Gap Analysis for Energy Network Design

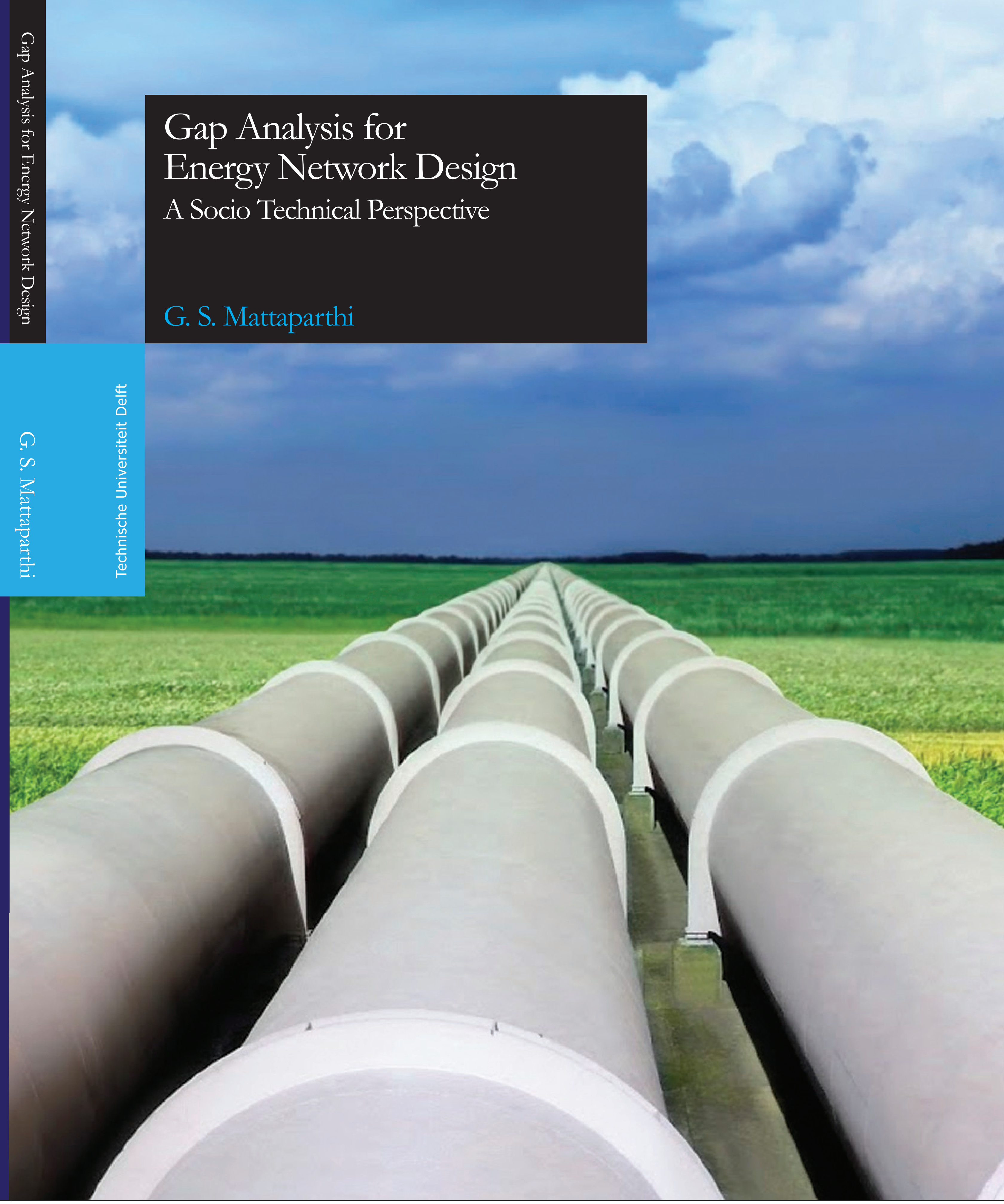
A research into possible ways of enhancing the scientific models of network planning, to ensure their usability among decision makers, through user friendly decision support tools.

A thesis, in partial fulfillment of the requirements for the degree of Master of Science in Engineering & Policy Analysis at the Delft University of Technology.

Gap Analysis for Energy Network Design

G. S. Mattaparthi

Technische Universiteit Delft



Gap Analysis for Energy Network Design

A Socio Technical Perspective

G. S. Mattaparthi

TU Delft
Delft University of Technology

Challenge the future

DELFT UNIVERSITY OF TECHNOLOGY

MASTER THESIS

FACULTY TECHNOLOGY, POLICY AND MANAGEMENT

Gap Analysis for Energy Network Design

A Socio Technical Perspective

Author:
Goutami Srideepti Mattaparthi
Student Id: 4312066
goutami.deepti@gmail.com

Graduation Committee:
Prof.dr.ir.P.M. Herder
Dr.ir.P.W. Heijnen
Dr.ir. Bert Enserink

A thesis submitted in fulfilment of the requirements for the degree of Master of Science in

Engineering and Policy Analysis

August 7, 2015

Acknowledgement

I take this opportunity to gratefully acknowledge the support and guidance of my graduation committee during this thesis. I would like to thank Prof. P. M. Herder for chairing the graduation committee and her clear and insightful comments on my thesis report. I am grateful to Dr. Bert Enserink for his pleasant constructivism which gave me a bunch of ideas to proceed whenever I was stuck to validate my research. I would like to extend my deepest thanks to Dr. P. W. Heijnen, my thesis supervisor for her inexhaustible enthusiasm in keeping me on track, within scope and excited about the subject till the end. Without her careful supervision and the dedicated discussions during our Thursday meetings every week, this thesis would never have taken shape.

Of course, I would like to credit each and every classmate with whom I have interacted during my study or otherwise. Without their company, this study wouldn't have been more exciting. The EPA journey which started in 2013 with a bunch of students from various parts of the World gave me a new family in this foreign land. You inspired me with the innumerable discussions on our EPA group, through EPA gatherings with fun games and international cuisines, during our coffee sessions between classes and our common lunches in 1st year. My deepest thanks to all of you for making this journey rewarding and memorable for the rest of my life.

I would like to thank my parents whole heartedly for believing in my decision to quit my job and chase my dreams. Without your constant support and belief this was not possible. I am grateful to my parents-in-laws for their understanding and encouragement throughout, which allowed me to reach here. Furthermore, I would like to thank my brother Tarun and my sister-in-law Sharvani for their support and taking greater responsibility of the family in India while I was pursuing my studies.

There is an adage which says ""Behind every successful man there is a woman ". I would like to redefine this today and say, behind my success there is a man, who completely deserves this credit - my loving husband Aniket. Without him, I wouldn't have joined EPA or pursued my Masters in fact. His love, trust and hard work have made my dream come true. I would like to dedicate this work to him, as this can be the best gift, I can give him today.

Thanks,
Goutami Srideepti Mattaparthi

Executive Summary

Energy network infrastructures form an integral part of continuous, stable and uninterrupted energy supply and transmission. These structures are complex and mostly consist of wired or pipeline networks. Some examples of these networked infrastructures can be oil and natural gas lines, electricity (grids), heat pipelines, biogas and green gas lines, Carbon dioxide (CO2) emissions capture and distribution etc. These energy infrastructures primarily transport energy from their entries (sources) to exits (sinks). Modern industrialised societies perception of demand for energy is seeing a dynamic change. When energy transport distribution using existing networks becomes insufficient, then topology extensions come into play or the need for new infrastructures is demanded. The big question for the network planners is to identify the positions where these extensions are to be placed, keeping the total extension costs to the minimum. Moreover, in case of rolling out new networks in areas where population density is high and with their associated technical complexity, demand for proper planning techniques to design the network layouts is increasing.

On the other hand, many scientific researchers have proposed different types of network optimization algorithms for routing in energy network planning from a system perspective. Models have been developed to simulate the networked infrastructures using several optimization techniques to provide cost efficient networks. Although these scientific models are proposed, either they are not well known or they are too complex for the network planners to use them in decision making for real world cases. These concerns led to the motivation of this research. In simple terms, there is a need to bridge the gap between the scientific knowledge and practical decision making for designing efficient energy networks.

The research question for analysing this situation is formulated as,

"In what ways can the scientific approaches for energy network design be enhanced to ensure their usability among decision makers?"

To answer the research question, the energy network of biogas and upgraded biogas (green-gas) in Netherlands was chosen for this study. The first phase started with an empirical study of the biogas energy network from a Socio-Technical (ST) perspective. This perspective was chosen to understand the network characteristics of the supply chain of biogas production and distribution. Literature study and interviews with experts were conducted to understand the technical aspects, the key stakeholders involved in the network planning and the institutional directives that drive the network design. From the ST study the main factors that can influence the network design, their inter-relations and the interests of the stakeholders were clearly identified. After gaining a system perspective of the biogas/ green gas network the various scientific approaches proposing different optimization techniques for network planning were studied closely. The advantages, limitations and the assumptions of these techniques were carefully studied to understand why they are not used for real world cases so far. After the empirical study, in the conceptualization phase, the factors needed for network design from the ST perspective were base-lined keeping in mind the various stakeholder interests, especially the needs of the network planners. Based on this understanding a design approach was proposed to adapt existing scientific models with the factors obtained from the ST study. In the synthesis phase, the base-lined user requirements of decision makers and the working principles of the adapted algorithms, were combined and a user friendly interface design was proposed. This User Interface (UI) aids decision making for network planners and can be regarded as a Decision Support

System (DSS). The DSS is proposed as a software application in the form of use cases, sequence diagram and screen layouts. The DSS incorporates the actual requirements of the decision makers and combines it with the adapted scientific approaches of network planning and optimization, bridging the gap between scientific knowledge and practical decision making.

Research Findings and Recommendations

The heterogeneity of different energy networks, network characteristics and the different actors involved makes the notion of decision making as "one size fits all" less suitable. The different technical components, energy characteristics and the network equipment are specific to each energy network and they need to be separately considered while planning a network design. The empirical study of the socio technical analysis for biogas energy networks and the study of the scientific optimization methods, have been successful in drafting the characteristics of biogas networks which are important for network planning. A pipeline transporting gas over long distance has larger diameter and has compressor stations spread in the area to maintain the operating pressure of the gas in the pipeline. The article 12b of the Dutch Gas Act governs the rules for gas transmission and distribution in NL. The network facilitators are obliged to connect the gas producers to the grid if they meet the gas quality and grid specifications. In climate sensitive areas, the demand for gas can be low in summer and can be very high in winter. Gas storage's and flexible production units are introduced to balance the demand of gas against supply depending on the specific region and the operating pressure of the pipeline. The desired specifications of these technical components may influence the building costs of network design and have to be considered while designing solutions for network optimization.

The non overlapping factors from the ST study like the passive pipe profile and the active controllable components like compressor station, valves etc need to be considered by researchers while creating scientific models. A design approach is proposed to enhance the functionality of the existing models through newer cost equations and decision making logic. The sociological study concludes that the main stakeholders display network characteristics of variety, inter dependencies and closeness. All of them share different goals and interests and want to maximize their interest. Using the scientific models directly is still very complex for them. Thus, there is a need for increased collaboration among different stakeholders and a transparent system where all of them can come together and make decisions in the interest of all. The proposed decision support system combines the realistic requirements of the decision makers, simulates a real environment of an energy network and also inherits the benefits of the adapted scientific approaches.

From the study it is recommended that, the scientific community should extend the existing models to accommodate the network specific characteristics and consider adding the multi-actor context to their models to bring them closer to reality. They will need to improve their cost functions and the performance criteria to focus not only on costs but also the energy efficiency, safety and reliability of the network. Other recommendations are for the software developers to implement the design of the DSS and create a market strategy to diffuse this innovation into the market. Additionally, the study has focused on only biogas/greengas networks and hence it is important to consider other energy networks to validate their specifications.

Although this is not the scope of this research, mentioning it will boost biogas production in NL. From a policy perspective, Government needs to increase the depreciation period of subsidies for biogas production and also regulate the biogas market. This move can ensure more production and also safety and reliability of the grid. Stakeholder collaboration is also seen as an important aspect and there is a need for conducting Constructive Technology Assessment of biogas through scenario workshops. These moves will bring the different stakeholders together, reduce uncertainty and decisions can be taken in the interest of all.

Contents

Chapter 1

Introduction

1.1 Designing Energy Networks

Energy Networks transport energy, from one or several sources to one or several sinks. The different sources and sinks can be identified as nodes and are interlinked to form a network (Heijnen et al., 2013). Examples for networked infrastructures can be heat pipelines distributing energy for heating districts, oil and natural gas transmission lines, electricity transmission and distribution, CO2 capture and transmission, bio-gas and upgraded bio-gas distribution etc. The energy infrastructure mainly includes facilities like, oil refineries, power plants, energy storage units, distribution and transmission units, pipelines, electricity grid(wires), regulators etc to name a few (Ang et al., 2015). These infrastructure facilities can act as nodes which interlink the entire network and facilitate the distribution of energy from the producers to the consumers. Routing of the network layouts can be based on the preferences of the decision makers, location of the nodes, the legal constraints, resource availabilities and much more.

Need for designing efficient energy networks
Modern industrialized society's perception of the demand for energy is witnessing major changes. This change in demand can lead to the possibility of building topology extensions to existing infrastructure or building entirely new network designs. The task of rolling out new infrastructure networks in densely populated areas or re-modelling the existing networks in a cost efficient way demands proper planning of network design (Fugenschuh et al., 2011). Due to liberalisation of the energy markets like electricity and natural gas, a discrimination free access to the energy networks is expected to be granted to everyone. To fulfill this flexibility, network planners need to have higher degree of operational flexibility for the energy vendors and the customers. Each single investment to achieve this flexibility can cost the network planners several hundreds of million Euros (Fugenschuh et al., 2011). Thus, network planners see a need to determine the position of the network extensions in a cost effective way. To find a minimal cost topological extension can be complex, as it can include upfront capital intensive construction costs, appropriate land use agreements, suitable setting of the controllable items like shut off valves, pressure regulators etc and most importantly dealing with the interests of the multiple actors who can be affected with such decisions.

Challenges faced while designing energy networks
Infrastructures are capital intensive and the investments are up-front with return on investment coming long after the initial investments are made. This makes it more challenging for funding approvals (Chappin, 2011). Designing new infrastructures or extending existing ones involves construction costs not just for building material but also for satisfying the varying capacities at different times, costs for land usage and environmental permits. Decision making with the social actors and involving them in the planning, development, implementation phases makes it challenging for the network planners (Heijnen et al., 2013). During the planning phases, there can be a great deal of uncertainty concerning the interests of the participating actors, the amount of resources they are ready to use, their supply and demand capacities etc. which make the process of decision making even more cumbersome (Heijnen et al., 2013).

From a technical point of view, network designing poses another obstacle for concluding on the position of the topological extensions. Network planners need to have agreements for crossing some restricted zones, rivers/waterways, historical buildings etc. and be cost-efficient at the same time (Heijnen et al., 2013). Time varying demand for energy and dynamic aspects of the network add a lot of uncertainty to the planning. Government regulations and policies also affect the construction costs. As energy infrastructures are massive projects, to include technical uncertainty of completion, they need robust planning and insight into future consequences (Pindyck, 1993).

Such challenges mentioned above can lead to an inferior but expensive network or valuable network infrastructures not constructed at all. Most researchers have tried to study and overcome some of these challenges by proposing different scientific approaches to network planning and optimization. Some of them approach it to find an optimal solution while others try to present a robust solution which stands the test of time. According to (Heijnen et al., 2014)) routing in infrastructures is the most common challenge for many decision makers as it directly affects the land prices, technical difficulties and costs of the project. According to (Fugenschuh et al., 2011) finding an accurate position for the topological extensions, a suitable setting for the active components like valves and passive components like pipes is crucial for network planning. Other researchers (Adeyanju and Oyekunle, 2011) believe that balancing the demand and supply capacities through proper sequencing of the network equipment is crucial to keep the costs low and thus efficient network layouts need to be designed. Although, these researchers have tried to overcome these challenges using various scientific optimization techniques, these practices are still not adopted in real world cases.

The limitations for adopting these real world decision making parameters into scientific optimization techniques can be attributed to their mathematical complexity, their lack of simulating networks closer to reality, uncertainty regarding the network participant views and their information or it can merely be concerned with the network planners lack of knowledge about their existence.

Purpose of the research
This research is oriented towards bridging the gap between the scientific knowledge of network planning and more pragmatic decision making strategies. The study aims to clearly understand the actual needs of energy networks to simulate realistic layouts. The various factors , the interests of different stakeholders that can influence the network design planning are studied in detail. It further explores the scientific solutions for optimal network planning and outlines their advantages and shortcomings. Having obtained an overview of the network characteristics, the actors and the scientific solutions, a consensus on the different factors that clearly impact the network design is drawn. A design approach to include these factors to enhance the use of existing scientific models for realistic decision making is achieved. This can provide an overview of various alternate solutions for their network design in terms of cost, energy efficiency, safety, reliability, varying constraints and possible futures. Although, based on this proposal, the models become scientifically rich and closer to reality, they still are not adopted due to their complex nature. Hence, a design for a user friendly Decision Support System (DSS) for network planning will be proposed, which will cover the requirements of the decision makers, and also inherits the intelligence of the scientific approaches. This DSS can act as a support tool for network planners and decision makers to make sound and meaningful decisions.

1.2 Problem Definition

Energy infrastructures in general are complex and can be seen as socio-technical systems with inter-relations between the technical and social elements of network. They connect the producers and the consumers providing services to interconnect. The technical complexity of transporting energy from the source to their destinations is not just dependent on the engineering technology used for the transfer but also on the decisions and actions of various actors who are involved in the operation of such networks (Chappin, 2011). As mentioned previously, there are various challenges for designing an energy network which range from technical complexities to the social complexities of multi-actor preferences. Considering these networks to fall under the system's perspective, it makes planning cumbersome due to varying capacities, network characteristics and different perspectives of the decision makers. This causes a desire to have a system which can aid decision making for network planners overcoming the challenges presented.

Scientific contributions that address designing efficient energy networks

Many researchers have tried to simulate the system's perspective of the energy networks and have proposed network optimization algorithms for routing in energy network planning. Routing is seen as a key for planning efficient networks which can make the whole infrastructure to be cost-efficient. Different literature studies are available where researchers have proposed solutions or methods to approach the energy network planning of new infrastructures or extending existing ones. For the research here, we restrict ourselves to the work of relevant literature of Heijnen et al (2013, 2014) and other researchers who are involved in modelling from the Energie and Industry section at TU Delft. The reason for making this choice is due to the fact that these methods and their simulations can directly be accessed and any proposed evaluation and improvements can be incorporated into these models.

(Heijnen et al., 2013; van Tol, 2014) proposed scientific methods to design energy networks that can incorporate varying capacities, minimise the construction costs, introduce the realistic constraints of cost differentiation among regions into the model to connect multiple sources and sinks. These optimization algorithms are based on geometric graph theoretical approach and are mostly considered to be a top down approach. These methods try to find an "optimal solution" and rely on access to complete information. They can come up with single optimal solution and guarantees a solution when they have reached highest cost efficiency. Furthermore, (Heijnen et al., 2013) have proposed a combination of graph theory and exploratory modelling approach to analyse the most likely pathways and to maximise the value for the planners. They propose a practical method that can support decision making, by keeping in mind the uncertainties that occur in real projects. The uncertainties can be in the area of unknown capacities, limitations of routing, uncertainty about the participants, locations and required capacities. Thus in totality they build their scientific model to simulate the closest form of realistic projects.

The other kind of approach that were proposed are the "Bottom Up approaches" (Heijnen et al., 2014).They use distributed entities in a multi-dimensional space to find a "good enough solution " and rely on local information which is available. (Heijnen et al., 2014; Viet, 2015) have modelled the network infrastructure using an ant colony optimization technique where the ants act as agents and try to find the food from different food sources in a bounded region. They use an agent based modelling technique and through various simulation runs try to traverse the best path, the ants (agents) take from the source (nest) to the sink (food source). Both the methods use the same input parameters to design network layouts, although in the bottom up approach the agents act on local information, the final decisions made are based on information gathered by the agents- centralised in nature similar to a top down approach. Even though such algorithms ensure system reliability, cost efficiency and aid decision makers with the best strategies to plan infrastructures, it is still challenging to put them to practical use. Hence, there is a need for careful consideration while designing these algorithms and widespread adoption of these optimization techniques.

Knowledge gap

> Even though different scientific approaches to design cost-effective networks for new energy infrastructures are proposed by researchers, they are complex and difficult to adopt for decision makers. Although they provide design solutions within the given constraints simulating a realistic project, they still lack flexibility to incorporate the decision makers perspective, technical constraints, energy characteristics and uncertainties. It is unclear what kind of factors can influence directly a network planning phase and how can the scientific approaches be utilised to answer this complexity.

Having outlined the problem definition, the challenges and the knowledge gap in the use of the scientific approaches for network planning , there is great level of uncertainty in formulating the requirements for optimal network planning. Such uncertainty also forces us to consider the interests of the impacted stakeholders, what the decision makers look for while making decisions and how these scientific approaches can aid them to make such decisions. Thus there is a need for flexible systems which can combine the realistic requirements of the decision makers, simulate a real environment of an energy network and also inherit the benefits of the scientific approaches. The next chapter will focus on the research objective, scope and methodologies that can help us attain the goal of this study.

Chapter 2

Research Methodology

This chapter covers the exploratory part of the research, starting with the research objective (section 2.1), research questions (section 2.1.1), and a research framework (section 2.2). The different research methods that will be used to answer the research questions will be detailed in the section 2.3 along with the expected outcomes from the study. The chapter closes with a reading guide of the thesis structure in section 2.4.

2.1 Research objective

Based on the problem definition and research scope in the previous chapter, the challenges in network design planning and the issues related to practical use of the scientific approaches lead us to look for solutions. These solutions can overcome the challenges and provide decision makers a medium to incorporate their preferences along with adopting the scientific approaches. On one hand, it is important to identify the factors that can overcome the challenges in adopting the scientific models. A design framework to modify the existing methods will be needed to answer how the gap between scientific solutions and real world needs of the decision makers can be achieved. On the other we also note that adopting these models directly is complex and hence a study is needed that can focus on designing a practical decision making tool for the user, which covers the requirements of the potential users along with integration of the scientific optimization algorithms to simulate different network layouts. The tool should be able to simulate a real environment for decision making, enable user inputs to network planning, be easy to use, and also reflect the multi-actor preferences. The objective of this research can thus be clearly outlined as,

> ”To understand the potential requirements of the decision makers for planning the routing of energy networks and to bridge the gap between user’s needs and the application of scientific approaches in decision making”

2.1.1 Research Questions

With respect to the knowledge gap identified in section 1.2 and the proposed research objective, the research question is formulated as

> ”In what ways can the scientific approaches for energy network design be enhanced to ensure their usability among decision makers?”

The research question focuses on finding different ways to enhance the scientific approaches to simulate more realistic factors of energy network planning which in turn will satisfy the needs of the decision makers. The understanding of the characteristics of different energy networks like varying demand and capacities, physical and chemical characteristics of the energy outputs, grid infrastructure, spatial/geographical constraints, technical characteristics will need to be analysed if these factors influence network layout planning and if they are used in the existing scientific approaches. The second part of the question deals with identifying the different actors involved, their interests, preferences and constraints which give us the requirements of potential users in planning network layouts. Based on the research output, comprehensive requirements can be outlined for enhancing the existing scientific models and additionally designing a decision support system based on this. In order to answer the main research question, it is further sub-divided into sub questions.

1. Which network characteristics can influence the routing of energy network layouts?
2. Who are the different actors involved in the planning, what are their interests and decision making strategies for planning energy network layouts?
3. How do different optimization algorithms aid decision makers for planning network layouts?
4. What kind of tools are currently used by decision makers in planning network layouts?
5. How can the scientific models be enhanced based on the socio technical study and how can the researchers approach this change?
6. How can a Decision Support System be designed for planning efficient network layouts, integrating the scientific optimization algorithms and the requirements of potential users?

2.1.2 Research Scope

Biogas production is seen as a source of renewable energy technology as well as a source for reduction of CO2 [1] emissions. For the study here, the application and developments for the biogas/greengas production and distribution in the Netherlands (NL) have been considered. In NL the share of sustainable energy produced is close to 3% of which the share of biogas is less than 2% (Bekkering et al., 2010). Biogas is produced by the fermentation of organic wastes which is seen as a way to solve a lot of environmental problems (ProBioPol, 2010) like,

Greenhouse effect: The production of biogas results in reduced greenhouse gas (GHG) emissions which thereby mitigates global warming. The carbon cycle of biogas is closed in a shorter span of time as compared to CO2 emissions from the fossil fuels.

Waste reduction: Most countries on the planet are facing problems associated with the over production of organic wastes from industry, households and agricultural sectors. Biogas production is an excellent way to utilize the organic wastes and recycle digested substrates as fertilizer.

Limited availability of fossil fuel: Fossil fuel resources are limited to specific geographical areas across the planet. Thus, there is high demand for these fossil fuels to be imported to meet the needs of energy. With biogas production, this demand can be complemented based on the biomass resources that the country can produce.

Contribution towards EU Energy and Environmental targets: EU member states targets of renewable energy production, reduction of GHG emissions, and sustainable waste management can be achieved by the production and utilization of Biogas (DutchMinistry, 2010).

Considering the aim of the Dutch government to meet its goal of 30% reduction of GHG gases by 2020, a future expectation of replacing 10% of natural gas by greengas is under consideration. The depletion of natural gas from the Groningen fields also marks the transition of energy market from the supply-driven to a demand- driven one (Bekkering et al., 2010). The above considerations and the decreasing supply of natural gas, justifies the research to analyse the dynamics of biogas/greengas. It lays emphasis on decision makers to make informed decisions investigating the entire supply chain from the producers of biogas to its distribution satisfying the demand of consumers.

[1] CO2: Carbon dioxide

Specific network integration projects on behalf of the NL government, regional and national system operators are being undertaken to reach the NREAP targets (DutchMinistry, 2010). But in order to allow this kind of distribution, there is a clear need for construction of new infrastructures to allow bio gas distribution or there is need for extension of existing grid to allow the upgraded bio gas to join the natural gas grid. Hence, choosing the energy network of biogas/green gas distribution will be an important case to analyse as it is a sustainable solution for fulfilling the future energy demand in NL.

2.2 Research Framework

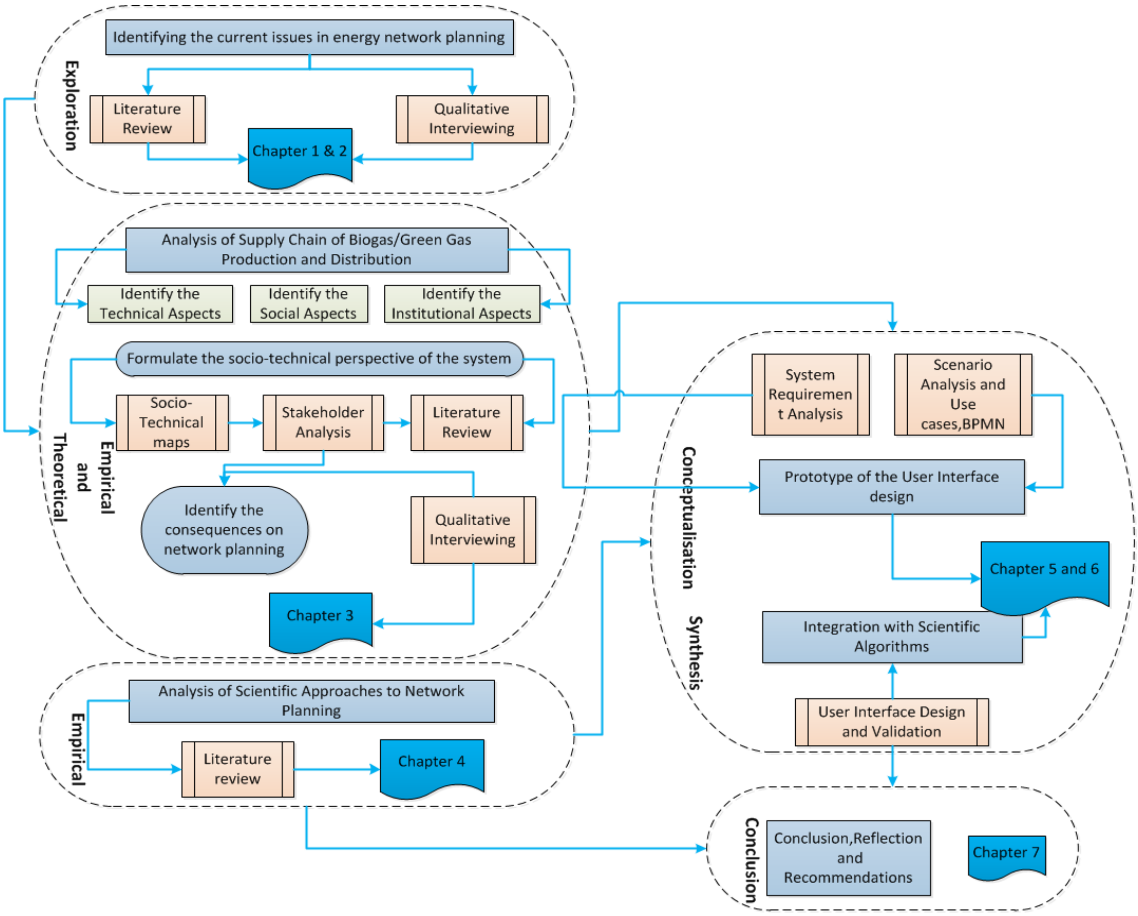


Figure 2.1: Research Framework

The research consists of various phases as presented in figure 2.1. The research starts with an exploratory phase to identify all the issues in planning of energy network layouts. This phase aims in realising the complexity of the issue and brings in more clarity to the research objective and the actual research problem that the study needs to address. In order to address the research questions, an empirical and a theoretical study will be needed to understand the supply chain of biogas/green gas production and distribution in Netherlands. A socio-technical perspective of the technology is formulated and the key stakeholders that can influence network planning are identified. The main characteristics of the biogas/green gas networks and their interrelations can be identified during this phase. Further, the concepts of scientific algorithms which can provide solutions for efficient energy network layouts are studied. This is complemented by understanding the advantages and the challenges of adopting these approaches. A comparative analysis between the user defined requirements and the algorithmic parameters is achieved. Based on this undesrtanding a design process to extend the functionality of the scientific approaches is proposed. To enable, user friendliness a design framework for a software based DSS (user interface tool) is proposed. During the synthesis phase, the main characteristics of the energy network are combined with the adapted scientific algorithms to form user specific design prototypes. Lastly, conclusions, reflections and recommendations based on the research are given.

2.3 Research Methodology

The following research methods will be adopted to answer the sub questions mentioned in the section 2.1.1.

Table 2.1: Sub Question and Research methods used

Sub Question	Research Method
Which network characteristics can influence the routing of energy network layouts?	Literature Review, Socio-Technical Maps and Qualitative Interviewing
Who are the different actors involved in the planning, what are their interests and decision making strategies for planning energy network layouts?	Stakeholder Analysis, Qualitative Interviews, Causal Loop Diagramming
How do different optimization algorithms aid decision makers for planning network layouts?	Literature review
What kind of tools are currently used by decision makers in planning network layouts?	Literature review and Qualitative Interviewing
How can the scientific models be enhanced based on the socio technical study and how can the researchers approach this change?	System Requirement Analysis, Scenario Analysis
How can a Decision Support System be designed for planning efficient network layouts, integrating the scientific optimization algorithms and the requirements of potential users?	System Requirement Analysis, User Interface Design and Use cases

2.3.1 Research Methods

Literature Review
Literature review refers to the study of various scientific articles, book sections and web articles to gain access to information in order to answer the research questions. The research focuses on understanding the characteristics of energy networks especially natural gas, biogas and green gas production and distribution technologies. The study demanded a thorough understanding of the scientific approaches implemented for optimised network planning. Hence this method of reviewing existing literature will be useful for gathering requirements and also to understand the scientific algorithms in a more detailed way.

Socio-Technical Maps
The concept of socio-technical maps present a description of the state of development of a specific technology, its dynamics and the stakeholders who are involved in the development of such technology. It presents an assessment of technology from a social, technological and an institutional perspective.It gives an overview of the barriers and the solutions that a technology confronts in its phases of development. The study focuses on understanding the biogas/green gas production and thus it needs to reflect on the social, technological and institutional aspects of the technology to derive any logical information. Hence this method of analysis will help the research to formulate the requirements needed for the user tool.

Stakeholder Analysis
Stakeholder analysis is a process of identifying the stakeholders or groups who influence a specific system or get impacted by the system. It is an approach to identify the interests of the stakeholders, their role and their attitude towards any potential changes to the existing system or new system being built. This analysis can be made using stakeholder maps where various

stakeholders (groups) and their interactions with each other are represented. A stakeholder grid can be created mapping the role, goal, interests and power relations of specific stakeholders in a system. This method is essential in the study to identify various stakeholders involved in the natural gas, biogas/greengas production and distribution. Their role and interests will have a major influence on the potential planning of energy network because of their power and the resources they have.

Qualitative Interviewing
Qualitative interviewing approach is an open ended interviewing technique where information is gathered from interviewees based on their experience and expertise in the field. Primarily this method of interviewing can be an informal conversation or it can follow a standardised approach with a generic view or set of questions (Patton, 2002). The primary goal of conducting these interviews are to validate the requirements gathered during the literature research and to gather specific requirements, users can have while using a software tool for designing energy networks.

Causal Loop Diagramming
System Dynamics(SD) is a field of study which researchers use to analyse the behavior of dynamic complex systems. The method of Causal loop diagramming (CLD) technique enables us to identify the causal relations between different variables influencing each other and their feedback loops. This visualisation gives an overview of the system and helps decision makers make more informed decisions (Eker and Daalen, 2015). The dynamics of the biogas production and distribution needs to be understood in detail during the planning phases of network designing. The interactions between the gas characteristics, gas production and its network used for distribution of the gas needs to be understood before designing a network planning user tool. Thus CLD technique for understanding the dynamics of the system is an appropriate method for analysis.

System Requirement Analysis
System Requirement Analysis for software development is a process where the user requirements are gathered. It is a process of understanding, specifying, validating and identifying the functionality that a user intends to have from an application (Escalona and Koch, 2004). For the design of a software prototype tool we will need to gather the actual requirements of the users and create the requirement specifications for the developers. For the study, requirements are gathered based on literature study and desk research followed by interviews with some industry experts in the field. The requirement specifications are delivered in the textual format or in the form of graphical representations. This will be an input to the ”Scenario Analysis” and ”User Experience Modelling”.

Scenario Analysis and Use Cases
Scenarios are represented as a sequence of steps either in the textual format or graphical representation. They are the characteristics of the application which relates to specific functionality of the user requirements. Scenarios can also be represented further in the form of Use Cases through Use Case diagrams. Use Cases represent detailed series of interactions between the user and the system. Scenarios are instances of the Use Cases and follow a specific path through a Use Case (Kulak and Guiney, 2004). Through Use Cases an overall view of the application functionality can be visualised. Having gathered the requirements for the user tool, they need to be specified with their respective functionality based on the user's needs. Thus we need these methods to define user requirements and how they need to interact with the system. These will form the basis for input to Use Case Sequence diagrams which can be used by software developers while programming the system.

2.3.2 Possible outcomes of the research

The possible outcomes of the research are,

1. A socio-technical map explaining the supply chain of the biogas/greengas network.

2. A stakeholder map with a power interest grid identifying their strategies, interests and preferences.
3. A list of different network characteristics (technical, geographical, social, institutional) that will need to be used for planning.
4. A reflection on the working principles of the scientific approaches and a list of recommendations to incorporate network specific requirements to enhance the model functionality.
5. A causal loop diagram of the inter-relations among all the network characteristics will be defined.
6. A prototype of a user tool for planning efficient energy network layouts combining the scientific approaches, network characteristics and potential user's needs.
7. A technical and functional design of the Decision Support System detailed through Use Cases, Use Case Sequence Diagrams and Wire frames.

2.4 Reading Guide

As previously discussed, the research will study the biogas and green gas energy networks in Netherlands. Chapter 3 will focus on understanding the entire supply chain of the biogas network planning from a socio-technical perspective. The technical study of the infrastructure will determine the factors that can influence the planning of these energy network layouts. The sociological study will identify the different stakeholders, their interests in the energy network layouts and how they can influence the planning. This chapter will answer the first two sub questions of the research. Chapter 4 will focus on the working principles of different optimization algorithms and the factors which are used to create network layouts. An overview of the advantages and challenges with respect to adopting these scientific approaches by decision makers is provided. This chapter will answer the third and fourth sub questions of the research.

Chapter 5 summarises all the research findings. The factors identified in the chapters 3 and 4 will form a preamble to create the design approach to enhance the working principles of the scientific models. These factors are carefully studied, for their inter-relations with each other and their influence on network planning is translated into either decision logic or costs. Then a design flow is proposed to integrate them into the models. Since these models are still complex, decision makers cannot directly use them and seek a user friendly interface. Using the consensus from Chapter 5 and the latest enhanced scientific models the system requirements for the decision support system to plan energy network layouts are baseline. Chapter 6 creates an overview of the decision support tool incorporating the research findings briefed in Chapter 5. The user experience models and the prototype of the software tool are provided in this chapter. Chapter 7 gives the conclusions from the research followed by recommendations, reflections on the research and future work.

Chapter 3

Biogas as a Source of Energy and its Network

This chapter covers the empirical approach of the study, starting with an explanation of the biogas production and its supply chain section 3.1, followed by a Socio Technical mapping (STM) of the biogas energy network (3.2). The section of STM further explores the subsystem of the biogas supply chain from a technical (3.2.1) , sociological (3.2.4) and institutional perspective (3.2.5). The factors identified in the STM will answer the first two sub question of the research identifying the network characteristics and the actors who are involved in the planning .

Why is it important to study the socio-technical aspects of the system for network planning?

