Beck, Ruud Kempener, Brett Cohen, and Jim Petrie. A complex systems approach to planning, optimization and decision making for energy networks. *Energy Policy*, 36:2803–2813, August 2008. 65

Behzad Behdani. Critical evaluation of paradigms for modeling supply chains as complex socio-technical systems, April 2012. URL http://dx.doi.org/10.2139/ssrn.2048588. working paper series. 66

René Belderbos, Martin Carree, and Boris Lokshin. Complementarity in r&d cooperation strategies. *Review of Industrial Organization*, 28:401–426, 2006. 21

Christina Bicchieri. *Cooperators and coomunication: group identity or social norms?*, chapter in: Teamwork - a multidisciplinary perspective. Palgrave Macmillan, New York, 2005. 20

Ian Bogost. *The Rhetoric of Video Games*, chapter in: The Ecology of Games: Connecting Youth, Games, and Learning, pages 117–140. The John D. and Catherine T. MacArthur Foundation Series on Digital Media and Learning. The MIT Press, Cambridge, MA, 2008. 85

Andrei Borshchev and Alexei Filippov. From system dynamics and discrete event to practical agent based modeling: Reasons, techniques, tools. In *Proceedings of the 22nd International Conference of the System Dynamics Society*, pages 24–29, 2004. 64, 66

Kenneth E. Boulding. General systems theory: the skeleton of science. *Management Science*, 2: 197–208, 1956. 64, 123

Choaib Bousba and Laurence A. Wolsey. Finding minimum cost directed trees with demands and capacities. *Annals of Operations Research*, 33:285–303, 1991. 54

John Brätland. Resource exhaustibility: a myth refuted by entrepreneurial capital maintenance. *The Independent Review*, XII(3):375–399, Winter 2008. 70

Rudi K. Bresser and Johannes E. Harl. Collective strategy: Vice or virtue? *Academy of Management Review*, 11(2):408–427, 1986. 21, 78, 119

Garry D. Brewer. Scientific gaming : The development and use of free-form scenarios. *Simulation Gaming*, 9:309, 1978. 26, 83, 107, 110, 126

Christoph Bronder and Rudolf Pritzl. Developing strategic aliances: Conceptual framework for successful co-operation. *European Management Journal*, 10(4):412–421, December 1992. 21, 22

Michael Brookes, Chris Brewster, and Geoffrey Wood. Social relations, firms and societies: A study of institutional embeddedness. *International Sociology*, 20(4):403–426, December 2005. 25

Brian Burrough and John Helyar. *Barbarians at the gate*. Harper Paperback, New York, December 2009. 47

Colin J. Campbell and Jean H. Laherrère. The end of cheap oil. *Scientific American*, pages 78–83, March 1998. 2, 152

Emile J.L. Chappin. *Simulating Energy Transitions*. PhD thesis, Delft University of Technology, 2011. 66, 68, 88, 110

Emile J.L. Chappin and Andreas Ligtvoet. The difference between transition and transformation: a bibliometric analysis of two scientific networks. In *IST 2012 - International Conference on Sustainability Transitions*, Kopenhagen, Denmark, September 2012. 10

Emile J.L. Chappin, Gerard P.J. Dijkema, and Laurens J. de Vries. *Carbon policies: Do they deliver in the long run?*, chapter in: Carbon Constrained: Future of Electricity. Elsevier, 2010. 87

Peter Checkland. *Systems thinking, systems practice*. Wiley, 1981. 64

Peter Checkland. From optimizing to learning: A development of systems thinking for the 1990s. *The Journal of the Operational Research Society*, 36(9):757–767, September 1985. 5, 102

Peter Checkland and Sue Holwell. Action research: Its nature and validity. *Systemic Practice and Action Research*, 11(1):9–21, 1998. 126

Marian R. Chertow. Industrial symbiosis: Literature and taxonomy. *Annu. Rev. Energy Environ.*, 25:313–337, 2000. 2

Marian R. Chertow. Uncovering industrial symbiosis. *Journal of Industrial Ecology*, 11(1):11–30, 2007. 2

Catherine M. Chiong Meza. *Understanding socio-technical change: a system-network-agent approach*. PhD thesis, Delft University of Technology, 2012. 24, 122

Andrew M. Colman. Cooperation, psychological game theory, and limitations of rationality in social interaction. *Behavioural and Brain Sciences*, 26:139–198, 2003a. 14, 17, 19

Andrew M. Colman. Beyond rationality: rigor without mortis in game theory. *Behavioural and Brain Sciences*, 26:139–198, 2003b. 17

Andrew M. Colman. The puzzle of cooperation. *Nature*, 440:745–746, 2006. 9, 15, 78

Roger C. Conant and W. Ross Ashby. Every good regulator of a system must be a model of that system. *International Journal of Systems Science*, 1(1):89–97, 1970. 110

Richard C. Connor. Pseudo-reciprocity: investing in mutualism. *Animal Behaviour*, 34:1562–1566, 1986. 15

Aad Correljé and Coby van der Linde. Energy supply security and geopolitics: A european perspective. *Energy Policy*, 34:532–543, 2006. 57

Leda Cosmides and John Tooby. Better than rational: Evolutionary psychology and the invisible hand. *The American Economic Review*, 84(2):327–332, May 1994. 25

Paul Coughlan and David Coghlan. Action research for operations management. *International Journal of Operations & Production Management*, 22(2):220–240, 2002. 126

John W. Creswell. *Research design: qualitative, quantitative, and mixed-method approaches*. Sage Publications, 3rd edition, 2009. 10

Richard M. Cyert and James G. March. *A behavioural theory of the firm*. Prentice-Hall, Englewood Cliffs, New Jersey, 1963. 79

Hans de Bruijn and Ernst ten Heuvelhof. *Management in networks*. Routledge, 2008. 3, 5, 20, 27, 98, 122

Klaas de Jong. *Warmte in de Nederlanden; Warmte- en koudeprojecten in de praktijk*. Uitgeverij MGMC, 2 edition, 2011. 30

Richard de Neufville, Olivier de Weck, Jijun Lin, and Stefan Scholtes. *Identifying real options to improve the design of engineering systems*, chapter in: Real Options in Engineering Design, Operations, and Management. CRC press, 2009. 51

Laurens J. de Vries and Emile J.L. Chappin. Power play: Simulating the interrelations between an electricity market and a CO_2 market in a simulation game. In *33rd International Association for Energy Economics Conferece*, Rio de Janairo, Brazil, 6-9 June 2010. 85, 86

Laurens J. de Vries, Eswaran Subramahnian, and Emile J.L. Chappin. A power game: simulating the long-term development of an electricity market in a competitive game. In *Second International Conference on Infrastructure Systems and Services: Developing 21st Century Infrastructure Networks (INFRA)*, pages 1–6, Chennai, India, 9-11 December 2009. 85, 86

Bas de Zwart and Peter Heijboer. Uniek geothermieproject in Den Haag Zuidwest. *VV+*, November:704–707, 2010. 36

Gabi dei Ottati. Cooperation and competition in the industrial district as an organization model. *European Planning Studies*, 2(4):463–481, 1994. 3, 23, 100

Desertec Foundation. *Clean power from deserts – The DESERTEC Concept for Energy, Water and Climate Security*. Protext Verlag, Hamburg, Germany, 4 edition, February 2009. 2

Pierre Desrochers. Industrial symbiosis: the case for market coordination. *Journal of Cleaner Production*, 12:1099–1110, 2004. 3

