Uncertainty in electrified industrial systems

Towards a method for the identification and exploration of uncertain factors

Master Thesis report

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Preface

This report presents the final product of my master thesis. The master thesis is developed to partially fulfil the requirements of the Master of Science degree in Complex System Engineering and Management at the Delft University of Technology. This research considers the development of a method to identify and explore uncertain factors in electrified industrial systems. The dilemma between the deep uncertain factors related to electrification investments and the societal renewability objectives was an intriguing topic to study. The research was performed in collaboration with the Dutch energy utility provider Eneco and the industrial companies involved in the FlexNet project.

This thesis could not have been completed without the support of several people. First of all, I would like to thank my committee. I would like to express my thanks to Rob Stikkelman, my first supervisor from the Tu Delft. Rob Stikkeman introduced me to the topic. Our meetings were very valuable for the structure of my research. I enjoyed these meetings as we always added some humour in our conversations. I would also like to thank Jan Kwakkel, my second supervisor from the Tu Delft. Jan Kwakkel helped me a lot with questions regarding 'uncertainty in decision-making'. His direct and clear feedback helped me to structure difficult and abstract uncertainty concepts in this research. I also would like to thank Andrea Ramirez-Ramirez, the chair of the committee from the Tu Delft. Her critical reflections on the scientific narrative during our meetings have greatly improved the quality of my work. And last, I would like to thank Roald Arkesteijn, the company supervisor from Eneco. His enthusiasm and industrial knowledge helped me in this research. I enjoyed all the different energy-related conversations we had. I also valued our off-work discussions.

Secondly, I would like to thank all the interviewees of this thesis. Without them, I would not be able to conduct this research. I also would like to thank all my colleagues at Eneco, especially Floor, Jesse and Jilles. They helped my gaining new insights and knowledge.

Lastly, I want to thank family and friends in their support during the off-work hours. Special gratitude goes to my girlfriend Lizet, who supported me throughout my master. I also want to thank my parents, Sylvo and Yvonne, and my brother and sister, Romain and Marie-Claire, for their interests and help.

Overall, writing the thesis was interesting and rewarding, but also a big challenge. I really enjoyed focussing on a specific research topic for a longer time. Hopefully, with this thesis, I have contributed to the state of academic knowledge by providing a valuable method for future use.

Maurice Thijsen
Delft, 17 November 2018

Summary

Industrial companies use lots of energy resources for maintaining their industrial processes. In order to reduce CO_2 emissions and provide continuity to the energy transition, it is important that the industrial sector electrify their processes. An important aspect of why the industrial actors have not invested in electrification technologies is due to uncertainty in these investment decisions. Future research by analysts is required to explore the potential of electrified industrial systems in their uncertain environments. To enable research to uncertainty, an appropriate method to identify and explore uncertain factors for analysts is required. Given the characteristics of an industrial cluster, a bottom-up approach specific for industrial systems is necessary to identify and explore uncertain factors for scientific research. This resulted in the following research question.

How can analysts be supported in the identification and exploration of uncertain factors in electrified industrial systems?

The product of this thesis is the Industrial uncertainty scan, to support analysts in the identification and exploration of uncertain factors in electrified industrial systems. The method consists of the following actions:

1. Demarcate the industrial cluster
2. Define system, policy and objectives of actors
3. Identify uncertain factors
4. Select most important uncertain factors
5. Explore the dimensions of uncertainty
6. Model future range
7. Analyse the impact on system performance

When using this method in an industrial cluster, you can retrieve the most important uncertain factors. The method explored these uncertain factors based on their location, level and nature dimension characteristics. The method also explores the impact of uncertainty on the cluster system.

The research methodology used for the development of this method consists of a combination of literature analyses with a case-study application. The first literature analysis consists of analysing the uncertainty inducing system components of electrified industrial systems. The second literature analysis identifies the uncertain factors of industrial systems in literature. This analysis provides a broad overview of the possible types of uncertainties that are present in electrified industrial systems. The third literature analysis retrieves information about how uncertainty is conceptualised, identified and explored in literature. The insights gathered from the literature analyses are synthesised into a formal method. The formal method has been applied to a case-study, to demonstrate how the method works in practice and to discuss its value. The case-study consisted of interviews with industrial actors from a small entwined cluster.

The synthesis consisted of connecting the established methods, frameworks and theories in uncertainty management. Some modification for the established methods, frameworks and theories were required to study uncertainty specific for electrified industrial systems and to enable the involvement of industrial actors in the process.

The ‘system model perspective’ theory is used to identify uncertain factors. The *system* and *policy* component in the ‘system model perspective’ theory was specified for electrified

industrial systems. The cluster conceptualisation theory was used to develop the *system* component. Literature about electrification strategies was used to define the *policy* component. An argumentation line was derived from the 'system model perspective' by the author to provide a structured process for the identification of uncertain factors with industrial actors. The uncertainty content taxonomy was created to guide the identification process along different topics of uncertainty with industrial actors. The identified uncertain factors from the 'system model perspective' are used as input in the uncertainty framework to explore the dimensions of uncertainty (location, level and nature). A revision of the location dimension was needed, to assess uncertainty specific in industrial cluster environments. The location dimension revision was based on the cluster conceptualisation theory, to reflect the uncertain connections of actors in a cluster. A link was made between the assessed level dimension of uncertain factors and the paradigms for modelling the future. These paradigms are used to model future ranges of uncertain factors. These future ranges can be used as input to a Sobol analysis, to explore the effect of uncertainty of the *system* and *objectives* components from the 'system model perspective'.

When applying the Industrial uncertainty scan to the case-study, we conclude that the method meets overall the stated criteria of supporting analysts in identifying and exploring uncertain factors. The method enabled the analyst to identify and argue for a broad set of uncertain factors, using the systematic 'system model perspective' argumentation and the uncertain content taxonomy. The revised uncertainty framework in the method helped the analyst in exploring the characteristics of uncertainty in industrial environments. The criterium for creating support towards the use of the uncertain factors was partly met. The respondents sensed support because they valued the idea that they had influence on the selection of the uncertain factors. At the other hand, indications about future ranges of uncertain factors couldn't be provided by the respondents. Therefore, the modelled future ranges were heavily influenced by grey literature and assumptions of the author.