A gas transmission system includes gas production sources and delivery sites based on the number of producers and consumers. But according to (Roelse, 2012), a gas transmission network involves a variety of design parameters which need to be considered while designing a gas transmission network. These design parameters consist of pipe segments which are passive in nature and other active controllable elements such as valves and compressors. Designing such complex structures will need to control the active and passive components and find a suitable setting for the gas to be transmitted from the entries to exits without violating any of the physical and operational constraints of the network (Fugenschuh et al., 2011).

Thus it is important to understand the entire supply chain of the biogas/ greengas to be able to design cost-effective installations for transmitting gas. Biogas infrastructure consists of a variety of technological components and a number of stakeholders who can have an influence on the network design and hence it is important to analyse it from a system's perspective. A socio-technical mapping of the biogas system will present the relations between the technological and social elements that can influence the system throughout its supply-chain.

3.1 Biogas production and its importance

Biogas is a gaseous fuel that is produced in the absence of oxygen by the biological breakdown of organic matter like waste residual of livestock (dung, manure and uneaten food), food production (fruits and vegetable green wastage, residual waste from meat, fish and dairy processing) and effluents from industrial and municipal waste treatment plants (Weidenaar, 2014).

The resultant of such a process generates gases like methane, hydrogen and carbon monoxide which can further be combusted or oxidized to generate biogas. The gas thus produced in this way is called raw biogas and can be used as a fuel after removal of sulphurous compounds especially H2S (Hydrogen Sulphide). The raw biogas needs to undergo further treatment, if it needs to be injected into the gas grids that carry natural gas presently. This upgraded biogas is known as bio-methane or greengas (Weidenaar, 2014).

The organic matter used for biogas production is also termed as "biomass" which according to the new EU directive is described as the biodegradable fraction of products, wastes and residues of biological origin from agriculture, fisheries, aquaculture, forestry and industrial/municipal wastes. More details about the biogas production methods and the available sources of biomass in the Netherlands are explained in Appendix A.1.

Network layout structure of Biogas/ Greengas
Till now, the most convenient way of distributing biogas is by its conversion to electricity or heat. For small quantities this is a feasible solution but when biogas distribution is seen as an alternative for fossil based energy, it becomes important to consider other routes of transformation as well. The possible routes of biogas transformation are producing heat and electricity separately or combined heat and electricity production (CHP), or upgrading to green gas and injection into natural gas grid. According to (Bekkering et al., 2010), the most efficient way of biogas transformation to meet the sustainability goals, is through green gas production and injection into natural gas grids. In order to achieve this transformation it is important to understand the network layout structure of gas production and distribution.

The biogas transmission and distribution network can either have a fish-bone structure, a tree network structure, or a one-to-one mapping depending on the number of producers and consumers (van Eekelen and Wolters, 2011, see pg 10). The producers of biogas are represented as biogas digesters to maintain simplicity and the consumers can either be centralized upgrading plants or the local households, hospitals, vehicle fuel stations etc. The network layouts can be divided broadly into 4 specific topologies as shown in figure 3.1.

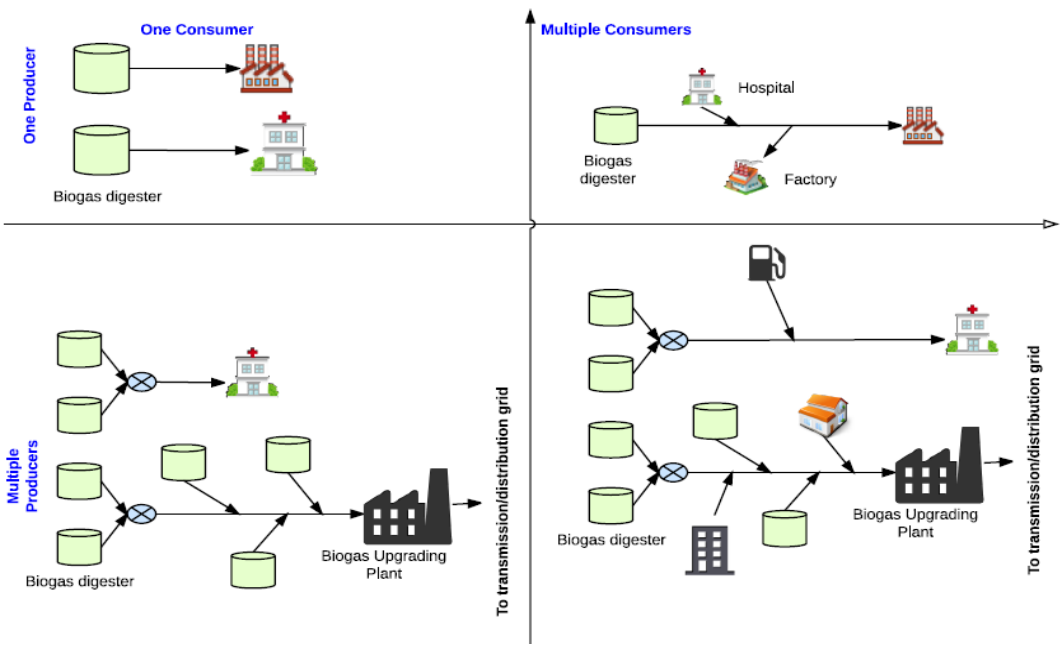


Figure 3.1: Network layout structure

One producer-One consumer:
Biogas production can be restricted locally to one producer and one consumer. Biogas digester installed in the locality serves only the single household/building or a standalone hospital makes one-to-one network. The gas produced is not shared across and only a direct connection between the producer and consumer is needed.The only possibility of network in this configuration is the biomass supply network for biogas production. **Since the distribution is to a single**

consumer from the biogas production plant there is no need for any optimization or network planning in this case.

One producer-multiple consumers:
This network resembles a fish-bone structure which can have multiple consumers being served from a single producer. If there is biogas production of large capacity it can be distributed in a network with multiple exit points. The exit points are connected from the single pipeline originating from the biogas digester. The exits can possibly be hospitals, households, offices, or even factories depending on the capacity of the digester. This influences the network design and is a good case to investigate further.

Multiple producers-one consumer:
This kind of network can either have a fish-bone or a tree shaped network structure. One or more suppliers with their own pipelines can connect to a centralized location through a central pipeline for upgrading and have one exit point to be injected into the natural gas grid for further distribution. In some cases multiple digesters can provide biogas for local use like hospitals directly. In other cases, we can have multiple digesters connecting to a centralized location for up gradation. One of the main characteristics of these local biogas grids is that, unlike the conventional gas grids there is a need for specific gas measurement devices like gas metering for measuring the quality and quantity of biogas at each entry and exit points. The calorific value of natural gas is standardized whereas biogas value depends on the biomass used for its production (van Eekelen and Wolters, 2011). Hence there is a need for biogas to be checked at each entry point before injection into the natural gas grid.

Multiple producers-multiple consumers:
These networks have a tree shaped structure, as it includes multiple suppliers and multiple consumers. Many entry points and exit points will form the network. In some cases they can join the centralized up gradation plant for further injection into national grid. In other cases they can be produced by multiple suppliers and consumed by multiple consumers itself. As in the previous case for biogas gas measurement devices will be necessary specifically in this case too. The connection of the producers to the consumers in a cost effective way demands cost minimal network planning and hence a need for network optimization.

Having understood the main network layout structure of gas grids, it becomes important to now understand what factors can influence the planning of such infrastructures. To ensure the construction of cost minimal networks, understanding the technical, social and institutional aspects can make the design more realistic and robust with an approval from all stakeholders.

3.2 Socio-technical mapping of biogas energy network

Socio-technical perspective of a system is seen to establish the openness of the system itself. This approach of analysing a system provides us an understanding about the mutual influences of the system and its environment.The openness of the system thus gives us an overview of the dynamic elements of the system and how they are influencing each other (Zwaan, 1973). To be able to assess the factors that influence network planning we start with the technological subsystem followed by the sociological and institutional subsystems.

3.2.1 Technological subsystem of Biogas/Greengas supply chain

As a starting point the socio-technical subsystem as proposed by (Chappin, 2011) has been used. The technological subsystem mainly focuses on the supply chain of the biogas production and distribution network. Gas structures are complex systems and include many technical components which need to be considered for network planning. They consist of the passive components (pipes) and active controllable components like valves and compressors (Fugenschuh et al., 2011). Controlling a network that transmits a nominated amount of gas from an entry point to an exit needs careful consideration for the deployment and use of the technical equipments. From a practical point of view, large scale gas networks will need to be simulated before the real application of a network, to visualise and understand the influence of the gas grid in its construction, maintenance and operation phases. Figure 3.2 provides an overview of the technological subsystem of biogas and greengas infrastructure.

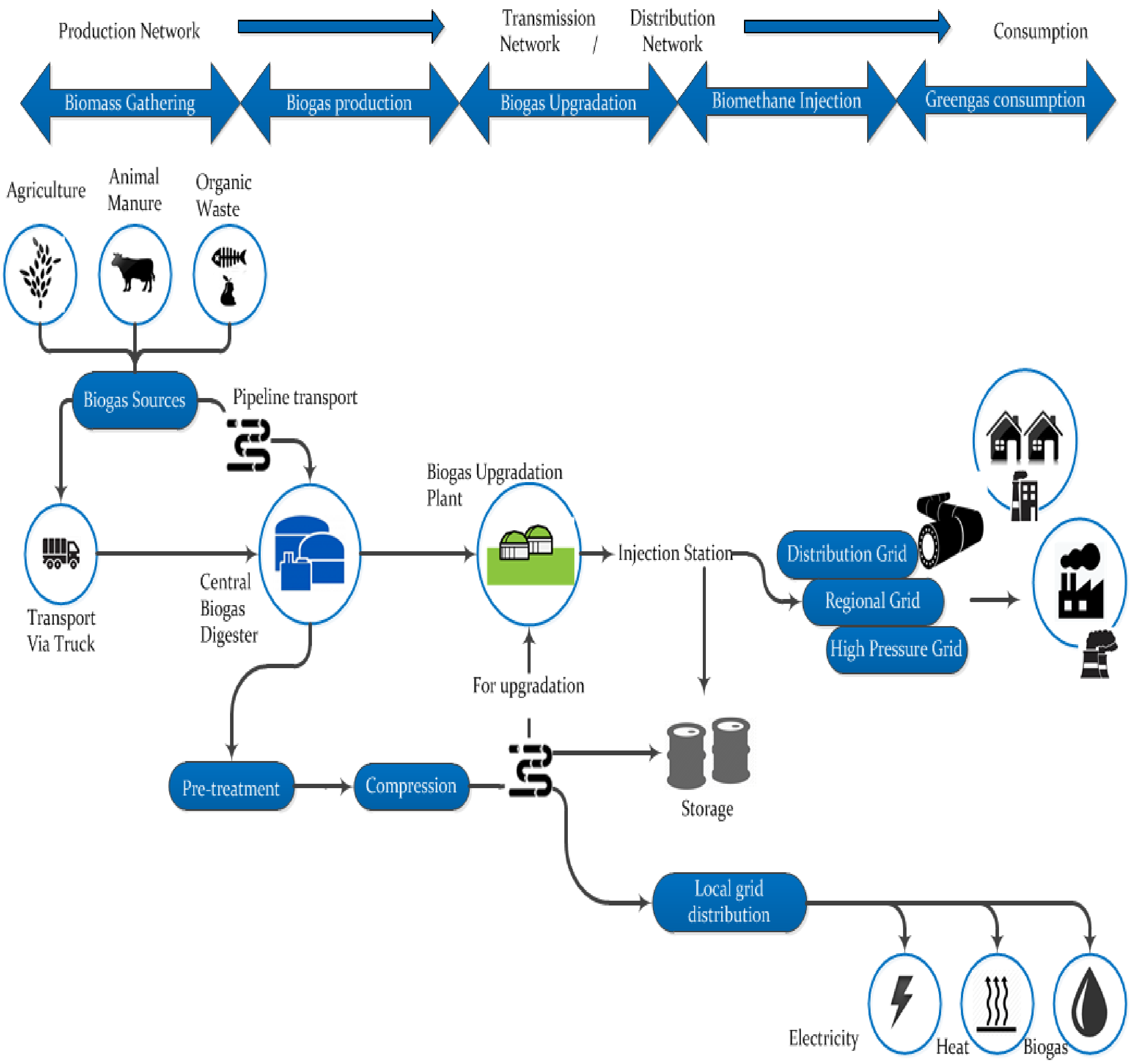


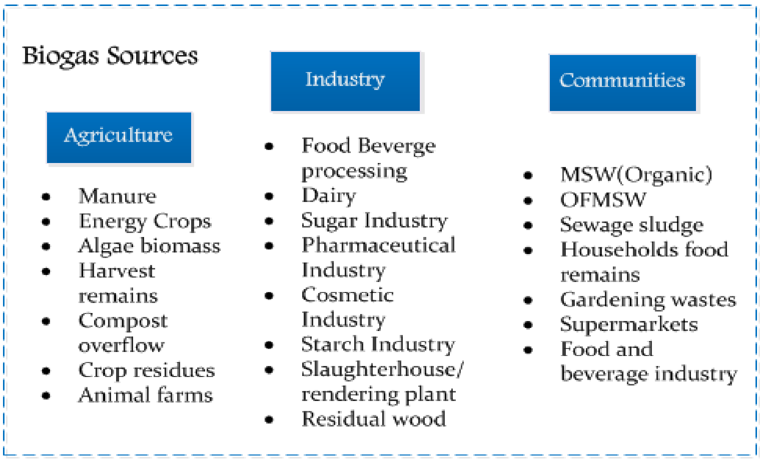
Figure 3.2: Technological subsystem of bio gas supply chain

Biogas and Greengas Supply Chain

Conventional gas grid networks follow a tree layout structure in reality with specific transmission and distribution grid layouts. The production network is centralized and the transmission network is a high pressure grid connected to the distribution grid which is at a pressure lower than the transmission grid (Weidenaar, 2014, see pg.5). The distribution network supplies gas to the consumers in the form of distributed mesh grid layouts. Biogas network supply chain also needs to fall under this network layout structure, if it needs to be injected into the natural gas grid. As we have seen in the previous section 3.1, the biogas produced can either be locally distributed or it can be upgraded to join the natural gas grid. The injection points where the biogas is injected into the natural gas grid can either be the transmission grid or the distribution grid.

The pressure levels need to be maintained for such injection (van Eekelen and Wolters, 2011).

Biomass Gathering



Biomass gathering is a process of collection of biomass from various sources. To maintain simplicity, the biogas sources are divided into 3 main categories such as biomass from agriculture, industry and the communities. For instance waste water treatment plants (WWTP) receive free sludge from the households and the cities through an agreement with the local water board and the municipality. The wastes from the waste producers like households, supermarkets, dairies etc are directed through a pipeline network that carries the sludge. For more solid sludges, transport takes place using trucks. Similarly all the other biomass sources deliver the biomass to the production facilities. The sludge networks are out of scope of this study and it is assumed that WWTP's collect biomass centrally for biogas production.

Biogas Production

The biogas production can happen directly at the location where the raw material is produced Example: agricultural farm. In case of a system like a green gas hub, the raw material from various biogas sources can be transported to a centralized location via a pipeline or vehicle transport using trucks. Thus the biogas will then be produced at a centralized biogas digester. Pipeline transportation is not a very common mode of transporting biomass and mostly the raw material is transported to the central digester via trucks using the road transportation.

When the raw material from various sources has reached the central biogas production plants, there are various methods to produce biogas. Appendix A.1 has outlined the most common methods of biogas generation such as Anaerobic digestion and Co-digestion. The resulting gas is usually called the raw biogas which further needs to be cleaned for removal of hydrogen sulphide and water components. This cleaning is subjective and depends on the raw material and the type of biogas production process used. Thus after the pre-treatment process, biogas can be compressed to be injected into the pipeline network and distributed to the local biogas consumers or be directed for temporary storage. For details on the quality requirements for cleaning biogas refer to appendix A.3. If the biogas is in excess, or if no local consumption is intended and it cannot be stored locally it can further be directed to the biogas up gradation plant for biogas upgrade.

Biogas Upgradation

The biogas is transported through a centralized pipeline that connects to the centralized up gradation plant. When the biogas reaches the centralized up gradation plant it can be subjected to various methods of upgrading. There is no International standard for biogas injection into natural gas grid whereas different European nations have set specific standards for biogas injection to avoid contamination of their gas grid or end use. Some very common standards are, demand for specific Wobbe index level, limits on certain components like sulphur, oxygen and water dew points etc.

Bio methane Injection
The upgraded biogas which is termed as bio-methane/green gas can now be injected into the natural gas grid for further distribution or transmission. The injection into the natural gas grid is the most efficient way of utilizing biogas (Bekkering et al., 2010). The strategic injection points can be selected based on the gas pressure and the nearest available injection point. The injection can be either in the distribution grid or the transmission grid as long as the required grid pressure is achieved. The costs for green gas injection are case specific and is dependent on primarily the location of the green gas producer, the grid pressure where the injection needs to happen, the scale of injection and the type of compressor (Butenko et al., 2012). When the green gas is injected into the natural gas grid it joins the usual network of gas distribution/transmission to the end users.

Biogas/Green gas Consumption
The green gas attains the property of the natural gas and thus it can be used in most gas appliances that work on natural gas. The basic ways in which biogas/upgraded biogas is utilized are in the form of electricity, production of heat and steam, vehicle fuel and production of chemicals.

Having understood the supply chain of the biogas/greengas production and distribution, it is important to identify what kind of factors play an important role for network providers who design the network. In the course of liberalisation of the Dutch Gas markets, a discrimination free access has to be granted to everyone. The increase in flexibility for gas producers and consumers calls for higher degree of operational flexibility from the gas network operators. Thus a gas network provider concludes gas transportation contracts between the gas suppliers/ vendors and the gas consumers, agreeing the right to feed in at entry points and/or to feed out gas at the exit points of the network (Fugenschuh et al., 2011).

For allowing access to transfer gas, a gas supplier needs to nominate the amount of gas to be transferred some time before the actual feed in and feed out. The gas supplier needs to ensure that amount of gas fed in, is fed out somewhere thus balancing the nomination. For this, they need to sign supply contracts among each other. The network operator has no knowledge of such contracts and is obliged to provide infrastructure to transfer the gas and fulfill each nomination. It is the responsibility of the network provider to route the gas through the network in an efficient way and match the nominated amounts (Butenko et al., 2012). Although the network providers are obliged to connect the producers to their network, the maximum volume that can be injected into a grid is situation specific and is based on a number of different specifications. Different specifications of the agreement are valid for the entire period agreed with the gas suppliers. Some of these specification are discussed below.

3.2.2 Specifications of the network

A gas network consists of both active and passive components. These can relate to the technical components that are used in a network operation. But the use of these components is based on different specifications which can differ for independent networks (grid) and expansion of existing networks (grid).

Entry and exit points:
The entry and exit points are different for local biogas grids compared to the conventional gas distribution grids. The entry points can be a biogas digester where biogas is produced centrally or a small sized biogas producing installation at small farms for domestic use. The latter type of entry points need a network only if they wish to transmit any excess gas. The exit points can relate to central biogas upgradation points which will join natural gas grid after upgradation or it can be also the end consumer demanding gas supply.

In local biogas grid there can be multiple entry points ranging somewhere between 1 to 25 connecting all the biogas producers in the region. The exit points can range from 1 to 2 nodes either to a central collection/distribution point that connects the national grid or the central biogas up gradation units. The possible layout structure is defined in section 3.1. For designing a gas grid it is important to identify the total number of entry and exit points in a region with their location and supply and demand capacities. The total geographical area under consideration for the grid also needs to be known by the network provider.

Grid load patterns:
The conventional natural gas grids have a constant supply pattern which allows the network provider to know the grid load at any time. They can easily make decisions either to inject the biogas into that grid or find other alternatives for injection. On the contrary, the local biogas grid patterns are dependent on the supply of biomass/organic matter available which determine the biogas supply. Sometimes for large farms this can be known but there is always an uncertainty involved for the local supply of biogas (Butenko et al., 2012). As the network provider is obliged to join the gas producers to the grid, they will need to always have information regarding the grid load and balance the grid at all times. If there is a time-varying gas demand in a geographical region due to its climate sensitivity, there are two main possibilities to overcome this fluctuation. There can be flexible production based on the number of digesters in the location and its influence on the costs, and on the other hand, there can be production storage which can meet the demand in winter and constant production all through the year (Bekkering et al., 2010). The decision to design a layout with more production flexibility or with more storage possibilities has a direct influence on the construction costs and need to be considered while network planning.

Grid Capacity:
The biogas grid capacity depends on the maximal gas demand at each exit point, that the grid connects to. The maximum volume of gas that can be injected into the grid is determined by the total number of gas producers in a given area and their supply. Although conventional grids transporting natural gas have standardised grid capacity based on the future demand of customers (extrapolated), it is also limited. The gas pressure levels and the diameter of the pipe play an important role to maintain the capacity (Butenko et al., 2012). If a specific producer wants to inject gas to the grid, the decision is made by the DSO to inject based on the grid capacity and gas demand. In cases where the grid is operating at full capacity, it is observed that DSO's can direct the injection to an alternate grid or allow small scale storage temporarily. Article 12b of the Dutch Gas Act (NMa, 2012) obliges the network facilitators to facilitate gas injection into grid if it meets the specifications but the injection costs are to be borne by the producer. The producer has flexibility to join the transmission or the distribution grid if they can invest and ensure the pressure ranges and quality of their gas supply.

Grid Pressures:
The operation of a gas grid requires a working gas pressure within an acceptable specified range. If there is any failure in complying to the grid pressure, the gas cannot be transported. If pressure is in excess, it can be dangerous and compromise the safety of the grid. If the pressure is below the grid pressure level, the transfer cannot happen to the consumer. Also there is a need for network providers to maintain the information about the maximum allowable operating pressure" (MAOP) for the grid (Butenko et al., 2012). It is important for the network provider to maintain the grid pressure while injecting greengas into the natural gas distribution grid. The gas pressures and the gas flow rate that is needed for this while planning. Using the grid pressure equipment, measurement devices, compressors etc. the grid pressure can be regulated (van Eekelen and Wolters, 2011).

Technical Components of the grid

Different technical components are needed to transfer the biogas/greengas from the suppliers to consumers. The specifications of the grid configuration components must be included for designing the network as they can directly influence the costs and operation of the grid (van Eekelen and Wolters, 2011). Some of these components identified are,

Pipeline

The natural gas pipeline grid is either made out of cast iron, steel or plastic materials. The steel pipelines are more mechanically durable than plastic but they are expensive and corrosive. The plastic ones are cheaper, and anti-corrosive with insulating properties. The choice of this material for pipelines does make a difference in the cost analysis of a biogas grid injection. The pipeline integrity needs to be maintained when the greengas needs to be injected into the existing grid (Weidenaar, 2014). The other properties of the pipeline itself that are important are the nominal diameter and the pressure level that such a connection line can carry. Due to a possible loss of pressure at transfer points, it is necessary to have the gas supplied at higher flow speeds (Ex. 30-40 m/s @PN >16, 20 m/s @ PN 16 and 5 m/s @ PN 0.1), where PN refers to nominal pressure. Sometimes pre-warming equipment might be required to avoid cooling down of transported gas. Anti-corrosive techniques should also be implemented in case of condensation (van Eekelen and Wolters, 2011).

Pipeline fittings:
Various types of fittings are possible for the pipelines. One can be cut-off devices like slide valves, stop clocks, and balanced disk stop valves. They can act as the first line of protection for isolating a specific pipeline from the network (Adeyanju and Oyekunle, 2011). Condensation separators are another type of fittings which function for the expulsion and collection of condensed water from the gas grid. Important parameters are the type of fittings, their quantity, state and the investment costs.

Gas metering devices :
Devices that measure the injected gas quality, quantity, and the Wobbe index values should be fitted at injection points to ensure quality checks and also for monitoring the gas impurities just in case. The quality requirements of the biogas differ due to multiple producers. Hence there is a need for installing gas metering devices at each exit point to measure the gas quality to ensure transparent billing and grid maintenance (van Eekelen and Wolters, 2011).

Gas Compressor stations:
This equipment is needed to overcome any friction losses in the long distance transfer of the gas supply (transport compression). Sometimes they are needed also to maintain high pressure for underground storage as well (storage compression). Network providers will need these compressor stations to maintain the pressure of gas based on the grid. When there is a need to increase gas pressure to inject gas into higher pressure grid, compressor stations will be needed (Weidenaar, 2014). Factors important for network planning are the inlet and outlet gas pressures, discharge or suction pressure losses, operating costs and location of the stations.

Gas Storage:
Biogas production is not continuous and is subject to constant fluctuations usually. This is due to the fact that biogas production is subject to irregular formation of gas and different decomposition times. Gas storage might be necessary before conditioning of biogas, buffer storage for injection, storage for liquid/gaseous mixture. These units are needed when there is a need for storage of gas injected into the grid. The storage is subjected to balance the pipeline flow and is dependent on the capacity and demand for gas. In climate sensitive areas the seasonal pattern of gas demand influences the construction costs of network layouts. In such periods, investment in gas storage either temporary or permanent locations can balance the off peak and on peak periods. The location of these storage units, either underground or temporary if in closer proximity of the production or the consumption nodes deems more cost effective (Bekkering et al., 2010). The storage process is categorized based on the pressure levels and specific storage constructions (see appendix B.1) are to be considered while designing the network layouts (Butenko et al., 2012).

Gas Pressurization Systems:
The gas pressure regulators and the gas measurement devices need to be installed at the injection/transfer points to ensure the right pressurized gas is inlet into the pipeline (Weidenaar, 2014).

3.2.3 Physical and Chemical characteristics of Biogas

The physical and chemical compositions that characterize biogas in comparison to natural gas can be important while planning, as upgraded biogas is seen as a sustainable alternative to natural gas. The knowledge of biogas/ green gas characteristics can help gas network providers to design the infrastructure to support the transport of gas from the source to destination. They can get an overview about the important factors of the gas itself which can influence the network design and its costs. In cases where the green gas is to be injected into the natural gas grid, knowledge of these factors can influence the operation and maintenance of such a multi-gas grid.

Physical characteristics of Biogas
Understanding the physical characteristics of biogas is important for network planners as they need to take into consideration the environmental safety and the precautionary measures to mitigate any risks that can be encountered during the construction and operation of the network. Moreover the combustion of gas depends on the Wobbe index associated with the gas (van Eekelen and Wolters, 2011). This measure for biogas/ green gas is dependent on the biomass that was used in its production. Thus it is of importance for network providers to deploy the active components of quality measurements at every entry and exit point of gas distribution/injection. The physical characteristics of biogas in comparison to natural gas can be seen in appendix A.2.

Chemical characteristics of Biogas
Biogas is primarily a mix of methane (CH4) and inert carbonic gas (CO2) and its composition varies on the type of production and processing (Naskeo, 2009). Different sources of production can lead to different types of biogas compositions. Natural gas on the other hand differs from biogas mainly due to higher presence of methane and nitrogen and absence of carbon dioxide and hydrogen sulphide. Appendix A.4 gives the details about the chemical composition of biogas.

The presence of carbon dioxide, hydrogen sulphide and water makes biogas corrosive and results in the need for biogas infrastructure that can withstand these chemical compositions. The natural gas which is presently transmitted through the gas grids has different composition when compared to biogas and leads to some incompatible issues if we need to re-use the infrastructure of present gas grids for biogas transmission too. The relative humidity of biogas is higher than that of the natural gas due to its wet nature of digestion process (van Eekelen and Wolters, 2011). This makes it important to consider this characteristic of biogas before planning the design of the new network or joining an existing grid. Moreover the composition of natural gas remains constant but biogas can vary based on different production sources and the digestion process used for it. If biogas needs to be injected into the existing gas grids, it needs to be upgraded to attain the properties of natural gas to avoid any incompatibilities during transport.This feature can also impact the costs as it influences both the active and passive components of the network planning. The information about the pipe material, pipe diameter etc. used for gas transportation and the use of appropriate quality evaluation equipment will be needed at the entry and exit points (DutchMinistry, 2010).

Consequences for planning energy layouts:
From the technological perspective, it is important to gather information about the producer and consumer profiles, their capacity and location as it can influence the length and costs of the network layout. Furthermore, the layout can be designed over long distances, the capacity of gas that needs to be transported will need optimum pipes with specific diameter. Hence the pipe profile is important as it can impact the costs and reliability of the grid. For the injection of greengas into national grid, it is important to check the quality specifications of the gas characteristics and if it suits the existing infrastructure or not. Other information needed for optimising the network layout is the potential use of compressors to maintain the pressure levels for transfer of gas. Their location and capacities will play a role for efficient gas transport and will also influence the costs. Other factors that can influence are the soil profiles to insert pipes, the spatial constraints like cost dif-

ferentiation of regions, the land use agreements etc.

3.2.4 Sociological subsystem of Biogas/Greengas supply chain

Many actors are involved in the whole supply chain of biogas production, up gradation and distribution. Figure 3.3 shows an overview of the stakeholder map, the different stakeholder groups and their interactions. The different stakeholders have been categorized based on their roles and responsibilities. The stakeholders in the inner circle are the primary actors in the supply chain who interact with each other and are dependent on their next levels ordered from high to low in each circle. We discuss further in detail about each category of actors, their roles, interests and power positions.

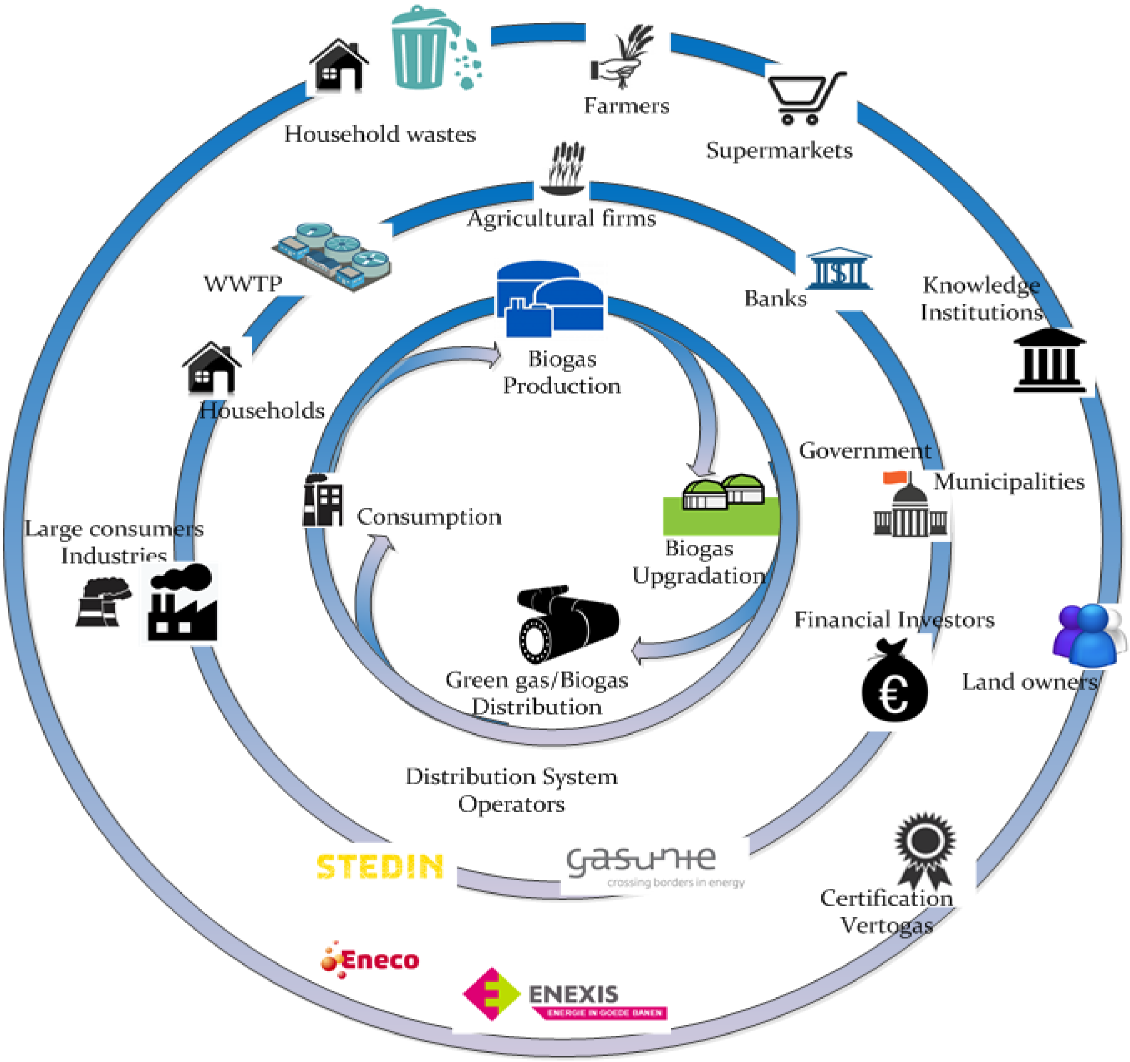


Figure 3.3: Sociological subsystem of bio gas supply chain (ordered inwards)

Biogas Producers
The biogas producers have a common role of producing biogas or greengas. They are mainly divided into three types, agricultural firms, industrialized firms, and water treatment plants. Their goal is to maximize the profit and they can be termed as producers.

Agricultural Firms :
Agricultural firms are primarily involved in the small scale production of biogas using the manure from farming/cattle residues. Agricultural firms collect feedstock from individual farmers for biogas production. They can be considered as small scale industries, where farmers from a

common location come together and produce biogas centrally to avoid individual infrastructure costs. They have low interest and power as their production is small scale and also they are dependent on other farmers for feedstock.

Industrialized firms :
The farmers face financial issues for large investments in setting up a biogas plant. Each biogas plant in NL can approximately cost 2,500 Euro/KWe and makes the farmers dependent on the financial institutions for capital (Roelse, 2012, see pg.80). Therefore, biogas production happens in industrialized biogas digesters where the feedstock from different farmers and other biogas sources are delivered to a centralized location for biogas production. The technology used for biogas production can vary based on the kind of feedstock used. The resulting biogas produced can be distributed in its raw form or upgraded to bio-methane and further distributed by injection into natural gas grid. These stakeholders have high interest for biogas production but have moderate power due to dependency for supply of feedstock.

Biogas up gradation plants are industrialized large scale producers of biogas and are responsible for its up gradation to bio-methane/green gas. These producers are responsible for the quality of green gas produced and they will have contractual agreements with the network providers for supply of green gas. They will need to ensure an agreed supply for the demand of gas in the locations they operate (Pijnenborg, 2011, see pg. 45)

Waste Water Treatment Plants (WWTP) :
Silt digestion is a process used in waste water treatment process. The biogas production from silt in waste water has continuous supply of waste from households, supermarkets, dairies or industries. This kind of production yields high content of biogas without the need for any co-substrates. This is one form of biogas production which makes productive use of waste streams.

Delftluent Services BV is a WWTP in Delft NL, which produces 17,500 Nm3/day of biogas and consumes it in the form of electricity to meet their energy need (BV, 2015). Although the WWTP's can be sources of biogas producers, most of them currently are being used to meet their own energy demands. But in future they be seen as potential producers of biogas for distribution or upgradation (see interview in Appendix C.1).

Feedstock Suppliers
These stakeholders relate to the biomass sources for production. They play an important role as they produce biomass which is the crucial for biogas production. Mainly there are two types of feedstock suppliers the farmers and the waste stream producers. Their main goals are to reduce the manure disposal costs and reduce waste treatment processing costs (Verhoog, 2013, see pg.43).

Farmers :
Farmers play a specific role in biomass production. The biomass can be the production of cattle manure or agricultural residues or it can be through energy crops production. The farmers gather biomass at their farms and transport it to biogas production plants (agricultural firms) through pipeline networks or through trucks. They have high interest as manure disposal costs are high but have low power as different farmers can substitute them in case they don't have yield.

In the past, farmers used to dispose manure directly into the soil for agricultural purposes as a fertilizer. This led to pollution which degraded the air, soil and water resources. Thus the nitrates directive was drawn by EU in order to protect the environment from the pollution caused by contaminants especially manure (Kuik, 2006). The implementation of the nitrate directive was expensive and led to seek other alternatives. One of the solutions to handle this, is the use of anaerobic digestion on the manure which was cost-effective as well as sustainable in nature. The process is advantageous as it can recover energy in the form of biogas, use the digestate as a processed fertilizer to return nutrients to soil, reduce risks of pathogens from spreading pollution (Gebrezgabher et al., 2010).

Waste stream producers :
The suppliers for biogas production can also come from waste water treatment plants, supermarkets, food industries, dairies where there is biodegradable form of waste production. They can be collected and centrally treated for biogas production. Their interest is high as waste processing can be expensive and biogas production makes it cost friendly. But their power is low as they are restricted by legislation's for the kind of wastes they transport before treatments (Gebrezgabher et al., 2010).

Biogas/ Greengas Consumers
Biogas can be utilized for various applications and most commonly it is used in bio-CHP plants for production of electricity and heat. This energy produced can be used for powering local households, restaurants, industry etc. Heat produced can thus be also used for district heating. Upgraded biogas is also another option of consumption on the large scale using the natural gas grid. After up gradation it can be further compressed to become liquefied for use as vehicle fuel (Bekkering et al., 2010). Based on the utilization of the biogas applications, the biogas/green gas consumers can be broadly divided into small consumers and large consumers. Their primary role is the consumption of the energy delivered to them for their needs in the form of biogas, electricity, heat or green gas. Their location and demand capacity information is required for network planning.

Small Consumers :
These consumers can be the households, small industries, restaurants or individuals who are willing to consume the energy delivered for their needs. They can use the biogas for cooking purposes, or the electricity and heat produced for powering their appliances or to have district heating. Thus these users have low interest in what kind of gas they use to solve their energy needs as long as the costs are reasonable for them. They have low power as they form a small segment of the society individually.

Large Consumers :
These consumers can be the industrial consumers who need the energy to meet their production needs either in the form of biogas or electricity or heat or green gas. The industries have high interest in this kind of energy as it is a sustainable alternative. This helps them reduce their CO2 emissions and at the same time become environment friendly at a much cheaper price compared to the fossil fuel based energy use. Their main interest lies in having a reliable supply of energy which is sustainable too. They have high power as they consume more and can influence the demand for energy production too.