Nicholas Dew, Stuart Read, Saras D. Sarasvathy, and Robert Wiltbank. Outlines of a behavioral theory of the entrepreneurial firm. *Journal of Economic Behavior and Organization*, 66:37–59, 2008. 79, 80, 104, 121, 126

Frank Dignum, Virginia Dignum, and Catholijn M. Jonker. Towards agents for policy making. pages 1–12, 2008. 122

Michael Doebeli and Christoph Hauer. Models of cooperation based on the prisoner's dilemma and the snowdrift game. *Ecology Letters*, 8:748–766, 2005. 14, 17

DOE/NETL. Peaking of world oil production: recent forecasts. Technical Report DOE/NETL-2007/1263, National Energy Technology Laboratory, US Department of Energy, February 2007. 2

Dietrich Doerner. On the difficulties people have in dealing with complexity. *Simulation & Games*, 11(1):87–106, March 1980. 93, 95, 107

Dietrich Doerner. The logic of failure (and discussion). *Philosophical Transactions of the Royal Society* *of London. Series B, Biological Sciences*, 327(1241):463–473, April 1990. 93, 95, 107

Emmanuel Dubois, Olivier Barreteau, and Véronique Souchère. What's going on in a role playing game? an agent-based model to explore game setting effects on attitude change. In A. Ernst and S. Kuhn, editors, *Proceedings of the 3rd World Congress on Social Simulation WCSS2010*, Kassel, Germany, 2010. 84

Faye Duchin and Edgar Hertwich. Industrial ecology. *Online Encyclopaedia of Ecological Economics*, May 2003. 13

Richard D. Duke. *Gaming: the future's language*. Sage Publications, 1st edition, 1974. 85

Richard D. Duke. A paradigm for game design. *Simulation & games*, 11(3):364–377, September 1980. 84

Gilles Duranton and Matthew A. Turner. The fundamental law of road congestion: Evidence from us cities. Working Paper Series 15376, National Bureau of Economic Research, September 2009. 5

David Eberly. Triangulation by ear clipping. Technical report, Geometric Tools, LLC, 2008. 55

John Ehrenfeld and Nicholas Gertler. Industrial ecology in practice: the evolution of interdependence at kalundborg. *Journal of industrial ecology*, 1(1):67–79, 1997. 114

Kathleen M. Eisenhardt. Agency theory: An assessment and review. *The Academy of Management Review*, 14(1):57–74, January 1989a. 48

Kathleen M. Eisenhardt. Building theories from case study research. *The Academy of Management Review*, 14(4):532–550, October 1989b. 29

Kathleen M. Eisenhardt and Melissa E. Graebner. Theory building from cases: opportunities and challenges. *Academy of Management Journal*, 50(1):25–32, 2007. 29

ELI. Actieplan aardwarmte. Technical report, Ministry of Economics, Agriculture, and Innovation, The Hague, the Netherlands, April 2011. 38

Frederick E. Emery and Eric L. Trist. *The Causal Texture of Organizational Environments*, chapter in: Organization change: a comprehensive reader, pages 7–20. 1965. 4, 6, 117

Joshua M. Epstein. Why model? *Journal of Artificial Societies and Social Simulation*, 11(4-12):n/a, 2008. 64, 110

European Commission. Decision c(2010) 7499 final, November 2010. 41

EWG. Coal: Resources and future production. Technical Report 1/2007, Energy Watch Group, Ottobrunn, July 2007. 2, 57

Anthony J. Faria, David Hutchinson, William J. Wellington, and Steven Gold. Developments in business gaming: A review of the past 40 years. *Simulation Gaming*, 40:464, 2009. 84, 85

J. Doyne Farmer and Duncan Foley. The economy needs agent-based modelling. *Nature*, 460: 685–686, 6 August 2009. 65

Ernst Fehr and Urs Fischbacher. The nature of human altruism. *Nature*, 425:785–791, October 2003. 15, 16, 20

Guido Fioretti. Agent based models of industrial clusters and districts. March 2005. 66, 78, 100, 123

Bent Flyvbjerg. From Nobel prize to project management: getting risks right. *Project Management Institute*, 37(3):5–15, 2006a. ISSN 8756-9728/03. 29

Bent Flyvbjerg. Five misunderstandings about case-study research. *Qualitative Inquiry*, 12(2):219–245, April 2006b. 109

Jay W. Forrester. Counterintuitive behavior of social systems. *Technology Review*, 73(3):52–68, January 1971. 84

Charles François. Systemics and cybernetics in a historical perspective. *Systems Research and Behavioral Science*, 16:203–219, 1999. 64

Silvio O. Funtowicz and Jerome R. Ravetz. Science for the post-normal age. *Futures*, pages 739–755, September 1993. 7, 29, 97, 125

José Manuel Galán, Luis R. Izquierdo, Segismundo S. Izquierdo, José Ignacio Santos, Ricardo del Olmo, Adolfo López-Paredes, and Bruce Edmonds. Errors and artefacts in agent-based modelling. *Journal of Artificial Societies and Social Simulation*, 12(1):1, 2009. URL http://jasss.soc.surrey.ac.uk/12/1/1.html. 107

Andy Garner and Gregory A. Keoleian. Industrial ecology: an introduction. Technical report, National Pollution Prevention Center for Higher Education, University of Michigan, Ann Arbor, MI, USA, November 1995. 13

Frank Geels. *Understanding the dynamics of technological transitions*. PhD thesis, Twente University, 2002. 24

Amineh Ghorbani, Andreas Ligtvoet, Igor Nikolić, and Gerard Dijkema. Using institutional frameworks to conceptualize agent-based models of socio-technical systems. In Susan Stepney, Peter H. Welch, Paul S. Andrews, and Adam T. Sampson, editors, *Proceedings of the 2010 Workshop on Complex Systems Modelling and Simulation*, Odense, Denmark, August 2010. 142

David Gibbs. Trust and networking in inter-firm relations: the case of eco-industrial development. *Local Economy*, 18(3):222–236, August 2003. 23

E. Gilbert and H. Pollak. Steiner minimal trees. *SIAM Journal on Applied Mathematics*, 16(1):1–29, 1968. 52, 129, 130, 131

Andrea Ginzburg. *Biological Metaphors in Economics: Natural Selection and Competition*, chapter in: Complexity Perspectives in Innovation and Social Change, pages 117–152. Methodos series. Springer Science+Business Media, 2009. 3

Natalie Gold. *Introduction: Teamwork in theory and in practice*, chapter in: Teamwork – a multidisciplinary perspective, pages 1–20. Palgrave Macmillan, New York, 2005. 23, 46, 97

Luis Gouveia and Maria João Lopes. Valid inequalities for non-unit demand capacitated spanning tree problems with flow costs. *European Journal of Operational Research*, 121:394–411, 2000. 54

R.L. Graham and Pavol Hell. On the history of the minimum spanning tree problem. *Annals of the history of computing*, 7(1):43–57, January 1985. 52

Mark Granovetter. Economic action and social structure: The problem of embeddedness. *The American Journal of Sociology*, 91(3):481–510, 1985. 3, 16

D.L. Greene, J.L. Hopson, and J. Li. Have we run out of oil yet? Oil peaking analysis from an optimist's perspective. In *Energy Policy* Campbell and Laherrère (1998), pages 515–531. 70

Hilary G. Grimes-Casey, Thomas P. Seager, Thomas L. Theis, and Susan E. Powers. A game theory framework for cooperative management of refillable and disposable bottle lifecycles. *Journal of Cleaner Production*, 15:1618–1627, 2007. 16, 19