This method can be the first step towards a scientific argued overview of uncertain factors which can be used for research to electrified industrial systems in uncertain environments. This research has several limitations. First, the method should be tested more to be able to provide a better evaluation of the workability of this method. Second, future research should look more into the involvement of respondents; involving more respondents and support diversity. This could lead to a better representation of industrial actors and a broader identification of uncertain factors due to the specific knowledge a diverse group of people have. At last, the data gathering process could be improved to develop better-supported future ranges of uncertain factors.

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Part I: Research definition

1. Introduction

1.1 Societal climate objectives

Climate change has become an increasingly more important topic over the last couple of years. According to the Paris Climate Agreement, different countries across the world are taking action to reduce CO_2 emissions (Mooney, 2015). The energy sector is a large CO_2 emitter in the world. In order to decrease the CO_2 emissions, an energy transition from fossil energy to renewable energy sources is required. At the moment, a large focus in the energy transition is on providing renewable electricity to small- and medium-consumers; by providing decentralised renewable energy generation systems (such as solar panels) for home or office use and by developing electric cars with smart grid integration (Lin, Omoju, & Okonkwo, 2016).

Meanwhile, industrial companies still make mostly use of conventional energy forms (coal and gas) for the industrial processes they operate. They caused about 20% of the global CO_2 emissions in 2014, even after excluding the CO_2 emissions caused by the industrial processes itself (e.g. chemical products industries) (IEA, 2015). The industry is currently not investing in renewable energy technologies, while they are a major client to the energy sector. There is much to gain in these industrial processes and the industry could play an important role in the continuity of the energy transition.

To reduce CO_2 emissions and provide continuity to the energy transition, it is important that the industrial sector also makes use of renewable energy for their industrial processes. The focus of this research is on the electrification pathway. The electrification of industry entails the change in energy-use for the industrial processes, from conventional to (renewable) electric energy. Therefore, the electrification makes it possible for the industry to use renewable energy sources. The important question which follows is: why haven't industrial actors changed their energy needs from conventional to renewables sources, since it provides major societal benefits? This question defines the gap between the current situation and the societal preferred situation. The question forms the guiding line for the problem analysis (section 1.2) in constructing the specific research topic.

1.2 Problem analysis

A problem analysis using a literature review is conducted, to understand why industrial actors haven't changed their conventional energy needs. Section 1.2.1 discusses the current state of knowledge in literature about the policy and technology of the electrification in the industry. Section 1.2.2 explains the obstructing role of uncertainty in the decision-making for electrification investments. Thereafter, in section 1.2.3, current methods to identify and explore uncertainties are discussed. This results in the knowledge gap regarding the need for an appropriate method to identify and explore uncertain factors in electrified industrial systems.

1.2.1 State of knowledge

A transition of energy needs in the industry is required to achieve the societal renewability goals. The industry sector acts in a worldwide competitive market. Unfortunately, industrial companies are reticent to invest in renewable energy technologies. This is mainly because the renewable energy technologies are considered more expensive compared to their conventional counterparts. To achieve the societal goals of CO_2 emission reduction, the government has to intervene in the market (Lin et al., 2016; Shin & Managi, 2017).

Policy
Scordato et al. (2018) state that a sustainable transition of industries is driven by a mix of destabilising policies. These destabilising policies include creating incentives for actors in the industry sector to reorient, in order to maintain their competitiveness and meet sustainable policy goals. The destabilising policies (e.g. environmental regulations, licencing requirements, subsidies) are considered crucial for accelerating the energy transition for industrial companies. An example of a destabilising policy is the European CO_2 trading system. The European Union tried to create destabilising policies by internalising the costs of emitting CO_2 with a cap-and-trade system (Woo et al., 2017; Brink, Vollebergh, & van der Werf, 2016). Using this system, a cost incentive has been created. The cap-and-trade system caps the total amount of allowance for emitting CO_2 in the energy and industry sector and provides a mean to trade allowances between parties on the CO_2 market. The system provides incentives for companies in the energy and industry sector to emit less CO_2 since buying allowances costs extra money. On the other hand, selling allowances generates extra income. At this moment the cap is set too high, resulting in a low CO_2 allowance price and low investments in renewable energy technologies. In order to incentivise the energy and industry sector, changes in the costs of emitting CO_2 are needed.

Technology
The development of policies by governments with costs incentives for CO_2 emissions resulted in the exploration and development of renewable energy technologies for the industry sector. There are three main categories of technical options for reducing CO_2 emissions in the industry sector (Lechtenböhmer, Nilsson, Åhman, & Schneider, 2016):

- Improving process efficiency
- Improving energy efficiency
- less carbon-intensive energy supply or carbon capture and storage (CCS)

Since European policy focuses on eventually phasing out conventional energy forms like gas and coal, a major challenge exists in the electrification of the industrial processes (den Ouden et al., 2017). For the Netherlands in 2016, the industry used 656.9 PJ energy for energetic use and 557.0 PJ energy as feedstock (for the production of e.g. plastics) (CLO, 2018). The total use of electricity by the industry was 112.3 PJ. This resulted in electricity having a share of just 14.2% of the total energetic energy-use.

Den Ouden et al. (2017) defined the potential application areas for electrification using the following energy utility operations: process heat, drying, distilling/separation, sterilization & pasteurization and direct electric process input. This results in the development of the following electrification categories (van Delft & de Kler, 2017): Power-to-heat, Power-to-hydrogen, Power-to-products, Power-for-mechanical drive and Power-for-separation. Yilmaz et al. (2018) and van Delft & de Kler (2017) analysed the maturity of the different technology categories. Some technologies like ethylene production using electricity driven cracking (power-to-products) have a low maturity level and a technology readiness level (TRL) of three. The most mature category is power-to-heat, with technologies like caustic evaporation for chlorine electrolysis, achieving a high TRL of nine (actual system proven in an operational environment).

1.2.2 Uncertainty in decision-making
The previous section indicated that the policy incentives and (some) technologies are already in an advanced stage. What is currently withholding actors in the industry to invest and implement electrification technologies? In this research, we focus on the role of

uncertainty in the decision-making of such investments. Energy transition technologies for the industry entail large sunk costs. When a decision has been made to invest in such a new technology, the sunk costs cannot be recovered should e.g. market conditions change adversely in the future (Caballero & Pindyck, 1992). The dependency on future market conditions, which are not completely in your control, induce uncertainty. Therefore, uncertainty affects the riskiness of future cash flows. This results in uncertainty having a large impact on investment spending and decisions being made. When making these investment decisions under uncertainty, Atrill (2014) indicated that there may be an opportunity cost in the form of the benefits lost from later information. Decisions taken later with possible new or better information could reduce the uncertainty in decision-making and result in a higher payoff. As the industry sector acts risk-averse, the uncertainty resulted in actors ignoring or delaying these electrification investment decisions.