Network facilitators
In Netherlands, more commonly, the distribution/ transmission of natural gas and other energy forms is mainly handled by the DSO (Distribution System Operators) and the TSO (Transmission System Operators). Some third party distributors are also involved for energy distribution locally. They play an important role in network planning as they need to operate and maintain the distribution grid and they are obliged to connect the suppliers to the grid based on the specifications (discussed in section 3.2.2).

Distribution System Operators (DSO) :
These stakeholders come into picture only when the biogas has been upgraded to natural gas quality called as green gas. The distribution grid comprises of high pressure and low pressure distribution grids. The high pressure grids transport gas further to the local industry users and other commercial purposes. The DSO's are responsible for the operation of the distribution grids and the gas compressor stations (Weidenaar, 2014).

In Netherlands, Enexis, Alliander and StedIn etc. are the DSO's and are responsible for the distribution of natural gas across the country (Pijnenborg, 2011). They are obliged to allow the injection of upgraded biogas into the natural gas grid if it meets the gas quality and pressure requirements based on the capacity of the grid. Contractual agreements are to be made between the local biogas producer and the DSO to ensure smooth distribution of the upgraded biogas. They have high interest as they need to devise cost-effective network plans to inject the green gas into the national grid. They also have high power as they are the main channels connecting the small and large consumers.

Transmission System Operators (TSO) :
These stakeholders also come into picture only when the biogas has been upgraded to the natural gas quality. Their role is primarily in the operation of the transmission grid. In Netherlands, Gas Transport Services (GTS) owned by Gasunie which in turn is fully owned by the Dutch government operates as a TSO. These TSO's are responsible for distribution of gas to large scale industries directly and are supported by the DSO's when they need information regarding consumer demands (Weidenaar, 2014). They have high interest and power as they specify the grid quality requirements for any kind of injection. They play an important role to enforce the quality, pressure requirements of the kind of gas that is injected into the grid. The transmission grid operates at high pressure levels and is a rather rare option to allow the injection of green gas. It mostly directs the requests to DSO's unless it's inevitable.

Third Party Network facilitators :
These stakeholders are mainly involved in the operation of local biogas networks. The biogas that is generated in centralized production plants can be distributed in the network locally through these parties. They distribute biogas in its original form or distribute it as electricity or heat. The local biogas grid network has dedicated pipeline network and is focused on transfer of biogas from the production site to the consumers. They have high interest as they are involved in the planning, building, and operation of local biogas networks. They have low power as they don't intend to connect to the national grid unless they have an excess of supply.

Funding Organisations
Capital investments for biogas production plants are large and the farmers cannot bear the costs of the whole investment themselves. They rely on external capital investments like banks or other capital investors. These investments mostly cover the costs for the storage, digesters, cleaners, bio-CHP units or the entire set up of production plant itself. These investments can be risky and makes these organizations to have a stake in the renewable sector investments. They have high power and interest as they provide the capital for biogas production and also get a stake in the renewable sector. In NL, Rabobank has a financing scheme to encourage farmers to produce biogas (Hahn et al., 2010) .

Subsidies like SDE+ are applicable to green gas, electricity and heat production and not directly on raw biogas production. Agentschap NL assigns the subsidies in the NL but the amount of money for subsidies in a year is dependent on the national government/ministry (Butenko et al., 2012). Even though subsidies play an important role in biogas production they are also offered on first come first serve basis or randomly drawn. Hence the biogas producers need to opt for external financial aids or any available regional subsidies of renewable energy projects.

Public Authorities
Local municipalities play the role of granting environmental permits and land use. In most cases the local population, households are represented by the municipalities and the biogas producers need to rely on them for permission to establish biogas plants. The biogas producers need to have approval and receive permits for land use, environmental impacts etc. The permits mostly relate to pollution from leakages, safety aspects, traffic impacts and any specific rules in relation to digestate and input regulation (AgentschapNL, 2012).

The Ministry or the Government plays a key role in designing national policies for renewable projects. Feed-in-tariff policies can be determined at a uniform level depending on the kind of renewable energy production. The biogas producers are guaranteed a fixed amount per unit of output N/m3 of biogas/green gas (Hahn et al., 2010).

Knowledge Institutions
The production of biogas/ green gas involves sharing of knowledge and best practices. Some knowledge institutions like Energy Research centre (ECN) in Netherlands are working on research for producing synthetic natural gas from biomass. ECN works closely with the Dutch

universities like TU Delft, Wageningen agricultural university and research institutes like TNO to perform technological research for implementation of biomass related projects. Edgar- Energy Delta Gas Research, also researches on local biogas grids projects like “Towards Sustainable Gas Distribution Systems” (EDGaR, 2015). Their power and interest is moderate and contribute towards technological development.

Others
Vertogas is an authority in NL founded by Gasunie which certifies the green gas that is injected into the natural gas grid. A producer of green gas asks Vertogas to register their installation. Then Vertogas does a physical inspection and an audit on the production of biogas.Based on the quality of gas produced and several operational procedures the certificates are issued to the producers. Such certification ensures to maintain the quality of green gas injected into natural gas grid and helps in determination of gas price too. They have moderate interest as they can only give certifications and have low power as they are dependent on producers who seek certifications and do not impact biogas production otherwise (Pijnenborg, 2011).

Gasterra trades in natural gas and is responsible for gas pricing in Netherlands. Even though the impact is high on the gas prices, the stakeholder doesn’t directly influence the biogas production and planning. The influence can be in cases where green gas is injected into natural gas grid (Pijnenborg, 2011).

Power Interest Grid of Stakeholders
The power interest grid of stakeholders (see figure 3.4) clearly shows us the network facilitators

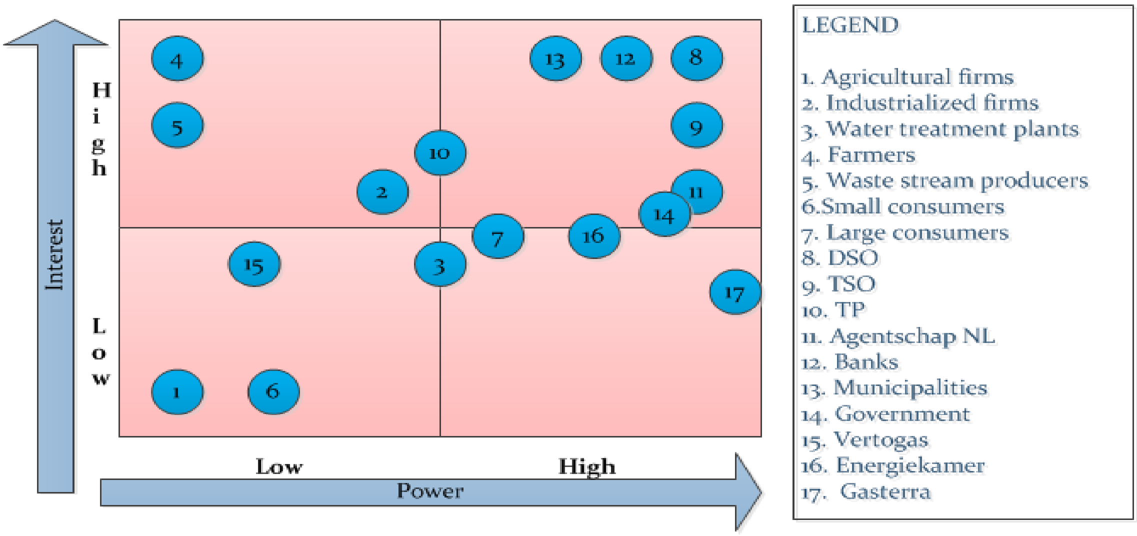


Figure 3.4: Stakeholder Power Interest Grid

like DSO, TSO, Government authorities, funding organisations and Gasterra have high interest and high power. On the contrary, the large scale producers and the large consumers have low power and high interest. The small producers and the small consumers have low interest and low power. This infers that, small producers do not have an incentive to distribute their excess gas as they neither can influence the network nor meet the demand. Also, large producers like industrial firms cannot influence the grid operators to facilitate the distribution because of their low power. Similarly, the government has the authority to allow or stop the injection of the greengas into the distribution grid if it doesn’t meet the required quality specifications. Although different stakeholders have different interest and different power positions there is always a need for collaboration as each of them are interdependent on each other for either their resources or services.

Consequences for planning energy layouts:
The actors involved in the supply chain of biogas/greengas production and distribution display network characteristics like variety, inter dependencies and closeness. Each of the actors are varied in their roles have different goals and interests. The power interest grid shows us the main actors who have high interest and power to influence the network planning. The network facilitators like the DSO's, TSO's and third party network providers play a main role in managing and planning network infrastructure for transporting gas. In order to do so, they are dependent on the gas producers and the consumers. They need information about their location and capacities to balance the distribution of gas across the grid. The biogas producers need to actively interact with the feedstock suppliers, buyers and the network facilitators. Moreover the regulatory authorities also impose specific rules on the producers as well as the network facilitators to produce gas and transport it. Additionally the different directives influence the decisions of the producers and the network facilitators. Hence it is important to provide a platform for these different stakeholders to simulate a network layout based on their interests and validate if their decisions for producing and distributing it is efficient in terms of both cost and energy.

3.2.5 Institutional Characteristics

From an institutional perspective, there are a number of directives which have been taken by the Dutch government under the European Law to promote the use of biofuels and the use of upgraded biogas as an alternative for natural gas. Some of the policies that speak of this are

European Law I
RES-Directive 2009/28, Annex III[1] is a directive which promotes the use of energy from renewable sources. Biogas is recognised as a fuel gas which is produced from biomass or the fraction of biodegradable wastes, which on further upgradation can attain natural gas quality to be used as a biofuel or wood gas. Under article 1 paragraph 12, biogas installations are recognised as sustainable due to their GHG emission saving potential and contribute towards sustainable development in rural area and income opportunities for farmers.

Gas-Directive 2009/73, art. 1 paragraph 2 [2] directive proposes non discrimination between liquified natural gas and biog or any gas created from biomass. These gases should be allowed injection into the natural gas transmission system as long as they satisfy the technical and safety constraints.

European Law II
As seen in section 3.2.1 biomass sources can originate from agriculture, industry or from communities. They can be agricultural residues, animal by products or wastes from human uses. Although the production of biogas is non regulated, the raw materials used for biogas production fall under the European Law. Some of the regulations are,
Regulations 1069/2009 and 142/2011 [3] regulate the movement, processing and the disposal of animal by products which can be harmful to human health and environment if not handled carefully.

Regulation 1013/2006 and the directive 2008/98 establish a legislative framework for the member countries to ensure safe waste management plans. They provide specific key concepts for establishing installations for waste reuse or disposal.

European Law III
The upgraded biogas can be injected into the natural gas grid if it meets the safety and techncial requirements of the natural gas system. The access to the grid is a regulated area under the EU Law and some of the directives promote this access.

[1] http://eur-lex.europa.eu/legal-content/en/TXT/?uri=CELEX:32009L0028
[2] http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32009L0073
[3] http://ec.europa.eu/food/food/biosafety/animalbyproducts/index_en.htm

Gas-Directive 2009/73, Considerations 26 and 41 promote non-discriminatory access for biomethane to join the grid.
RES-Directive 2009/28, Considerations 60-61 promote priority for electricity produced from renewable energy sources.

Support for Biogas projects in the Netherlands
In NL since 2008 the SDE (Besluit stimulering duurzame Energie) programme, gives a bonus payment for electricity produced from biogas. The allocation of these payments is limited and only 30% of the applicants receive it. Thus the production of biogas as electricity did not attact producers due to lack of funding. Another program is the EOS-Programme (Besluit EOS: demo en transitie-experimenten - Order on the Allocation of Grants) that grants subsidies for research, development and market research projects in the field of renewable. These subsidies are granted only to companies and not to individuals (Hahn et al., 2010). Some other financing tools available are, Rabobank's "Green Finance Scheme", which finances large scale biogas plants. The scheme is successful as it is a tax incentive scheme of the Dutch government for capital intensive investments.

Consequences for planning energy layouts:
Having understood the variety of institutional policies available to promote the biogas or greengas projects of its kind in NL, it is important to reflect further if they influence network planning. Firstly according to the directives, the green gas should be given non discriminatory access to join the national grid if it meets the quality requirements. The DSO's who are obligated to inject the gas are reluctant to bear the costs, if they need to invest in new pipeline infrastructure to join the aspiring green gas producer. Also, the grid connection costs are borne by the producer (Butenko et al., 2012) which leads to reluctance of farmers to join the grid . Moreover there is a serious problem of capacity balancing if the green gas has to be injected into the distribution grids. Currently, natural gas distribution is more centralised and constant whereas injection of green gas from decentralised sources can imbalance the network when the supply exceeds the demand.

Secondly, most of the biogas produced is consumed in the form of heat or electricity at the consumer side. The transport of biogas locally is handled by third party network providers which are non regulated and the network is comprised for its safety and reliability (Pijnenborg, 2011). These kind of network planning by inexperienced third party providers can lead to gas leakages and more accidents.

Chapter Summary
The chapter has identified several network characteristics that play an important role in planning network layouts. The supply chain of the biogas network has close inter-relations with the technical subsystem and the sociological subsystem. The different network characteristics of biogas infrastructures are unique to itself but they share a close proximity with the natural gas characteristics too. From a technical perspective it is found that the passive components like the pipe characteristics, grid characteristics and the active controllable components like the compressors, valves and gas measurement devices influence the costs of the overall network layout. Also the gas characteristics influence the use of different grid components and the costs of transporting it. The chapter also identifies the different stakeholders who play an important role in network planning and how they are interdependent on each other. The institutional perspective complements the decision making strategies used by the stakeholders which can indirectly influence the planning. These factors will be used in chapter 5 to identify the interrelations with other factors of the biogas production and distribution lifecycle.

Chapter 4

The Scientific Approaches to Network Planning

Network design issues have been extensively studied in the past by many researchers. The chapter focuses mainly on understanding the working principles of the most prominent network layout optimization techniques used by the researchers at TPM faculty of TU Delft . The chapter starts with an explanation of the problem the researchers are trying to address, followed by a discussion on the top down approaches 4.1, and the bottom up approaches in section 4.2. Section 4.3 gives the working principles of the implemented models, followed by the most recent developments on these models (section 4.4). The main factors and functions used in these models are outlined in the section 4.5. The chapter closes with the research findings of other researchers and industry users in the area of network planning (section 4.6).

Problem Definition
Network planners face a routing problem in network design, to decide the best possible way to connect the producers (sources) and the consumers (sinks). Even when they have definite information regarding the locations of the producers and consumers, their capacities and the cost differentiation of different regions, they still find it difficult to take a decision. Construction costs for network infrastructures are capital intensive and play an important role in decision making. Designs are more acceptable if the costs incurred for construction are minimal. Thus network planners look for solutions that can reduce the construction costs.

Solution Approach
Some of the researchers approach the routing problem to find an optimal solution while others try to present a robust solution which stands the test of time. The approaches studied further, attempt to design a layout for an energy network with minimal construction costs. They approach the same problem in two different ways. They are broadly classified as ”Bottom Up” and ”Top Down” approaches based on their problem solving technique.

4.1 Top Down Approaches

Top down approaches use optimization algorithms to find an “optimal solution” and rely on access to complete information. They are used to come up with single optimal solution. 3 types of top down approaches used by researchers are discussed below,

Mixed Integer Linear Programming (MILP):
MILP is one of the widely used mathematical models which can include multi-dimensional constraints that energy networks include. (Middleton and Bielicki, 2009) used MILP to design an integrated cost minimizing carbon capture and storage infrastructure model. They provide a systematic approach to carbon capture, storage, pipeline construction and CO2 disbursement from the source to sinks considering the spatial obstacles while planning the network.

(Unsihuay-Vila et al., 2010) used a MILP model to design an integrated natural gas pipeline with the electricity transmission value chain. The framework was proposed to minimize the investment and operational costs to determine the optimal location, technology, installation time and dispatch of facilities over a long time horizon.

Steiner minimal trees:
Definition: *"A Steiner minimal tree for given points A_1,...,A_n in the 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 can contain other vertices (Steiner points) besides A_1,...,A_n (Gilbert and Pollak, 1968)." The extra vertex that is added to the tree to reduce its length is called the "Steiner Point".*

Networks connect one or several sources to one/several sinks. These sources and sinks can be identified as points/nodes in the network. The concept of Steiner minimal trees as defined above aim to find tree shaped networks that minimizes the total length of the network. This is very useful if the construction costs are dependent on the length of the pipelines. However, it is also seen that these trees do not take into account the extra costs if pipelines have different capacities.

Edge Weighted Steiner minimal trees (EWSMT):
The Steiner minimal trees does not work with varying pipeline capacities. Thus EWSMT's need to be used to design networks with varying capacities (Heijnen et al., 2013). Each edge represents a pipeline connection between the nodes. The weight given to an edge represents the capacity of the pipeline connecting the nodes. In combination with other heuristics from geometric graph theory, the EWSMT's can be used to find the cost minimal network layouts (Heijnen et al., 2013).

The minimum cost network obtained sometimes is not a tree if the network has more than one source/sink. These networks are commonly known as Gilbert networks. They can be defined as,
"A Gilbert network is a network connecting a set A of n given points a_1,a_2,...,a_n (referred as terminals) and a (potentially empty) set S of additional points s_1,s_2,...,s_n in the Euclidean plane. The network is designed to accommodate a given set of bilateral flows $q_{i,j}$ between points a_i and a_j where f(q) is the cost per length unit of each edge in the network. (Heijnen et al., 2013)"

4.2 Bottom Up Approach

Bottom up approaches use distributed entities in a multi-dimensional space to find a "good enough solution" and rely on local information which is available. One such approach is the creation of network layouts using an Agent Based Model (ABM). It is a computational modeling technique which considers that individuals do not live in isolation and are interdependent on their surrounding environment. These models have a collection of heterogeneous, intelligent interacting agents and through their interactions they generate patterns of complex dynamic behavior (Held et al., 2014). Ant colony optimizations (ACO) can be implemented using the ABM methods where the digital ants are used as agents to find an optimal path given a bounded region and its constraints.

Ant Colony Optimization (ACO):
ACO is a swarm intelligence technique which is based on the real behavior of how ant colonies operate. The ants set out of their nests (source) in the quest of finding food (sink). On finding food, the ants return back to their nests leaving pheromone trails on the path. If other ants happen to find a path having pheromones they are more likely to traverse the same path in search of food rather than moving randomly. More the number of times a path is traversed by the ants, a likely shorter path to reach a food source is achieved (Chandra Mohan and Baskaran, 2012). This concept leads the ants to find the best possible shorter paths connecting the sources and the sinks. ACO can thus be broadly classified to follow 3 sets of decision making behavior (Heij-

nen et al., 2013). Firstly, the ants (agents) wander randomly in the given graphical/bounded region and react to their surrounding environment conditions. Secondly, during their movement they find paths connecting the source and sinks and leave pheromones trails making changes to the environment. Thirdly, based on the information collected from the different agents, centralized decisions are taken to find the cost minimal networks. Different routes can be obtained by having the ants traverse through a bounded region.

4.3 Working Principles of the Algorithms

The scientific approaches considered in this study is a top down approach, which is implemented using geometric graph theory (GGM) and the bottom up approach of Ant Colony Optimization which is implemented using an Agent Based Model. An overview of the main functions of these algorithms are discussed below. It is important to identify the input and the output parameters of these algorithms, followed by a comparison with the factors found in the socio-technical research.

Geometric Graph Methodology (GGM):
In this method, the researcher tries to find a minimal cost network in a closed region along with obstacles. The approach is based on the work of (Heijnen et al., 2013, 2014) where the focus is to connect a single source to multiple sinks. The main goal of this approach is to maximize the worth of a decision given the different configurations each network can take. This can be achieved when the investment costs of building the network are low and the expected incomes from the network built capacities are high.

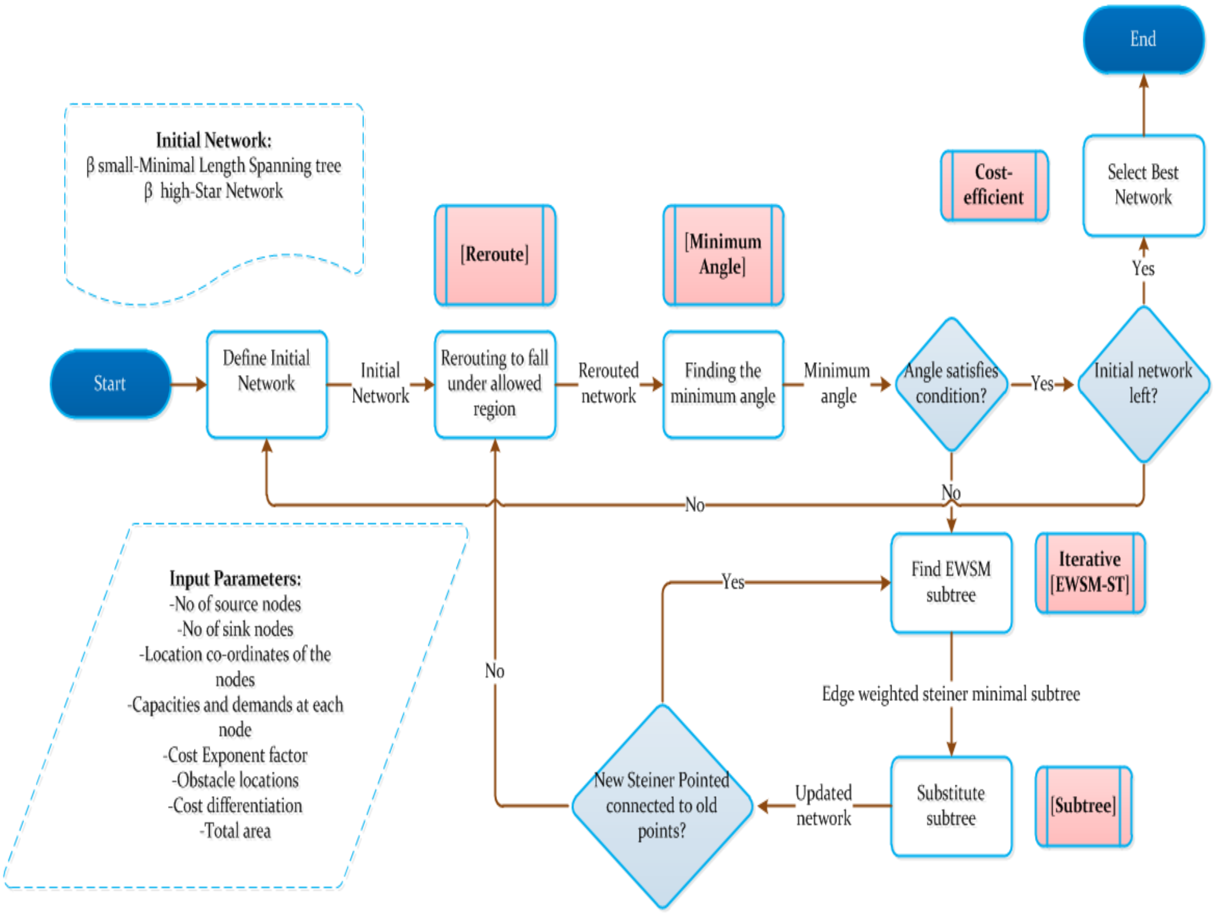


Figure 4.1: Flowchart of main procedures of GGM

Figure 4.1 shows the flowchart of the main procedures of the GGM as explained by (Heijnen et al., 2013). The network participants (source and sinks) locations and capacities, cost differentiation of regions , allowed region and the cost exponent details are fed into the algorithm. The cost function used by the algorithm to calculate the total investment costs of a network T is,

$$C(T) = \sum_{\forall_e \in E(T)} l_e q_e^{\beta} \tag{4.1}$$

where l_e is the length of the pipeline e and q_e is the capacity of the pipeline e. The β is the cost exponent for the capacity with $0 \leq \beta \leq 1$. If $\beta = 0$, the pipeline capacity has no influence on the costs and if $\beta = 1$, building two pipelines of capacity 1 is just as expensive as building one pipeline of capacity 2. E (T) is the set of all edges in the tree T.

The algorithm starts to find an initial network which connects all the sources and the sinks and has the required capacities as weights on the edges. The initial tree thus formed can represent a minimal spanning tree [1] or a star network [2]. Based on a selected initial network, the algorithm now checks if the tree chosen lies outside the allowed region. If it lies outside, it tries to reroute it to fall under the allowed region. At each change the algorithm preserves its properties and keeps changing until a lower total building cost is achieved.

The rerouted network is further improved by adding Steiner points. A Steiner tree is locally minimal when every angle in the tree is greater than or equal to $120°$ (Gilbert and Pollak, 1968). Hence, the algorithm searches for the angle between two edges for the entire tree. In case of Gilbert networks, Thomas and Weng (2006) have proposed an angle condition which is used to find locally minimal Gilbert networks. In both cases, for angles that do not satisfy the angle condition in the tree, it might be profitable to add a Steiner point. These steps are iteratively performed until a minimal cost edge weighted tree (EWSMT) is formed. Wherever required Steiner points are added and such modified trees are substituted to the original network and validated again for minimal costs. The addition of Steiner points is locally optimal and thus the iteration is needed to achieve minimal costs. In the end when no more substitution happens and the angle conditions are satisfied, the best network is chosen. The recent developments to this algorithm has been addition of multiple sources and cost differentiation among regions. For more detailed information about the working principles of these algorithms refer to (Heijnen et al., 2013, 2014; van Tol, 2014)

Agent Based Model (ABM):
Agent based model is implemented using the concept of ant colony optimization (ACO). Here, the researcher tries to find a minimal cost network which connects all the sources (nest) to the sinks (food sources) in a closed region. The network paths are built based on ant interactions which use local information to make decisions to find a food source. Network paths emerge when a specific path is traversed by ant between a source and a sink.The main goal is to connect multiple sources and the sinks and find networks which have minimal building costs.

Figure 4.2 shows the flowchart for the main functioning of an ABM as implemented by (Heijnen et al., 2014; van Tol, 2014; Viet, 2015). The algorithm starts with no pre-defined network, and all the ants are distributed randomly in the total distributed area. The input parameters are fed into the model and the ants start looking for food sources (sink) as they leave their ant nests (source). When an ant finds a food source it makes a return to the nest. The ants return to the nest by using the pheromone trails left by other ants or by getting attracted to the scents emitted by the nests. A network path traversed by an ant between a source and a sink is tracked. The costs are calculated for each network path and these costs are validated to see, if that is the cheapest alternative else the algorithm continues to search for the cheapest path.

This process is repeated until all the sources and sinks are connected. The algorithm stops when all network paths are built, or when the demand of food sources is satisfied, or when the supply capacity = 0. The recent developments to these algorithms are the construction of central

[1] If β is small or the source/sink is not central to other network participants
[2] If β is high or the source/sink is relatively central to other network participants

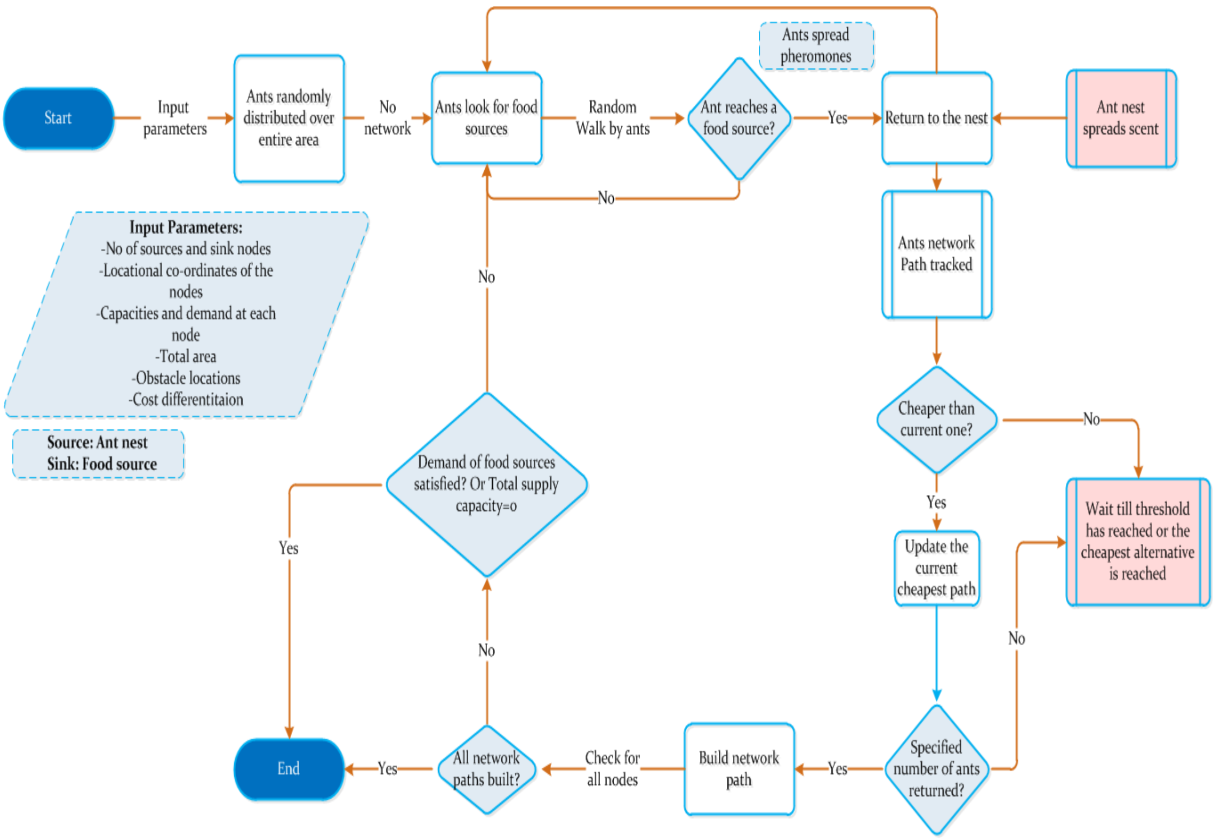


Figure 4.2: Flowchart of the working of the ABM

branch link where all additional sources and sinks can be connected to it and form cost minimal networks, cost differentiation among regions etc. For more detailed information about the working principles of these algorithms refer to, (Heijnen et al., 2013, 2014; van Tol, 2014; Viet, 2015)

4.4 Recent developments of these approaches

In the past 2 years there has been more development on the scientific algorithms proposed by (Heijnen et al., 2013). These developments have to a large extent tried to overcome some of the issues cited in the literature before. Below are some of the results of the recent research carried out by the students at TPM faculty of TU Delft.

- (van Tol, 2014) has succeeded in embedding cost differentiation of regions to the existing methods. In his research he has modelled the network with different cost regions instead of allowed and no-go areas. Accounting for such differentiation in costs makes the models more realistic. The resulting networks based on such methods will be beneficial to the network planner to reduce their building costs. The results of the research by (van Tol, 2014) show that geometric graph theoretic approach yields better results than the agent based modelling approach, but not significantly. Thus the research proves that the inclusion of cost differentiation enables planners to simulate network layouts to either partially or fully cross an expensive region or advises to take a roundabout. Thus, this new addition to the research is beneficial to expanding network designs too which is crucial for realistic network planning.

- (Viet, 2015) has addressed the issues of uncertainty in a multi-actor context of the supply/demand and the network participants while designing network layouts. The author has built a non-deterministic model for multiple producers and multiple consumers which remains flexible to future needs of the network participants. The author uses an agent based model to simulate the changing demands of the network participants and validate the results for minimal cost networks. (Viet, 2015) proposes a generic design approach which can be applied to different networks for network planning. The design approach if implemented as a model can create a network connecting multiple sources and sinks with known capacities. It further provides flexibility to identify and feed in the uncertainties of the participants into the model and provide a multitude of different network topologies and investments costs . These flexible set of solutions given to the network planners brings his scientific model closer to reality as decision makers can select a solution from the set of results.

4.5 Main factors used in scientific modelling

Having understood the behavior of different scientific algorithms that use geometric graph methods and agent based models by (Heijnen et al., 2013, 2011, 2014; van Tol, 2014; Viet, 2015), table 4.1 gives an outline of the different requirement parameters (inputs) that are covered in these methods.

Input parameters	GGM	ABM
No of Sources and sinks	Yes	Yes
Location of sources and sinks	Yes	Yes
Total allowed area	Yes	Yes
Location of obstacle regions	Yes	Yes
Costs for different regions	Yes	Yes
Demand capacity for each sink	Yes	Yes
Supply capacity of each source	Yes	Yes

Table 4.1: Input parameters of algorithms

Table 4.1 lists the input parameters used in both the algorithms. Although both the algorithms use same input parameters they function differently to reach the same goal of building minimal cost networks. In reality, based on interviews with the industry experts from Gasunie and Delfluent services C.1 , costs play a very important while planning energy infrastructures and hence it is one of the most important performance criteria for validation. The cost function used by both these algorithms to calculate the total investment costs of a network T is the same as shown in equation 4.1.

On comparing the factors identified from the literature for biogas networks, the input parameters shown in Table 4.1 infer that, the factors used by the scientific models form a subset of the research findings from the literature. All the parameters used in the models are relevant for network planning and they play an important role to realise networks for real infrastructure projects. Furthermore, these models are generic and can be applied to different networks to achieve minimal building costs.

Although these models are generic and helpful, the cost function used here, does not include all the costs for the infrastructure development. Also, it is important to consider the realistic requirements of decision makers. E.g. For biogas networks, the total costs depend on the compression costs, use of different pipeline diameters and pipe material, installation labor costs, operational costs etc to name some. Furthermore, there is a need to look at the different performance criteria like cost of distribution grid components, fixed investment costs, operational costs, amount of CO_2 emissions, energy efficiency of the layout and the components used while evaluating a network design. Hence, it is also important to look at other scientific models which are being used in the industry or developed by other practitioners . The study of these models can assist in gaining more insights to extend the existing functions of the scientific models.

4.6 Findings from the Industry and other researchers

There are different studies which focus on network design optimization but the scientific model studies selected below are more related to the networked infrastructure of natural gas. Although they used different methods, their goal was also to achieve minimal building costs for a natural gas transportation network. These specific studies were chosen as they share the same objective in their research. They wish to determine cost minimal network plan to transport gas. Their study is more relevant to this research because it gives a direction to think about the cost equations that were used. This understanding can provide better ideas on how to enhance the existing cost equations to incorporate the variables relating to the active and passive components.

(Adeyanju and Oyekunle, 2011) have developed a workable procedure adapting the "Generalised Reduced Gradient Algorithm" to determine optimum economical conditions to transport natural gas through a series of pipeline and compressor stations. Their study found that, transport of natural gas in a cost effective way depends on the flow rate of gas, outlet pressure, cost of pipeline, compressor stations, operation and maintenance costs, pipe characteristics like pipe diameter and gas characteristics like the flow rate. The total cost of the pipeline network development used in their research was,

$$[TotalCost] = [InvestmentCost + OperatingCost]_{pipeline} + [InvestmentCost + OperationCost + EnergyCost]_{compressor} \tag{4.2}$$

The model developed determines the optimum conditions for the pipe diameter, the use of compressor stations based on the gas outlet pressure and flow rates. Their main assumption is that gas transported over long distances has a drop in pressure over the pipeline and hence the compressors are needed to keep the pressure levels accurate. For details of the parameters considered in the equation 4.2, please refer to their publication (Adeyanju and Oyekunle, 2011).

Another researcher, (Gunes, 2013) has used the cost equation used by (Adeyanju and Oyekunle, 2011) and proposed a model for minimizing the maintenance and operation costs of compressors and capital costs of pipeline segments and compressors. Both these researchers have implemented the models by using the inequality constraints for the operation of each compressor and the equality constraints for fixed length of the pipe segments. Although these models achieve the cost minimisation, by incorporating the different influencing factors like the pipe diameter, costs and length, gas flow rate, outlet pressures and compressor costs etc there is no evidence of their use by real decision makers for real time infrastructure projects of natural gas planning. Hence it is difficult to say which specific studies are the best to be considered for enhancing the cost equations. These studies are a good starting point but it is advisable to work closely with a pipeline engineering expert in the field to understand the intricacies of each variable.

During the research conducted so far, there is no evidence of the real use of the discussed scientific approaches by decision makers. Either it is due to the limitations of the research scope or the algorithms are not well known among the network planners. One of the network planners in Netherlands discussed in section 3.2.4, Gasunie was approached for an interview to know the industry approach of network planning. GTS, a subsidiary of Gasunie in NL are responsible for the operation of the transmission grid in NL. Based on the email discussions with them (see appendix C.1), it is understood that, they use a commercial software called SIMONE[3] which was developed by GTS in collaboration with KEMA. This application is based on linear optimization techniques and focuses mainly on the network flow optimization to achieve cost effective gas flows rather than a cost effective solution for planning the network layout itself. Although, it is important to consider the optimization of gas flow over a pipeline, neglecting the simulation of minimal cost network layout, can lead to more expensive networks built. The research that has been used for the network flow optimization is also relevant to this research and can help enhancing the existing cost calculations. References to their research is provided in Appendix C.1. This discussion with the network provider validates the knowledge gap existing in this area of research, it emphasises the need for applications which can simulate minimal cost network

[3] http://www.simone.eu/simone-simonesoftware-onlinesimulation.asp

layouts which are flexible to meet the user's needs and the future capabilities.

Chapter Summary

The chapter provides a detailed understanding of the working principles of the scientific algorithms of top down and bottom up approaches. The chapter further updates the readers with the most recent developments in these areas and summarises the main factors used in their functionality. The chapter closes with the findings of other researchers who have designed similar optimization algorithms for gas networks and their approaches. This chapter will be an input to chapter 5 which summarises all the research findings to apply them to the final design of enhancing the scientific models.

Chapter 5

Research Findings

In order to determine how the network layouts need to be designed to meet the future needs of gas transport systems, the requirements of such a system need to be summarized. Based on the research so far, it has been identified that various characteristics of both the gas and the network itself plays a vital role in decisions taken for designing an energy layout.