Volker Grimm, Uta Berger, Finn Bastiansen, Sigrunn Eliassen, Vincent Ginot, Jarl Giske, John Goss-Custard, Tamara Grand, Simone K. Heinz, Geir Huse, Andreas Huth, Jane U. Jepsen, Christian Jorgensen, Wolf M. Mooij, Birgit Muller, Guy Pe'er, Cyril Piou, Steven F. Railsback, Andrew M. Robbins, Martha M. Robbins, Eva Rossmanith, Nadja Ruger, Espen Strand, Sami Souissi, Richard A. Stillman, Rune Vabo, Ute Visser, and Donald L. DeAngelis. A standard protocol for describing individual-based and agent-based models. *Ecological modelling*, 198:115–126, 2006. 141

Anne-Marie Grisogono and Vanja Radenovic. The adaptive stance. In *Eighth International Conference on Complex Systems*, June 26 - July 1 2011. 5, 107

Leonidas J. Guibas and John Hershberger. Optimal shortest path queries in a simple polygon. *Journal of Computer and System Sciences*, pages 50–63, 1989. 56

Charles Hall, Dietmar Lindenberger, Reiner Kümmel, Timm Kroeger, and Wolfgang Eichhorn. The need to reintegrate the natural sciences with economics. *BioScience*, 51(8):663–673, August 2001. 1

Charles A.S. Hall, Robert Powers, and William Schoenberg. *Peak oil, EROI, investments and the economy in an uncertain future*, chapter in: Biofuels, solar and wind as renewable energy systems, pages 109–132. Springer Science+Business Media, 2008. 1

William D. Hamilton. The genetical evolution of social behaviour. i & ii. *Journal of theoretical biology*, 7(1):1–16, 1964. 15

Garrett Hardin. The tragedy of the commons. *Science*, 162:1243–1248, December 1968. 13, 14

Caper Harteveld. *Triadic game design*. Springer, 2011. 90

Friedrich A. Hayek. The use of knowledge in society. *American Economic Review*, XXXV(4): 519–530, September 1945. 22

Brian Heath, Raymond Hill, and Frank Ciarallo. A survey of agent-based modeling practices (january 1998 to july 2008). *Journal of Artificial Societies and Social Simulation*, 12(4):9, 2009. 105

Petra W. Heijnen, Rob M. Stikkelman, Andreas Ligtvoet, and Paulien M. Herder. Using Gilbert networks to reveal uncertainty in the planning of multi-user infrastructures. In *International Conference on Networking, Sensing and Control*, Delft, the Netherlands, 11-13 April 2011. 51

Petra W. Heijnen, Andreas Ligtvoet, Rob M. Stikkelman, and Paulien M. Herder. Maximising the worth of nascent networks. *Networks and spatial economics*, submitted. 56, 121

Paulien M. Herder, Ivo Bouwmans, Gerard P.J. Dijkema, Rob M. Stikkelman, and Margot P.C. Weijnen. Designing infrastructures using a complex systems perspective. *Journal of Design Research*, 7(1):17–34, 2008a. doi: 10.1504/JDR.2008.018775. 3, 51, 68

Paulien M. Herder, Rob M. Stikkelman, Gerard P.J. Dijkema, and Aad F. Correljé. Design of a syngas infrastructure. In Bertrand Braunschweig and Xavier Joulia, editors, *18th European Symposium on Computer Aided Process Engineering*. ESCAPE 18, Elsevier, 2008b. 57, 58

Paulien M. Herder, Jeroen de Joode, Andreas Ligtvoet, Sigrid Schenk, and Poonam Taneja. Buying real options – valuing uncertainty in infrastructure planning. *Futures*, 43:961–969, 2011. 51, 77

Andrés Guillermo Hernández-Martínez. Estrategia y cooperación: una visión de la gestión desde el paradigma de la colaboración interfirmas. *Revista Facultad de Ciencias Economicas de la Universidad Militar Nueva Granada*, XV(2):113–129, 2007. 20

Geert Hofstede and Gert Jan Hofstede. *Cultures and organizations: software of the mind*. McGraw-Hill, 2005. 25

Jennifer Howard-Grenville and Raymond Paquin. *Organizational dynamics in industrial ecosystems: insights from organizational theory*, chapter in: Changing Stocks, Flows And Behaviors In Industrial Ecosystems, pages 122–139. Edwin Elgar, 2009. 122

Paul Hoyningen-Huene. Context of discovery and context of justification. *Studies in History and Philosophy of Science*, 18(4):501–515, 1987. 107

Thomas P. Hughes. *The evolution of large technological systems*, chapter in: The Social Construction of Technological Systems; New Directions in the Sociology and History of Technology, pages 51–82. MIT Press, Cambridge, MA, 1987. 4

Chris Huxham and Siv Vangen. *Managing to Collaborate: The Theory and Practise of Collaborative Advantage*. Routledge, Oxon, UK, 24 February 2005. 99

Frank Hwang, Dana Richards, and Pawel Winter. The Steiner tree problem. *Annals of Discrete Mathematics*, 53, 1992. 130

IEA. World energy outlook 2008. Technical report, International Energy Agency, 2008. 2

IPCC. Climate change 2007: synthesis report. Technical report, Intergovernmental Panel on Climate Change, November 2007. 1

Almerima Jamaković. *Characterization of complex networks – Application to robustness analysis*. PhD thesis, Delft University of Technology, the Netherlands, 2008. 52

Vincent A. A. Jansen and Minus van Baalen. Altruism through beard chromodynamics. *Nature*, 440:663–666, March 2006. 16

Marco A. Janssen, Robert Holahan, Allen Lee, and Elinor Ostrom. Lab experiments for the study of social-ecological systems. *Science*, 328(5978):613–617, 2010. 84

Ralph L. Keeney. Using values in operations research. *Operations Research*, 42(5):793–813, September-October 1994. 48, 119

René Kemp and Derk Loorbach. *Dutch policies to manage the transition to sustainable energy*, chapter in: Jahrbuch Ökologische Ökonomik, pages 123–151. Number 4. Metropolis Verlag, Marburg, 2005. 24

Richard A. Kerr. World oil crunch looming? *Science*, 322:1178–1179, November 2008. 70

Craig W. Kirkwood. *Strategic decision making: multiobjective decision analysis with spreadsheets*. Duxbury Press, 1997. 59

Alfred Kleinknecht and Jeroen O.N. Reijnen. Why do firms cooperate on r&d? an empirical study. *Research Policy*, 21:347–360, 1992. 21

Andreas Klinke and Ortwin Renn. A new approach to risk evaluation and management: Risk-based, precaution-based, and discourse-based strategies. *Risk analysis*, 22(6):1071–1094, 2002. 6, 51, 107

Frank H. Knight. *Risk, Uncertainty, and Profit*. Hart, Schaffner and Marx; Houghton Mifflin, 1921. 6, 107

Thorbjorn Knudsen. Simon's selection theory: Why docility evolves to breed successful altruism. *Journal of Economic Psychology*, 24:229–244, 2003. 16, 20, 29

Timothy A. Kohler. *Putting social sciences together again: an introduction to the volume*, chapter in: Dynamics in human and primate societies. Santa Fe Institute studies in the sciences of complexity. Oxford University Press, Oxford, 2000. 24

Peter Kollock. Social dilemmas: the anatomy of cooperation. *Annu. Rev. Sociol.*, 24:183–214, 1998. 14, 17, 25