Uncertainty in policy, technology and economy

The studies in the literature review (section 1.1.2) support this theory about uncertainty, by concluding that the success of the electrification of industry is dependent on the future development of uncertain factors. Lechtenböhmer, Nilsson, Ahman & Schneider (2016) indicated that the relative prices between using electricity compared to sustainable biomass or CCS need to change for making electrification a competitive option. This results in the need for sufficient carbon prices, which is dependent on the (uncertain future) stance of governments and the development of their policies. Yilmaz et al. (2018) confirmed this by stating, based on the development of business cases, that financial support via future policy has a great influence on the economics on electrification projects. Yilmaz et al. (2018) also concluded that the technologies with a low maturity level are considered as uncertain factors since their future potential regarding competitiveness is uncertain. Van Delft & de Kler (2017, p.32) stated that "the true potential of electrification technologies remains uncertain because the structuring of future markets is not well understood." The dynamics in the future energy market (e.g. demand side response) could affect the effectiveness of renewable energy technologies. How these dynamics develop over time is highly uncertain.

Uncertainty in industrial environments

Industrial environments entail specific uncertainty inducing characteristics. This is because industrial companies often act within an industrial multi-actor cluster. Industrial actors have their own interests and objectives but are dependent on each other for achieving these interests and objectives. This is because the industrial processes of different actors in a cluster are entwined, as they deliver each other semi-finished products. The entwinedness and dependency of processes that are not in your control induce information asymmetry and uncertainty (Alexander et al., 2012).

Investment decisions are made on individual actor level, using actor objectives as parameters. When an actor makes the decision about changing its own system, it also affects the processes of others cluster actors (Porter, 1990) due to the entwinedness and dependency of their processes and systems. Electrification is an investment that can induce variability of industrial processes, affecting the semi-finished product delivery and processes of cluster partners. The dynamics of electrification in multi-actor cluster systems could result in uncertainty among cluster actors. This uncertainty affects the decision-making for electrification technologies by industrial actors.

Importance for future research

Although the knowledge of policy and technology regarding electrification in the industry is already in a somewhat advanced state, the states of these factors are not static. They are subject to future change and therefore uncertain since the future cannot be predicted. The literature acknowledged the obstructing effect of uncertain factors in the decision-making of electrification investments for industrial actors (using policy, technology and economic trends). The future developments of these uncertain factors are decisive for the electrification technologies to be a competitive option. Research to these uncertainties is important, as they obstruct the decision-making of electrification investments and therefore the continuity of the energy transition. In the literature review, the studies made assumptions about the future conditions (using a single static scenario) while making their technological or economic assessment. Further research by analysts should indicate how electrified industrial systems interact with a complex uncertain future environment.

1.2.3 Identifying and exploring uncertainty

To enable research to electrified industrial systems in their uncertain environments, analysts should first of all identify the relevant uncertain factors in the system. Yet, only a list of uncertain factors explains very little. Therefore, it is important to consider what the identified uncertain factors actually mean for the system of interest. The analyst should explore the characteristics of the uncertain factors. The exploration of the characteristics should provide an indication of: how are the uncertain factors caused, where are they located and how do they influence the system of interest? These are fundamental questions for providing the appropriate treatment of uncertainty in research. In literature, there are different methods available to identify and explore uncertain factors. This section considers a few applications of these methods to understand how uncertain factors were identified and explored in various studies.

Current techniques

An important approach to support analysts with uncertainty identification and exploration is scenario planning (Amer, Daim, & Jetter, 2013). Using this approach, the analyst identifies uncertainties or basic trends and creates scenarios using a causal and consistent storyline to explore the uncertain effects (Schoemaker, 1995). An often used and simple technique within scenario planning is the scenario-axis. This technique is aimed towards the identification of the two most important driving forces of uncertain factors by the user (van 't Klooster & van Asselt, 2006). By placing these driving forces along two axes in a quadrant, a structured overview of future scenarios can be generated. The scenarios could be used to explore the system in different uncertain contexts. An example of an application of this technique has been done in ethnographic research at the Dutch RPB institute (van 't Klooster & van Asselt, 2006). Using the scenario-axes approach, the project team identified driving forces of uncertainty and their respective scenarios using: discussions within the project team, Delphi consultations with experts and workshops with stakeholders. At first, all the respondents identified a large list of driving forces. Although, this process was led towards consensus. The project team selected just three driving forces from the large list. They used different criteria during the selection, e.g. *high uncertainty*, *high impact* and *strong relation with the topic*. This resulted in two scenario quadrants (axis: economic development vs. climate change, economic development vs. environmental awareness). The expert in the Delphi process had a dominant role in the identification process. Therefore, many stakeholders experienced that the scenario axes were imposed on them without their consent. Therefore, the stakeholders didn't accept the scenario axes as scenario foundation.

A more comprehensive technique to identify and explore uncertainty has been developed by PBL and CPB in the Netherlands (PBL & CPB, 2015). This technique is also derived from the scenario planning approach. Analysts of PBL and CPB used the following themes as sources for their scenario planning: demography, macro-economy, regional development, mobility, climate and energy and agriculture. Within these themes, the relevant uncertainties were identified based on literature, developments from the past and expert judgement. Thereafter, the relevant uncertainties with their respective future developments were combined into the (two) WLO scenarios (high: technological and demographical growth, low: slow technological growth and demographical decrease). The top-down scenarios are widely used by public departments to evaluate policy, but also by some private organisations to evaluate corporate strategy (Dammers, 't Klooster, & de Wit, 2017).

A different technique to identify and explore uncertain factors has been proposed by Walker et al. (2003) and Kwakkel, Walker & Marchau (2010). They developed a framework to provide a conceptual basis for the systematic treatment of uncertainty in model-based decision support. The framework defines uncertain factors using three dimensions: location, level and nature. These dimensions provide information about where the uncertain factor is located, how severe the uncertain factor is perceived and how the uncertain factor is caused. Understanding the dimensions of uncertainty helps in identifying and exploring uncertain factors in models. Refsgaard, van der Sluijs, Højberg and Vanrolleghem (2007) used this framework during their work in environmental modelling. They indicated that the uncertainty framework was a good platform to facilitate a structured dialogue between stakeholders on possible sources and types of uncertainty. It helped in creating a common understanding of the uncertainties and their importance.