This chapter will focus on the aspects of the requirements that need to be considered for planning a network layout. Section 5.1 summarises the factors that influence network planning based on findings from Chapter 3, section 5.2 provides an overview of the inter-relations among these factors, section 5.3 shows the research findings on the scientific algorithms based on Chapter 4. Finally in section 5.4 a comparative analysis of the identified factors and the existing algorithmic inputs will be done and validated with the inputs from the interviews conducted. Based on this analysis a consensus on the factors that needs to be incorporated into the existing scientific models is discussed in section 5.5. The results will form a basis for the discussion in Chapter 6 to provide a design framework to extend the functionality of the scientific models.

5.1 Research findings based on empirical study

The principal requirement of gas distribution and transmission is to consider all the relevant elements of the supply chain. The design process will need to include cost estimates for using various gas transmission equipment, pipe profiles, compression equipment and the inter-distances between producers and consumers. The layout design will need to meet specific pre-conditions like local gas demand, availability of biomass/biogas for transmission, spatial restrictions, regulatory aspects and more importantly collaborative agreements between different stakeholders involved. Different variables will constitute the planning of biogas/ greengas networks and will influence the performance indicators of the resulting layouts.

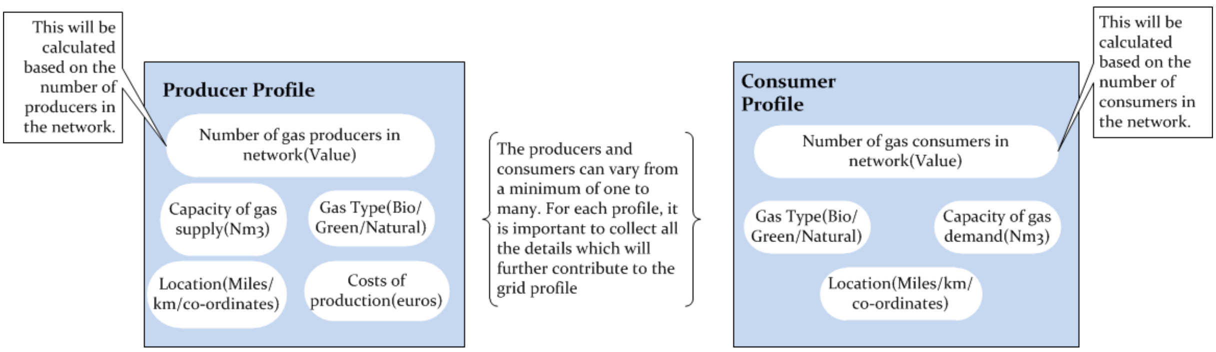


Figure 5.1: Producer and Consumer profile

While designing networks for gas distribution and transmission, gas can be injected or delivered at various injection points along the pipeline. Thus it becomes very important to gather information about the location and capacities of the producers and consumers participating in the network for a specific region. There are 2 possibilities of designing a network layout of biogas/bio-methane. For both possibilities, there are some overlapping factors which need to be clearly outlined by the decision maker. The performance indicators of the resulting layouts can be determined by the cost of distribution grid components, fixed investment costs, operational costs, amount of CO2 emissions, energy efficiency of the layout and the components used etc.

- Scenario1(Sc1) : If the network under consideration is for designing a new layout for biogas production and transmission, different factors are important for planning
- Scenario1(Sc1) : If the network under consideration is for injecting bio-methane to existing natural gas grid, different factors will be seen as important.

In Chapter 3, section 3.2.1, biomass gathering, biogas production and up gradation concepts are briefly discussed. For both the scenarios identified above, it is important to know the details of the producers and consumers. For producer profile, it is important to know the type of gas they are producing, capacity of their supply, location of production or injection, cost of production or injection and the total number of participating producers in the specified region. For consumer profile, it is important to know the type of gas they want to consume, capacity of their gas demand, their location, and the total number of participating consumers in the network. Figure 5.1 shows the variables with their units to be used. The total number of participating producers and consumers can be calculated based on the details entered for each profile.

Biomass sources and other raw material which is used for biogas production can also lead to network formations. Since, the procurement of biomass can be achieved through local transport or any existing pipeline routes, it is assumed that its costs are included in the biogas production costs. Thus only the biogas plant producing biogas is considered for the layout design and the manure/raw material networks are considered implicit to the biogas producer profiles.

Chapter 3, section 3.2.3, discusses the importance of the physical and chemical characteristics of biogas and natural gas. The biomass used for biogas production determines the quality of biogas/ green gas . Natural gas differs in its properties from biogas and it is also seen that upgraded biogas will need to meet the quality requirements of natural gas grid before it is injected into it. The existing infrastructure of natural gas grid is designed specifically for itself and the injection of green gas is possible only if it meets the quality requirements set by the network operators and the national standards. Thus, the gas characteristics become important when the gas needs to be injected into the natural gas grid. For new networks, the gas characteristics can only influence the costs of the layout as it can lead to usage of specific pipe material, purchase of gas metering and quality measurement devices etc. Figure 5.2 shows the variables and the units to be used for the design.

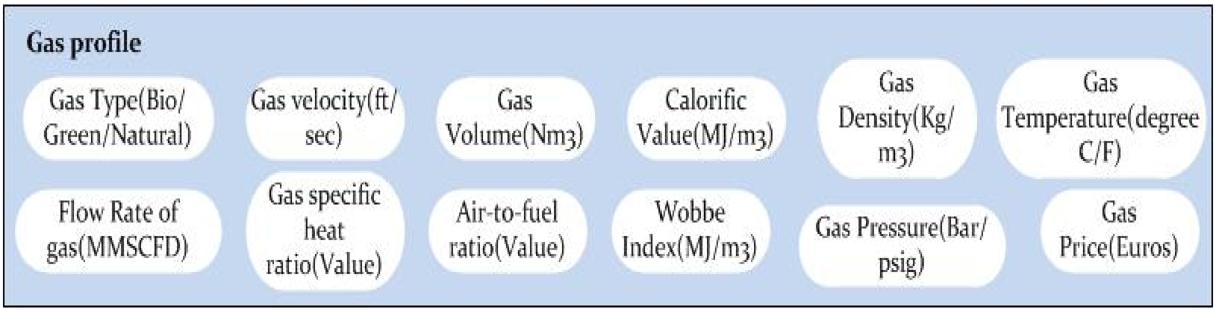


Figure 5.2: Gas Profile

Chapter 3, section 3.2.2 discusses the technical components that a gas grid comprises. The distribution network design is complex as it consists of passive pipes for transmitting gas along with other controllable active elements like the shut off valves, compressor stations, odorisation equipment etc.For designing a network layout, it is important to find suitable settings for

all the active elements to transmit gas between the entry and the exit points. Thus the profile data of these active and passive elements of the network is necessary for designing layouts to ensure non-violation of physical and operational constraints(Fugenschuh et al., 2011).
The pipe specific data like the pipe diameter for network design needs to be aligned with the

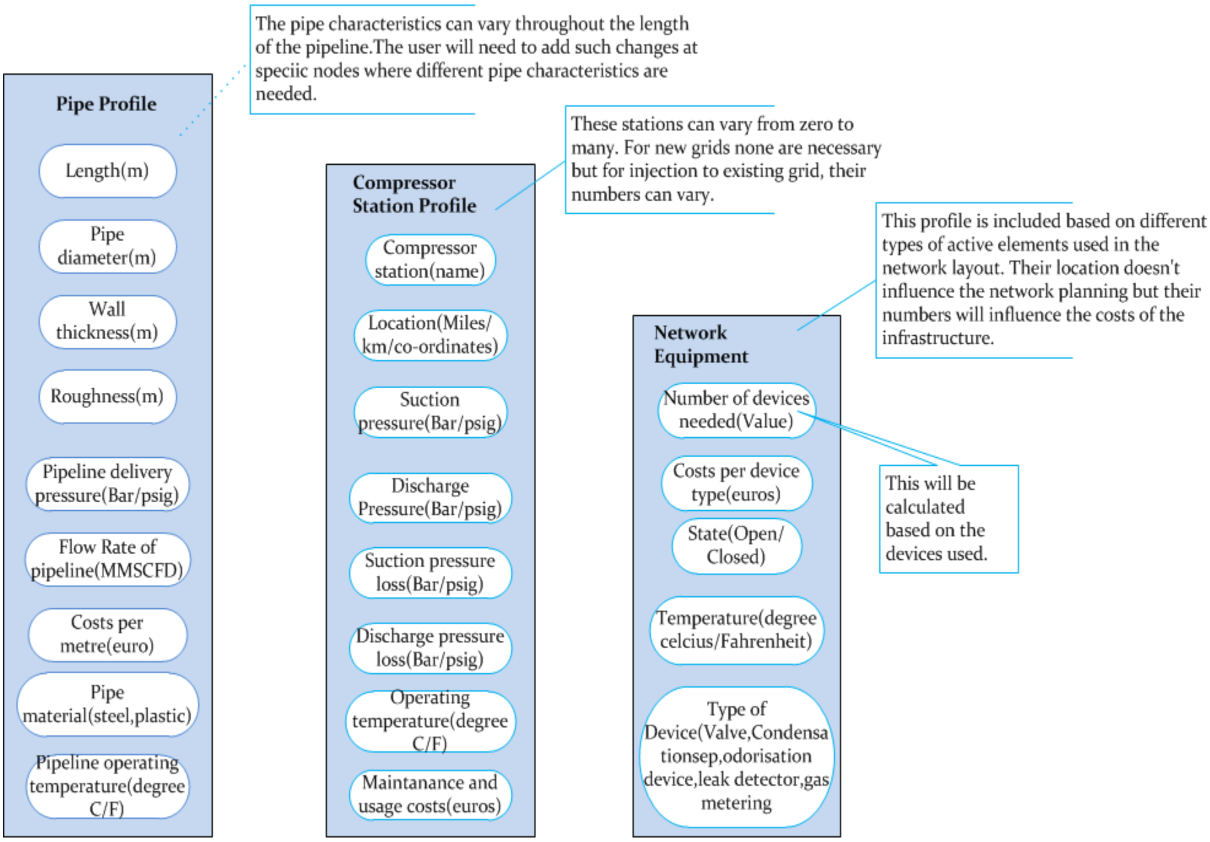


Figure 5.3: Active and Passive Components Profile

supply and demand capacities of the producers and consumers respectively. Pipelines with larger diameter are more expensive and also are influenced by regulatory constraints for usage in high density neighborhoods. The compressor stations are needed to regulate the gas pressure through the network as there can be varying pressures at entry and exit points. The process control for monitoring the gas flow, fulfilling the safety aspects will be achieved by the choice of different active elements like gas regulators, gas leak detectors, shut off valves, filters etc. The network layout design needs to be cost and energy efficient and thus needs a strategic use of these active and passive components while planning. Thus, the pipe profile, compressor station profile and the network equipment data becomes important for network planning. Figure 5.3 shows an overview of the variables and the units to be used for the design.
The spatial constraints can play a role while designing network layouts and it is important to take these factors into consideration. These constraints can be cost differentiation of regions, the land use rights for digging, labor costs, surrounding soil characteristics etc. The soil profile influences the type of pipe material to be chosen, the elevation at which the pipeline needs to be placed. This indirectly can also be influenced by the local stakeholders living in the neighborhood or by the regulatory constraints. Although this is not directly useful for network planning it is a good to have information. Figure 5.4 provides details for the soil profile and spatial constraints that can be necessary in planning
In case, there is excess of gas produced there is need for gas storage or gas flaring. Thus it is necessary for network planners to collect information regarding the available gas storage profile data. For cases of gas flaring there needs to be locations identified in the network where such flaring is possible. Figure 5.5 gives the variables needed for gas storage profile.
All the components discussed above will contribute towards the grid profile. The details for a resulting grid can be calculated if the comprehensive data is provided for all the above factors.

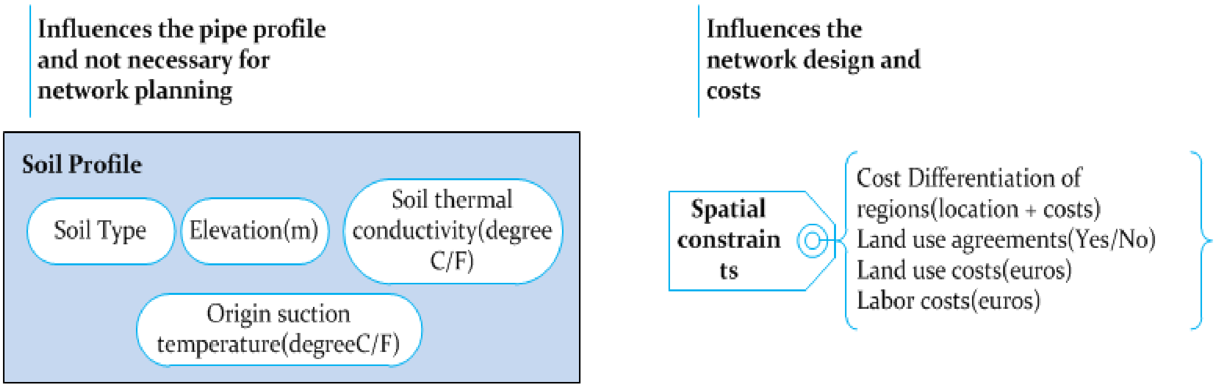


Figure 5.4: Soil Profile and Spatial constraints

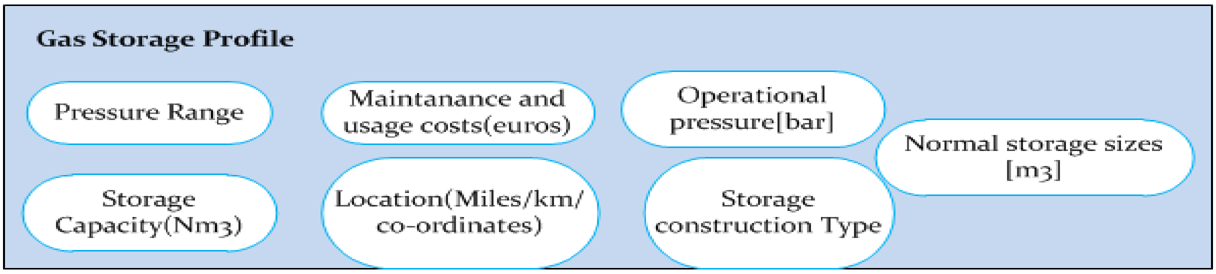


Figure 5.5: Gas Storage Profile

In some exceptional cases, where gas needs injection into existing grid, the grid constraints will need to be made available/provided to find the strategic injection point for new producers/consumers.Figure 5.6 gives an overview of the variables of the grid profile.

5.2 Interrelations between the factors

The dynamics of the biogas production and distribution needs to be understood in detail during the planning phases of network designing. Biogas infrastructure planning can involve a lot of uncertainties about the participating parties, their resources and capacities . Thus, it is important to explore further the inter-relations of the different characteristics of biogas and its networks. The method of Causal loop diagramming (CLD) technique enables us to identify the causal relations between different variables and the feedback loops. Thus this visualisation gives an overview of the system and helps decision makers make more informed decisions.

For this research the qualitative CLD model analysed by Sibel (Eker and Daalen, 2015) has been adapted and extended to include both biogas production and distribution analysis. This is done by using the factors which were identified during the research (discussed in section 5.1. This CLD can help decision makers to identify the feedback loops and see the socio-technical, economic and institutional aspects and their inter connections in the supply chain of the energy network.

Figure 5.7 shows an overview of the relationships between the main elements of the biogas production and distribution model and the feedback loops that arise from such relations. Each arrow shows a causal relation with a polarity shown at the arrow head. Positive polarity relates to a change in the same direction of second variable, for every change in the first variable. Negative polarity relates to a change in the opposite direction of second variable for every change in the first variable.

The element of biomass supply depends on the number of biomass producers in a given area and the willingness of these producers to participate for the overall supply. The biogas pro-

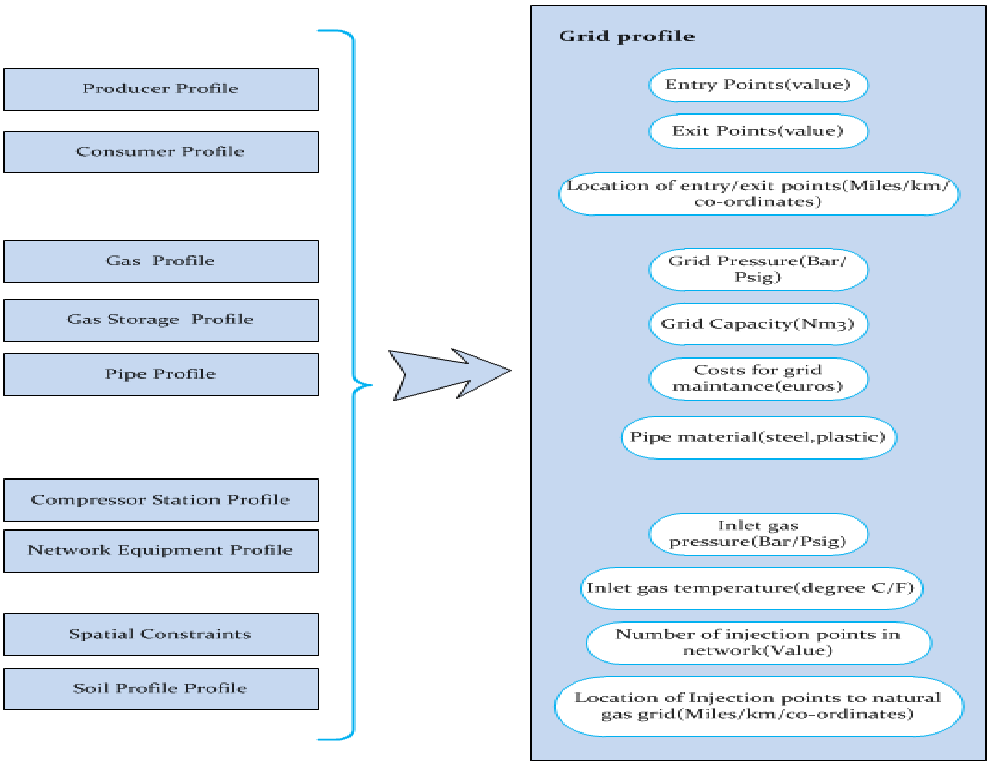


Figure 5.6: Gas Grid Profile

duction rate relates to the total amount of biogas produced and it depends primarily on two factors, the amount of biomass allocated for production and the biogas demand. If there is high demand for biogas and the allocated biomass for production is high, the production rate is also positive. Similarly we can see a feedback loop (R2), if the biogas production rate is high,the biogas price decreases which thereby increases the demand for biogas, this further increases the biogas production rate.Thus it is a reinforcing feedback loop. The NREAP [1] renewable target in NL promote SDE+policies for biogas investments and provide subsidies. Higher number of subsidies reduces the biogas price which further increases the demand for biogas.The higher demand can indirectly lead to CO2 emissions reduction which satisifies the NREAP goals of NL.

Biomethane production and distribution also has similar characteristics as that of Biogas production and distribution, but with minor differences (see figure 5.8). The bio-methane production primarily depends on the amount of biogas allocated for up gradation. It might be possible that although natural gas/bio-methane demand is high there is not enough biogas allocated for upgradation. Similar to biogas, subsidies play an important role here. Another important factor that influences the price of bio-methane is the natural gas price which decides the green gas price based on its quality.

By looking at all the interactions, the behavior of the entire system is clearly understood. The CLD brings out the systematic feedback between the variables and how they affect each other. The performance indicators like cost of distribution grid components, fixed investment costs, operational costs, amount of CO2 emissions, energy efficiency of the layout and the components used are all influenced in one way or the other by these factors. Hence, these variables need to be considered by decision makers and scientific modellers while planning network layouts and for simulating realistic network layouts.

[1] National Renewable Energy Action Plan

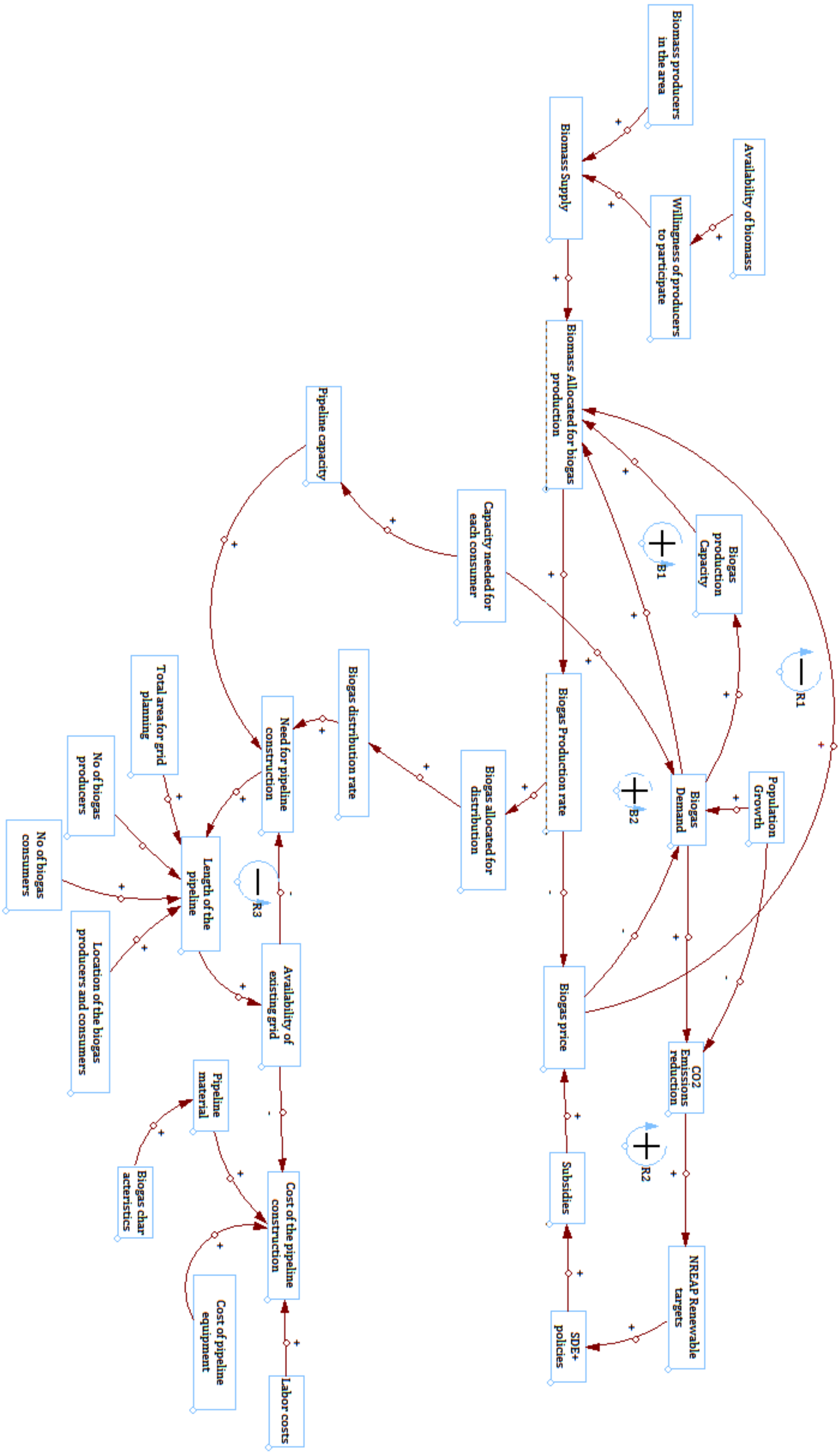


Figure 5.7: CLD of Biogas Production and Distribution

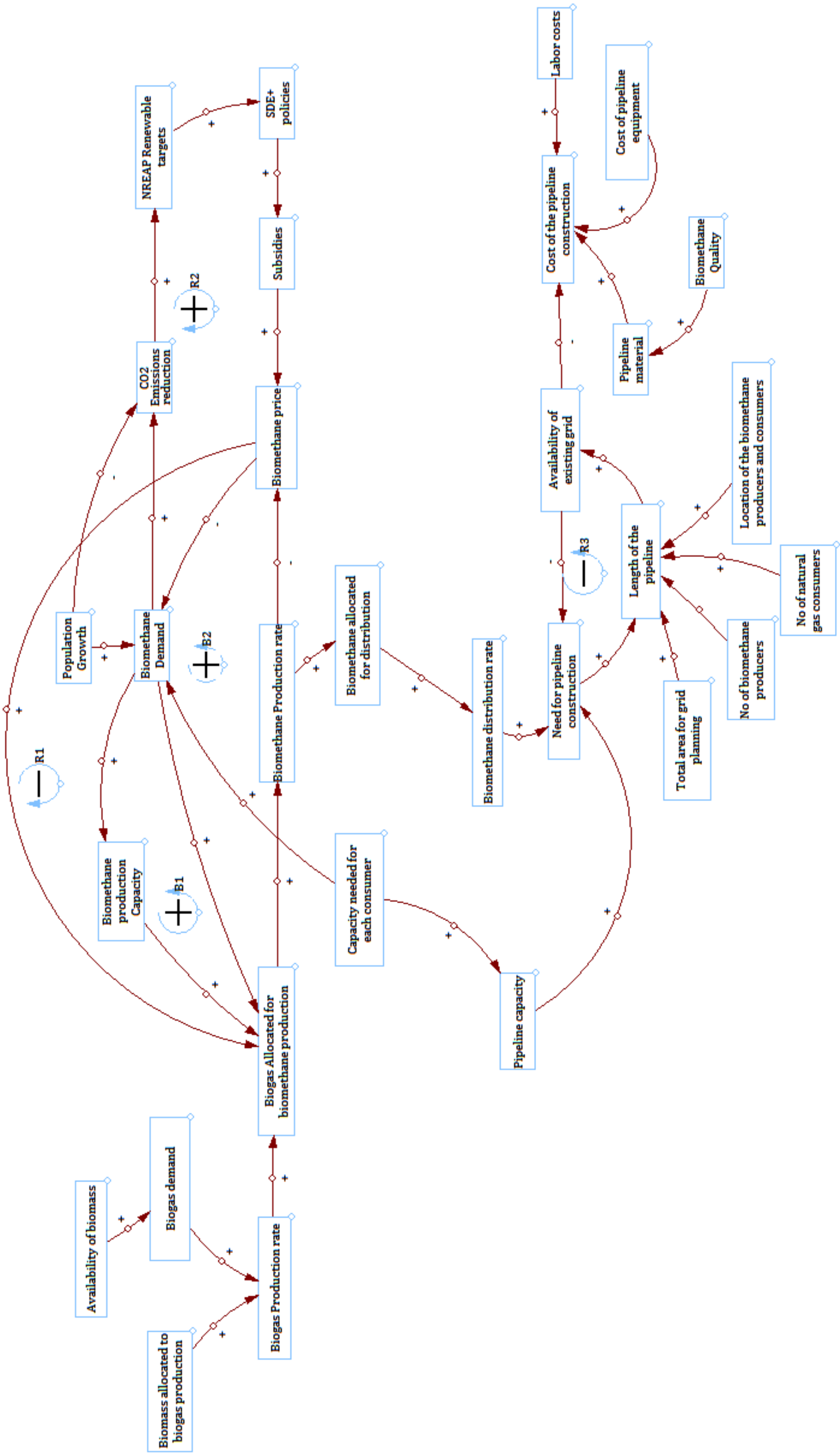


Figure 5.8: CLD of Biomethane Production and Distribution

5.3 Research findings from the scientific approaches

From Chapter 4, section 4.5, the various factors used by the scientific researchers were identified. These factors form a subset (see figure 5.9) when compared with the factors identified in this research so far. The existing scientific algorithms are generic and can be applicable to any kind of network. There are many advantages for using the scientific approaches in real decision

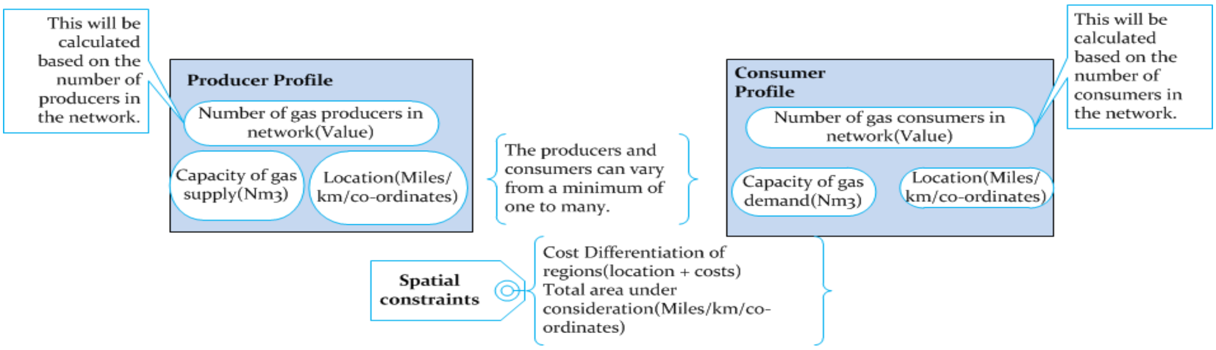


Figure 5.9: Producer and Consumer profile

making. These approaches address some of the needs of the decision makers by giving them more clarity and visualisation. The existing algorithms allow network planners to simulate the initial network layouts with minimal factors. If the additional factors identified for biogas/ green gas are also included in the algorithms they can be more widely used for decision making. Some of the advantages of these are,

- The modeling approaches enable designing network layouts with minimal constructions costs which is one of the key criterion for network planning. Finding optimal routing paths reduces the pipeline length and makes the network more cost-efficient
- These approaches simulate the actual location of the producers and the consumers along with the geographical obstacles like rivers etc presenting a realistic case for decision makers to connect the producers and the consumers.
- The scientific approaches also provide flexibility to add additional producers or consumers to the design with varying capacities and demands simulating the future scenarios of the network. Such flexibility leads to simulate future scenarios and incorporating varying values for factors.
- (Heijnen et al., 2013) proposes algorithms that can maximize the worth of a decision given the different configurations each network can take.

From the research on scientific approaches some of the barriers in adopting these techniques can be clearly identified. The access to right information is highly uncertain and involves cost and time for running such large scale study. If models need data for each specific energy network, it can be more complex as it can vary based on location, network characteristics, and resources available to gather etc. This is a limitation for decision makers without scientific models as well, but its importance is multi-fold as models rely on data for processing their simulations.

Energy networks are socio-technical systems. In a multi-actor context, there can be high uncertainty about the participants and their resources(Chappin, 2011). In a multi actor context there are conflicting interests between the planning of optimal networks based on user requirements. Many researchers allocate probabilistic participatory variables in their models to overcome this preference but it still misses the real factor that different actors behave differently and have different preferences over different time periods of the planning phases. It is very challenging for these scientific approaches to reproduce the realistic environment of decision making arenas. Additionally, the planning of energy networks is also driven by local regulations and political decisions which are not considered while modeling these approaches. Even though optimized models are built to be cost-efficient, they still lack the integration with co-operative game strategies imitating realistic behavior of decision makers and the political situations(Darmer and Kuyper, 2000)

Moreover, if we consider gas distribution networks, they have the complexity of both physical and operational constraints. They consist of the passive pipelines and the active controllable elements like valves, shut off valves and compressors etc(Fugenschuh et al., 2011). Design of any new infrastructure for a gas distribution network or expanding an existing one needs careful consideration of the position of the active components in the layout, their control and the length and criteria for selection of the passive components(pipes) without distracting the physical and operational constraints. Also, the cost function used by the models , does not include all the costs for the infrastructure development. It is important to consider the realistic requirements of decision makers. E.g. For biogas networks, the total costs depend on the compression costs, use of different pipeline diameters and pipe material, installation labor costs, operational costs etc to name some. Thus the scientific approaches to network planning are expected to allow the flexibility to introduce these kind of important factors while designing networks.

The comparison leads the research to conclude that, if customised energy networks like biogas/ green gas are to be planned, it is necessary to add more customised factors to existing algorithms. There is a growing need for tools and methods which integrate these optimization algorithms with specific energy networks based on network characteristics . The notion of "one size fits all" leads to complexity for decision makers to use them. This addition will create networks closer to reality and can directly be used by decision makers to approve network designs by evaluating their performance criteria.

5.4 Validation of the research findings

The research findings were validated through qualitative interviewing with 3 stakeholders (see Appendix C.1) in the field of biogas infrastructures. The interviewees selected were, a biogas producer, an academic researcher and a network provider. The background and expertise of these different actors allowed us to validate the requirements that were drawn for network planning.

From the perspective of the academic researcher, the main factors that can influence the network planning is the multi-actor context. The land use for digging the pipelines fall under certain regulations and the DSO's will need to collaborate with the land owners, ministry, producers, and environmentalists before laying out a plan for the network layout. Appropriate agreements need to be obtained from each stakeholder. The second factor which was important was that every network planner needs to contact a company called Kadaster BV [2] in NL, and seek information regarding the land registry and underground mapping of all types of grids that flow in a given area. The agreements need to be obtained if any new grid is planted on the existing one (see Appendix C).

Moreover, the interview further validated that, pipe characteristics are important to maintain network integrity. The most important criteria for network planners is to maintain low costs, safety and reliability of the grid. Additionally, the operational costs of compressor stations are seen as the most expensive costs of a gas network over longer pipelines.

From the perspective of the producer, Delftluent Services BV [3] which produces largest amount of biogas in NL as part of their waste water treatment facility, biogas distribution in its raw form is a niche concept and is generally not used. Mostly the biogas produced is transported after conversion to heat and electricity and in most cases consumed internally to meet the company's energy needs. In their opinion it was too early to think for biogas distribution or the need for building such networks for them. However in their perspective the most important criteria in network planning is to maintain low costs for distribution and maintenance along with increase in energy efficiency. As they have to follow the government regulations to increase their energy

[2] https://www.kadaster.nl/web/english.htm
[3] http://delfluent.nl/plant/awzi_harnaschpolder/

efficiency, they look for lower CO2 emissions (see Appendix C).

From the perspective of the network provider, Gasunie which is a TSO in NL was contacted. Although they were not directly available for interview, they have shared their insights through email conversations. They use simulation software of SIMONE as discussed in section 4.6 which primarily focuses on network optimization and not network layout optimization techniques. For this optimization they use the gas, pipe, compressor station characteristics for optimising the flow of gas in the network. They have no real software which focuses on network layout optimization and usually create network topologies based on experience (see Appendix C.1).

5.5 Consensus on using the factors identified in the research

Section 5.1 presents various factors influencing network design of gas grids, which if adopted by the scientific modellers can bring the scientific models closer to reality. These factors thus identified are also inter-related and can influence each other as shown in section 5.2. In section 5.3 we have seen that the scientific models use various factors which are a subset of the findings we have from empirical studies of gas systems. Based on validation conducted, it can be considered that a step towards adapting existing scientific models with the additional factors can bridge the gap between scientific research and the needs of the decision makers. So, it becomes important to answer the question, what kind of factors are overlapping? and how can they be used to extend the scientific models.

Overview of factors from study of Scientific models

The scientific models mainly focus on minimizing the building costs by satisfying the demand and supply capacities. The existing factors used for finding these cost minimizing networks are,

- Location of producers and consumers in Network (Producer/Consumer Profile).
- Supply capacity at producer location (Producer Profile).
- Consumption demand at consumer location (Consumer Profile).
- Cost differentiation among regions (Spatial Constraints).
- Location of regions cost differentiation (Spatial Constraints).
- Total area under consideration.

Overview of factors from the Empirical Study

The empirical study focuses on the requirements from the decision makers perspective and hence it has additional goals to meet. The decision makers want both cost minimal networks for identifying the fixed costs but also want to have an overview of the operational costs for that design. Additionally, they want to measure the energy efficiency levels for a specific design in terms of energy savings and the number of CO2 emissions emitted to meet their environmental interests and national sustainability goals.

Given this consideration, the key performance indicators should be,

- (Fixed + Operational) Costs($)
- Energy Efficiency (kWh)
- Amount of CO2 Emissions (gram/km)

In order to achieve the additional performance criteria, the factors being proposed should be added to the functionality of existing scientific approaches in addition to already existing factors,

- Land Use agreements for designing the network layout (Spatial Constraints).
- Land Usage costs (Spatial Constraints).

- Costs for labor and maintenance.
- Location of the gas storage sites to deal with load balancing and excess gas storage (Gas storage Profile).
- Specific characteristics of gas storage like storage size, storage capacity, operational pressure, installation and operational costs etc. (Gas storage profile).
- Pipe characteristics like the length, diameter, pipe material, operating pressure, thickness, insulation, flow rate and pipe costs (Pipe Profile).
- Characteristics of the compressor station to maintain pressure levels- location, suction and discharge pressure, operating temperature and installation/maintenance costs (Compressor station profile).
- Usage of network devices to support the network flow like valves, metering devices to maintain maintain pressure, check quality and their installation/maintenance costs (Network Equipment).
- Gas characteristics can influence the number of network devices, need for compressor stations and the type of pipe profile needed to transport the gas based on its type - Gas type, pressure, volume, density, Wobbe index, temperature, flow rate etc (Gas Profile).

Figure 5.10 gives an overview of the different factors identified during this research. The figure also shows the specific profiles which can act as nodes (node identifiers **) and the performance indicators influenced by the profiles.