Jouni Korhonen. Industrial ecology for sustainable development: Six controversies in theory building. *Environmental Values*, 14:83–112, 2005. 3

Joseph B. Kruskal. On the shortest spanning subtree of a graph and the traveling salesman problem. In *Proceedings of the American Mathematical Society*, volume 7, pages 48–50, February 1956. 52

Rolf Kümmerli, Caroline Colliard, Nicolas Fiechter, Blaise Petitpierre, Flavien Russier, and Laurent Keller. Human cooperation in social dilemmas: comparing the snowdrift game with the prisoner's dilemma. *Proceedings of the Royal Society B*, 274:2965–2970, 2007. 18, 19

David Lane, Robert Maxfield, Dwight Read, and Sander van der Leeuw. *From Population to Organization Thinking*, chapter in: Complexity Perspectives in Innovation and Social Change, pages 11–41. Methodos Series 7. Springer Science+Business Media, 2009. 5

Richard N. Langlois. Cognitive comparative advantage and the organization of work: Lessons from herbert simon's vision of the future. *Journal of Economic Psychology*, 24:167–187, 2003. 7

Ervin Laszlo and Alexander Laszlo. The contribution of the systems sciences to the humanities. *Syst. Res. Behav. Sci.*, 14(1):5–19, 1997. 24

John Lazarus. Let's cooperate to understand cooperation. *Behavioral and brain sciences*, 26:139–198, 2003. 13, 15

Der-Tsai Lee and Franco Preparata. Euclidean shortest paths in the presence of rectilinear barriers. *Networks*, 14:393–410, 1984. 55

Douglass B. Lee. Requiem for large-scale models. *Journal of the American Institute of Planners*, 39 (3), 1973. 107, 141

Robert J. Lempert, Steven W. Popper, and Steven C. Bankes. *Shaping the next one hundred years : new methods for quantitative, long-term policy analysis*. Number MR-1626. RAND Corporation, Santa Monica, CA, USA, 2003. 52

Andreas Ligtvoet. Using an agent-based model for analysing the robustness of a syngas cluster. In *Workshop on Agent Technologies for Energy Systems ATES 2010, The 9th International Conference on Autonomous Agents and Multiagent Systems*, Toronto, Canada, May 10-14 2010. 63

Andreas Ligtvoet. Cooperation as a complex, layered phenomenon. In *Eighth International Conference on Complex Systems, June 26 - July 1*, 2011. 9, 142

Andreas Ligtvoet. Factors supporting cooperation in district heat networks in the Netherlands. In *Third International Engineering Systems Symposium – Design and Governance in Engineering Systems*. Council of Engineering Systems Universities (CESUN), 18-20 June 2012a. 29

Andreas Ligtvoet. When pig meets pencil: the beauty of complexity in industrial networks. In *European Conference on Complex Systems 2012*, Brussels, 3-7 September 2012b. 5, 117

Andreas Ligtvoet and Emile J.L. Chappin. Experience-based exploration of complex energy systems. *Journal of Futures Studies*, 16(5), September 2012a. 83, 97

Andreas Ligtvoet and Emile J.L. Chappin. Observing player behavior in an electricity market game. In *8th Conference of the European Social Simulation Association*. University of Salzburg, Austria, September 10-14 2012b. 83

Andreas Ligtvoet and Paulien M. Herder. Simulation and gaming for understanding the complexity of cooperation in industrial networks. In Omar Hammami, Daniel Krob, and Jean-Luc Voirin, editors, *Proceedings of the Second International Conference on Complex Systems Design & Management CSDM 2011*, volume XXIV, 2012. 97

Andreas Ligtvoet, Emile J.L. Chappin, and Rob M. Stikkelman. Modelling cooperative agents in infrastructure networks. In A. Ernst and S. Kuhn, editors, *Proceedings of the 3rd World Congress on Social Simulation WCSS2010*, Kassel, Germany, 2010. 63

Andreas Ligtvoet, Amineh Ghorbani, and Emile Chappin. A methodology for agent-based modelling using institutional analysis – applied to consumer lighting. In *Agent Technologies for Energy Systems, Tenth international conference on Autonomous Agents and Multi Agent Systems (AAMAS)*, Taipei, May 2011. 101

Charles E. Lindblom. The science of 'muddling through'. *Public Administration Review*, 19(2): 79–88, Spring 1959. 121

Bjorn Lomborg. *The Skeptical Environmentalist: Measuring the Real State of the World.* Cambridge University Press, 2001. 1

Derk Loorbach, Rutger van der Brugge, and Mattijs Taanman. Governance in the energy transition: Practice of transition management in the Netherlands. *Int. J. Environmental Technology and Management*, 9(2/3):294–315, 2008. 2

Michael W. Macy and John Skvoretz. The evolution of trust and cooperation between strangers: A computational model. *American Sociological Review*, 63(5):638–660, October 1998. 16

James G. March. Bounded rationality, ambiguity, and the engineering of choice. *The Bell Journal of Economics*, 9:587–608, Autumn 1978. 26

James G. March. Exploration and exploitation in organizational learning. *Organization Science*, 2 (1):71–87, 1991. 101

Paolo Mariti and Robert H. Smiley. Co-operative agreements and the organization of industry. *The Journal of Industrial Economics*, 31(4):437–451, June 1983. 20, 21

Harold E. Marshall. Techniques for treating uncertainty and risk in the economic evaluation of building investments. NIST special publication 757, U.S. Department of Commerce, September 1988. 60

Igor S. Mayer. The gaming of policy and the politics of gaming: A review. *Simulation & gaming*, X: 1–38, 2009. 84, 85, 102

Jane McGonigal. *The Puppet Master Problem: Design for Real-World, Mission Based Gaming*, chapter in: Second Person. MIT Press, 2006. 85

McKinsey. Oil's uncertain future. Technical report, McKinsey Quarterly, November 2011. 57

Dennis L. Meadows. Learning to be simple: My odyssey with games. *Simulation Gaming*, 30: 342–351, 1999a. 85

Donella Meadows. Leverage points: Places to intervene in a systems. Technical report, Sustainability Institute, 1999b. URL http://www.sustainabilityinstitute.org/pubs/Leverage_Points.pdf. 107

Donella H. Meadows and Jennifer M. Robinson. The electronic oracle: computer models and social decisions. *System Dynamics Review*, 18(2):271–308, Summer 2002. 64, 65, 79, 102, 106, 110, 123, 141

Ineke S.M. Meijer, Marko P. Hekkert, and Joop F.M. Koppenjan. The influence of perceived uncertainty on entrepreneurial action in emerging renewable energy technology; biomass gasification projects in the Netherlands. *Energy Policy*, 35:5836–5854, 2007a. 2

Ineke S.M. Meijer, Marko P. Hekkert, and Joop F.M. Koppenjan. How perceived uncertainties influence transitions; the case of micro-chp in the Netherlands. *Technological Forecasting & Social Change*, 74:519–537, 2007b. 2

Sebastiaan Meijer. *The organisation of transactions*. PhD thesis, Wageningen University, 2009. 102, 122

Zdzislaw Melzak. On the problem of Steiner. *Canadian Mathematical Bulletin*, 4:143–148, 1961. 52, 54

Donald C. Mikulecky. The emergence of complexity: science coming of age or science growing old? *Computers and chemistry*, 25:341–348, 2001. 4, 97

Manfred Milinski. Tit-for-tat in sticklebacks and the evolution of cooperation. *Nature*, 325:433–435, January 1987. 16