Need for an adequate method

When considering electrified industrial systems, the traditional top-down scenario planning approach to identify and explore uncertainties may not be appropriate for scientific research. First of all, the systems of industrial actors are complex and unique, as well as the cluster environment where they operate in. A generic top-down scenario logic developed by an expert about the future cannot grasp the specific uncertainty of unique system characteristics in industrial environments (entwined cluster system). Second, this approach falls short in their potential when applied in a diverse multi-actor system, due to the different perceptions of the actors about future developments (Bryant & Lempert, 2010). The different perceptions could lead to ambiguity, as described in the case for RPB with the scenario-axes (van 't Klooster & van Asselt, 2006). Ambiguity is also a form of uncertainty (Brugnach, Dewulf, Pahl-Wostl, & Taillieu, 2008), as people seemed not to agree upon the identified uncertainty or its effect. A small group of experts defining these uncertainties, of which its process is meant to achieve consensus, may not encounter the ambiguous uncertainties. Third, experts defining what is uncertain for industrial actors in their system does not create support towards the use of the uncertain factors in future research (Baudry, Macharis, & Vallée, 2018).

Given these three restrictions, a bottom-up approach specific for industrial environments is necessary to identify and explore uncertain factors in electrified industrial systems. Involvement by industrial actors is important. Industrial actors have the specific knowledge about their system and their relation to the cluster. They are also experiencing the uncertainties, since they have to make the investment decisions to electrify their energy needs. Also, involving industrial actors creates support towards the use of the uncertain factors in research. A limitation is the difficulty for industrial actors to understand complex and abstract concepts as uncertainty (Refsgaard et al., 2007). Therefore, a method for analysts is required which also aid the involved of industrial actors.

Studies by Walker et al. (2003) and Kwakkel, Walker & Marchau (2010) showed that work has been done in the conceptualisation and communication of uncertainty. The uncertainty framework can be used to identify and explore uncertainty in multi-actor systems. This framework "focuses on the uncertainty perceived from the point of view of those providing information to support policy decisions, i.e. the modellers view on uncertainty" (Walker et al., 2003, p.5). Therefore, a challenge remains in involving industrial actors as input in the assessment process of this framework (instead of the modeller) and applying the framework to the specific characteristics of industrial systems. Also, a challenge remains in exploring the (quantitative) impact or influence of uncertainty on the system.

1.3 Research objectives & questions

The problem analysis indicates that research has been done regarding the policy, technological potential and economic feasibility of the electrification in the industry sector. These studies conclude that the success of the electrification depends on the future development of uncertain factors, regarding policy, technology and economy. As the industry often acts within an entwined cluster, the flexible nature of electrification induces also uncertainty among cluster partners. Since the success depends on the development of these uncertain factors and the future cannot be predicted, the industry is reticent to invest large sunk costs in these very new technologies. This is because of the risk that sunk costs cannot be recovered should unpredictable uncertain factors change adversely in the future. Research to uncertainty is important, as uncertainty obstructs the decision-making of electrification investments and therefore the continuity of the energy transition.

To enable research to electrified industrial systems in their uncertain environment by analysts, there is a need to identify and explore uncertain factors. *However, a challenge remains in providing an adequate method to support analysts in the identification and exploration of uncertain factors in these systems.* The method should embrace the specific characteristics of industrial environments while enabling involvement by industrial actors.

This resulted in the following research question:

How can analysts be supported in the identification and exploration of uncertain factors in electrified industrial systems?

In order to answer the main research question, the following sub-questions are formulated:

- *S1:* *What specific characteristics of electrified industrial systems are inducing uncertainty?*
- *S2:* *What types of uncertainty are present in electrified industrial systems?*
- *S3:* *What is the state of knowledge regarding uncertainty conceptualisation, identification and exploration in decision-making?*
- *S4:* *How to come towards a synthesis in the conceptualisation, identification and exploration of uncertainty for electrified industrial system.*
- *S5:* *What is the value of using a formal method to identify and explore uncertainty in practice by analysts?*

The product of this research is a formal method to support analysts in the identification and exploration of uncertain factors. This method is the first step towards better acknowledgement of uncertainty in electrified industrial systems.

1.4 Report outline

The report consists of three parts. The first part (chapter 1-2) entails the conceptualisation of the problem. Chapter 1 discusses the problem regarding the uncertainty in electrified industrial system. The problem analysis resulted in the formulation of a research question and its sub-questions. Chapter 2 describes the research methodology of this research.

The second part (chapter 3-6) of the research entails the development of the formal method using literature analyses. Chapter 3 elaborates on the uncertain characteristics of electrified industrial systems, while chapter 4 describes the types of uncertain factors in industrial environments. Chapter 5 explains the theoretical framework of uncertainty management. The findings from the literature analyses are synthesised and used to develop the formal method in chapter 6.

The third part (chapter 7-10) describes the application of the formal method on a case-study to demonstrate its use and to obtain observations about its workability. The formal method consists of 7 steps. Step one and two of the method is applied in chapter 7, discussing the industrial actors and their cluster environment. Step three till five of the method is applied in chapter 8, discussing the identification, selection and dimensioning of the experienced uncertain factors. Step six and seven of the method is applied in chapter 9, discussing the impact of uncertainty on the cluster system. Chapter 10 reflects on the application of the formal method and discusses the value of the method. Lastly, in chapter 11, conclusions and recommendations are provided by answering the research questions.

2. Research methodology

This chapter discusses the research methodology to answer the research question. Section 2.1 discusses the approach taken in this research. Thereafter, in section 2.2, the methodological steps used for this research are described. An explanation has been given what the methodological steps entailed and why these are essential for answering the sub-questions. Concluding in section 2.3, a synthesis has been made to describe how the different methodological steps contribute to answering the main research question. A research flow diagram is used to explain this relation.