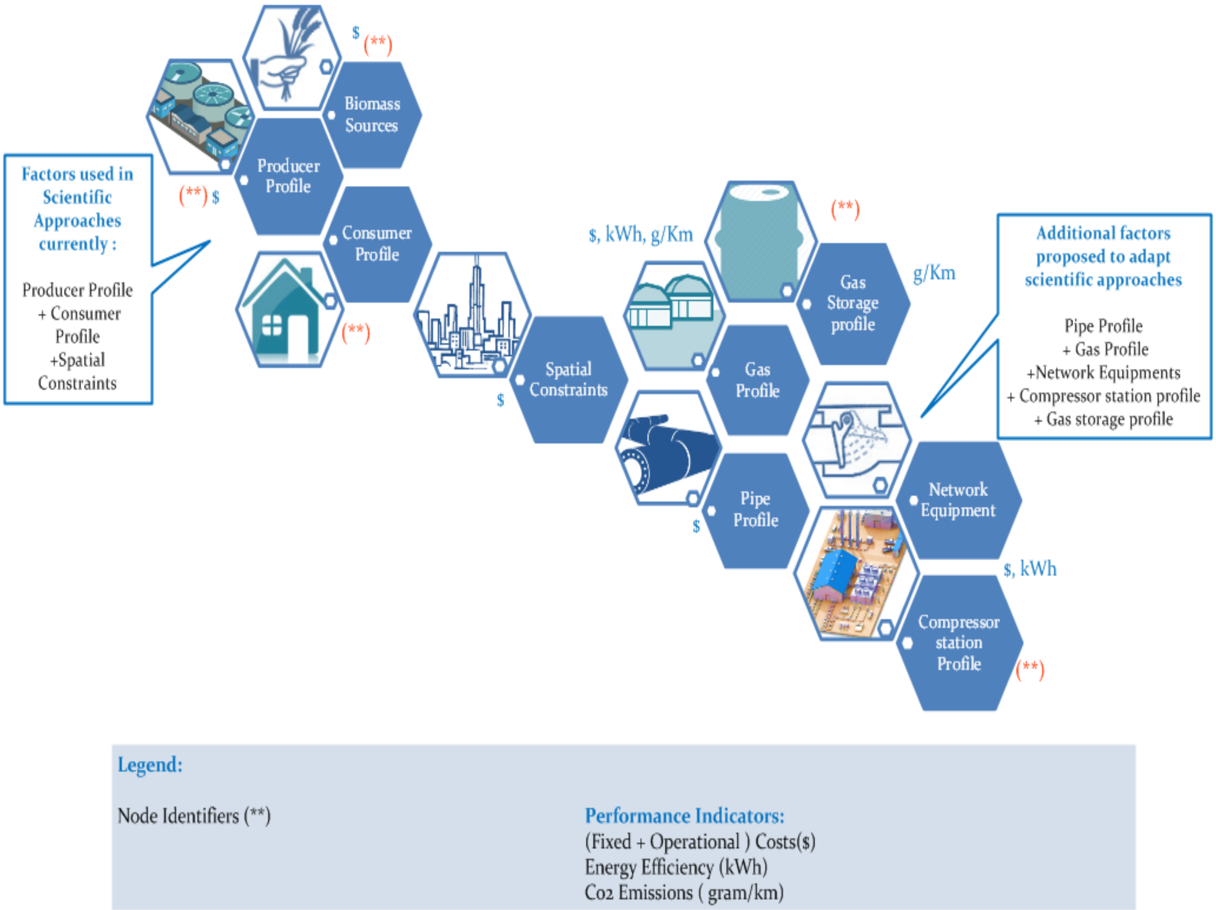


Figure 5.10: Overview of factors influencing network layout planning

Importance of considering these additional factors

The design criteria for distribution of gas (natural gas and green gas) demands a balance of the economic requirements and efficient mix of delivery techniques without disrupting the operational flexibility of the existing gas grids. The network layout design process needs to estimate various possible combinations of the pipe size, compressor stations and network equipment based on the inter-distances between producer and consumers, their demand and supply capacities to come up with the optimal installation and transportation costs.

Various factors can determine the amount of gas a specific pipeline can carry but the most important determining factors are the pipe diameter and its operating pressure. Pipelines over long distances are usually of larger diameter to enable larger quantities of gas, due to future expandability options. Compressor stations will be needed in areas where the pressure needs to be regulated, to match the pressure level of joining grid. Compressors are useful, when the demand increases, gas can further be compressed for transport using the existing pipelines enabling higher flexibility of transport. Standard design codes demand for reduced operating pressures while crossing densely populated areas (EIA, 2009).

Gas storage needs to be integrated to the pipeline system design not just to balance the flow levels in the system but to also deal with varying utilization rates of gas. Seasonal requirements of energy in certain areas can see a rise in demand for gas in the winter months and lower summer utility. The cost incurred for building pipelines with this additional capacity which is needed only for certain period of the year, can be mitigated by the installation of underground gas storage (EIA, 2009). Installing them closer to the consumption areas saves costs of transportation. Additionally, the unused gas produced during summer months can also be injected into the gas storage for meeting the peak demand of winter season.

Gas and the gas grid characteristics play an important role if a gas of specific quality needs to be injected into the national grid. In Netherlands, the producers intending to upgrade the biogas to green gas in order to inject it into the natural gas grid should meet the gas/grid quality requirements as per the article 12b of the Dutch Gas act (NMa, 2012, see 2.9). The regulatory conditions for following the safety aspects while crossing densely populated areas and receiving the agreements for land use should be considered before designing the network layouts.

Having understood the various factors and their importance in network design of gas grids, it is necessary for scientific modellers to consider these findings while designing the optimization models for network design. It is not straightforward to extend existing scientific models of GGM and ABM to directly include these factors. Thus there needs to be a careful reconsideration of how these models can be adapted to include the said factors and make them more useful for decision makers. The following chapter will start with a proposal on how the scientific models can be adapted based on which a design for user friendly decision support system is provided.

Chapter Summary

The chapter has summarised all the factors that are needed to design biogas and greengas network layouts. The network characteristics, their relevance for planning, their inter-relations along with their unit of measurement are clearly outlined. The research findings of the scientific models their advantages and limitations are carefully outlined and compared with the network characteristics found in literature and useful recommendations based on this analysis is presented. Furthermore, the chapter closes with the validation of these ideas with the viewpoint of the stakeholder interviews. This leaves a good impression about what is existing and what can be expected for these stakeholders. Lastly, this chapter is a crucial input for enhancing the scientific models and thereby designing the prototype of the decision support system to fulfill the objective of this research.

Chapter 6

Proposed Design Approach

The chapter starts with a discussion on identifying the specific factors that need to be added to enrich existing scientific models (section 6.1), followed by the proposal represented as a step wise process of extending the functionality (section 6.2). Section 6.3 discusses the prevailing user perspective issues even after adapting the scientific models and discusses options to overcome them. Section 6.4 and 6.5 propose the design for a user friendly interface to enable multi stakeholder participation and efficient use of the scientific models.

6.1 Discussion for the use of identified factors

Each networked infrastructure has some characteristics which are specific to that sector. In case of energy networks, natural gas and green gas can have more common characteristics as compared to electricity or CO2 networks. Thus, it becomes important to understand and carefully adapt existing generic scientific models of network design to cater to these requirements of the network infrastructures. From the study so far, Chapter 5 has clearly outlined the various factors that play an important role for designing natural gas or green gas grids. Existing scientific models of GGM and ABM, use a subset of these factors in their implementation. Fig 6.1 gives an overview of all the factors that are proposed to be considered for network planning with a clear distinction (center circle) of the existing factors which are already used in the models.

The stacked concentric diagram has the common factors which are already implemented by the scientific models of ABM and GGM. It will be a good choice to follow an iterative way of extending the functionality of the models. The producer and consumer profile factors given in the blue circle are currently being used in the scientific models to design cost minimal networks. The second circle surrounding it, gives the factors relating to gas profile, gas storage and pipeline details. These factors should be taken as input to existing models in the first iteration of their adaptation. These factors directly influence the costs and the energy efficiency levels for transporting gas from the producers to consumers. The gas profile properties will influence the use of pipe profile in deciding the pipe material, diameter, pressure levels etc for transmission. The gas storage locations will need to be identified during this phase to meet the demand in climate sensitive zones. Summer months see lesser utilization of the gas produced which can be directed for storage in these sites and network planners can decide based on the spatial constraints if these measures are indeed needed or not. Similarly winter months can have peak demand for gas due to heating and the storage sites can fill this extra demand and save additional costs for the network planners. The spatial constraints and the soil profile will need to be provided by the user, before the design for the network layout is finalised as it can sometimes happen that a solution is best in theory but not in practice.

The next iteration can use the detailed flow parameters like the use of specific network devices to control and optimize the gas flow for each network path previously defined. The use of compressor stations can regulate the gas pressure over long distance pipelines. It is not straightforward, to just include these factors to the existing algorithms. Hence, it important to classify these factors based on their impact on the network planning and then propose steps for extend-

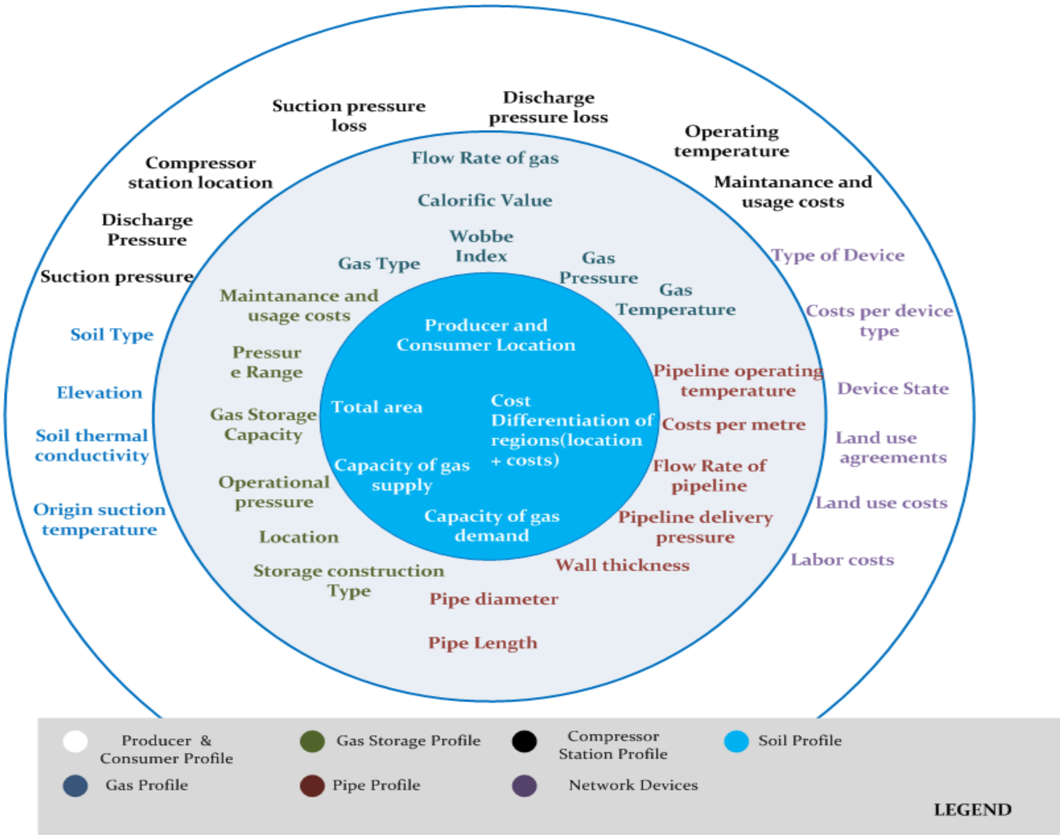


Figure 6.1: Overview of the factors from research

ing the application of the models.

- The producer profile influences the gas profile which thereby determines the supply capacity.
- The consumer profile influences the demand for gas based on the gas profile.
- The pipe profile is influenced by the gas profile as it impacts the choice of pipe material, pipe diameter, pipe length, pipe operating pressure and temperatures. This will impact not just the network flow optimization but the network layout investment costs as well.
- The gas storage profile is influenced by the supply and demand capacities of the producers and the consumers. Their location and preference of storage capacity influences the investment costs of a specific network layout.
- The use of compressor stations will affect the network flow optimization levels maintaining the pressure levels of gas flow over long distance network designs and also the investment costs.
- The network devices influence the fixed and operational costs of the design. They are assisting in gas transport but not necessary for network planning directly.
- Soil Profile, legal, regulatory, spatial and safety aspects come into play and reject a cost effective and efficient network layout. Hence, if this information is already available it is better to provide this to the algorithm in the early stages itself. The decision making logic of the algorithm can than consider these factors and make more effective decisions.

6.2 Proposal for extending the functionality of scientific algorithms

Although both GGM and ABM methods are successful in designing effective cost minimal networks, the ABM model has proven to be more intuitive and easily extensive (Viet, 2015). Due to higher flexibility and ease of adaptability the ABM method is being considered for the proposal. Based on the understanding of the influence of factors on network planning, a basic design approach in the form of flow diagram (see figure 6.2) is being proposed to extend the functionality of the ABM. The method is a 10 step process which can be adopted to extend the functionality of the scientific model.

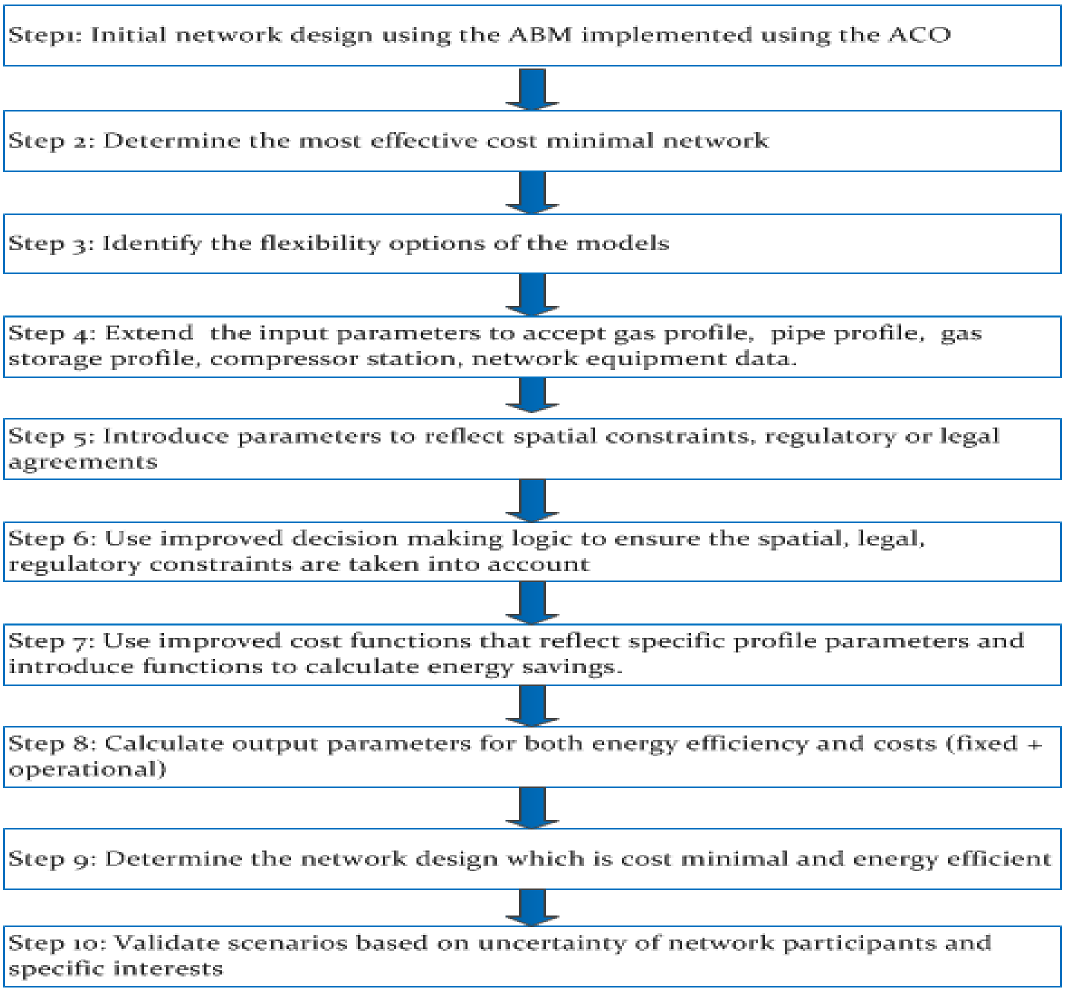


Figure 6.2: Design process flow for extending model functionality

The starting point in the process is to determine an initial network based on the existing ABM models. The input parameters here are the producer and consumer profile data along with other constraints like capacity cost component and cost differentiation among regions. The cost minimal network from the different layouts should be determined. Furthermore in step 3, it is important to identify different flexibility options to introduce additional parameters or constraints to the model. In step 4, additional input parameters like gas profile, gas storage, compressor station profile, pipe profile and network equipment data should be taken. Step 5 should introduce the spatial, legal and any other sort of constraints which can influence the decisions of the network layout. Decision making logic should be added which influences route selection like legal aspects, land use agreement, soil profile etc. The cost functions will need to be extended to reflect the specific profile impacts taking into account the fixed and operational costs. Additionally, new equations to calculate the energy efficiency or energy savings of specific design solution should be introduced. Based on these parameters, it is important to determine the cost minimal networks.

Step 8 proposes to define output parameters that can calculate both energy and costs for the design solutions. Step 9 is to determine the cost minimal and energy efficient network layout which has considered the realistic parameters of various technical components and the legal social impacts. Various scenarios need to be validated to evaluate the performance of the model when there is uncertainty of network participants or lack of information.

To provide additional clarity, producers and consumers which act as nodes in the design will continue to be the same. Each additional gas storage, compressor station in the network will be an additional node. The details of pipe, gas and network devices will be taken into account through the equations measuring cost and energy efficiency. The decision making logic in the algorithm will need to consider scenarios of legal, spatial and other constraints that can influence the route selection of the network.

It is important to note that all the information related to specific profiles, available to users should be given to the algorithm in the initial stages. This will ensure that the algorithm considers all possibilities and produces more robust solutions that can be used by decision makers. In some cases, there is lack of information or a decision maker weighs factors differently, than users should be able to give weights (co-efficients) to specific profile data depending on their interest. This preference should also be introduced into the cost equations and the decision making logic of the algorithm. This flexibility is important as it will ensure that some solutions which are actually good enough are not lost as they failed to satisfy other unimportant criteria.

The design flow of the agent based model for this adaptation can be visualised as shown in figure 6.3. As discussed in the design flow process, the input parameters are adjusted to take the additional pipe, gas, gas storage and compressor station profile data before looking for cost minimal and energy efficient network layouts. Based on the best alternative achieved by the model it needs to be further validated if it meets the spatial and legal constraints like land use, safety matters etc. If this condition is satisfied the decision maker can then have cost minimal and energy efficient solutions to make decisions for network layout design.

6.3 User perspective design Modelling

Although, the scientific approaches are adapted to simulate more realistic network layouts to aid decision making the problem of their complexity and ease of use difficulty still prevails. The end users or the decision makers cannot handle the mathematical complexity of using these models for their decision making. Hence, there is a need for User friendly system which can be easily accessible and allow decision makers to simulate network layout designs. For the design of such a system there are multiple possibilities like outsourcing services, software based tools that can provide insights or self handling software tools that can be accessed directly by the decision makers themselves. One such solution is being proposed in this research from a users perspective that uses the intelligence of the scientific models to simulate network designs. The system design is based on the participation of relevant stakeholders who are interested and can influence network planning. As discussed in Chapter 3, section 3.2.4 stakeholders have different interests and they can directly or indirectly influence the network planning. They have resources, or information which can be fed to the User Interface (UI) reducing uncertainty of network participants to a large extent.

Figure 6.4 gives an overview of the specific interests of the stakeholders involved in the entire supply chain process of Biogas/greengas production and distribution. Stakeholders who will directly influence the network design are the Biogas/Green gas producers, DSO's, TSO's, researchers, regulators and consumers.

The biogas producers can provide information about their location, the biogas/greengas sup-

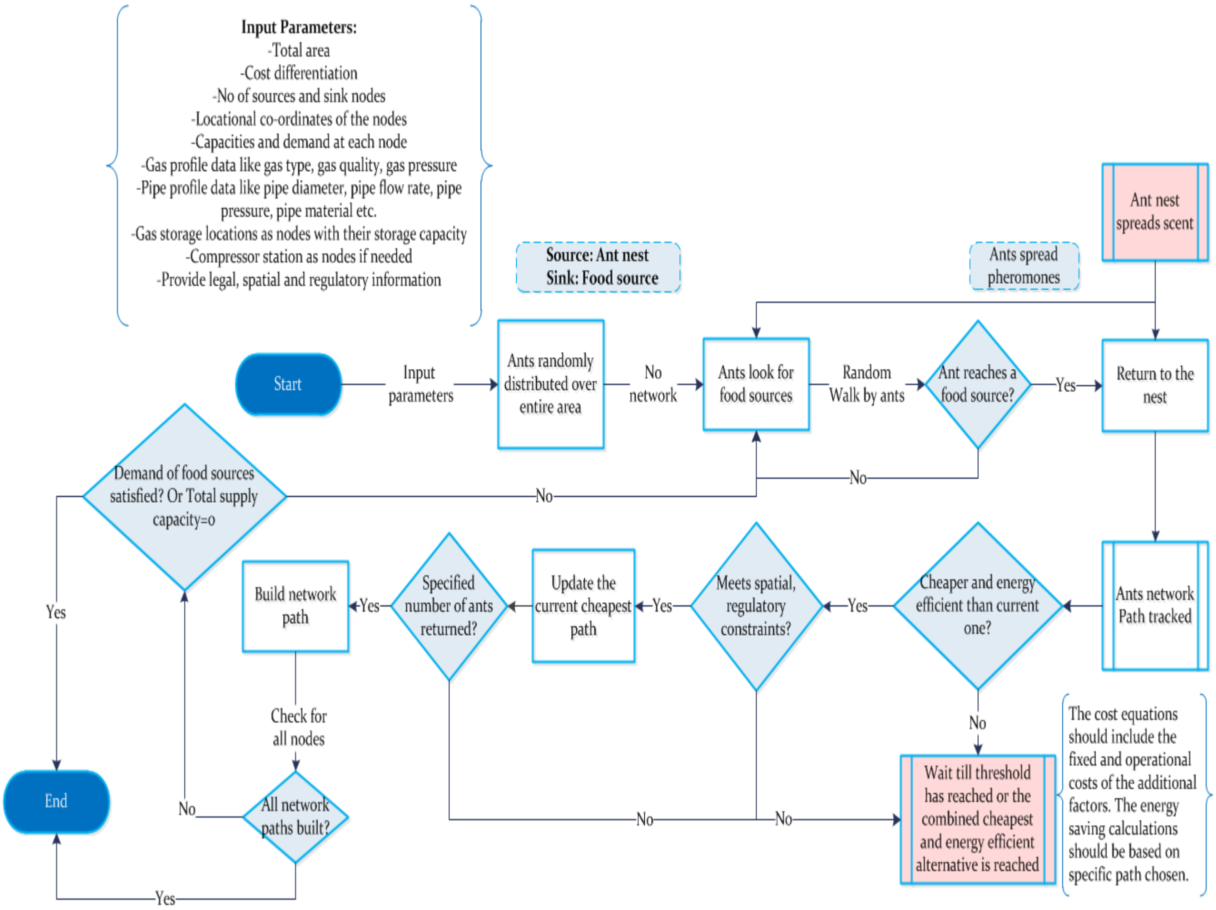


Figure 6.3: Adapted Agent based Model using ACO

ply capacity which is beneficial while designing the network. Also these stakeholders will need access to the UI to get an overview of the total costs they will incur to join the grid. The UI will simulate these network layouts and aid the producers to decide about their participation and upfront get an idea of the total costs they will incur. They can also negotiate with other stakeholders if needed to choose alternate grid layouts, if that is beneficial for them.

The TSO's and the DSO's commonly known as the network facilitators will be the main owners of this UI as they are obliged by law to connect the producers to the national grid if they meet the network specifications. They will use the UI to identify the topological extensions, get an overview of the network layouts, identify injection points, alternative paths, incurred costs, energy efficiency levels and overall the network integrity. The UI can provide them with insights into making more informed decisions by using the information given by other stakeholders. It can help them simulate the network layouts in a realistic and robust way by the use of scientific models reducing human errors.

Although researchers have no direct interest in such a UI, they are the main backbone for this application. They are responsible to adapt existing scientific models for network design to meet the requirements of the stakeholders and simulate the realistic gas network. Hence they will need to closely associate themselves with this application and facilitate the widespread use of their scientific contributions to the industry.

Regulators can be the public authorities like the Government and Ministry who define the policies and standards that the network has to adhere. The code of conduct (COC) can be set for gas quality standards, grid safety, land use agreements etc. This information is vital for decision making and hence needs to be fed to the scientific models. They can use the UI for an overview about the energy efficiency levels a design caters, as that is the main interest of the regulators.

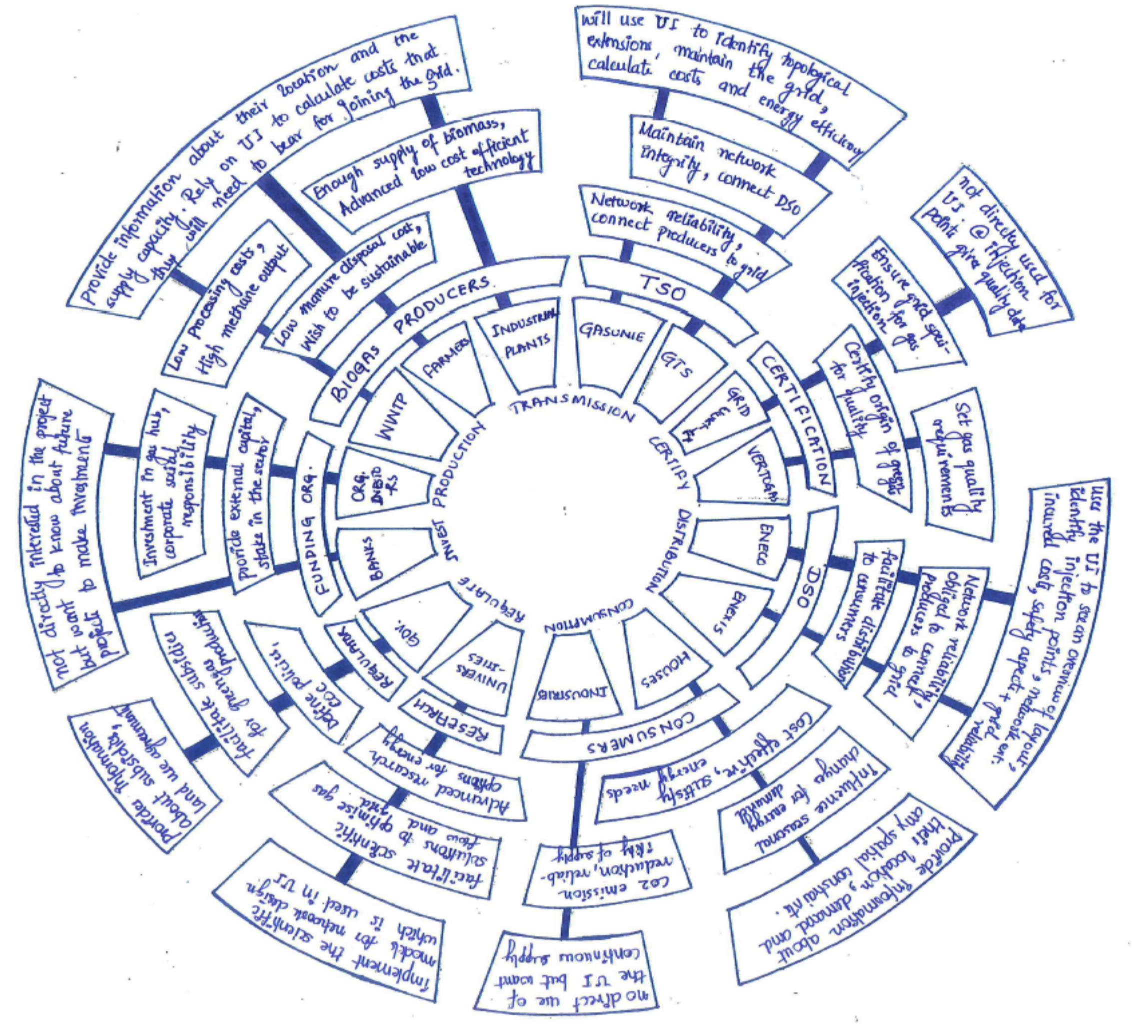


Figure 6.4: Actor interests and their influence on UI

Consumers do not need access to the UI and are not directly interested in how the network is planned. They are interested in the continuous supply of gas to meet their energy needs. Consumer data is needed for the UI to identify their location, demand capacity, seasonal requirements if applicable and any spatial constraints.

The study so far, has successfully attempted to bridge the gap between the scientific models and the decision makers requirements in reality. Section 6.1 and 6.2 have proposed a design framework to extend the functionality of the ABM model to simulate a biogas/greengas network closer to real world. Section 6.3 has focused on how the adapted scientific model can be put to practice for decision making. Based on this understanding a user friendly interface design which can act as a Decision Support System (DSS) for network planning is being proposed in the following section. This DSS can be used by network planners, producers, regulators and researchers to validate the routing designs of biogas/green gas networks. The implementation of the DSS is software based and hence, it is expected to follow a software development life cycle (SDLC). The study conducted so far can be attributed to the requirement specification phase of the SDLC. Based on these system requirements, the overall functional design of the DSS will be briefed in the following sections.

6.4 Software Development LifeCycle

Software development lifecycle (SDLC) follows a series of phases to provide a model for the development of a software application. The SDLC process is used to create cost effective, efficient software with high quality (Davis, 1993). The SDLC is mainly divided into 5 phases as shown in figure 6.5. SDLC starts with a ”requirement analysis” phase where the business requirements are

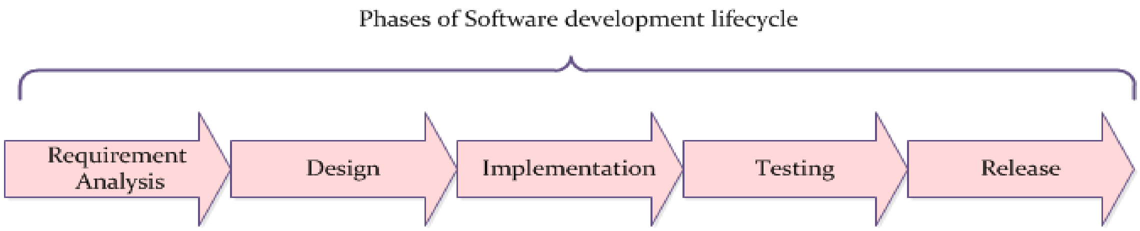


Figure 6.5: Software development lifecycle

established through client discussions. The purpose of the software application or the system needs to be clearly determined and definite system requirements for the application should be collected. The functionality that needs to be achieved by the system is detailed in the requirement specification document. This phase is followed by a ”design” phase where the the design features of the system are clearly defined using prototypes, use cases, use case sequence diagrams, screen layouts and business process diagrams. After having the baseline requirements and design prototypes, the software developers implement the design prototypes based on the requirements. The actual code is written during this phase and the system architecture is built. When the system is built, it moves to the ”testing” phase where it is verified for its correctness and validated if it meets the requirements. During this phase, the software testers can raise defects for any errors and these defects can be fixed and tested again. On successful testing, the software is deployed in the ”release” phase into production or actual business. For understanding the different types of SDLC models refer to appendix D.1

Based on the literature study and discussions with potential users, the various system requirements to plan network layouts are collated and briefed in Chapter 5 and Chapter 6 (section 6.1 to 6.3). Based on these requirements, the overall functional design of the software application is discussed in the following sections.

6.5 Design Specification of the UI

The section will provide the functional design for the DSS and also provide visualisations of specific functionalities. The application behavior is derived based on the user experience and is depicted by use cases, sequence diagrams and class diagrams (Kulak and Guiney, 2004).

6.5.1 Overall Purpose

The user tool allows the decision makers to simulate a network layout giving an overview of the different possible designs. The simulation can be achieved manually as well as scientifically based on optimization algorithms. The tool provides a dual functionality by allowing the decision makers to design a network layout based on their experience and expertise (user-defined) along with a comparative analysis between the user-defined designs and scientific algorithm based designs. The two scientific optimization algorithms used are based on GGM and ABM methods. Although in this research in section 6.2 only ABM is chosen, the UI focus has been on both algorithms to maintain flexibility.

The target users of the tool can be the network planners like DSO’s, TSO’s, producers or researchers or the municipal authorities who overlook land use in specific areas. The tool can be used repeatedly by the users to simulate as many designs possible during the planning stages of the decision making process. In later stages they can use the chosen design to further test for

any ongoing changes or to introduce new factors that can influence the network layouts.
The main characteristics of the tool are,

Web based application: It needs to be created as a web-based application that runs on different browsers. The tool must be accessible to all the users via Internet.

Data accessibility: The tool should be able to access data from the relevant open data sources as well as upload data from private users. This feature will enable users to access data dynamically through the Internet open data platforms as well as upload any specific data that is collected by the user in their research. The data uploaded by private users must be protected and must be accessible to the specific user who has uploaded it or has been granted permission to access it.

Flexibility: The tool provides flexibility by allowing the users to create networks manually in an iterative way. The users can provide data inputs and simulate the network layouts before they can use the optimization networks. A comparative analysis of both methods gives the users flexibility to test the outputs of both methods before they can make final decisions.

Transparency: The tool gives transparency by allowing the users to know all the input factors given for the manual and scientifically created network layouts. The comparative analysis uses the same performance criteria for evaluating the results from both resulting networks. The users can also access information on the assumptions and working principles of the scientific approaches in the "Help" section.

Visualisation: The tool provides users the results in a combination of network layouts (maps),graphs and dashboards. Users can access the dashboards and graphs to get a complete overview of the results based on specific performance indicators(costs,energy efficiency, CO2 emissions etc). In the network layouts they can see the different possible combinations of the network layouts and with color coding see the differences in each layout.

6.5.2 Overall Functionality

The journey of a specific user starts from accessing the application until he quits (see figure 6.6). The application should have an opening page that describes about the purpose of the tool, access to the application (log-in) and a short demonstration on how to use the tool. Based on the user type "new/existing user" the next course of actions follow. If the user is new, the application prompts for user input to create a new user. Based on the user input it stores the information in the database and allows the user to access the application. If it is an existing user, the user is allowed to log in to the application directly by using their credentials. Based on each user profile, their navigation rights are assigned by the application (see appendix D.1.1).
When an existing user is logged in, the application prompts the user to either access existing files or create new file. For new users(first time lo-gin), the application should always ask for new file creation. Based on these selections, the users can be directed to different functionalities. If the user chooses the option to create a new network, he/she can do it either using a graphical input or spreadsheet based inputs. For both kind of inputs, the user has an iterative way of creating network layouts. As With the use of adapted scientific models, the user can also provide all the information at once and simulate the network designs. The UI provides flexibility to the user based on the information available to the user for planning.

If the user selects a graphical input (see figure 6.7), the application provides various tools to create a network layout in a graphical pane. The user can add the source, sink nodes with their capacities and try to link them based on their expertise in the first iteration. Application can request for more specific data at each node or for any components the user adds to the network. Thus an initial network is created by the user and displayed as results. The application further provides the user with all the analysis related to the initial network is created. The user can further modify the results and redraw the initial network. The application should allow the user to iteratively modify the networks and provide a comparative analysis for each network created by the user. The results at each iteration need to be saved and allowed to be exported and printed. On a parallel front, the user can use the application to create networks using the scientific algo-

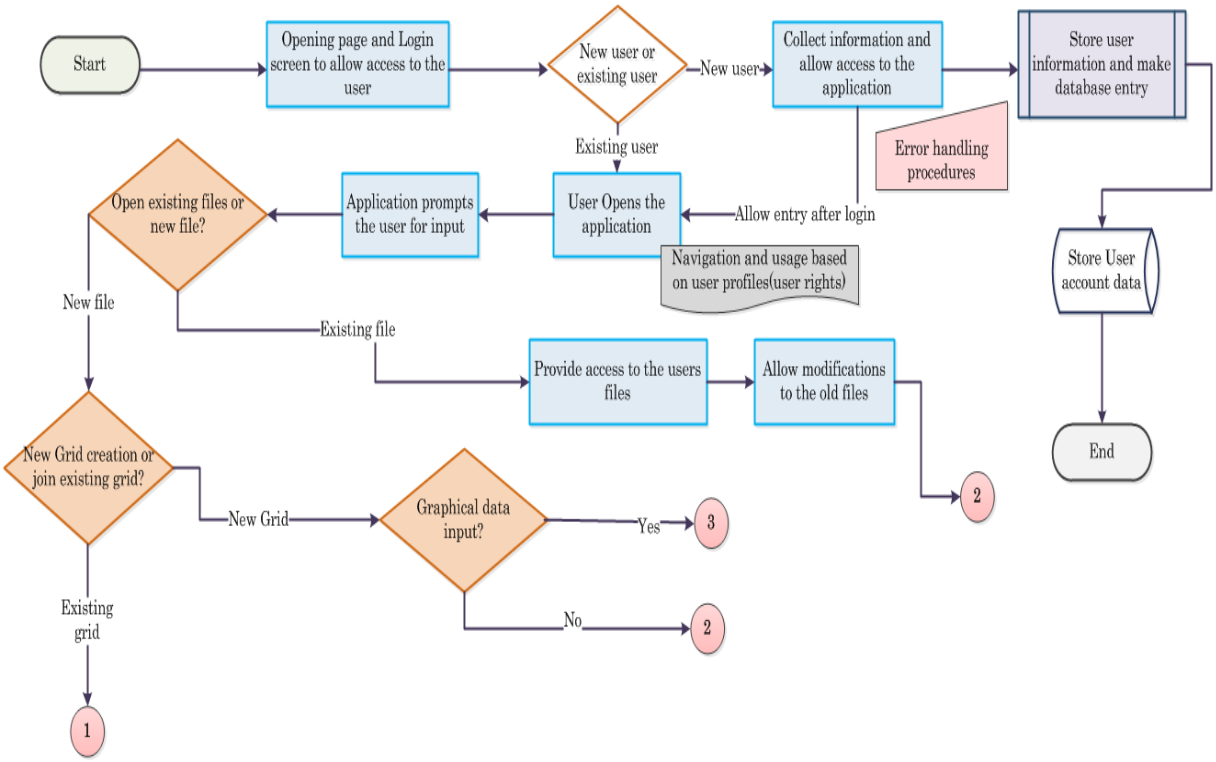


Figure 6.6: Overall Functionality of the user tool

rithms for the same inputs. Furthermore, the application should provide a comparative analysis between the user-defined and scientifically drawn network layouts. The results can be exported or printed based on users requirements.