Manfred Milinski, Dirk Semmann, and Hans-Jürgen Krambeck. Reputation helps solve the tragedy of the commons. *Nature*, 415:426–428, January 2002. 15

John. H. Miller, Carter T. Butts, and David Rode. Communication and cooperation. *Journal of Economic Behavor and Organization*, 47:179–219, 2002. 20

MINEZ. Warmte op stoom. Technical report, Ministerie van Economische Zaken, Den Haag, december 2008. 2

Luis Miotti and Frédérique Sachwald. Co-operative r&d: why and with whom? an integrated framework of analysis. *Research Policy*, 32:1481–1499, 2003. 21

Mark S. Mizruchi. What do interlocks do? an analysis, critique, and assessment of research on interlocking directorates. *Annual Review of Sociology*, 22:271–298, 1996. 14, 125

Thomas P. Moliterno and Douglas M. Mahony. Network theory of organization: A multilevel approach. *Journal of Management*, 37:443, 2011. 125

Ethan Mollick. Establishing moore's law. *IEEE Annals of the History of Computing*, 28(3):62–75, July-September 2006. 106

Gareth Morgan. *Images of organization*. Sage Publications, 1986. 4

Municipality of Delft. Warmte voor Delft. Technical report, Gemeente Delft, August 2006. 32

Municipality of Delft. Heat for Delft. Technical report, Municipality of Delft, May 2009. 31, 32

Municipality of Delft. Doorontwikkeling Warmtebedrijf. brief, 29 March 2011a. letter of the Mayor and Aldermen 1145208. 33

Municipality of Delft. Doorontwikkeling Warmtebedrijf, wensen en bedenkingen van de raad. brief, 19 April 2011b. letter of the Mayor and Aldermen 1150405. 33

Municipality of Delft. Doorontwikkeling Warmtebedrijf. nota, 31 March 2011c. letter of the Mayor and Aldermen 1145206. 33

Municipality of Delft. Voortgangsrapportage Warmtebedrijf. brief, 9 November 2011d. letter of the Mayor and Aldermen 1188096. 35

Mark Newman, Albert László Barabási, and Duncan J. Watts, editors. *The structure and dynamics of networks*. Princeton University Press, Princeton and Oxford, 2006. 52

Richard P. Nielsen. Cooperative strategy. *Strategic Management Journal*, 9:475–492, 1988. 3, 9, 13, 20, 21, 22

Igor Nikolić. *Co-Evolutionary Process For Modelling Large Scale Socio-Technical Systems Evolution*. PhD thesis, Delft University of Technology, Delft, The Netherlands, 2009. 68

Bart Nooteboom. Innovation, learning and industrial organisation. *Cambridge Journal of Economics*, 23:127–150, 1999. 79, 120, 122

Bart Nooteboom. *Inter-firm collaboration, learning and networks*. Routledge, 2004. 9, 108, 118

Martin A. Nowak. Five rules for the evolution of cooperation. *Science*, 314:1560–1563, December 2006. 9, 14, 15

OCAP. Ocap nieuws. (6), May 2005. 44

OCAP. Ocap nieuws. (21), July 2009. 44

Jasmina Omić. *Epidemics in networks*. PhD thesis, Delft University of Technology, the Netherlands, 2010. 40. 52

Elinor Ostrom. A behavioral approach to the rational choice theory of collective action. *American Political Science Review*, 92(1):1–22, March 1998. 14, 22, 98

Elinor Ostrom. Collective action and the evolution of social norms. *The Journal of Economic Perspectives*, 14(3):137–158, Summer 2000. 14, 20

Elinor Ostrom, Roy Gardner, and J. Walker. *Institutional analysis and common-pool resources*, chapter in: Rules, games, and common-pool resources, pages 23–50. University of Michigan Press, 1994. 26, 141

Raymond Paquin and Jennifer Howard-Grenville. *Facilitating regional industrial symbiosis: network growth in the UK's national industrial symbiosis programme*, chapter in: The social embeddedness of industrial ecology, pages 103–127. Edward Elgar Publishing, 2009. 23

Bernard Pavard and Julie Dugdale. *The Contribution Of Complexity Theory To The Study Of Socio-Technical Cooperative Systems*, volume IIIB of *New Research*, proceedings from the third international conference on complex systems in: Unifying Themes in Complex Systems, pages 39–48. Springer, 2006. 5

PoR. Port compass. Vision document, Port of Rotterdam Authority, the Netherlands, December 2011. 57, 66

Robert C. Prim. Shortest connection networks and some generalizations. *Bell System Technical Journal*, 36:1389–1401, 1957. 52

RCI. The new Rotterdam. Technical report, Rotterdam Climate Initiative, Rotterdam, the Netherlands, June 2009. 40

RCI. CO_2 energie capture and storage in Rotterdam. Technical report, Rotterdam Climate Initiative, Rotterdam, the Netherlands, May 2011. 2nd updated edition. 41

Rick L. Riolo, Michael D. Cohen, and Robert Axelrod. Evolution of cooperation without reciprocity. *Nature*, 414:441–443, November 2001. 16, 26

Horst W.J. Rittel and Melvin M. Webber. Dilemmas in a general theory of planning. *Policy Sciences*, 4:155–169, 1973. 5, 7, 121

Gilbert Roberts and Thomas N. Sherratt. Cooperative reading: some suggestions for the integration of cooperation literature. *Behavioural Processes*, 76:126–130, 2007. 9, 13

Everett M. Rogers. *Diffusion of Innovations*. The Free Press, New York, 4th edition edition, 1995. 5, 122

Arturo Rosenblueth and Norbert Wiener. The role of models in science. *Philosophy of science*, 12 (4):316–321, October 1945. 63, 123

Jens R. Rostrup-Nielsen. New aspects of syngas production and use. *Catalysis Today*, 63:159–164, 2000. 57

Jens R. Rostrup-Nielsen. Syngas in perspective. *Catalysis Today*, 71:243–247, 2002. 57

Jan Rotmans, René Kemp, and Marjolein van Asselt. More evolution than revolution: transition management in public policy. *Foresight*, 3(1):15–31, 2001. 2, 24

Denise M. Rousseau. *Issues of level in organizational research: multi-level and cross-level perspectives*, volume 7, chapter in: Research in Organizational Behavior, pages 1–37. JAI Press Inc., Greenwich, Connecticut | London, England, 1985. 24

Zhenhua Rui, Paul A. Metz, Douglas B. Reynolds, Gang Chen, and Xiyu Zhou. Regression models estimate pipeline construction costs. *Oil & Gas Journal*, 109(27), April 2011. 54

Alex Ryan. What is a systems approach?, September 2008. URL http://uk.arxiv.org/abs/0809.1698v1. 5, 63, 108

Thomas C. Schelling. *Micromotives and Macrobehavior*. W.W. Norton and Company, 1978. 5

Benno L. Schepers and Margaret P.J. van Valkengoed. Warmtenetten in Nederland. Technical report, CE Delft, Delft, October 2009. 30

Nadine Schieritz and Peter M. Milling. Modeling the forest or modeling the trees: A comparison of system dynamics and agent-based simulation. In *21st International Conference of the System Dynamics Society, New York*, Mannheim, Germany, 2003. 65

Richard Schuster and Amir Perelberg. Why cooperate? an economic perspective is not enough. *Behavioural Processes*, 66:261–277, 2004. 16, 19

Peter M. Senge. *The fifth discipline*. Doubleday/Currency, New York, 1990. 5

Shell. Shell energy scenarios to 2050: Scramble or blueprint, 2008. 2

Fritz B. Simon. *Einführung in die systemische Organisationstheorie*. Carl-Auer Verlag, Heidelberg, 2007. 3, 20, 26