2.1 Approach

The electrification process exists in a socio-technical environment, involving multiple actors with new technologies in uncharted policies territories. In order to gain insight in socio-technical systems, these systems should be analysed based on its technical, institutional and process components. Technical, Institutional and Process (TIP) components are connected to each other in socio-technical environments (Geels, 2004). The TIP-interdependencies approach structures the interrelations between the technical, institutional and process design of systems. This approach is used to explore the electrified industrial systems and their context.

The case-study approach is used to analyse the value of the developed formal method for the identification and exploration of uncertainty. By using a case-study, real-world information about the technical, institutional and process components of electrified industrial systems can be learned (Eisenhardt, 1989). The case-study will provide an overview of the electrification process within its broader (socio-technical) context (Yin, 2013).

Since the effects of an energy transition within the industry sector are unknown, an explorative approach will be used during the application of the formal method to the case-study. The explorative approach is used to gather insights into what could be decisive uncertain factors for the industry. The flexibility and adaptability of this approach support the unknown characteristics of the electrification process and the future (uncertain) developments (Dudovskiy, 2016).

2.2 Methodological steps

Two methodological steps form the basis for this research: *literature analysis* and *case-study research*. The literature analysis is used for constructing the formal method to assist analysts in the identification and exploration of uncertain factors in electrified industrial systems. Thereafter, the formal method is applied to a case-study to demonstrate its use and discuss its value.

2.2.1 Literature analyses

First of all, an extensive literature analysis was conducted to gain insights into electrified industrial systems (sub-question 1; chapter 3). The literature about electrified industrial systems is used to analyse what specific components or characteristics of electrified industrial systems are inducing uncertainty. In other words, it provides an indication of the unique *sources* of uncertainty in these systems. These uncertainty inducing system components need to be conceptualised, to support analysts in the identification and exploration of uncertainty in electrified industrial systems. The outcome of the literature analysis is a summary of the uncertainty inducing systems components regarding industrial electrification.

Second, a literature analysis was conducted to gain insight into what is currently identified as uncertain in industrial systems by literature (sub-question 3; chapter 5). Studies in specific fields of electrification (e.g. technology, economics) often identified constraints that could be caused by uncertain factors. These uncertain factors in literature are extracted. The TIP-approach was used as possible uncertainty axis (technology, institutions and process) while analysing the literature for uncertainty. This literature analysis provided an indication of what *types* of uncertain factors are affecting electrified industrial systems. First, this information can be used for the development of the method, to include and discuss different topics of uncertainty during the identification of uncertainty with industrial actors. Second, this information can be used to discuss and compare the uncertain factors from literature and from the method, to assess the value of the method. The outcome of this literature analysis is an overview of uncertain factors from literature, categorised based on their content.

A third literature analysis was conducted to gain insights into the current work about the conceptualisation, identification and exploration of uncertainty (sub-question 2; chapter 4). This literature analysis provided information about the currently established methods for uncertainty management in academic literature. A discussion of the literature findings has been held, about how the established method could contribute to the identification and exploration of uncertain factors, specific to the case of electrified industrial systems. As indicated in the problem analysis (section 1.2), a bottom-up approach is required, specified for the characteristics of electrified industrial systems and with the involvement of industrial actors. The methods to identify and explore uncertainty should be compatible with the specific uncertainty inducing system components and types of uncertainty in industrial environments (from the first and second literature analysis). Therefore, some modifications and connections between established methods were made and discussed. The outcome of this literature analysis was a summary of the established methods in the conceptualisation, identification and exploration of uncertain factors, made applicable for electrified industrial systems.

Table 1 presents the databases, keywords, search strategy and selection criteria used when conducting the literature analyses. The literature analyses are used for the development of the formal method to support analysts in identifying and exploring uncertain factors in electrified industrial systems. The insights gathered from the uncertainty conceptualisation, identification and exploration are synthesised with the specific characteristics of uncertainty in electrified industrial systems (sub-question 3; chapter 6).

Table 1 Literature analyses overview

Topic	*Electrified industrial systems*	*Uncertain factors in literature*	*Uncertainty*
Database	Elsevier, Scopus, Researchgate, Google Scholar & Grey literature	Elsevier, Scopus, Researchgate, Google Scholar & Grey literature	Elsevier, Scopus, Researchgate & Google Scholar
Keywords	Electrification, strategies, industry, renewable energy, policy, technology, environment, cluster, industrial symbiosis, power-to-x, power-to-heat, power-to-product, power-to-hydrogen, power-to-mechanical drive, power-to-separation	(Deep) uncertainty, risks, electrification, strategies industry, renewable energy, policy, technology, environment, cluster, industrial symbiosis, power-to-x, power-to-heat, power-to-product, power-to-hydrogen, power-to-mechanical drive, power-to-separation	(Deep) uncertainty, risk, uncertainty factors, management, scenario development, decision-making, decision-support
Search strategy	Scanning title (+ sub-titles), abstract/summary and table of content; backwards snowballing	Scanning title (+ sub-titles), abstract/summary and table of content; backwards snowballing; TIP approach as uncertainty axes.	Scanning title (+sub-titles) and abstract; backwards snowballing
Selection criteria	Specific characteristics of electrified industrial systems	Technological and economical assessment studies for electrification.	Conceptualisation, identification & exploration of uncertainty
Used literature sources	16	27	25

2.2.2 Application to case-study

In order to demonstrate the use of the formal method and to evaluate its value, the formal method is applied to a case-study (sub-question 4).

Case-study selection

The case-study had to meet several requirements for this research. First of all, it is important that the case-study entails the characteristic industrial cluster properties. As indicated in the problem analysis (section 1.2), electrified industrial systems entail some specific characteristic uncertainties regarding the dependency between industrial actors in a cluster environment. To demonstrate and evaluate how the developed formal method can cope with this specific uncertainty, the case-study should consist of a multi-actor industrial cluster with entwined process. Considering a single actor in isolation as case-study would cancel out the characteristic uncertainties. Industrial actors within the entwined cluster are used as input for the identification and exploration of uncertain factors, to enable a bottom-up approach. The industrial actors should have specific knowledge about their electrifications plans (how it is incorporated in their system) and their position within the cluster. This is important because these characteristics of electrified industrial systems are possible sources of uncertainty. Without being able to structure these sources, it would be difficult to identify uncertain factors. Given these requirements, the Flexnet project of the Tu Delft is selected as case-study.