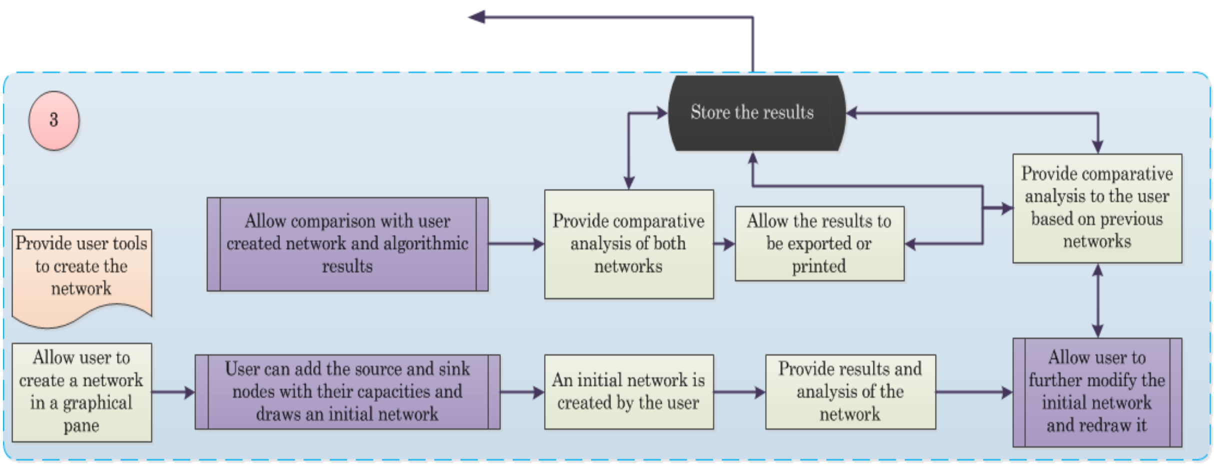


Figure 6.7: Graphical network creation flowchart

If the user selects to provide input to the application in iterative fashion (see figure 6.8) and validate results at each iteration the application prompts for specific data inputs. In first iteration, the user needs to specify the type of gas network, location and capacities of the source/sink nodes, total area under consideration. When the user hits the run command, the option for choosing either the GGM or ABM method is prompted to the user. Based on the selection an initial network will be created. The application provides the analysis of resulting network in the form of map, charts and graphs. At this stage if the user is satisfied with the results, application provides the facility to save,export or print the results. Else, the user can further modify the network in second iteration by adding more factors that can influence the network layout design. In second iteration, the user can add the pipe, soil and gas characteristics. The user can add the location and characteristics of the compressor stations, other components like valves, regulators, odorisation equipments etc. The compressors can act as additional nodes, but all other technical components like valves, gas measurement devices etc will be added at the existing nodes or the edges(pipe segments). These additional components will influence the overall costs of the layout but not their topology. On running the simulation the application gives a new network layout and provides a comparative analysis of both the networks. At this stage if the user is satisfied with the results, application provides the facility to save,export or print the results.

In the third iteration the user can add more constraints to the network like cost differentiation of regions, costs of all the components used, land usage pricing and other institutional subsidies. The user can also add storage locations if the supply exceeds demand and any other components that seem important. The iterations can be 'n' numbered by adding new nodes or injection points to the resulting grids. The application should provide the resulting network every time with a comparative analysis to the users. The users also should be given an option for usage of only single algorithm if needed. Lastly users can select only specific network for comparison and need not always refer to the previously created network. At each result the application should allow to export or print the results.

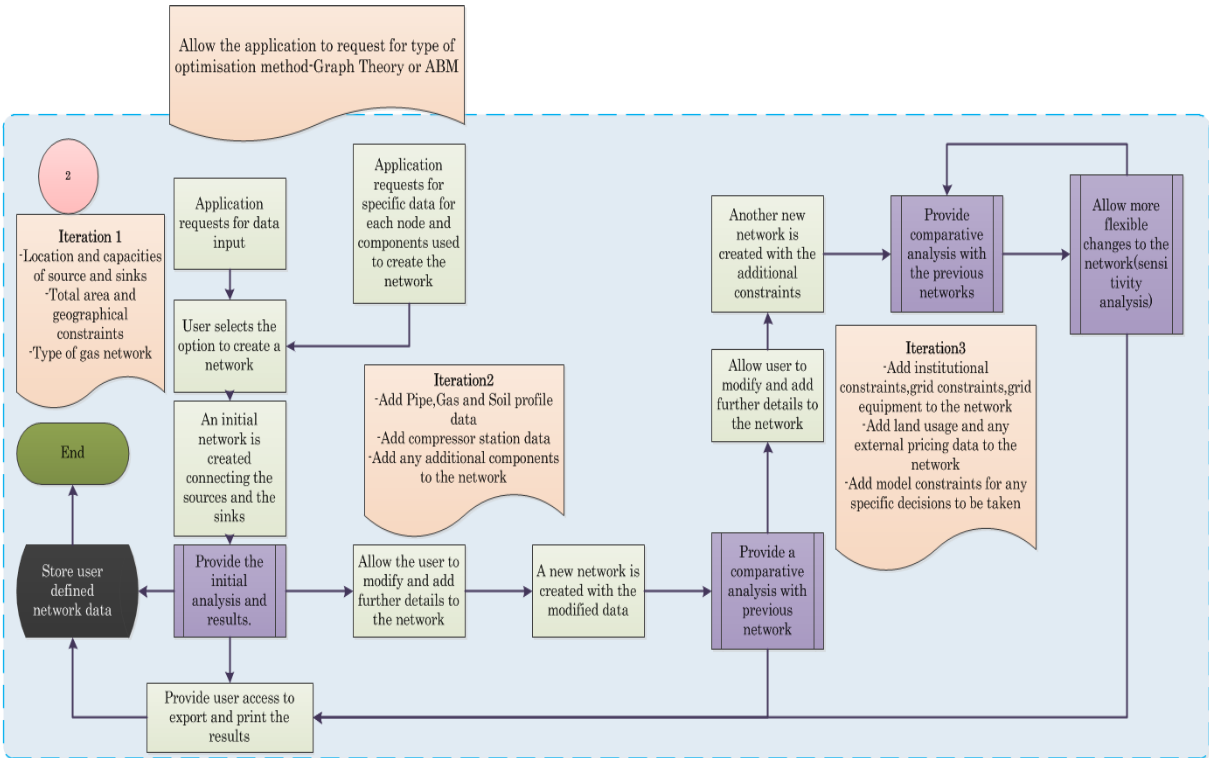


Figure 6.8: Algorithmic network creation flowchart

If the user chooses to create a new file and wants to join an existing grid the application should allow the user to do so. For this, the application should have previous access to the network layout data of the existing grid and its characteristics. Based on this information the application should be able to measure the capacity of the entire grid as well as each node characteristic. As the user intends to join an existing grid, the first check the application needs to perform is to validate if the production capacity is exceeding the energy demand at a given point in time. If yes, then the application should direct user options to either allow gas storage or gas flaring.Otherwise, the application needs to check if the nearest grid of the injection point is at full capacity or not. If it is operating already at full capacity the algorithm must direct to an alternative grid for injection. Otherwise, the injection can be done at the closest transmission/distribution grid after validating the pressure and other constraints for injection. Again

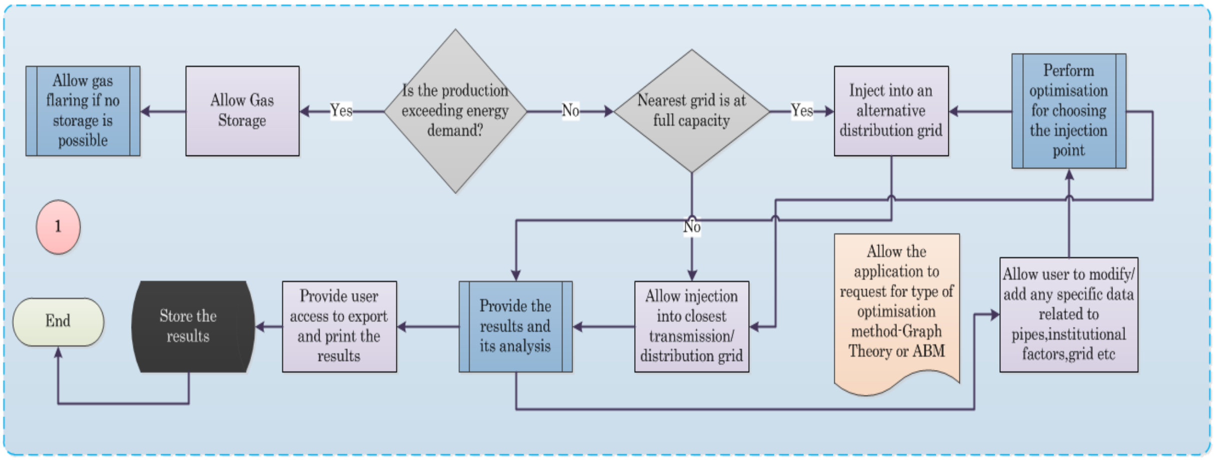


Figure 6.9: Injecting into existing grid flowchart

the application should provide users option to choose the scientific methods of GGM or ABM to run the simulations. At each iteration the application should provide comparative analysis to the users. The application should allow the results to be exported or printed.

To add further clarity, if a user creates a new network or injects into existing grid, using the graphical method, or both the algorithms, the results from all the 3 methods will be compared based on the common Key Performance Indicators (KPI's) respectively. The input specifications for the tool remain the same for all 3 methods, thus the output result comparison is also based on same KPI's. Although the choice of which results (best or second-best) to compare from each method will be user defined. The tool is expected to compare results based on KPI's and not based on layouts (tree or central branching). The user will need to use their intuitiveness eventually to make a final decision.

6.5.3 User Experience Modelling

Appendix D.2 gives detailed use cases for the user behavior. Based on the use cases flow of events, the user experience modelling will support further to make design decisions for development. This model gives an overview of the different elements of the system, the input/output screens, the navigation between different screens and how the user will experience the functionality in a sequential way. Although, the use cases and functional design are discussed, it is still a black box to understand the concrete flow of events between screens. Figure 6.10 is a user experience model in the form of a sequence diagram created using the functional system specification, the requirements and the use cases. Such a design will simulate the user/system behavior and make the User Interface design specification more clearer for the developer to implement it.

In the figure 6.10, <<Boundary >>classes represent an interface of the application to the outside world(to a human actor who accesses the screens).
<<Controller >>classes represent the use case's actual flow of events, representing the set of input and output operations. Each use case needs to identify a specific controller which realises the functional specification as conveyed in the use case.
<<Entity >>classes represent the input and output data flowing into/out of the system.

The use case analysis and the user experience model (sequence diagram) help us identify the classes with the relationships between the different classes. The responsibilities of each class are added as methods. Each class calls another class which can be shown as a relationship between the classes. This forms a class diagram which can be a basis for system development defining the architecture of the system. Figure 6.11 shows an overview of the class diagram that has resulted with our understanding so far. The associations and the variables have been omitted from this diagram as they are bound to more changes during development.

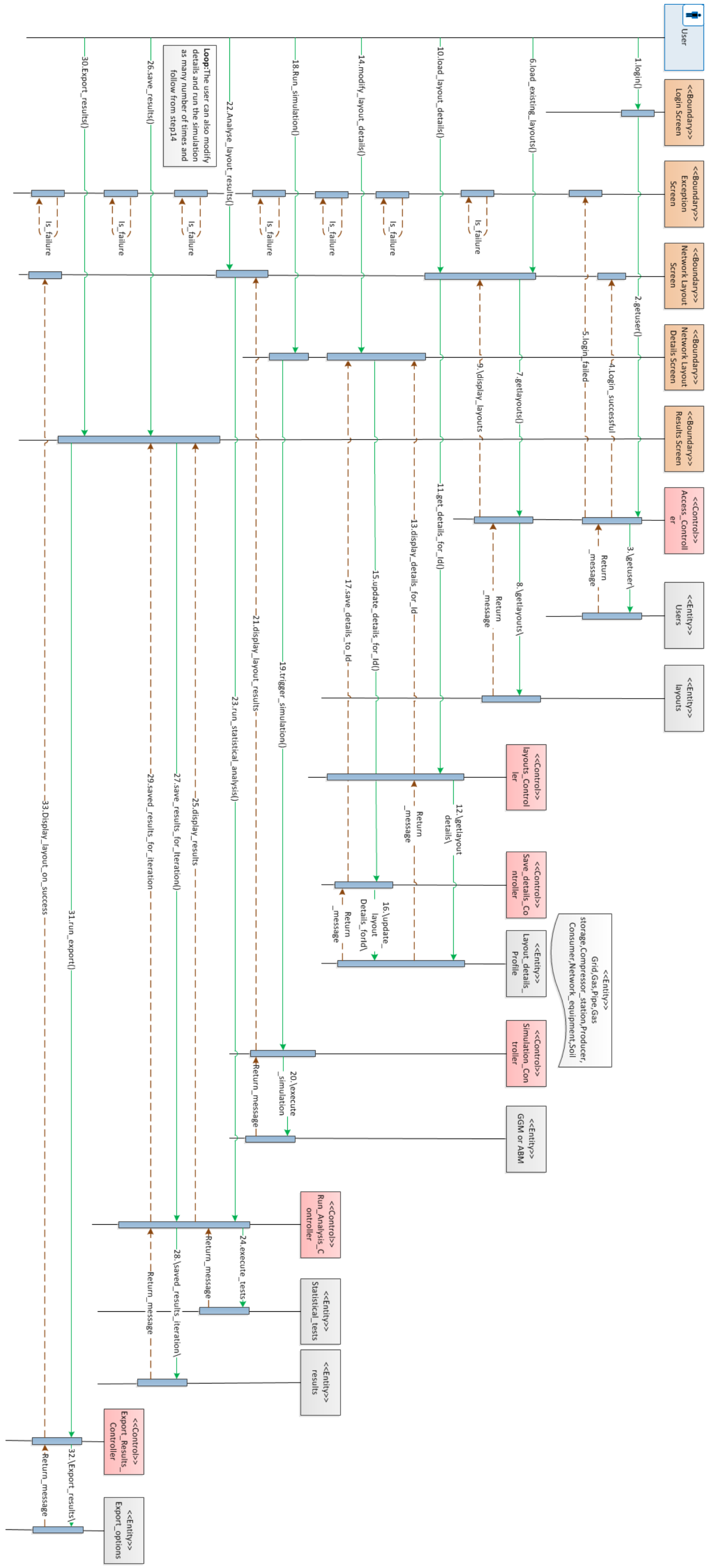


Figure 6.10: Sequence Diagram

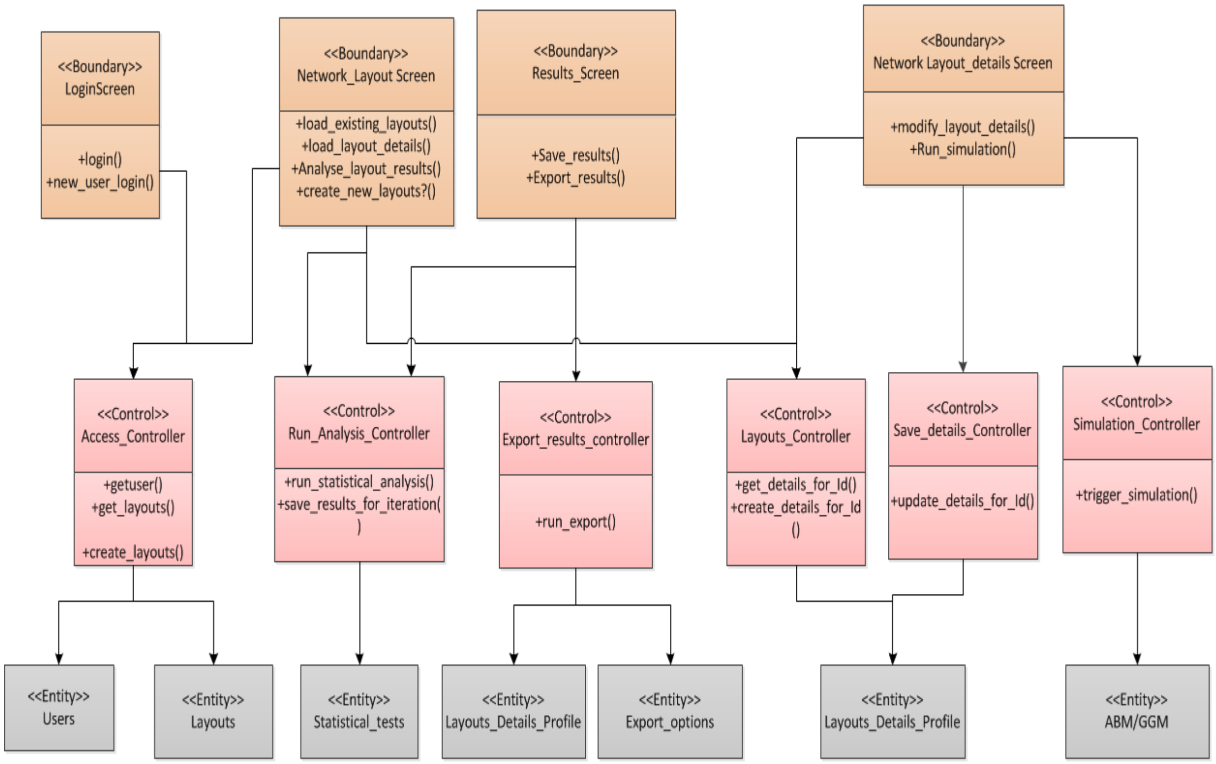


Figure 6.11: Class Diagram

6.5.4 User Interface Prototypes

Wire framing is an easy way to design the hierarchy of the screen layouts. Based on the use cases and the sequence diagram the functionality and the number of screens can be easily identified. The prototype of the UI should meet the specifications as mentioned in the section 6.5. The prototype of the screen layouts are very elementary and are only designed to give the developer and idea of the screen layout based on the requirements. These screen layouts will be useful for software developers to implement them as a software application (see appendix D.3).

Chapter Summary
The chapter starts with a discussion extending from the previous chapter about the various factors that influence network design for biogas/green gas networks. The discussion of the different profiles (factors) identifies the influence of the profiles on each other and their relevance for network planning. Based on this understanding, a step wise process to extend the existing ABM model has been proposed. The various constraints of the proposed design are well justified and the working flow chart of the adapted ABM is achieved. This activity helps researchers to use this design to adapt their models much easily for these specific networks. Although, the adaptation is more realistic, the complexity of using these models demands more user friendly options. Thus the main stakeholders interests who can possibly use such a decision support system are discussed and a software based design for the User Interface is proposed. This user interface combines the network characteristics of the energy network and the requirements of the stakeholders with the optimization methods to design efficient network layouts. The basic version of the tool translating the requirements into a software design has been proposed through use cases, use case sequence and the class diagram.

Chapter 7

Conclusion, Recommendations and Reflections

The goal in this chapter is to answer the research question that was formulated in Chapter 2, section 2.1.1 and share the insights that were gained during the research (section 7.1). Based on the conclusions derived from the research, recommendations for future research are provided in section 7.2 followed by critical reflection on the research limitations and personal learning experiences and contributions of the research are discussed (section 7.3).

7.1 Conclusion

The thesis started with the main research question as,

"In what ways can the scientific approaches for energy network design be enhanced to ensure their usability among decision makers?"

In the exploratory phase of problem definition, the current situation of different energy networks were explored (electricity grids, oil and gas). Due to the heterogeneity of these networks and their implementation across geographies it was difficult to come to any conclusion, on the factors which influence the planning of efficient network layouts. The research was then restricted to analyse the biogas/greengas networks in Netherlands to understand closely the dynamics of this system as it is considered to be a sustainable alternative to fossil based energy networks (Bekkering et al., 2010). The starting point of the research was the analysis of the biogas network from a "system" perspective. To achieve understanding of this perspective, a socio technical study was necessary. Based on this study, a clear understanding of the characteristics of the energy source and the energy network was achieved. Furthermore, an understanding of the scientific models led to the creation of the requirement specifications for decision making.

Conclusion based on the socio-technical study
From the empirical study, it can be concluded that, the principal requirement for gas transmission and distribution will need to consider the relevant characteristics of the energy source, the network equipment, the network participants and the spatial constraints. **To be more specific it is found that, it is important to consider the profile data regarding the producers and consumers, their geographical location, their supply and demand capacities respectively. Moreover, it is also important to consider the characteristics of passive components like pipes and the active controllable components like shut off valves, compressors, pressure regulators etc.** The main reason for considering them is because, the pipe characteristics like the pipe length, pipe capacity, pipe material, insulation and flow rate can influence the costs and the operation of the gas distribution. Gas pressure drops over longer pipelines and can lead to inefficient networks. Thus it is important to consider the placement of compressor stations to regulate pressure in strategic positions relative to the pipeline length, the shut off valves can be used to control the passage of gas. **In cases of injecting the greengas to natural gas, it is important to consider the gas characteristics while planning the network layouts. Green gas needs to**

attain specific quality requirements before it can be injected into the natural gas distribution system. It is also important to understand the physical and chemical characteristics of the gas because this can influence the pressure levels of the flow, corrode the pipelines or cause damages to network equipment. **Gas storage meets the temporary or permanent issues to balance gas demand. In summer, when demand is low, gas storage can be used to store gas to be used only in Winter peak demand periods and it becomes important to locate or install them wherever necessary.** All these characteristics can influence the building and operational costs of the entire network. Although these technical constraints influence the network planning it is also observed that some institutional constraints also play a major role in planning. **The land use agreements can influence the decision of routing the pipeline across specific regions. Sometimes the regulatory aspects of elevation, safety precautions in densely populated areas lead us to consider the soil characteristics of the region. Cost differentiation among various regions, quality specifications of biogas/greengas can directly influence the cost and energy efficiency of the network layouts.**

The socio-technical study also concludes that the main stakeholders involved in the entire supply chain of biogas, display network characteristics of variety, inter dependencies and closeness. All of them share different interests and want to maximise their interest. Intrinsically these actors are also interdependent on each other for their services or resources. In network planning , the problem owner to design efficient networks can be the " Network Facilitators", but they are driven to make efficient networks based on the influence of meeting the sustainable goals of the Government who have higher power position. They are also expected to collaborate with the energy producers and the consumers to maintain the supply chain. These dependencies can increase the uncertainty about the participating stakeholders, their interests, their decision strategies which will directly influence the costs and operations of the network. **Thus, there is a need for increased collaboration among different stakeholders and a transparent system where all of them can come together and make decisions in the interest of all.**

Conclusion from the study of scientific approaches

The scientific approaches of (Heijnen et al., 2013, 2014; van Tol, 2014; Viet, 2015) which were studied during the research prove to be useful tools with a lot of flexibility for achieving simulation of minimal cost networks. The factors used in the models are a subset of the factors which were identified during the research. Although, these scientific models are useful, either they are not well known, or they lack the customised factors of specific energy networks, which hinders their use in decision making for real world cases. The notion of "one size fits all" can reduce the flexibility of the system and compromise the characteristics of specific network layouts. **Based on the study of biogas and green gas networks, a design process to enhance the working of the scientific models was proposed. The working principles for extending the decision making logic and possible improvements to cost equations, additional performance criteria are proposed.** If this can be implemented, these adapted algorithms can be used by decision makers, it can be more beneficial if their complexity is reduced and their ease of use for network planners is increased.

Conclusion for the Decision Support System(DSS)

Based on the empirical study of the biogas energy network and the scientific models, a user interface design of the Decision Support System has been proposed. This user interface combines the network characteristics of the energy network and the requirements of the stakeholders with the optimization methods to design efficient network layouts. The basic version of the tool translating the requirements into a software design has been proposed. Additional functionality for adding different kind of users can be further added in the future iterations of the stakeholder requirements.

Overall Conclusion

The empirical study on the socio technical analysis of biogas energy network and the study of the optimization models, have been successful in drafting the proposal for the design of scientific models that can simulate network designs closer to reality. The specific characteristics of the energy network influence the network planning and if these factors are incorporated into existing models, their value becomes multi fold. Although the adaptation can bridge the gap between the scientific methods and pragmatic decision making, using them can still be complicated for a decision maker who has no knowledge in that field. Thus a user friendly interface design of a DSS was also proposed to overcome this difficulty. As seen above, the research question aimed to understand that network characteristics can play a role in network planning and why they can be useful in bringing the scientific approaches closer to reality. Thus, the study has broadened the understanding of the complexities of designing energy network layouts and has shown different possibilities to overcome these complexities. The proposed enhancements to the models and the design for decision support system can combine the realistic requirements of the decision makers, simulate a real environment of an energy network and also inherit the benefits of the scientific approaches. No research is ever complete and hence there is always room for something more. The next sections will continue with some recommendations on the research and some reflections.

7.2 Recommendations and Future Research

The research conducted, can further be enriched by aspiring researchers in future. Some of the pointers to these future research areas are,

Extend existing scientific algorithms functionality
The scientific algorithms of GGM and ABM models which were studied during this research have been modelled in a very generic way. Although, these approaches work efficiently, they can be further adapted to incorporate specific network characteristics of the energy networks. The notion of ”one size fits all” leads to complexity for decision makers to use them in real world cases. In case of the biogas and the green gas networks it is important to extend the existing functionality to consider the use of controllable items like compressor stations, technical components like valves, the pipe characteristics, gas characteristics, legal obligations etc without distracting the physical and operational constraints of the network. The cost function that is currently used does not take into consideration the investment costs of all the other components in the network and their operational costs. The consideration of these specific network characteristics will bring the scientific approaches much closer to reality and can be useful for network planners.

Additionally, there is also a further need to start considering possibility of including ”prosumers” into the scientific approaches. The models currently work on the concepts of producers and consumers who have specific supply and demand capacities. But with the growing nature of hybrid energy grids, there can be a specific customers also known as ”prosumer” who can act as a producer as well as a consumer at different time periods. Such complexity will need the network to balance the supply capacities to meet demand without distracting the operations of the network.

Lastly, there is a need to incorporate the multi-actor context and the institutional constraints into the models. The stakeholders involved in network planning can have different interests and power to influence the entire planning. It is important to consider their perspective and incorporate these as decision making strategies in the models. For example: In existing methods, all the consumers and the producers are equal and the type of energy transmission is also same. In a multi gas grid where green gas needs to be injected into the natural gas system, it is expected to gain higher priority due to regulations or due to a high power stakeholders interest. Thus it is important for the models to be flexible enough to accommodate these kind of differentiations.

Development of the software application
The user friendly Decision Support System (DSS) which is proposed in the research is still in the design phase of the SDLC. It is important for this design to be implemented into a working prototype. The design criteria proposed for biogas/greengas grids and the combination of the scientific approaches will bridge the gap and can be directly used by network planners for decision making. Furthermore, it can also be necessary to extend the design criteria by taking into consideration the pipeline engineering principles from Civil Engineering experts.This validation can further help the tool to be robust in terms of the engineering principles.

Study on the market implementation of the DSS
If the DSS is built , this technology will be an innovation in the field of energy network planning for sustainable future. Thus it is important for this application to cross the barriers of already popular incumbent players and be adopted in the market. Thus it is important to conduct a study which identifies the drivers for the technological diffusion into the market. The business model, market model and the cost specifications for the DSS will need to be studied carefully before it can be launched for commercial use.

Study of other energy networks
The scope of this research has been restricted to only biogas/green gas networks and to an extent the natural gas system as well. Other energy networks like CO2 transmission networks, heat pipelines or electricity grids can be studied closely to understand their network characteristics which influence the network layout planning. Furthermore, it can be beneficial to compare the findings from different energy networks and come up with common characteristics and specific characteristics. This will help the decision support system to be useful for different energy network planners and result in widespread adoption.

From the Socio-technical study, there is also room for proposing some recommendations for promoting the use of biogas and green gas as a renewable alternative in Netherlands.

Policy recommendations
The European Commission directives define most of the legislation's and policies for sustainable energy development in the Netherlands. As part of these directives, Netherlands has set a target to achieve 14% of the total energy production from renewable sources by 2020. The growth of the market for biogas and green gas which are renewable alternatives to help NL achieve these targets is still very feeble. Some of the reasons are related to the subsidies available to promote these technologies. Currently the SDE+ subsidies allow green gas producers to apply for subsidies but they are awarded for a depreciation period of only 12 years. Moreover the cost of biogas upgradation is very expensive in itself and hence majority of the biogas producers do not upgrade biogas. Hence it is important for the Dutch government to take initiatives to promote the production of biogas and green gas. More subsidies with longer depreciation periods will encourage a number of producers to upgrade biogas. Moreover, the government can also consider the possibility of adding the biogas to the Gas act and regulate the biogas market. Such a regulation will reduce the commercialisation of biogas in unregulated markets , which is currently distributed by third party network providers. This will act as a dual incentive for the existing DSO's to have complete hold on the gas distribution grids and can also ensure safety and reliability of the grid.

Stakeholder Collaboration
The stakeholders involved in the production and distribution of biogas infrastructures have different interests and power positions but are highly interdependent on each other for either their resources or their services. The feedstock suppliers need to regularly collaborate with the biogas producers and network providers. At the same time they are dependent on the government for having more friendly regulations for disposal of animal manure or subsidies for manure treatment. In similar lines each stakeholder involved in the supply chain of biogas/greengas has to collaborate and share information transparently. Hence there is need for scenario workshops involving all the relevant stakeholders to come forward in order to discuss and provide solutions in the interest of all.

7.3 Reflection

The research conducted so far had its share of limitations and also very rich lessons that were learnt during its course. As a researcher, I wish to reflect on some of my observations both on the research methodology, its outcome, its contributions and my personal journey.

Research Contributions
This research contributes to the field of ”Applied Energy Research” and ”Innovation in Energy and Industry”. From a scientific perspective, because of its applied nature, this research makes a systematic analysis of the practical application of science. The socio technical approach of understanding the system behavior to identify the main characteristics, influencing network design and the combination of optimization techniques provides a novel approach to solve the problems of network designers. This conversion of the promising research when applied for real world problems opens up the problem space and drives researchers to look for solutions keeping in mind the socio-technical aspects.

Natural gas reserves and fossil based energies are becoming scare and the world is seeking alternatives to meet their energy needs. Biogas and greengas is one of the alternatives for meeting the energy demands in a sustainable way. The study of this field and the possibilities of promoting the greengas injection to National grid is a major contribution for the future of energy and the society at large.

The methodology used for the study of a specific energy network gave a deeper understanding of the field and allowed to customize the scientific approaches. Similarly, if other energy networks can also be studied using this approach, there is a possibility to create a system which can be customised and at the same time have wider applicability.

Research Limitations
The research methodology used for the understanding of the biogas/greengas networks was empirical in nature. Although some interviews were conducted to validate the empirical findings of the research they can never be deemed as complete because,

1. Biogas infrastructures are in its niche stage in Netherlands, and the presence of a complete overview of the biogas distribution or upgradation has not been taken up at large scale by the producers. It is found that large scale biogas producers like waste water treatment plants use it to meet their energy demands rather then distributing it further. The research focuses primarily on a future perspective for the need of efficient network layouts for biogas transmission for which the existing producers have not even thought about.

2. The network characteristics found in the literature study, were agreed by the interviewees as important but they were never sure if they really played a role in network planning. The decision support system is a proposition for an innovation in network planning. It is too early for the commercial producers to know what their needs will be for such infrastructures.

3. Two scientific algorithms based on GGM and ABM methods have been considered for the research. Although in literature, there were many other algorithms which were primarily built to optimise gas networks using other methods like ”Generalized Reduced Gradient algorithm”(Adeyanju and Oyekunle, 2011) and differential evolution (Babu et al., 2011). There could be possibilities to combine these models or equations to be adapted with the GGM and ABM methods. Such analysis or considerations have not been fully thought of, which could actually be beneficial to the extension of the GGM or ABM models.

Personal reflection
My journey through the research and this Master’s has been overwhelming and I have discovered some interesting facts about my style of working, some lessons were drawn for the mistakes I committed along with new scientific learning’s. The journey of this research has been very enriching. During the process I have gained knowledge in the field of energy, specifically natural gas and biogas grids along with the understanding of scientific solutions. I have learnt to have patience, think out of box, think about the larger picture than the problem itself. I have learnt to deal with my frustrations at times, I have cherished my successes, I have learnt to accept failures and overall I have learnt to believe in my thinking, my confidence , and I yearn to learn more and more every day. The mistakes and the failures have made me a better and stronger person today, I have learned to value life and my responsibility towards society in a better way. These experiences will be useful in shaping my future and making me a better person.

Bibliography

O.A. Adeyanju and L.O Oyekunle. Optimization of natural gas transportation in pipeline. Technical report, University of Lagos. Nigeria., 2011. URL http://papers.ssrn.com/sol3/papers.cfm?abstract$_i d = 2581450$.

AgentschapNL. Stimulering duurzame energieproductie (sde) — agentschapnl, 2012. URL http://www.agentschapnl.nl/programmas-regelingen/stimulering-duurzame-energieproductie-sde.

B.W Ang, W.L Choong, and T.S Ng. Energy security: Definitions, dimensions and indexes. *Renewable and Sustainable Energy Reviews*, 42:1077–1093, 2015. doi: http://dx.doi.org/10.1016/j.rser.2014.10.064.

B.V Babu, R Angira, P.G Chakole, and J.H.S Mubeen. Optimal design of gas transmission network using differential evolution. Technical report, Birla Institute of Technology Science,India, 2011.

J Bekkering, A.A. Broekhuis, and W.J.T. van Gemert. Optimisation of a green gas supply chain – a review. *Bioresource Technology*, 101:450–456, 2010.

A Butenko, M Boots, and J Holstein. Injecting green gas into the grid, dutch example. Technical report, DNV KEMA Energy and Sustainability, 2012. URL http://papers.ssrn.com/sol3/papers.cfm?abstract$_i d = 2581450$.

Delftluent Services BV. Factsheets wwtp harnaschpolder, January 2015. URL http://delfluent.nl/en/plant/wwtp-harnaschpolder/ratios/.

B Chandra Mohan and R Baskaran. A survey: Ant colony optimization based recent research and implementation on several engineering domain. *Expert Systems with Applications*, 39(4): 4618–4627, 2012.

É Chappin. *Simulating Energy Transitions*. PhD thesis, Technische Universiteit Delft.The Netherlands, 2011. URL http://chappin.com/ChappinEJL-PhDthesis.pdf.

M Darmer and L Kuyper. *Industry and the European Union: Analysing Policies for Business. Industry and the European Union: Analysing Policies for Business*. Edward Elgar Publishing, 2000.

A.M Davis. *Software Requirements Revision*. P.T.R Printice Hall,Inc, 1993.

DutchMinistry. National renewable energy action plan directive 2009/28/ec, July 2010. URL http://ec.europa.eu/energy/en/topics/renewable-energy/national-action-plans.

EDGaR. Partners, 2015. URL http://www.edgar-program.com/.

EIA. Network configuration and system design, 2009. URL http://www.eia.gov/pub/oil$_gas/natural_gas/analysis_publications/ngpipeline/transsys_design.html$.

Sibel Eker and Els Van Daalen. A model-basedanalysisofbiomethaneproductioninthenetherlands and the effectiveness of the subsidization policy under uncertainty. *Energy policy*, 82:178–196, 2015.

M. J Escalona and N Koch. Requirements engineering for web applications-a comparative study. *J. Web Eng*, 2(3):193–212, 2004.

A Fugenschuh, B Hiller, J Humpola, T Koch, T Lehmann, R Schwarz, J Schweiger, and J Szabo. Gas network topology optimisation for upcoming market requirements. *IEEE*, 2011.

S. A Gebrezgabher, M. P. M. Meuwissen, B. A. M. Prins, and A. G. J. M. O. Lansink. Economic analysis of anaerobic digestion—a case of green power biogas plant in the netherlands. *NJAS - Wageningen Journal of Life Sciences*, 57(2):109–115, 2010. doi: 10.1016/j.njas.2009.07.006.

E Gilbert and H Pollak. Steiner minimal trees. *SIAM J Appl Math*, 16(1):1–29, 1968.

Ersin Fatih Gunes. *Optimal design of a gas transmission network: A case study of the Turkish natural gas pipeline network system.* PhD thesis, Iowa State University, Paper 13294, 2013. URL `http://lib.dr.iastate.edu/etd`.

H Hahn, D Rutz, E Ferber, and F Kirchmayer. Examples for financing of biogas projects in the netherlands. Technical report, BiogasIn D.3.2.WP3, 2010.

P. W Heijnen, R. M Stikkelman, A Ligtvoet, and P. M Herder. Using gilbert networks to reveal uncertainty in the planning of multi-user infrastructures. *2011 International Conference on Networking, Sensing and Control, ICNSC 2011*, 14:371–376, 2011.

P.W. Heijnen, A. Ligtvoet, R.M. Stikkelman, and P.M. Herder. Maximising the worth of nascent networks. *Networks and Spatial Economics*, 14(1):27–46, 2013. doi: http://dx.doi.org/10.1007/s11067-013-9199-1.

P.W Heijnen, I Nikolic, and E.J.L Chappin. Infrastructure network design with a multi-model approach - comparing geometric graph theory with an agent-based implementation of an ant colony optimization networked infrastructures routing challenge top-down vs bottom-up approaches. *Journal of Artificial Societies and Social Simulation*, 17(4), 2014. URL `http://jasss.soc.surrey.ac.uk/17/4/1.html`.

F. P Held, I. F Wilkinson, R. E Marks, and L Young. Agent-based modelling, a new kind of research. *Australasian Marketing Journal (AMJ)*, 22(1):4–14, 2014. doi: 10.1016/j.ausmj.2013.12.003.

O Kuik. Ex ante and ex post costs of implementing the nitrates directive. Technical report, Vrije Universiteit,NL, 2006.

D Kulak and E Guiney. *Moving to use cases Use cases: requirements in context.* Addison-Wesley Professional., 2004.

R. S Middleton and J. M Bielicki. A scalable infrastructure model for carbon capture and storage: Simccs. *Energy Policy*, 37(3):1052–1060, 2009. doi: http://dx.doi.org/10.1016/j.enpol.2008.09.049.