Herbert A. Simon. Bounded rationality in social science: Today and tomorrow. *Mind & Society*, 1 (1):25–39, 2000. 3, 26, 47, 74

Jeroen Smit. *De Prooi*. Uitgeverij Prometheus, Amsterdam, 2008. 47

Ned Stafford. Gas for the greenhouse. *Nature*, 442(3):499, August 2006. 42

Ingolf Stahl. *Using operational gaming*, chapter in: Handbook of systems analysis, pages 121–171. Elsevier Science Publishing, 1988. 84, 102, 105

David W. Stephens and J. P. Anderson. Reply to roberts: cooperation is an outcome, not a mechanism. *Animal Behaviour*, 53:1363–1364, 1997. 99

Rob M. Stikkelman, Gerard P.J. Dijkema, Paulien M. Herder, and Aad F. Correljé. Van bloedgroep olie naar bloedgroep syngas. *Petrovision*, pages 62–67, September 2006. 57

David J. Teece. Competition, cooperation, and innovation: Organizational arrangements for regimes of rapid technological progress. *Journal of Economic Behavior and Organization*, 18: 1–25, 1992. 22, 25, 68

David J. Teece, Gary Pisano, and Amy Shuen. Dynamic capabilities and strategic management. *Strategic Management Journal*, 18(7):509–533, August 1997. 14

Ernst ten Heuvelhof, Martin de Jong, Mirjam Kars, and Helen Stout. *Strategic behaviour in network industries*. Edward Elgar, UK, 2009. 3

D. A. Thomas and J. F. Weng. Minimum cost flow-dependent communication networks. Technical report, University of Melbourne, Victoria, Australia, 10 March 2006. 54, 130

Endre Timár. Publiekprivaat warmtebedrijf in Delft. Technical report, Agentschap NL, 13 December 2010a. 31, 33, 35

Endre Timár. Den Haag primeur met aardwarmtewoning. Technical report, Agentschap NL, 6 July 2010b. 36

Emanuela Todeva and David Knoke. Strategic alliances and models of collaboration. *Management Decision*, 43(1):123–148, 2005. 3, 20, 77

John Tooby and Leda Cosmides. *The psychological foundations of culture*, chapter in: The adapted mind – evolutionary psychology and the generation of culture. Oxford University Press, New York, 1992. 121

Eric Trist. The evolution of socio-technical systems. Occasional paper 2, Ontario Ministry of Labour, Toronto, Ontario, June 1981. 4

Robert L. Trivers. The evolution of reciprocal altruism. *Quarterly review of biology*, 46(1), March 1971. 14, 15

Amos Tversky and Daniel Kahneman. Judgment under uncertainty: Heuristics and biases. *Science*, 185:1124–1131, 24 September 1974. 48

Tweede Kamer. Memorie van toelichting op de Warmtewet. 29048(3), 2003. 30

Tweede Kamer. Vaststelling van de begrotingsstaat van het Ministerie van Financiën (ixb) voor het jaar 2004, 2004. Brief van de Minister van Financiën, nr. 34, 29 200 IXB. 41, 42

UNDP. Inter-municipal cooperation webpage, 2010. URL http://www.municipal-cooperation.org. 47, 48

Marjolein B.A. van Asselt and Ellen Vos. The precautionary principle and the uncertainty paradox. *Journal of risk research*, 9(4):313–336, June 2006. 6, 107

Koen Haziël van Dam. *Capturing socio-technical systems with agent-based modelling*. PhD thesis, Delft University of Technology, Delft, The Netherlands, 2009. 66, 68, 69

Sander van der Leeuw, David Lane, and Dwight Read. *The Long-Term Evolution of Social Orga-*

nization, chapter in: Complexity Perspectives in Innovation and Social Change, pages 85–116. Methodos Series 7. Springer Science+Business Media, 2009. 5

Caroline van Leenders and Jolein Baidenmann. Tekens van transitie. Technical report, Energie Transitie, Mei 2010. 42, 44

Ian Vickers and Martyn Cordey-Hayes. Cleaner production and organizational learning. *Technology Analysis & Strategic Management*, 11(1):75–94, 1999. 99

Mariëlle Vosbeek and Hans Warmenhoven. Making large-scale carbon capture and storage in the Netherlands work. Technical report, Ecofys, 2007. 40

VROM. Nieuwe energie voor het klimaat – werkprogramma Schoon en Zuinig. Technical Report 7421, Ministerie van VROM (Dutch ministry of housing, spatial planning, and the environment), Den Haag, the Netherlands, September 2007. 1

Warren E. Walker, S. Adnan Rahman, and Jonathan Cave. Adaptive policies, policy analysis, and policy-making. *European Journal of Operational Research*, 128:282–289, 2001. 51

Warren E. Walker, P. Harremoës, Jan Rotmans, Jeroen P. van der Sluijs, Marjolein B.A. van Asselt, P. Janssen, and M.P. Krayer von Krauss. Defining uncertainty: A conceptual basis for uncertainty management in model-based decision support. *Integrated Assessment*, 4:5–17, 2003. 7, 51, 63, 107

Jennifer Waterhouse, Robyn Keast, and Kerry Brown. *Negotiating the business environment*. Tilde University Press, Prahran, Australia, 1st edition, 2011. 47

G.Campbell Watkins. Oil scarcity: what have the past three decades revealed? *Energy Policy*, 34: 508–514, 2006. 70

Jia F. Weng and James MacGregor Smith. Steiner minimal trees with one polygonal obstacle. *Algorithmica*, pages 638–648, 2001. 56

Birger Wernerfelt and Aneel Karnani. Competitive strategy under uncertainty. *Strategic Management Journal*, 8(2):187–194, March/April 1987. 7

Stuart A. West, Ashleigh S. Griffin, and Andy Gardner. Evolutionary explanations for cooperation. *Current Biology*, 17:661–672, August 2007a. 9, 14, 15, 19

Stuart A. West, Ashleigh S. Griffin, and Andy Gardner. Social semantics: altruism, cooperation, mutualism, strong reciprocity and group selection. *Journal of Evolutionary Biology*, 20:415–432, 2007b. 14, 15

Andrzej P. Wierzbicki. On the role of intuition in decision making and some ways of multicriteria aid of intuition. *Journal of Multi-Criteria Decision Analysis*, 6:65–76, 1997. 71, 119

Andrzej P. Wierzbicki. Modelling as a way of organising knowledge. *European Journal of Operational Research*, 176:610–635, 2007. 105

D.J. Wilhelm, D.R. Simbeck, A.D. Karp, and R.L. Dickenson. Syngas production for gas-to-liquids applications: technologies, issues and outlook. *Fuel Processing Technology*, 71:139–148, 2001. 57

Oliver E. Williamson. Strategizing, economizing, and economic organization. *Strategic Management Journal*, 12:75–94, 1991. 121

Oliver E. Williamson. Transaction cost economics: how it works; where it is headed. *De Economist*, 146(1):23–58, 1998. 13, 24, 25, 26, 122

Pawel Winter. Euclidean Steiner minimal trees with obstacles and Steiner visibility graphs. *Discrete*

Applied Mathematics, 47(2):187–206, 30 November 1993. 55

Pawel Winter, Martin Zachariasen, and Jens Nielsen. Short trees in polygons. *Discrete Applied Mathematics*, 118(1–2):55–72, April 2002. 55