Case-study description
The Flexnet project explores the potential of electrification for industrial systems. Three industrial companies are involved in this project: AkzoNobel, Huntsman and AirLiquide. These companies already have ideas about electrification investments to increase their sustainable energy-use. The companies are located in the Botlek, the Port of Rotterdam. The large industrial activity at the port produces lots of emissions. CO_2 emissions of the industries at the port consist of 15% to 20% of the total national CO_2 emissions in the Netherlands (Mebius, 2017). To reduce the amount of emissions produced at the port, The Port of Rotterdam maintains a progressive emission policy. Already in 2007, the Port Authority set ambitious goals of reducing the emissions of both the port and its industrial cluster by 50% in 2025 and by 60% in 2030 (compared to levels of emission in 1990). The Port Authority commissioned the Wuppertal Institute to analyse decarbonisation pathways, including the role electrification could have in the future (Samadi et al., 2016). An explorative study by the Tu Delft, Deltalinqs and Havenbedrijf Rotterdam shows that the Port of Rotterdam, and the Botlek area in particular, has a high potential for using renewable flexible electricity (t' Noordende, Stikkelman, Postema & Snaterse, 2017). The progressive policy of the port, the high potential for flexible electricity use, the specific electrification investment plans and the entwined processes makes the three companies located at the Botlek an interesting case to demonstrate and test the value of the formal method.

The Flexnet project uses linear modelling to optimise the use of energy (conventional energy versus electricity and by ramping up or down processes or generators) to find the financial optimum for the three companies in the case-study. Systems are subject to external influences, which cannot all be modelled. This research contributes to the Flexnet Project by developing a formal method to support the analysts in identifying and exploring the uncertainty space of the three participating companies. The uncertainty space provides insights into possible scenarios for the Flexnet models, to calculate the optimum energy-use under different uncertain future contexts.

Involvement industrial actors
Industrial actors were involved in the identification and exploration process of the formal method. Therefore, semi-structured interviews with the industrial actors were held during the application of the method. Semi-structured interviews provided the flexibility for identifying and exploring uncertainty with industrial actors while maintaining a structured (model perspective) style (Gill, Stewart, Treasure, & Chadwick, 2008; Wilson, 2014). Uncertainty is time-dependent. Looking further into the future results in more severe experienced uncertainty. Therefore, during the semi-structured interviews, a timeframe of 2030 was used for the identification and exploration of uncertain factors. This timeframe was chosen due to the time it takes to implement economic decisions. Economic investment decisions taken between 2018 and 2023, will be available and ready around 2030 (estimated). This means that the current electrification investment decision has to compete in a socio-technical (uncertain) environment of 2030.

Discussion criteria
The application of the formal method on the case-study is used to discuss its value in practise. Observations about the workability of the method are gathered during the application. A discussion will be held if the formal method, with its theoretical foundation, supported analysts with the identification and exploration of uncertain factors in electrified industrial systems. The following criteria, based on the method requirements in section 1.2.3, were used to reflect on the value of the formal method:

- The formal method should support the analyst in the identification and argumentation of a broad range of uncertain factors in electrified industrial systems.
- The formal method should support the analyst in exploring the characteristics and the effects of uncertainty in electrified industrial systems.
- The formal method should create support towards the use of the uncertain factors in research to multi-actor industrial clusters.

The application of the formal method on the case-study is conducted in chapter 7 till chapter 9. A discussion on the method's value is provided in chapter 10.

2.3 Conclusion

The research flow diagram synthesises the methodological steps (Figure 1). The large boxes illustrate the actions in this research: *analysing literature*, *synthesising findings*, *applying to case-study* and *reflecting on method*. These action boxes consist of smaller boxes. The smaller boxes define the content of the action, including their corresponding chapter within this research. The arrows in the diagram present the products produced from these actions.

The end-product of this research is a formal method to support analysts in the identification and exploration of uncertain factors in electrified industrial systems. Literature analyses are used to develop the formal method. The literature analyses consist of three chapters. First, literature about industrial systems is analysed to identify the specific system components of electrified industrial systems. Second, uncertain factors are retracted from literature to generate an overview of the types of uncertain factors in industrial systems. Third, the literature about uncertainty is analysed to gather insights about the conceptualisation, identification and exploration of uncertainty. The insights from the three literature analyses are used for the development of the formal method. The method is applied to a case-study for demonstration and to gather observations about the workability. The case-study consists of a small entwined cluster involving the companies AkzoNobel, Huntsman and Airliquide located in the Botlek. The observations are used to discuss the value of the method.