Naskeo. Biogas composition, 2009. URL `http://www.biogas-renewable-energy.info/biogas`$_{c}omposition.html.$

Office of Energy regulation NMa. Connection code gas - tso. Technical report, NMa, Office of Energy regulation, 2012. Part of the Dutch network code as referred to in article 12b of the Dutch Gas Act.

M. Q Patton. *Qualitative interviewing. In Qualitative research evaluation methods.3rd Edition.* Thousand Oaks: Sage Publications., 2002.

Frank Pijnenborg. The emergence of biogas infrastructures in the netherlands. diploma thesis, Technische Universiteit Delft.The Netherlands, 2011.

R Pindyck. Investments of uncertain cost. *Journal of Financial Economics*, 34:53–76, 1993.

ProBioPol. Frequently asked questions, 2010. URL `http://www.probiopol.de/Frequently`$_{A}sked_{Q}uestions.21.0.ht$ $gmrozxujdhn.$

Benny Roelse. Strategic niche management of biogas technologies in the netherlands. diploma thesis, Technische Universiteit Delft.The Netherlands, 2012.

C Unsihuay-Vila, J. W Marangon-Lima, A. C. Z DeSouza, I. J Perez-Arriaga, and P. P Balestrassi. A model to long-term, multiarea, multistage, and integrated expansion planning of electricity and natural gas systems. *IEEE Transactions on Power Systems*, 25(2):1154–1168, 2010.

R.N van Eekelen and M Wolters. Design,operation and maintanance of local biogas networks. Technical report, KIWA Gas Thechnology, 2011. International Gas Union Research Conference.

P.J.M van Tol. Advancing the roll-out of energy networks by embedding differentiation of costs in modeling approaches which minimize assessed construction costs. diploma thesis, Technische Universiteit Delft.The Netherlands, 2014.

Reiner Verhoog. Exploring biogas stakeholder interaction in the netherlands. diploma thesis, Technische Universiteit Delft.The Netherlands, 2013.

Q.A Viet. Non-deterministic networked infrastructure design of multiple sources and multiple sinks. diploma thesis, Technische Universiteit Delft.The Netherlands, 2015.

Taede D Weidenaar. *Designing the biomethane supply chain through automated synthesis*. PhD thesis, University of Twente, Enschede, the Netherlands, 2014.

Thodoris Zafeiris. Feasibility study substituting natural gas with biogas in industries. Technical report, Kenniscentrum Papier en Karton, 2013.

Van Der A.H Zwaan. The sociotechnical systems approach: A critical evaluation. *International Journal of Production Research*, 13(2):149–163, 1973.

List of Tables

List of Figures

Abbreviations

ABM	Agent Based Methodology
ACO	Ant Colony Optimization
AD	Anaerobic Digestion
CO2	Carbon Dioxide
CH4	Methane
CLD	Causal loop Diagramming
DSO	Distribution System Operator
DSS	Decision Support System
ECN	Energy Research Center
EDGAR	Energy Delta Gas Research
EWSMT	Edge Weighted Steiner Minimal Trees
GGM	Geometric Graph Methodology
GHG	Green House Gas
GTS	Gas Transport Services
H2S	Hydrogen Sulphide
MAOP	Maximum Allowable Operating Pressure
MILP	Mixed Integer Linear Programming
NREAP	National Renewable Energy Action Plan
PN	Nominal Pressure
SDLC	Software Development Life Cycle
STM	Socio Technical Map
TSO	Transmission System Operator
SD	System Dynamics
SDE	Stimulering Duurzame Energieproductie Subsidy
UI	User Interface

Appendix A

Appendix A

A.1 Understanding Biogas

Definitions

Raw biogas: It is a term used for gas that is produced through anaerobic digestion or fermentation of organic matter. Ex. Landfill gas and Sewage gas

Biogas: Raw biogas undergoes treatment for removal of H2S, after which it is dried to form biogas which can be further used to produce heat and electricity for local energy needs.

Bio-methane: Biogas is further upgraded to acquire the qualities of the natural gas before it is injected into the gas grid infrastructures.

What are the main sources of biogas production?

Primary	Ktonnes	Secondary	Ktonnes
Agricultural (straw)	270	Residual Wood	640
Grass seeds (graszaadhooi)	100	Food and Beverage Industry(dry)	5000
Agricultural Crop residues	985	Food and Beverage Industry(wet)	5000
Horticultural Crop residues	200	Waste from auctions	160
Household green residues	1000	Tertiary	Ktonnes
Manure	70000	Wastewater sludge	310
		Wastewater from constructions sector	1500
		Compost overflow	50
		GFT wastes	1600
		Combustible household wastes	1700
		Paper and board industry wastes	250
		Textile	18
		Solid recoverable fuels	130

Table A.1: Sources for biogas production in Netherlands

The sources of biogas relate to the primary, secondary and tertiary sources of biomass. They define the composition of the biogas that will be distributed as an energy source to consumers(Zafeiris, 2013, see pg 14). In Netherlands, biomass production is primarily based on either energy crops production or as by-products from other uses. Few examples of energy crops are rapeseed(koolzaad) which is used for biodiesel production, for ethanol production there is use of grain(graan) and maize(mais) for digestion. The by-products are a result of different activities and are residual or rest products. This can relate to waste wood from construction, paper/cardboard from industries, agricultural residues, household wastes and waste water from industries etc. Table A.1 gives an overview of some of the biomass that is available in Netherlands.

Multiple biomass locations can supply biomass to a single digester and multiple digesters can supply bio gas to a central bio-methane upgrading plant. Thus networks can exist at the biogas production level or at the green gas production too. The sources of biogas production are dependent directly on the biomass sources in its supply chain. Thus these manure networks also play an important role while designing network layouts. Dependent on the location and capacity of these biomass producers there are two possibilities.

One of them can be, formation of manure networks or biomass network. For instance, the animal manure or agricultural residue can be transported via pipelines or vehicular transport to centralised biogas production plant. Other such example can be the waste water treatment plants, which collect waste water sludge from the households with the help of municipal cooperation. They deploy their pipeline network and operate the transport using pumping stations which are installed along the given area of coverage.

Secondly, there is another possibility of biogas production independently by the biomass producer and thereby a network layout will be needed to transport this bio-gas for further up gradation to bio-methane at a centralised location. Therefore, it is important to consider the location and capacity of the sources of biomass and biogas for network planning.

What are the main methods of biogas production?

The organic matter is preprocessed before it is fed into the biogas plants for production. Each biogas plant consists of a mixer, 2 digesters and a storage minimally. The size of the plants can vary based on the capacity. All the organic matter both wet and dry wastes consisting of household wastes, waste water, industrial wastes, energy crops, manure, vegetable biomass etc. are transported to the biogas plants. The digesters are the fermentation tanks where all the substrates are continuously heated up and stirred. These provide the anaerobic conditions for fermentation and the bacteria grow in the organic matter to produce biogas. The digesters are equipped with an outlet for biogas and an overflow pipe for the outflow of the sludge or residue after the process(ProBioPol, 2010). The fermentation process can either be done using anaerobic digestion or co-digestion. There are different phases of biogas production in each type.

Anaerobic digestion (AD)

AD is carried out separately for specific kind of organic wastes and is subject to prepossess/ segregation before the digestion process. In hydrolysis phase, the anaerobic bacteria use enzymes to decompose the highly molecular organic matter which can be a mix of carbohydrates, proteins, fats and amino acids into lower molecular compounds. The acid forming bacteria continue to decompose further in the acidification phase and result in organic acids, CO2[1], H2S[2] and NH3[3]. During the acetogenesis phase the bacteria form the acetate, carbon dioxide and hydrogen. Finally in the methanogenesis stage, the methane forming bacteria form alkaline water, methane and CO2 (ProBioPol, 2010).

Co-digestion

Co-digestion is also a form of AD but in this case, the feedstock is not segregated but it is a process of simultaneous digestion of multiple sources of organic matter. The compatible organic matter is identified and fed together into the digesters for AD. The sole purpose of this kind of AD is to enhance the methane level in the biogas thus produced (ProBioPol, 2010).

[1] CO2: Carbon Dioxide
[2] H2S: Hydrogen Sulphide
[3] NH3: Ammonia

A.2 Physical Characteristics

Methane (CH4) which is the combustible element common to both Biogas and Natural gas determines the gas properties. Biogas has lower percentage of methane and also absence of other hydrocarbons that are present in natural gas makes the gas low calorific. The density of biogas is higher than the natural gas due to presence of carbon dioxide(van Eekelen and Wolters, 2011). Table A.2 gives an overview of the physical characteristics of biogas.

Physical Characteristics	Biogas	Natural Gas
Calorific Value(MJ/m3)	31.7	19 -25
Relative Density(Kg/Nm3)	0.65	1

Table A.2: Physical Characteristics of Biogas

The burning properties of natural gas differs from that of the biogas based on their compositions. The presence of carbon dioxide in biogas increases the air-to-fuel ratio (5.5:1) and makes the flames less stable for biogas. The optimum air-to-fuel ratio needed for combustion in a natural gas burner is (8.7:1). Combustion equipment for burning gaseous fuel is manufactured based on the gas family determined by Wobbe index for each gas composition. Natural gas falls under second family of gases with Wobbe index of (43.4-44.1 MJ/m3) and biogas might fall under the first family with an index of (22-28 MJ/m3)(van Eekelen and Wolters, 2011, see pg 6).

A.3 Quality Requirements for Biogas Cleaning

There are several incentives for using the natural gas grid for biogas injection,
The grid connects the production site with the largely populated areas enabling gas to reach to existing and new customers.

- It improves local security of gas supplies.
- As countries consume more gas than they produce, biogas can thus meet such demands locally.
- It allows to reach the EU renewable energy targets

The biogas utilization defines the quality requirements for biogas cleaning. Table 4.1 gives an overview of specific cleaning needed,[source: upgrading report final]

Application	H2S	CO2	H2O
Gas Heater(boiler)	<1000ppm	No	No
Kitchen Stoves	Yes	No	No
Stationary Engines	<1000ppm	No	No Condensation
Vehicle fuel	Yes	Yes	Yes
Natural Gas grid	Yes	Yes	Yes

Table A.3: Quality Requirements for Biogas Cleaning

Components	Household Waste	WWTP	Agricultural Wastes	Agri-food industry wastes	Natural Gas
CH4% vol	50-60	60-75	60-75	68	81
CO2% vol	38-34	33-19	33-19	26	<1
N2% vol	5-0	1-0	1-0	-	1.35
O2% vol	1-0	<0.5	<0.5	-	0.01
H2O% vol	6(á40° C)	6(á40° C)	6(á40° C)	6(á40° C)	-
Total% vol	100	100	100	100	100
Ethane	-	-	-	-	2.85
>C2 hydrocarbons%	-	-	-	-	3.41%
H2S mg/m3	100-900	1000-4000	3000 - 10000	400	1.5
NH3 mg/m3	-	-	50-100	-	-
Aromatic mg/m3	0-200	-	-	-	-
Organochlorina or organofluorated mg/m3	100-800	-	-	-	-

Table A.4: Chemical Characteristics of Biogas

A.4 Chemical Characteristics

Table A.4 shows the chemical composition of the biogas and natural gas(van Eekelen and Wolters, 2011).

Appendix B

Appendix B

B.1 Gas storage types

The gas storage type is selected based on the pressure range of the gas flow. Table B.1 gives an overview of the storage types.

Pressure Range	Operational Pressure[bar]	Normal Storage sizes[m3]	Storage Type
Non Pressurized	0 to 0.005	10 to 2.000	Fermenter,Balloon/Foil storage
Low pressure	0.01 to 0.05	100 to 2.000	Gasometer,double membrane storage
Medium Pressure	5 to 20	1 to 100	Steel pressure tank
High pressure	200 to 300	0.1 to 0.5	Gas bottles

Table B.1: Types of storage constructions

B.2 Socio technical Mapping of the Biogas Infrastructure

Energy network infrastructures can be regarded as a system i.e an entity of interdependent elements or factors.Socio-technical perspective of a system is seen to establish the openness of the system itself. The concept of socio-technical system was first noted at Tavistock Institute in London in the context of labor studies (Zwaan, 1973). The openness of the system thus gives us an overview of the dynamic elements of the system and how they are influencing each other. Thus, we adopt the method of socio-technical mapping as shown in figure B.1 to understand the dynamics of the technical and the social subsystems of the biogas energy infrastructures.

The conventional natural gas grids have hierarchical tree layout distribution/transmission of gas from centralized location with varying pressures. The pipelines transport gas at high pressure from the gas wells to the centralized gas stations (CGS) for processing. After processing from CGS, the pipeline further transports the gas to commercial large scale industries and the district stations for regional distribution. This then connects in the form of a ring layout to ensure transportation of gas to the district stations. It's more reliable as it ensures continuous delivery even when there is disruption in any specific node. The district stations are connected to the distribution network at low pressure in a meshed layout form.
As in the distribution network there are many connections to households, commercial establishments, offices and industries etc. they form such kind of a network. At CGS and DS pressure regulation systems, safety valves need to be installed to ensure the pressure level of the system itself and to control the maximum level of the inlet pressure at the injection points. Shut off

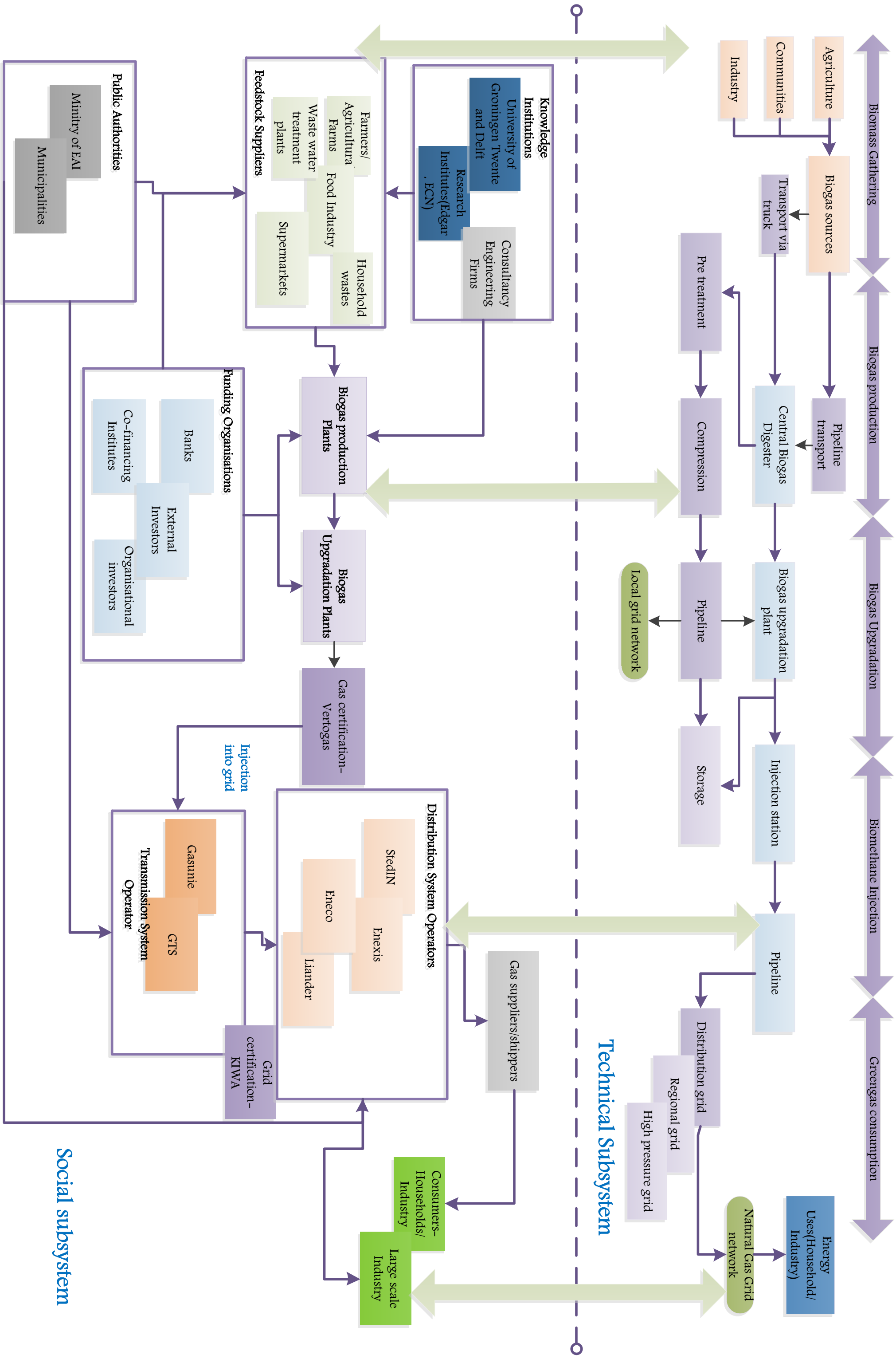


Figure B.1: Socio-Technical map of biogas/biomethane supply chain valves need to be also installed to ensure shutting off the gas supply in case of calamities. Compressors are needed in case of biogas specifically to ensure the right pressure of gas depending on the injection point of biogas . In some other cases blowers also are good enough to serve the purpose depending on the length of the pipeline.

B.3 Mapping the interests, preferences and power positions of key actors

Table B.2: Mapping the interests, preferences and power positions of key actors

Stakeholder	Role	Goal	Interest	Power
Agricultural firms	Produce Biogas	Maximization of profit	Low, not widespread production	Low, dependent on other firms for feedstock
Industrialized firms	Produce Biogas/Green gas	Maximization of profit	High, production of alternative energy like biogas, upgraded biogas	Moderate, dependent on centralized supply of feedstock
Water treatment plants	Produce Biogas	Maximization of profit	Moderate, has continuous supply	Moderate, independent and relies on self
Farmers	Supply Manure, energy crops	Reduce manure disposal costs	High, manure disposal is expensive	Low, possible substitution by other farmers
Waste Stream producers	Waste collection and processing	Reduce waste processing costs	High, waste processing is expensive	Low, restriction from legislation
Small consumers	Consume biogas/green gas	Reduce energy costs	Low, satisfy energy needs	Low, individually
Large consumers	Consume biogas/green gas	Reduce energy costs, Reduce CO2 emissions	High, to be sustainable and have reliable supply of energy	Medium, they can influence demand for energy

Distribution System Operators(DSO)	Operate distribution grid, obliged to connect biogas producers to network	Maintain network integrity	High, they need to plan the cost effective network to inject green gas to grid	High, As it connects the grid to large and small consumers
Transmission System Operators(TSO)	Operate transmission grid, obliged to connect biogas producers to network	Maintain network integrity	High, need to ensure upgraded biogas meets gas/grid quality requirements	High, important as it sets gas quality requirements to join the grid
Local third party network	Operate local biogas networks	Plan, build and operate local biogas networks	High, distribute biogas locally	Moderate, unless in excess they don't need to connect to national grid
Agentschap NL	Grant SDE+ subsidies	Increase renewable energy production	High, to meet national goals of reducing CO2 emissions	High, subsidies are essential for biogas production
Banks	Provide external investments	Increase profits, reduce risks	High, get a stake in the renewable sector	High, as their investments are risky and capital is crucial
Municipalities	Grant environmental permits, grants	Reduce environmental impact	High, to meet national goals of environmental sustainability and land use	High, land use and development permits are needed
Ministry, Government	Design renewable energy policies	Reduce environmental impact and move towards sustainable futures	High, to meet national goals of environmental sustainability	High, national reputation at stake

Research Institutes/Universiti	Research on biogas production and distribution methods	Create advanced technology solutions which are sustainable too	Moderate, contribute to technology development	Moderate, depends on the need for new technology solutions
Vertogas	Certify the gas quality	Allow the right quality of gas to be injected into the grid	Moderate, provide certification on origin of bio gas	Low, dependent on the bio gas producers who want to join the grid
Energiekamer	Enforcing laws	Ensure fair competition	High, can make regulations	High, can also stop project developments
Gasterra	Enables energy pricing	Ensuring market for gas trade	High, provide platform for gas trading	High, can impact the gas prices

Appendix C

Appendix C

C.1 Interview Summaries

The area of research for the energy infrastructure planning. To achieve this objective it is necessary to understand about different energy networks, their characteristics and how the experts have dealt with this issue so far. As this research involves multi-stakeholder analysis it is needed to conduct interviews with industry experts at the research units or the companies dealing with energy planning.

Two different sets of interviews were conducted with different people for the study. Initially, an interview was conducted with one of the assistant professors of TPM, TU Delft, to identify the knowledge gap and understand the problem that needs to be addressed in more detail. The second type of interviews conducted was to enhance the understanding in the research from different stakeholder perspectives.The set of questions used for both the types of interviews were different from each other.

C.1.1 Interview 1: Identifying the problem: Problem Analysis

Interviewee:
The interviewee is an Assistant Professor currently with the Energy and Industry Group of the department Technology Policy and Management of TU Delft. The choice of this interviewee for the research is important because of the knowledge and expertise he has in the field of energy networks. Also, the interviewee is active in projects ongoing for planning energy networks which is the main area of my research.

Place and Time of Interview:
The interview was conducted in Room a3.3XX, Department of Technology Policy Management at TU Delft. The interview was scheduled for 1 hour starting at 11:00 AM on 15th January.

Interview Topics and Discussion Summary
There were different topics that were discussed during this interview. It was open-ended and the questions were directed to get better understanding for the research. Some of the topics and questions covered were,

Energy network Characteristics:
The specific characteristics of routing in energy networks were discussed. How the network planning of oil and gas pipelines, electricity grids and CO2 transmission line were discussed. Also the key factors which are important to create a generic framework were also identified.

Multi-stakeholder Analysis:
The different actors involved in the planning of energy networks were discussed, their interests, preferences and how they can influence the decisions are mapped. The risks involved in decision making and the assumptions made while decision making were discussed.

Scientific approaches to network design planning:
The discussion about different types of scientific approaches to energy network planning was discussed. The interviewee gave more details how the agent based modeling and the ant colony optimizations aid in planning efficient networks. The advantages and also the disadvantages of such algorithms were discussed in detail.

Decision making strategies:
There were discussions on how the decision makers decide about a specific network plan. What different strategies, political influence, resource dependencies and the socio-technical characteristics of the system that can influence network planning were discussed. The traditional approach of network planning and why the optimization algorithms are not practically used were also briefed by the interviewee.

Question 1: What are the characteristics of different energy networks?
The interviewee responded as, "Energy infrastructures in general are complex and can be seen as socio-technical systems with inter-relations between the technical and social elements of network. They connect the suppliers and the consumers providing services to interconnect. The technical complexity of transforming energy from the source to the destination is dependent on the decisions and actions of various actors who are involved in the functioning of such networks".
Different energy infrastructures have specific characteristics and they are not always alike. The electricity grid is far more complex and is different from the gas grids or the water networks. The emphasis was made by the interviewee to focus on specific energy network and research in detail about one specific network at a time. The characteristics can range from a technical, spatial, social, and regulatory perspective. It is important to look at each of these perspectives to obtain a broader understanding of how there networks operate. Understanding these will help to design a network in a way that can satisfy various actors and have long term goals.

Question 2: What are the challenges of planning energy infrastructures?
The interviewee replied with multiple challenges for this question. Some of these are stated below,

- Infrastructures are capital intensive and the investments are up-front with return on investment coming long after the initial investments are made. This makes it more challenging for fund approvals.
- In the planning phases, there is a great deal of uncertainty of participants (actors), their interests/preferences, capacities that they need is still unknown. It makes decision making very difficult.
- Designing new infrastructures or adapting existing ones involves building costs not just for materials but also for varying capacities at different times (seasonal changes).

Question 3: What are the different scientific approaches for routing cost- efficient energy networks?
The interviewee responded mainly about the bottom up approaches and stated them as "They use distributed entities in a multi-dimensional space to find a "good enough solution "and rely on local information which is available to make decisions. They are used when there is inadequate information."
Examples of this approach were given as Ant Colony Optimization (ACO). The interviewee also explained further in detail about the functionality of this algorithm that is also discussed in the main text.

Question 4: Who are the different stakeholders that can influence the network planning?
Different stakeholders are involved in network planning but mainly the prominent players are the producers, consumers, distribution/transmission system operators, government or municipal authorities and the local citizens.

Question 5: Are you aware of any tools that are currently used by network planning in the industry to design efficient energy networks?

The interviewee responded based on his knowledge and specificity towards electricity grids. According to him, there is no direct tool that is currently deployed with the optimisation methods in the Netherlands. But he mentioned that it is important to cross very with the DSO's to know more on how they have been planning networks.

Question 6: If the scientific approaches developed in research needs to be implemented for large scale network planning, how can we do it?
According to the interviewee, it is important to take it step wise, the key to the adaptation is currently we are trying to connect, single source and multiple sinks with varying capacities. More research is underway to connect multiple sources and sinks along with varying capacities and cost differentiation among regions. To make it more adaptable in the industry we will need tools that can actually bring in the multi actor perspective along with the technical constraints for more realistic implementation. A platform will need to be designed that can bring different stakeholders together to share information about their interests and resources. The scientific community will need to expand existing optimization algorithms to include other performance indicators like energy efficiency of the layouts, cost of distribution grid components, fixed investment costs, operational costs, amount of CO2 emissions for each resulting layout.

C.1.2 Interview 2: Understanding the producers perspective

Interviewee:
The interviewee was an official who was closely involved in the production of the biogas at Delfluent Services BV. Through a Public Private partnership, Delfluent Services is responsible for the operational activities in the northern part of the region of the Water Boards. For the past 30 years, Delfluent services are responsible for the management and maintenance of the waste water treatment plants (WWTP) in the Hague, Den Hoorn and Midden Delfland spanning across the area with 19 stations.

Place and Time of Interview:
The interview was conducted at the office of Delfluent Services, Peuldreef 4, 2635 BX Den Hoorn. The interview was scheduled for 1 hour starting at 13:00 Hrs on 21st April.

Interview Topics and Discussion Summary
The company was chosen as it is one of the WWTP's which has large scale production of biogas as one of the resultants from their waste water treatment. The intention of the interview was to understand about their production cycle, their perspective towards usage of produced biogas and to know about the possibilities for distribution of biogas feasibility. If there is such a possibility, it was important to understand what factors can play a prominent role in their decision making.

Question 1: Tell us about yourself, about Delfluent Services (WWTP) and about various tasks you perform in the field of biogas.

The interviewee responded as "At our two waste water treatment plants (WWTP's) we produce biogas. We use it as fuel for our gas engines to produce electricity and heat. The electricity and heat are both used at the plants."
"So: yes, we produce biogas. And no, we don't distribute it. Nevertheless, there is a tendency going on that wwtp's 'transform' into energy plants. Producing energy (biogas, electricity, heat) out of waste water is becoming more important. So maybe in the future we will produce more energy than needed for our plants and we will need to distribute it. Your research might be interesting to us."

Question 2: What is your view on the main developments regarding biogas and green gas in the Netherlands?

In the interviewees opinion, biogas and green gas gas has very high potential for development in Netherlands. The government proposes firms like the WWTP to become more sustainable by treating waste and becoming more energy efficient. They are expected to contribute towards national goals of CO2 and GHG emission reduction. To achieve these objectives WWTP's are investing more in production of biogas using the waste water and are using it in the form of heat and electricity for fulfilling their energy purposes.

Question 3: How do you think internal biogas production and consumption can contribute to nation-wide goals?

The idea is to increase internal production and reduce the purchase of electricity (energy) from the national grid. The benefits of doing so are two-fold. We save the costs incurred to purchase the energy and secondly, most of the electricity in national grid is still widely generated from fossil based sources. Hence our contribution to nation wide goals will be indirect by reducing the demand of fossil based energy which eventually will lead to lower CO2 emissions and long term environmental sustainability.

Question 4: What are the main activities/projects in the field of biogas within your organization? Biomass collection? Amount of heat and electricity produced?

The interviewees response was, the biogas production is a by product of waste water treatment process that is installed in our facility. The waster water is received to our biogas digesters through various transport stations that are placed across the zonal area and are transported using our pipelines laid from 30 long years. This activity of collecting the waste water from the households, commercial establishments and local establishments is in collaboration with the municipalities (gemeente) and the water boards. This is free for us and through a public private partnership we have been dealing with the treatment of waste on behalf of the water board.

The process for treatment gives us waste sludge which is used for producing biogas and the resulting water is further purified and directed into North Sea through specific channel. These purification sis subjected to follow specific standards set by the Government policies and we adhere to them. The biogas thus produced is converted to electricity and heat to meet our internal energy demands.

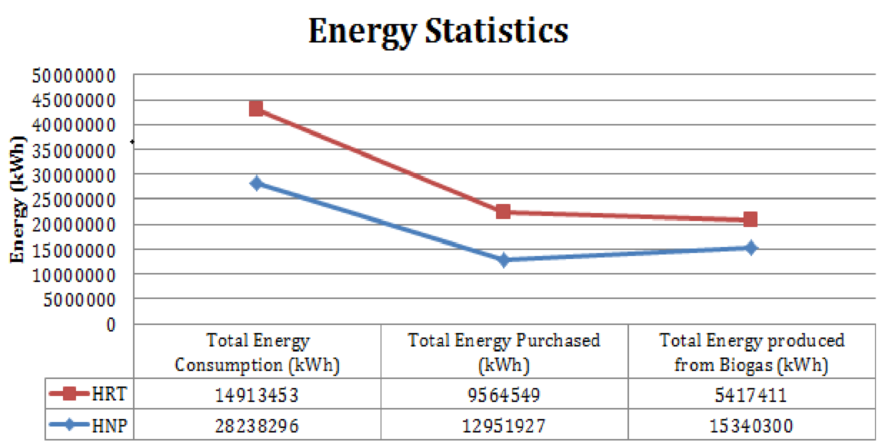


Figure C.1: Energy Statistics of Delfluent services

The amount of biogas produced and converted to heat and electricity statistics can be obtained from our website . As shown in the figure C.1, we have considerable amount of biogas produced which partially meets our energy demand. There is still a large amount of energy purchased to meet our energy demand. We are working towards improving our processes more so that, in future if we have any excess biogas we can think of distributing it.

Question 5: Is it cost-effective for you to generate biogas and use it?

Yes. Indeed it is today as we can partially cover the costs of the energy that we otherwise need to purchase. The operational cost is lower than the energy purchase costs. The fixed capital investments were done long back in time and today we do not see it as very capital intensive. But if tomorrow we need to establish newer digesters or pipelines to produce and distribute biogas, it is indeed questionable as it is highly capital intensive for us.

Question 6: Given a hypothetical scenario, you decide to distribute the excess biogas or electricity produced, what will be the most important factors that you will consider to do so?

The interviewees response was, it is difficult to answer this we have not thought in that direction yet. Right our goal is to be more energy efficient in our processes and reduce the energy purchase as much possible. If we decide to be selling energy in future, cost minimization is the most important criteria for us to venture in this area.

Question 7: Is Delfluent services interested to upgrade biogas to natural gas quality? And then further inject this gas to natural gas grid?
Biogas is still a niche concept to be distributed in its raw form. Upgradation of biogas is a good solution as it can attain natural gas properties. As a WWTP, we look forward to biogas upgradation only if have enough biogas produced in future. This is indeed a future possibility depending on the costs it incurs.

Although there were many other questions that were discussed during the interview, the interviewee's response was based on the ideas already presented above. Given below is the list of few questions that were asked but no concrete answers or short answers were given for the same.
1. Why is Delfluent services interested to distribute the biogas?
In future there is a tendency for WWTP's to turn into energy plants.

2. Are you planning to adopt any model from existing plants?Any tools to design such projects for you?
Too early to comment on this.

3. Would you decide it based on expert judgement or optimization algorithms?
Yes Experts will be consulted before we do so. If situation demands we will look for optimization tools.

4. What are the expectations of the project on technology (biogas production, efficiency, upgrading, installation, etc.)?
Too early to comment on this.

5. Will you need a user prototype tool to design such energy networks?
Too early to comment on this. If yes, what should that tool do for you? How will it help you decide? If no, why not?
Too early to comment on this.

6. Do you think the physical and chemical properties of biogas can affect the network design? Why do you think so?
may be they can influence in the design.

7. What are the expectations of the project at the economic level (expected costs to be incurred on maintenance and expected delivery contracts, the expected biogas market)?
Too early to comment on this.

8. What are the expectations of the project at the policy (available grants, legislation, etc.)?Are institutional characteristics important?(Subsidies)
Too early to comment on this.

9. What are the expectations at the social level (there are objections from the environment about the project and in terms of sustainability)?

Too early to comment on this.

10. What are the obstacles in the project in the technological, economic, social and legislation?
Too early to comment on this.

11. What else is needed (on technology, social, political and economic) to develop biogas networks in the Netherlands and to apply on a larger scale?
Too early to comment on this.

12. Who according to you are the key stakeholders in the current biogas developments you consider as important?
For us the water board, municipalities are the key stakeholders as they facilitate us with the waste water approvals. We need to adhere to government rules so they are an important actor as well.

13. What is the impact of developments in the gas sector on the developments in the biogas niche and vice versa (the influence of developments in the gas sector)?
No idea.

14. Where to achieve the greatest environmental gains concerning biogas compared to the natural gas sector?
No idea.

C.1.3 Interview 3: Understanding the network facilitator's perspective

Interviewee:
The interviewee is working in the field of gas grid planning for GTS, Gasunie, which is a TSO in the Netherlands. The person has knowledge in the area of gas network planning and the different kinds of optimizations currently being used by Gasunie to distribute natural gas.

Place and Time of Interview:
There was no formal interview conducted and only email conversations were held to discuss their viewpoints.

Discussion Summary

Common Question: How is energy network planning happening in Netherlands? Are there any kind of optimization methods that are currently under use by the network planners? If yes, which are those methods?

The responses for the email conversations were,
"I'm ask to respond to your quest for information on "gastransport network planning using optimization technique".

My first response would be, I'm glad it exists and that we are using it for many years. In the more recent years it's also implemented in commercial software like SIMONE or GTS in collaboration with KEMA, het referentie model."

SIMONE is an simulation software that is currently being used by GTS, Gasunie to simulate the network flows in gas distribution. It primarily focuses on network optimization and not network layout optimization techniques. For gas flow optimization they use the gas, pipe, compressor station characteristics. They have no real software which focuses on network layout optimization and usually create network topologies based on expert advice and judgement.
Website Link: http://www.simone.eu/simone-simonesoftware-simulation.asp

This tool is developed in house at NV Gasunie and is based on the PhD thesis work of Tom van der Hoeven. The scientific basis of the optimization method is MCA (MUlti criteria Analysis) to

optimize gas flow.
Website links given: https://www.rug.nl/research/portal/publications/pub%280bbb8138-6d96-4d79-aac3-e46983d1fd33% 29.html
or from the website of the author http://vanderhoeven.biz/
or from our Norwegian colleagues http://www.ii.uib.no/forskningsgrupper/opt/forskning/PhD_Hoeven.pdf

C.1.4 Interview 4: Understanding the academic researcher's perspective

Interviewee:
The interviewee is attached to the Economics of Infrastructures section of the Faculty Technology, Policy and Management, TU Delft, as an associate professor. The professor's current research theme involves an Economic/institutional approach to public policy and private strategy development and analysis in infrastructure-bound sectors (particularly oil, gas and water). he has vast experience and knowledge in the field of natural gas infrastructures.

Place and Time of Interview:
The interview was conducted Room number: C3.1XX at Faculty Technology, Policy and Management at 12:00 PM 29th April.

Interview Topics and Discussion Summary
There were different topics that were discussed during this interview. It was open-ended and the questions were directed to get better understanding for the research. Some of the topics and questions covered were,

Question 1: Who are the different stakeholders involved in gas network planning?

According to the Professor, there were multiple stakeholders in addition to the ones identified in the research who can actually play an important role in network planning of gas grids (both natural gas and biogas).

Waterschap NL handle the collection of the wastes from the households across Netherlands and they have their network of incumbent pipe structures that collect these waste water from the municipalities for further treatment and eventually in some cases production of biogas.

Land owners can influence network planning as they can pose restrictions to allow the network to cross their area. They can be expensive in some cases and hence it is important to obtain land use agreements before finalising a network plan.

Local municipalities provide permission for building a network path after consulting the overview of all the existing underground pipelines that are already there in the chosen network path. A company called KLIK NL maps the underground pipes in Netherlands and tracks the existing cables, wires for all types of networks.

The DSO is obligated to allow any additional pipeline to join the existing grid if it satisfies the constraints of grid. There are some exceptional areas like heavy industrial zones and sensitive areas do not fall under this obligation.

Question 2: What factors are important when a producer wishes to inject into national grid?

The injection can happen if the operation of the nation grid is not disturbed. The grid balance has to be maintained at all times. Another important factors is the quality of gas that is being injected. In NL we have specific standard codes which needs to be met for any specific gas that is to be injected to the grid.

Question 3: What factors play a role above ground as we only want to place the pipeline underground ?

Above ground safety and accessibility plays an important role. The gas should meet the safety constraints if the pipeline crosses densely populated areas. The accessibility relates to the access to dig the ground, the closest alternative pipeline, and its less impacting if it stays close to roads rather than populated areas.

Question 4: What is the shape of the gas grid ?
At the lowest level the grid is usually fishbone structured and at higher levels it follows a ring structure.

Question 5: What is the asset base for DSO ?

The distribution and the transmission grid in NLwas planned as early in the 1960's. This was a huge investment back then. After the liberalisation of the gas markets, the DSO, TSO's are designated to maintain the grid. The DSO needs to be compensated with a fee if anyone wishes to use the pipeline for transmitting gas. If the pipeline usage is proven than the DSO can reimburse the capital from the regulators.

Question 6: What are the concerns of the farmers related to manure disposal ?

The farmers are in most cases very conservative and want to get rid of the manure at low cost. Currently due to specific regulations by the government they find is very expensive to dispose manure directly without treatment.

Question 7: So, Do you think the farmers will establish biogas plants and generate biogas and make use of their manure?

That's complex to say, as presently the farmers do not have abundant subsidy options to do so. Secondly they prefer proven methods of energy production like the windmills and CHP installations in their farms rather than biogas plants. But on the other hand, manure markets in the NL is high in the South of Holland, Friesland and it is mostly transported through trucks.

Question 8: What factors can be important while designing a gas network?