Eric F. Wolstenholme. Qualitative vs quantitative modelling: the evolving balance. *Journal of the Operational Research Society*, 50:422–428, 1999. 123

Michael Wooldridge and Nicholas R. Jennings. Pitfalls of agent-oriented development. In *Proceedings of the Second International Conference on Autonomous Agents (Agents 98)*, pages 385–391, Minneapolis/St Paul, MN, USA, May 1998. 106

Michael Wooldridge and Nicholas R. Jennings. The cooperative problem solving process. *Journal of Logic Computation*, 9(4):563–592, 1999. 19

Martin Zachariasen. Concatenation-based greedy heuristics for the euclidean Steiner tree problem. Technical Report DIKU-TR-97/20, University of Copenhagen, 1997. 52

Martin Zachariasen. Local search for the Steiner tree problem in the euclidean plane. *European Journal of Operational Research*, 119(2):282–300, December 1999. 52

Acknowledgements

Even the preparation of a thesis is only possible through all kinds of collaborative efforts. The realisation of this fact has led me to use first person plural instead of 'I' (which I thought I would use). Of course, all choices and mistakes are mine, but my ideas were influenced by many others:

Paulien Herder allowed me to follow my own hunches, calmly observed the intellectual messes I got myself into, and radiated confidence – a true coach mentality. I learnt from her ability to provide a helicopter view of research and pull discussions one level higher than I would normally be content with. Furthermore, we had some fun listening to music of over-the-hill performers.

Margot Weijnen has organised the Energy and Industry section in such a way that it fosters true scientific experimentation and exploration of new paths. Her sharp insight was especially helpful in the final phase of this research. I also owe my invitation to the Santa Fe complexity summer school to Margot's appreciation of my singing 'talents'.

Special thanks go to Rob Stikkelman who, together with Paulien, was the first to drill me about my thoughts and ambitions. Where Paulien could be called the 'good cop', Rob always proved to be the 'confusing cop' who – just as I had determined a seemingly clear and logical path – came and asked the difficult questions or offered new disruptive ideas. I appreciate his struggle with the possibilities and impossibilities of thinking about socio-technical systems and his excellent cooking skills.

Émile Chappin also deserves a special mention: he spent many hours with me, explaining Java and discussing ABMs and serious games. Always thoughtful and precise, critical and open, he is a good example of what a scientist should be. We had fun playing around with models, criticising transition management thinkers, enjoying the beauty of graphs and latex lay-out, and making music.

It has been a pleasure to work with the smart and dedicated people of the Energy and Industry section: Chris Davis – wizard of the data world and generally a swell guy, Amineh Ghorbani – with her excellent idea of combining Ostrom's IAD framework with ABM, Petra Heijnen – who has shown me once again that mathematicians are precise and logical, Igor Nikolić – who has influenced my research more than I dare to admit, Anish Patil – co-struggler and squash buddy. Thanks go to roommates Alireza Abbasy – who shared my sense of the absurd and futile, Catalin Bucura – music man, Catherine Chiong Meza – cultural compass and serious discussant, Telli van der Lei – always optimistic, a good teammate at the Port of Rotterdam, Leentje Volker – sharp and critical, just what

our clients at Rijkswaterstaat ordered.

Finally my thanks go to my parents Joop and Anneliese Ligtvoet – who have always encouraged me to find my own path and who emphasised the importance of learning, my love and favourite world-travelling companion Rebecca van der Horst – who has shown me how to do a Ph.D. and keep calm (but she was much more organised), and my daughter Olivia – who generally just makes me very happy.

Curriculum vitae

Although science purports to be neutral and objective, this goal is never truly achieved. This curriculum vitae provides some background on the author, which may provide the necessary context to understand the research choices he made.

Andreas Ligtvoet was born in 1974 in Leidschendam, close to The Hague where he grew up. He enjoyed his secondary education at Het Nederlands Lyceum and later Aloysius College, The Hague, where he graduated in 1992 with a mix of science, humanities, and languages. He participated twice in the World Schools Debating Championships and continued debating throughout university.

Not wanting to be condemned to four years of monodisciplinary tedium, he chose the new interdisciplinary study of Science & Policy at Utrecht University. This study combined a majority of courses in natural sciences with electives in the humanities. He interned at Grontmij consulting engineers, where he investigated the organisation's approach to environmental impact assessment, and at the Dutch agency for energy and the environment (Novem, nowadays Agentschap NL), where he wrote his Master's thesis on technology transfer to improve energy savings in Polish housing. During his time in Utrecht, he founded the Utrecht Debating Society and chaired students' association Helix.

After receiving his M.Sc. degree in 1997 Andreas became a volunteer, working for the Jordanian Royal Society for the Conservation of Nature, in Amman. He spent a year setting up an environmental consultancy and performing several transnational projects on sustainable tourism, solar energy, and environmental impact assessment. Returning to the Netherlands in 1999, he worked at Holland Railconsult (nowadays Movares), Utrecht, on contingency plans for the Y2k (millennium) problem and the implementation of information technology systems. He became an active member of the Green Party and later treasurer of the board.

From 2000 to 2006 he joined RAND Europe, the Leiden-based subsidiary of the RAND Corporation think-tank. As policy analyst he researched a wide range of policy themes (science, education, technology, and health care) for clients in Dutch, English, German, and European governments. His methodological focus was on international policy comparisons and assessments, (technology) foresight, horizon scanning, and scenario studies. Around 2005 he became increasingly interested in energy and materials scarcity, and joined the Dutch Association for the Study of Peak Oil and Gas, of which he later joined the board as treasurer.

Giving in to his travelling nature, between 2006 and 2007 he travelled overland from Alaska to Tierra del Fuego (Argentina).

When returning to the Netherlands, he wanted to once again focus on energy issues and to expand his knowledge of (quantitative) research methods. He joined the Energy and Industry section at the Delft University of Technology, faculty of Technology, Policy, and Management to work on this thesis. In 2010 he was accepted to participate in the Santa Fe Institute's Complex Systems Summer School. Apart from educational activities, he participated in several contract studies for the Dutch Road Authority (Rijkswaterstaat), ProRail, and the Port Authority of Rotterdam (Havenbedrijf), investigating asset management. During his last year at Delft he was seconded to the Port Authority of Rotterdam supporting their asset management programme.

This curriculum vitae was last updated on the 11th of January 2013.

Next Generation Infrastructures PhD thesis series

1. Strategic behavior and regulatory styles in the Netherlands energy industry.
   Martijn Kuit, 2002, Delft University of Technology, the Netherlands.

2. Securing the public interest in electricity generation markets – The myths of the invisible hand and the copper plate.
   Laurens de Vries, 2004, Delft University of Technology, the Netherlands.

3. Quality of service routing in the internet – Theory, complexity and algorithms.
   Fernando Kuipers, 2004, Delft University of Technology, the Netherlands.

4. The role of power exchanges for the creation of a single European electricity market – Market design and market regulation.
   François Boisseleau, 2004, Delft University of Technology, the Netherlands and University of Paris IX Dauphine, France.

5. The ecology of metals.
   Ewoud Verhoef, 2004, Delft University of Technology, the Netherlands.

6. MEDUSA – Survivable information security in critical infrastructures.
   Semir Daskapan, 2005, Delft University of Technology, the Netherlands.

7. Transport infrastructure slot allocation.
   Kaspar Koolstra, 2005, Delft University of Technology, the Netherlands.

8. Understanding open source communities – An organizational perspective.
   Ruben van Wendel de Joode, 2005, Delft University of Technology, the Netherlands.