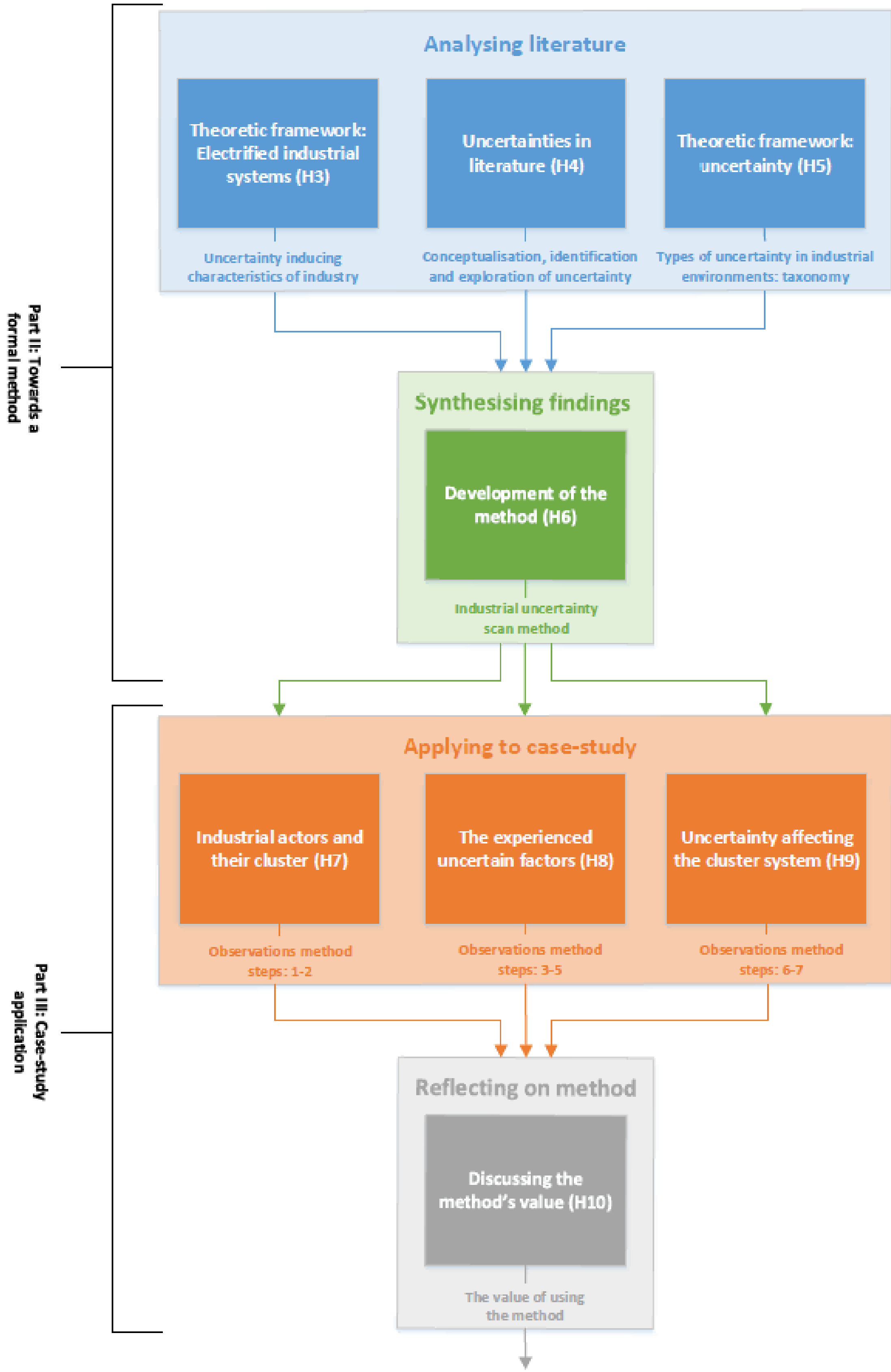


Figure 1 Research Flow diagram

Part II: Towards a formal method

3. Theoretic framework: Electrified industrial systems

This chapter describes and demarcates the industrial cluster system in combination with its electrification processes. This information helps in identifying what specific system characteristics are inducing the uncertainty and how they affect the electrified industrial systems. A literature analysis is used to gather this information. First, section 3.1 explains the concept of industry for this research. Section 3.2 describes how an industry acts within its cluster environment and how the link between cluster partners induce uncertainty. Thereafter in section 3.3, the electrification strategies with their uncertain effects on the cluster environment are elaborated. Lastly, a conclusion is provided in section 3.4.

3.1 Defining industry

The definition of 'industry' differs across countries. In Anglo-Saxon countries, the industry is defined by market-oriented activities. In this research, we use the Dutch definition of industry to describe the sector. The industry sector covers the large-scale production of materials or products. The productions processes of the industry sector generally consist of a transformation of raw materials or semi-finished products to end-products or new semi-finished products using a mechanised (automated or robotised) supply (Geertsma, 2013). The industry can be categorised by *the process industry* (production of materials or semi-finished products) and the *discrete product industry* (production of end-product) (Rouse, 2017).

In this research, the focus is on the process industry. The process industry uses a lot more energy resources compared to the discrete product industry. The process industry is in some definitions also categorised as 'energy intensive Industry' (or 'heavy industry'), while the discrete product industry is categorised as 'non-energy intensive industry' (or 'light industry'). The process industry also uses more conventional energy sources (natural gas, coal) compared to the discrete product industry (mostly electricity) (IEA, 2017). Therefore, the electrification of the process industry is a major challenge.

3.2 Cluster cooperation

The process industry is often concentrated in clusters. Porter (1998, p.81) describes the industrial cluster as "a host of linkages among cluster members" which "results in a whole greater than the sum of its parts". There are several benefits for firms when acting within an industrial cluster. First of all, a cluster allows industrial companies to have better access to employees and suppliers. A cluster consists of a pool of specialised and experienced employees. A cluster also provides access to suppliers for e.g. materials or transportation. The search for employees and suppliers in a cluster results in lower transaction costs and risks (due to local reputation) compared to a non-cluster environment. Second, in some cases, clusters are a better alternative to vertically integrated firms. Outsourcing of activities is in some instances more cost-efficient. A cluster provides the opportunity to work together with other local firms. Also, working together with others located nearby could result in synergy benefits (Porter, 1998).

In order to define a cluster and its boundaries, a conceptualisation can be used. Brown et al. (2007) build upon the description of a cluster by Porter (1998). Brown et al. (2007, p.6) argued that "a cluster should be viewed as a "value adding web" which can be understood as series of linkages between single firms and institutions in a defined interactive space." This implies that all actors are influencing each other and affect the value creation within the 'value adding web'. Industrial actors have their own interests and objectives but are dependent on each other for achieving these interests and objectives. This is because the industrial processes of different actors are entwined, as they deliver each other semi-finished products. Although, *decisions are not made on a cluster level but on individual actor level* using actor objectives as parameters. This results in a miss alignment of levels between the collective entwined cluster system and the individual actor objectives and decision-making. When an actor makes decisions about changing their system (actor level), it affects the cluster structure and therefore the processes of others (cluster level) (Porter, 1990). A single actor within the cluster does not only produce its own value. The misalignment of levels is visualised in Figure 2, with the arrows presenting its connections.