It is important to consider the gas characteristics, its quality parameters, and the pipe diameter and pressure levels. Compressor stations will regulate the pressure over longer pipelines but heir operation and maintenance is expensive.

C.2 Integrated Scientific Approaches

The top down approaches may have a disadvantage, it requires complete information and the bottom up approach has the disadvantage of being computationally inefficient. Hence some researchers use a combination of different algorithms to come up with solution. Additionally, there are attempts by researchers to devise strategic planning of networks by integrating these optimization algorithms with game theory and other socio-political concepts for decision making.

- Liu et al(2012) try to explore the multi-terminal routing of pipelines using a combination of Euclidean Steiner Trees with obstacles algorithm and Particle Swarm Optimization techniques. They observe that the proposed combination improves computer efficiency if run in polynomial time and finds satisfactory routing layouts.

- Jing et al(2008) explore a combination of graph theoretical rectilinear Steiner trees and ACO to find optimal routing paths with obstacles for Integrated Circuit design networks where there are hundreds of terminals. They also see positive results of routing layouts with multiple obstacles when run in polynomial times.

- Nguyen et al (2013) propose a game theory strategy to integrate the distributed agent based functions in smart grid planning. Agent based approach of planning helps optimization and reduces the costs of planning networks but doesn't address the conflict of interests among the actors involved. Hence they use the method of co-operative game theory where local actors can allocate their resources to the agents when conflict of interests arise and thereby facilitate network services in energy markets.

Appendix D

Appendix D

D.1 SDLC Models

There are two main types of SDLC methods that are implemented today. One of them is the traditional waterfall model which is based on a set of well defined requirements and takes much longer for development (see figure D.1). This model creates a software product which meets all the requirements of the customer int he first iteration itself. Any new requirements are considered for development only after the first iteration. This leads to longer SDLC cycles and less flexible options for the customer.

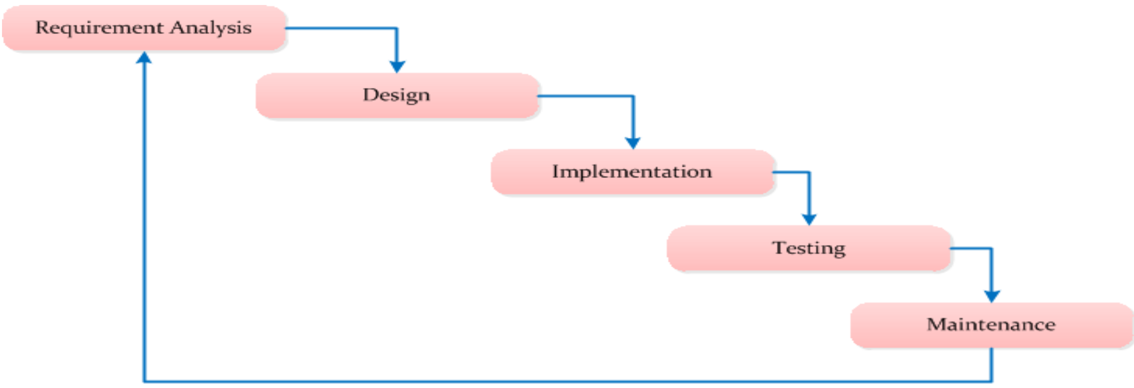


Figure D.1: Waterfall Model

The other form of SDLC used is the ”Agile” based model (Davis, 1993)which runs in small iterations and starts software development in small cycles (see figure D.2). This method ranks the most important requirements of the customer and starts building the product. A working prototype of the first iteration is already provided to the customer. The process has less stringent rules than the waterfall model and the customer experiences the product functionality much earlier. Short sprints of 2 weeks are taken up and the team conducts daily sprint meetings for updates and all the phases of the SDLC model take place within the 2 weeks. Thus at the end of each sprint, a finished product is delivered and the iterations are further continued.

D.1.1 User Profiles

User Profiles determine what specific users can see and do in the user tool.There are 3 types of users who can interact with the tool. Each of these users have different level of access to the tool based on their roles.They are broadly classified as tool administrators, project administrators and guest users.

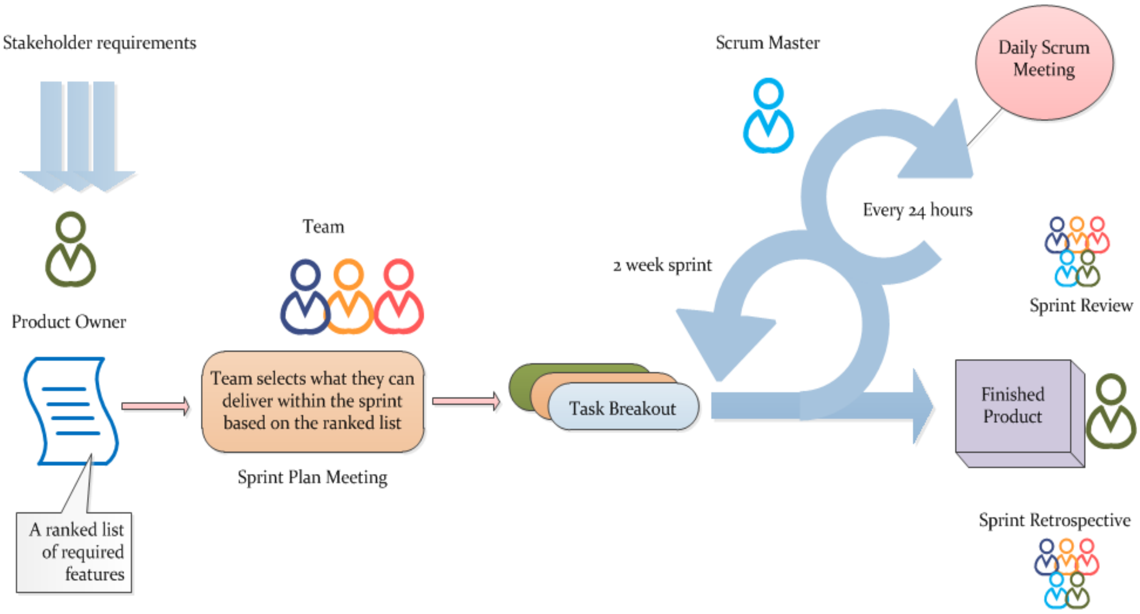


Figure D.2: Agile based scrum model

Tool Administrator: Tool administrators have full control access over the entire application. They are responsible for managing the entire application and all the users who can access the application. The people responsible for building, testing and maintaining the application are listed as tool administrators. If necessary, during development phase more subtypes can be created to restrict user access.

Project Administrator: Project administrators have full control access over the specific projects that they have created. They are responsible for managing all the properties of a specific network created. These users can be network planners like the DSO, TSO or third party grid operators. Also the municipality can act as the user creating new networks.

Guest User: A guest user has a controlled access to the application and they can only view some specific projects which are created by other users.

The user rights specific to each user are given in the table

D.2 Use Cases and User Interface

This section will deal with the actual use cases based on the overall functionality and give more details on the user actions,navigation's, screen designs which will relate to the overall visualisation of the tool.

Scenario: Create/Modify a network, analyse, save and export results

The first scenario relates to a user (project administrators) to build/modify a new energy network in a given area, analyse the simulation results, save a specific network layout and export the results. Figure D.3 shows black box specification of the scenario.

Scenario description:
The main objective of the user is to build and operate a cost-efficient network and ensure the network integrity of the grid. For any new network like a biogas grid to be built the simulation will need specific input parameters from the users. The input parameters can be provided in the form of data or in the form of a graphical layout.

Users /Access Rights	Tool Administrators	Project Administrators	Guest users
Access to all the files	Y	X	X
Access to files created	Y	Y	NA
Access to files with permission	NA	Y	Y
Create,edit and delete files	Y	Y	X
View existing files	Y	Y	Y
View,edit,set and update property values	Y	Y	X
View property values	Y	Y	Y
Manage saved files and back end functionalities	Y	X	X
Manage saved files	Y	Y	X
Import files	Y	Y	X
Export files	Y	Y	Y
Edit and manage user profiles	Y	X	X
Edit own profile	Y	Y	Y
Access favourite views	Y	Y	Y

Table D.1: User rights

1.A text format of input parameters receives direct input from the users and runs the simulations to fetch the final results.

2. A graphical format of an input gives flexibility to the users to design a given network layout themselves first and then fetch the results based on the algorithm functionalities. Thus this flexibility allows the users to compare their results with the results of the scientific approaches.

Based on the input parameters provided, the tool gives an overview of both the simulation runs that are optimal in nature and meet the objectives of the user. The user can further analyse these results, save them or even export them if needed.

Figure D.4 gives an overview of the Use case diagram where each use case is synthesising the necessary interactions represented by them in their names. The use cases are written in the perspective of the user ”Project Administrator”. Use case names are chosen to express the goals of the tool. In the figure D.3 <<include >>dependency represents additional functionalities which need to be achieved before the use case is executed. For example, user needs to log-in to their Id in order to save the results. The <<extend >>dependency represents additional functionality for specific use cases. The use case ”Output Results” is supported by other functionalities like ”email”,”export” and ”print”.

Use Case 1.1: Search for global data files (Additional Functionality)

Description:
The platform enables the user to search files that have specific global data sets uploaded to the application.

Used by:NA

Actors:
Project Administrator

Triggers:
Access to the available global data files in the application

Preconditions:

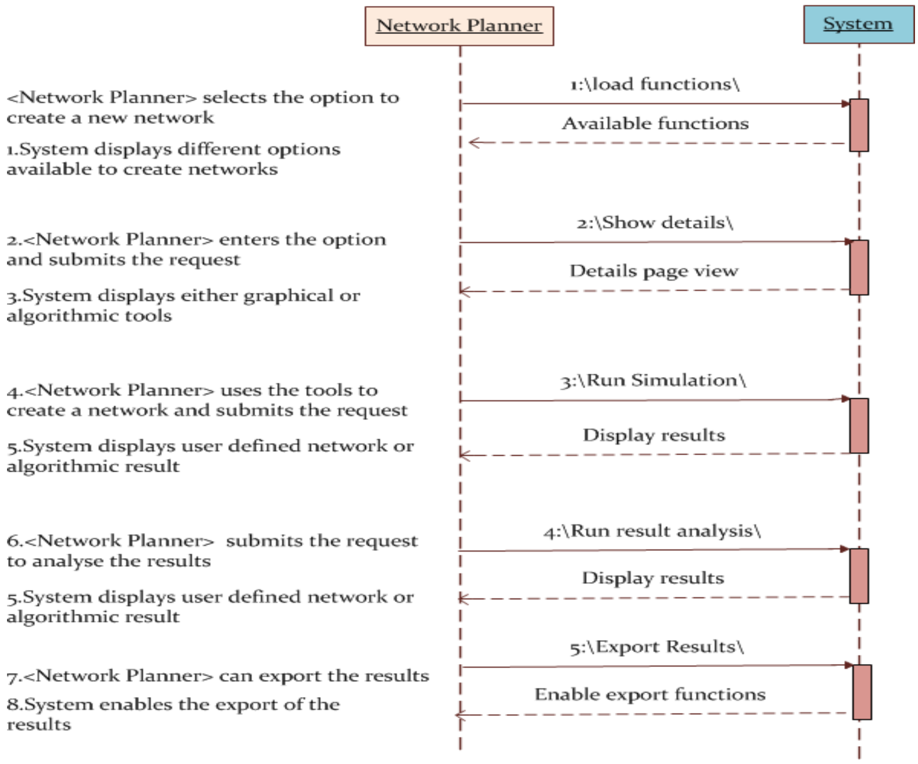


Figure D.3: Sequence Diagram showing black box specification

The user should have appropriate access to the pages/tools

Basic flow:
1. The user logs in to the application.
2. The system should allow the user to select different options to perform on their log-in.
3. The user selects the option to search available data sets/global data files.
4. The user enters a keyword in the search bar and submits the request.
5. The system looks for specific results and presents the user with all the relevant options in a list format. Along with it, the system also gives a separate pane on the left side with facets which can narrow down to specific results.
6. The system must provide filter functionality to select specific categories and search again.
7. The user can also search based on specific dates along with keywords.
8. The user can select a specific file and open it.
9. The system should provide the user an option to open the file in the application view or allow it to be downloaded to the local machine

Exceptions:
1. The system should pop up messages after every successful action.
2. If the user misses to feed data in required fields, pop up messages must be prompted to fill those fields.

Post conditions:
The user navigates the facets pane to choose specific categories to narrow down the search. The user is allowed to modify the keywords text anytime and search again.

Additional requirement:NA

Use Case 1.2: Create a new network

Description:
The platform enables the user to create a new network layout

Figure D.4: Use case diagram for project administrator

Used by:

Actors:
Project Administrator

Triggers:
Access to the specific tools/pages to create a network layout

Preconditions:
The user should have appropriate access to the pages/tools

Basic flow:
1. The user logs in to the application.
2. The system should allow the user to select different options to perform on their log-in.
3. The user selects the option to create a network layout.
4. The system should ask the user if they want to graphically create a network or create it using scientific approaches or both.
5. If the user selects a graphical option, the system should provide the user access to the graphical pane and the tools needed to create the network.
6. If the user chooses otherwise, the system should provide the choice of different algorithms and prompt the user for specific data input.
7. On simulation runs, in both cases, the energy network layout is created and displayed to the user.
8. The user should also be given set of analysis for the resulting networks.
9. The user can further modify these resulting networks if required.
10. Else, the user can save and export the results.

11. The system should allow the user to specific access for the user to export the results.
12. In case the user wishes to analyse and compare different results, the system must provide access to the user to do so.
13. The user can either save or export the results.

Exceptions:
1. The system should pop up messages after every successful action.
2. If the user missed to provide data in required fields, pop up messages must be prompted to fill those fields.

Post conditions:
The user navigates to create a new network or quit the application

Additional requirement:NA

Use Case 1.3:Output results

Description:
The platform enables the user to export or print the results

Used by:

Actors:
Project Administrator

Triggers:
Access to the directory of the users profile where all the results of the respective users are saved.

Preconditions:
The user should have appropriate access to the pages

Basic flow:
1. The user views different results in their specific directory.
2. The user analyses the results and selects the option to export the results.
3. The system responds by navigating to the output result page.
4. The system should respond 3 different options to export the results,"Export", "Print", "Send" .
a. To export the results , system provides 2 drop down menus to the user, one is for the "export format" and the other one is for selection of "output types".
1. Results can be exported in multiple formats such as PDF, JPG, Text, CSV, Excel depending on the type of data.
2. The result outputs can be in different formats such as data extracts , statistical results, graphs, maps, or a comprehensive report of an analysis.
3. The system allows the user to save the results in the directory as well as download them to the local system.

b. To print the results, system provides a drop down to choose a format for the result and a link to the locally connected printer.

c. To send an email of the saved results, the user is prompted to fill in the specific details of the email recipient and the output format to be attached.
1. To(Email recipient)
2. CC
3. BCC
4. Subject
5. Body of the email
6. Sender email address
7. Email format(HTML or text)

5. The user fills in the specific output type based on their preference.

6. The user provides the specific details for each output type selected.
7. The system responds to the specific actions.

Exceptions:
1. The system should pop up messages after every successful action.
2. If the user missed to provide data in required fields, pop up messages must be prompted to fill those fields.

Post conditions:
The user navigates to the results page

Additional requirement:NA

Use Case 1.4:Analyse the results

Description:
The platform enables the user to analyse the results achieved in each simulation run. The user can also compare across different results and save them separately as well.

Used by:

Actors:
Project Administrator

Triggers:
Access to the directory of the users profile where all the results of the respective users are saved.

Preconditions:
The user should use the application to create network layouts.

Basic flow:
1. The user either creates an energy network in the graphical format or uses the spreadsheets method or both.
2. The user selects the option to analyse the results(network layouts).
3. The system should provide the analysis of a specific network based on the performance criteria.
4. The analysis can be either in tabular or graphical format.In cases where statistical tests are triggered respective results should be shown.
5. If the analysis is comparative in nature, the system should allow the user to select different networks. 6. Both the networks should be analysed based on same performance criteria.
7. The system should provide the analysis results in the form of tabular or graphical formats. In cases where statistical tests are triggered respective results should be shown.
8. The system should then trigger options to save the results and also options to export or print the results.

Exceptions:
1. The system should pop up messages after every successful action.
2. If the user wishes to delete specific results(from the analysis), system should always ask for confirmation of the action.

Post conditions:
The user navigates to the results analysis pages

Additional requirement:
The analysis function is based on users account access rights.

Use Case 1.5: Save results to user account

Description:
The platform enables the user to save the results of the different simulation runs. These saved results can be accessed by the users when they want to preview the results.

Used by:

Actors:
Project Administrator

Triggers:
Access to the directory of the users profile where all the results of the respective users are saved.

Preconditions:
The user should use the application to create network layouts.

Basic flow:
1. The user either creates an energy network in the graphical format or uses the spreadsheets method or both.
2. The user saves the results choosing a specific title to the results.
3. The user can choose to save a group of resulting networks together or save them separately as well.
4. The system saves the results in the user profile.
5. The system has to notify to the user with a message on successful action.
6. If the user tries to search the "saved results", clicks on the button" "Search saved results".
7. The system navigates to the user directory where all the results are saved by the user previously.
8. The system responds to the user with all the details of the search results

    1. Title of each result.
    2. Last saved date.
    3. Last accessed date.
    4. Type of file.
    5. Result level-Parent/Child(either as folders or as files)

9. The system must allow the user to either select or delete specific entries.
10. If the user selects specific result to view, the system should navigate to specific page.
11. If the user selects specific result to delete,display a pop up message requesting to confirm and on confirmation display a message.
12. If the user aborts the selection,the system returns to previous view.

Exceptions:
1.The system should pop up messages after every successful action.
2.If the user wishes to delete specific results in a directory, system should always ask for confirmation of the action.

Post conditions:
Search result is stored in user profile and is shown when the user clicks on "Last preview results"

Additional requirement:
The list is presented based on users account access rights.

Use Case 1.6: Preview last viewed results

Description:
The platform enables the user to access last viewed results .

Used by:

Actors:
Project Administrator

Triggers:
Navigating to last saved results of the user.

Preconditions:
The user should have previously navigated to a results page which was saved as the users last viewed result.

Basic flow:
1. The user clicks on the button ”Last preview”.
2. The system provides list of ”last saved previews”.It contains specific details like

   1. Title
   2. Last saved date
   3. Network details(Performance Criteria)
   4. Remove ”preview from saved results”

3. The user selects a specific preview.
4. The system navigates to specific preview.
5. The user selects to return search result page.
6. The system navigates to the search result page.
7. The list of ‘last saved previews’ is displayed.

Exceptions:
If the user has deleted all entries, the system should pop up an informative message.

Post conditions:
The list is displayed in any ”last saved previews” and ”search result page” as long as the user does not delete it.

Additional requirement:
The list is presented based on users account access rights [1]

D.3 Screen prototypes

[1]Cover Image Courtesy: http://www.jsg.utexas.edu/lacp/files/PGC_Pipeline_Data.jpg

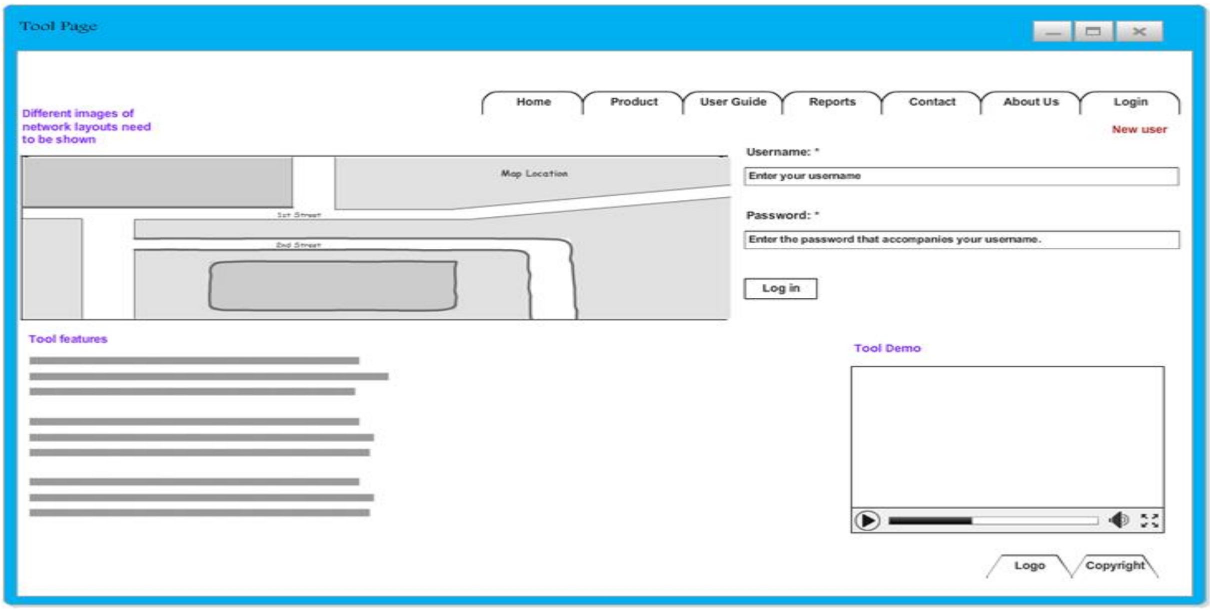


Figure D.5: Opening page and Login

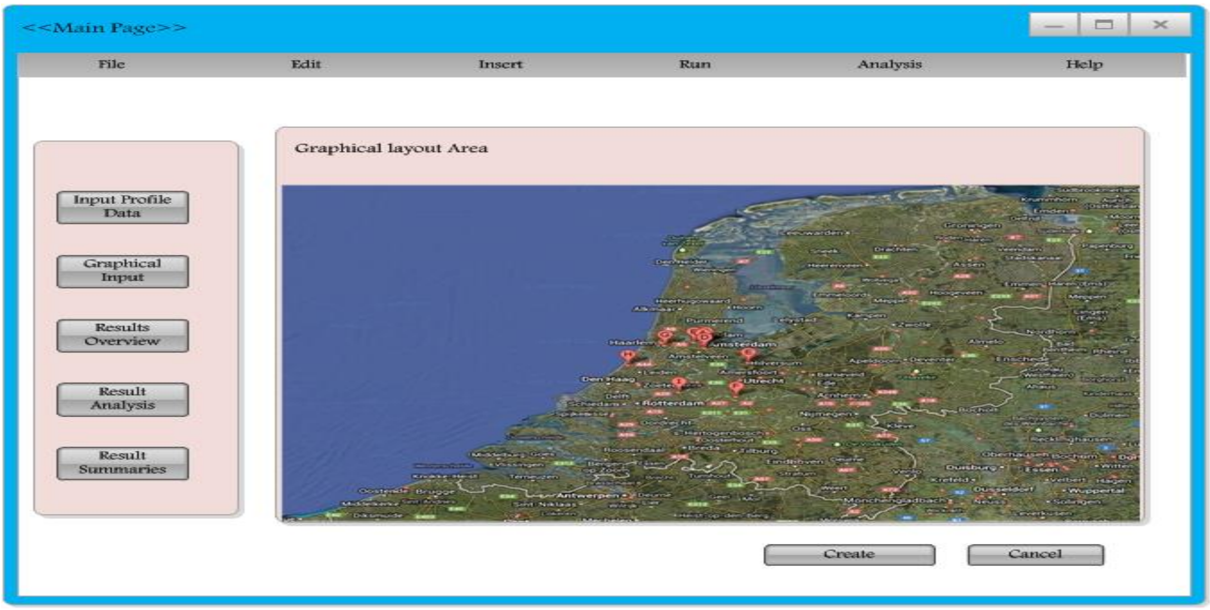


Figure D.6: After Login:Network Layout Screen

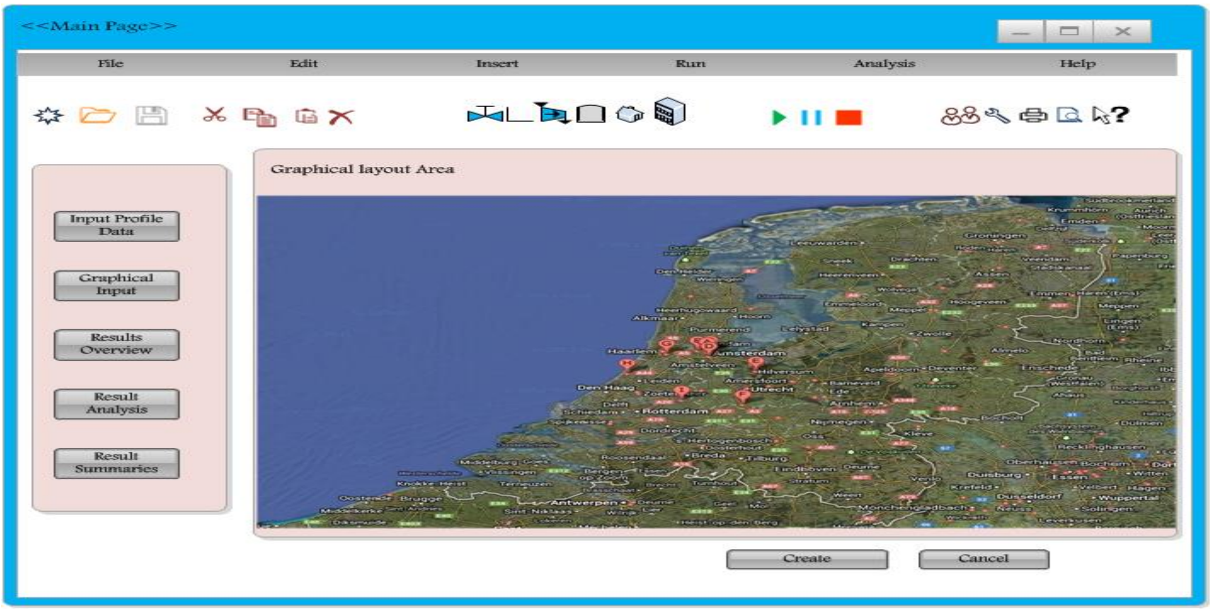


Figure D.7: Network Layout Screen:UI with quick icons

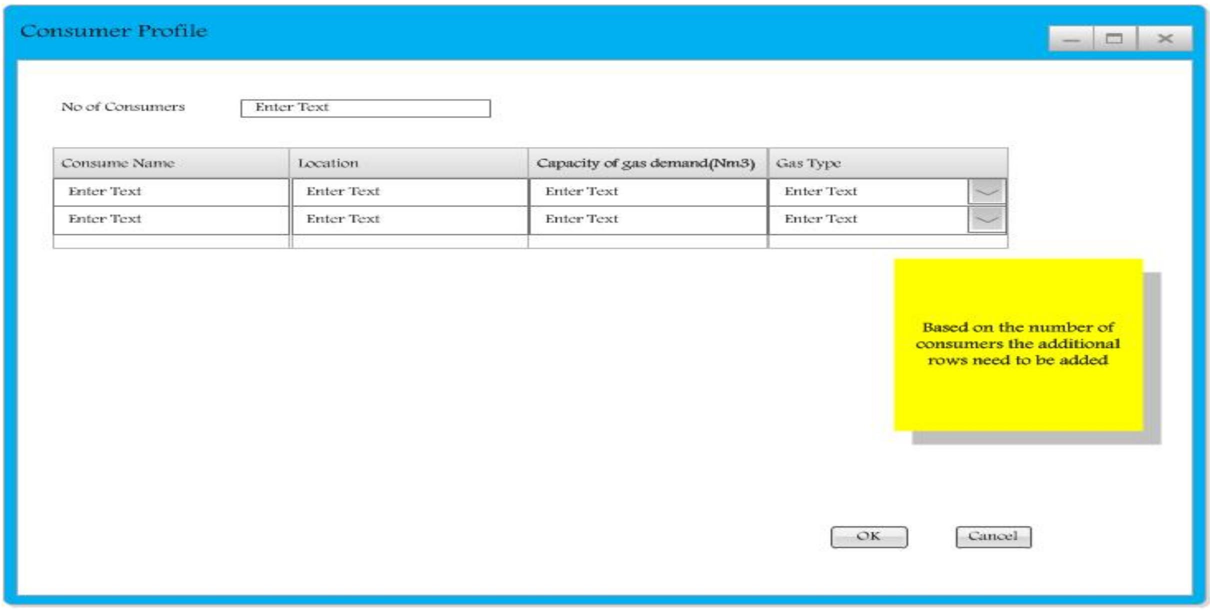


Figure D.8: Network Layout Details Screen:Consumer Profile data

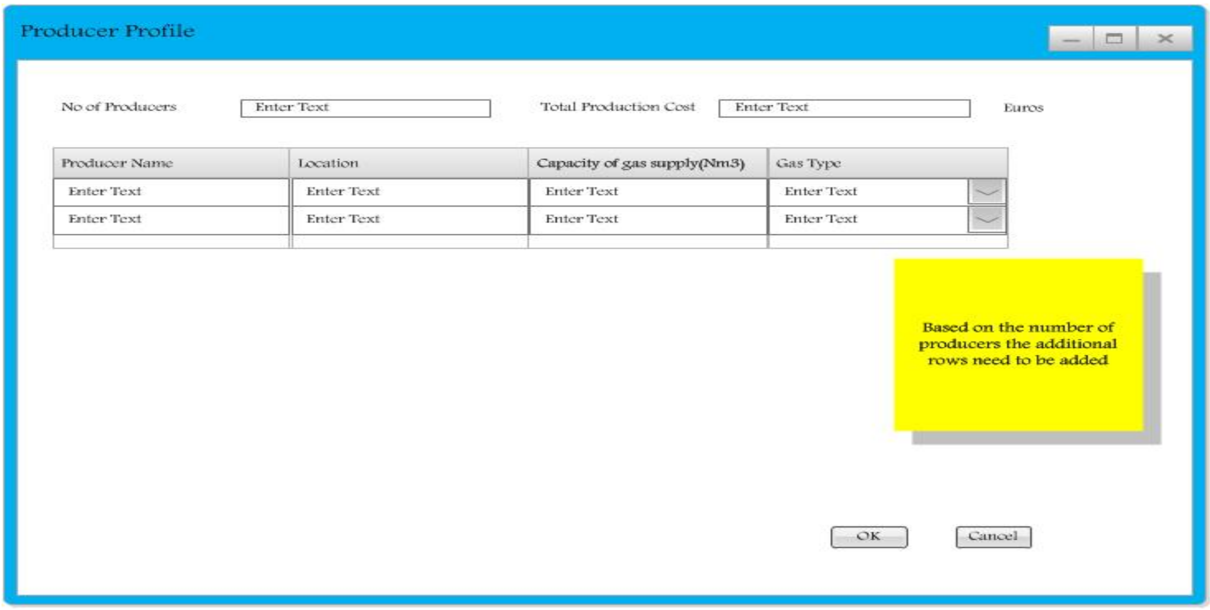


Figure D.9: Network Layout Details Screen:Producer Profile data

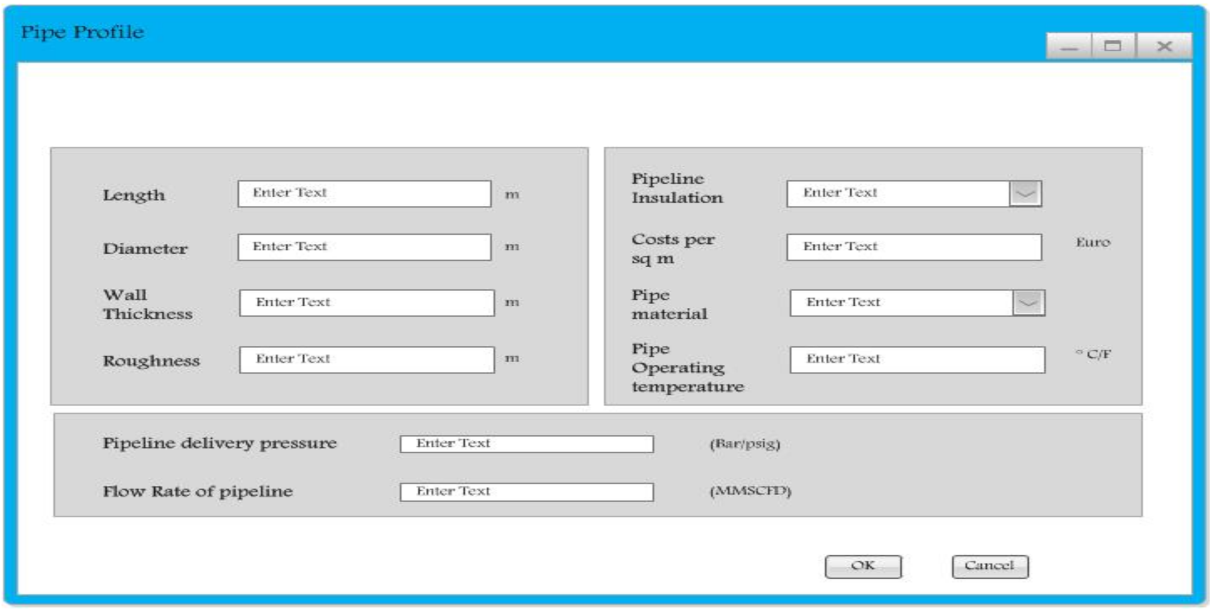


Figure D.10: Network Layout Details Screen:Pipe Profile data

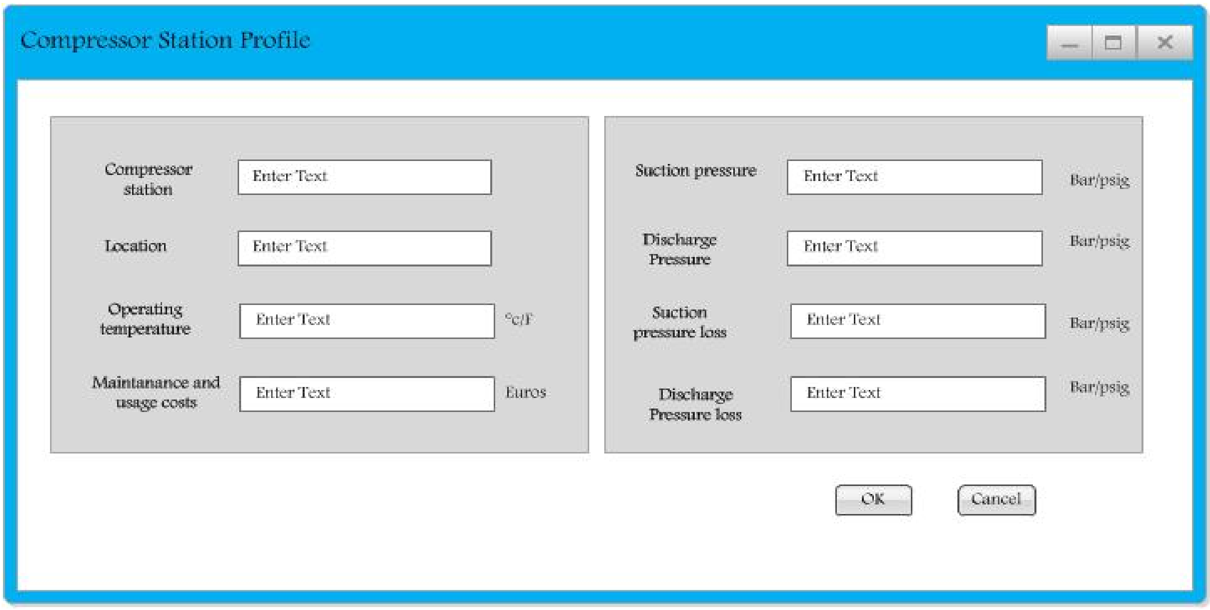


Figure D.11: Network Layout Details Screen:Compressor Station Profile data

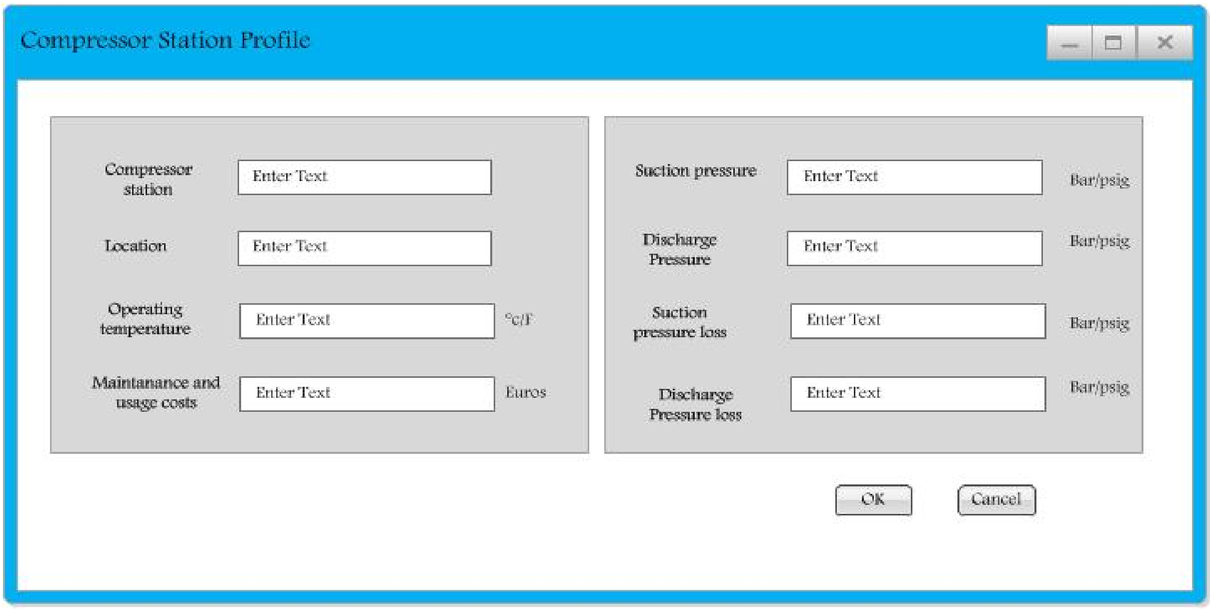


Figure D.12: Network Layout Details Screen:Compressor Station Profile data