9. Regulating beyond price – Integrated price-quality regulation for electricity distribution networks.
   Viren Ajodhia, 2006, Delft University of Technology, the Netherlands.

10. Networked reliability – Institutional fragmentation and the reliability of service provision in critical infrastructures.
    Mark de Bruijne, 2006, Delft University of Technology, the Netherlands.

11. Regional regulation as a new form of telecom sector governance – The interactions with technological socio-economic systems and market performance.
    Andrew Barendse, 2006, Delft University of Technology, the Netherlands.
12. The internet bubble – The impact on the development path of the telecommunications sector.
    Wolter Lemstra, 2006, Delft University of Technology, the Netherlands.
13. Multi-agent model predictive control with applications to power networks.
    Rudy Negenborn, 2007, Delft University of Technology, the Netherlands.
14. Dynamic bi-level optimal toll design approach for dynamic traffic networks.
    Dusica Joksimović, 2007, Delft University of Technology, the Netherlands.
15. Intertwining uncertainty analysis and decision-making about drinking water infrastructure.
    Machtelt Meijer, 2007, Delft University of Technology, the Netherlands.
16. The new EU approach to sector regulation in the network infrastructure industries.
    Richard Cawley, 2007, Delft University of Technology, the Netherlands.
17. A functional legal design for reliable electricity supply – How technology affects law.
    Hamilcar Knops, 2008, Delft University of Technology, the Netherlands and Leiden University, the Netherlands.
18. Improving real-time train dispatching – Models, algorithms and applications.
    Andrea D'Ariano, 2008, Delft University of Technology, the Netherlands.
19. Exploratory modeling and analysis – A promising method to deal with deep uncertainty.
    Datu Buyung Agusdinata, 2008, Delft University of Technology, the Netherlands.
20. Characterization of complex networks – Application to robustness analysis.
    Almerima Jamaković, 2008, Delft University of Technology, the Netherlands.
21. Shedding light on the black hole – The roll-out of broadband access networks by private operators.
    Marieke Fijnvandraat, 2008, Delft University of Technology, the Netherlands.
22. On Stackelberg and inverse Stackelberg games & their applications in the optimal toll design problem, the energy markets liberalization problem, and in the theory of incentives.
    Kateřina Staňková, 2009, Delft University of Technology, the Netherlands.
23. On the conceptual design of large-scale process & energy infrastructure systems – Integrating flexibility, reliability, availability, maintainability and economics performance metrics.
    Austine Ajah, 2009, Delft University of Technology, the Netherlands.

24. Comprehensive models for security analysis of critical infrastructure as complex systems.
    Fei Xue, 2009, Politecnico di Torino, Torino, Italy.
25. Towards a single European electricity market – A structured approach for regulatory mode decision-making.
    Hanneke de Jong, 2009, Delft University of Technology, the Netherlands.
26. Co-evolutionary process for modelling large scale socio-technical systems evolution.
    Igor Nikolić, 2009, Delft University of Technology, the Netherlands.
27. Regulation in splendid isolation – A framework to promote effective and efficient performance of the electricity industry in small isolated monopoly systems.
    Steven Martina, 2009, Delft University of Technology, the Netherlands.
28. Reliability-based dynamic network design with stochastic networks.
    Hao Li, 2009, Delft University of Technology, the Netherlands.
29. Competing Public Values – Coping strategies in heavily regulated utility industries.
    Bauke Steenhuisen, 2009, Delft University of Technology, the Netherlands.
30. Innovative contracting practices in the road sector – Cross-national lessons in dealing with opportunistic behaviour.
    Mónica Altamirano, 2009, Delft University of Technology, the Netherlands.
31. Reliability in urban public transport network assessment and design.
    Shahram Tahmasseby, 2009, Delft University of Technology, the Netherlands.
32. Capturing socio-technical systems with agent-based modelling.
    Koen van Dam, 2009, Delft University of Technology, the Netherlands.
33. Road incidents and network dynamics – Effects on driving behaviour and congestion.
    Victor L. Knoop, 2009, Delft University of Technology, the Netherlands.
34. Governing mobile service innovation in co-evolving value networks.
    Mark de Reuver, 2009, Delft University of Technology, the Netherlands.
35. Modelling risk control measures in railways.
    Jaap van den Top, 2009, Delft University of Technology, the Netherlands.
36. Smart Heat and Power – Utilizing the Flexibility of Micro Cogeneration.
    Michiel Houwing, 2010, Delft University of Technology, the Netherlands.
37. Architecture-Driven Integration of Modeling Languages for the Design of Software-Intensive Systems.
    Michel dos Santos Soares, 2010, Delft University of Technology, the Netherlands.
38. Modernization of electricity networks – Exploring the interrelations between institutions and technology.
    Martijn Jonker, 2010, Delft University of Technology, the Netherlands.

39. Experiencing Complexity – A gaming approach for understanding infrastructure systems.
Geertje Bekebrede, 2010, Delft University of Technology, the Netherlands.

40. Epidemics in Networks – Modeling, Optimization and Security Games.
Jasmina Omic, 2010, Delft University of Technology, the Netherlands.

41. Designing Robust Road Networks – A general method applied to the Netherlands.
Maaike Snelder, 2010, Delft University of Technology, the Netherlands.

42. Simulating Energy Transitions.
Emile Chappin, 2011, Delft University of Technology, the Netherlands.

43. De ingeslagen weg. Een dynamisch onderzoek naar de dynamiek van de uitbesteding van onderhoud in de civiele infrastructuur.
Rob Schoenmaker, 2011, Delft University of Technology, the Netherlands.

44. Safety Management and Risk Modelling in Aviation: the challenge of quantifying management influences.
Pei-Hui Lin, 2011, Delft University of Technology, the Netherlands.

45. Transportation modelling for large-scale evacuations.
Adam J. Pel, 2011, Delft University of Technology, the Netherlands.

46. Clearing the Road for ISA Implementation? – Applying Adaptive Policymaking for the Implementation of Intelligent Speed Adaptation.
Jan-Willem van der Pas, 2011, Delft University of Technology, the Netherlands.

47. Designing Multinational Electricity Balancing Markets.
Reinier van der Veen, 2012, Delft University of Technology, the Netherlands.

48. Understanding Social-technical Change – A System-Network-Agent Approach.
Catherine M. Chiong Meza, 2012, Delft University of Technology, the Netherlands.

49. National design and multi-national integration of balancing markets.
Alireza Abbasy, 2012, Delft University of Technology, the Netherlands.

50. Regulation of gas infrastructure expansion.
Jeroen de Joode, 2012, Delft University of Technology, the Netherlands.

51. Governance Structures of Free/Open Source Software Development. Examining the role of modular product design as a governance mechanism in the FreeBSD Project.
George Dafermos, 2012, Delft University of Technology, the Netherlands.

52. Making Sense of Open Data – From Raw Data to Actionable Insight.
Chris B. Davis, 2012, Delft University of Technology, the Netherlands.

53. Intermodal Barge Transport: Network Design, Nodes and Competitiveness.
Rob Konings, 2009, Delft University of Technology, Trail Research School, the Netherlands.

54. Handling Disruptions in Supply Chains: An integrated Framework and an Agent-based Model.
    Behzad Behdani, 2013, Delft University of Technology, the Netherlands.
55. Images of cooperation – a methodological exploration in energy networks.
    Andreas Ligtvoet, 2013, Delft University of Technology, the Netherlands.

Order information: info@nextgenerationinfrastructures.eu