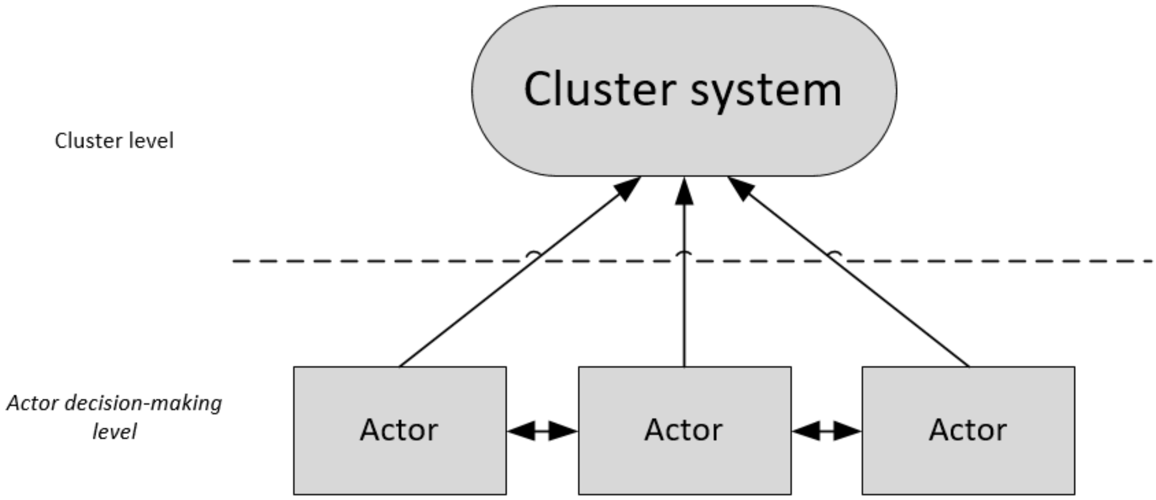


Figure 2 Misalignment of 'system' and 'decision-making 'level

Brown et al. (2007) conceptualised the interdependent connections in an industry cluster using a framework. The following description is used to conceptualize an industrial cluster:

"A cluster is a connection of horizontal, vertical and lateral value-adding activities contributed by different actors in proximity to one another which all act in relation to a specific industry. Together the actors are building a value adding web which defines the boundaries of the cluster. Direct and indirect interactions take place between these actors which may be reflected in strong, medium or weak links" (Brown et al., 2007, p.7).

The Brown et al. (2007) indicated that actors within a cluster can be categorised into horizontal, vertical and lateral actors. Horizontal actors are the central players in a cluster, producing the main product. Depending on the difference in the production of main products, a cluster can be divided into smaller groups with each producing a specific branch of main products (e.g. oil and steel sub-cluster). The 'value adding web' consists of many different sub-groups, which are connected to each other when considering the whole cluster. Vertical actors are the suppliers and/or buyers of the main products produced by the horizontal actors (e.g. plastics in the oil sub-cluster). The lateral actors are the institutions which supports the firms in a cluster with their performance (e.g. universities or cluster managers). Lastly, the connections between the actors have been conceptualised. The connections in a cluster can be divided into direct and indirect links. Direct links occur when two industrial firms within a cluster act directly with each other.

Indirect links occur when an intermediate act between two firms. The conceptualisation of the industry cluster is presented in Figure 3.

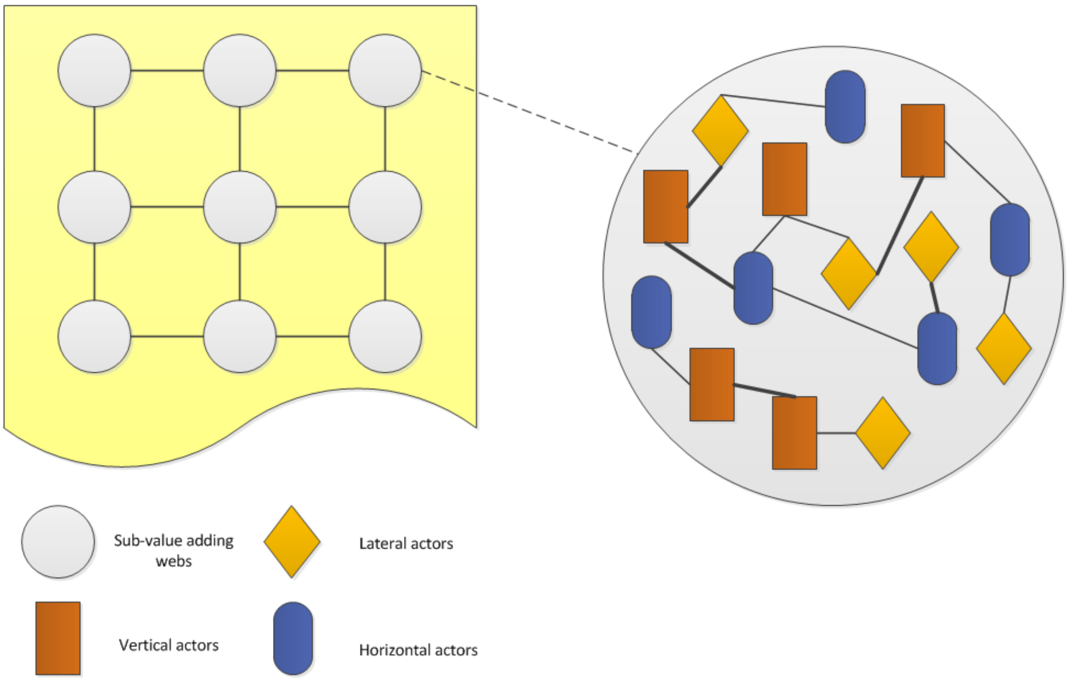


Figure 3 Cluster conceptualisation theory (recreation of Brown et al., 2007)

The conceptualisation of the cluster by Brown et al. (2007) can be used to analyse and demarcate the industry and its cluster environment. The conceptualisation shows the dependency between actors within a cluster. Therefore, the individual competitive advantage does not only depend on the firm-specific competencies, but is also the result of the ability to organise the whole value creation in a cluster. *The dependency and entwinedness between companies induce uncertainty among cluster partners.*

3.3 Electrification strategies

The electrification of the industry entails the transformation of using conventional energy to electricity. As discussed in the introduction, renewable energy using e.g. solar panels or windmills is generated in the form of electricity. If the industry wants to use renewable energy, their industrial processes need to electrified. There are two different strategies to electrify the processes of the industry (den Ouden et al., 2017):

- Flexible electrification: This strategy takes the intermittent characteristics of renewable energy generation into account. The technologies corresponding with this strategy is able to start and stop, ramp up and ramp down, or is able to switch between electricity or other energy forms. The flexibility of the production is depended on the fluctuations in output of the renewable electricity supply (Lewis & Nocera, 2007). Using the flexible electrification strategy, the processes are driven by demand-side response. When the demand for electricity is high compared to the supply, the electricity price increases (Albadi & El-Saadany, 2008). This results in industrial processes being stopped or ramped down. When the demand is low compared to the supply, the electricity price decreases. This result in industrial processes being started or ramped up. The industry could act as a balancing market for the electricity system (Schiffer & Manthiram, 2017). The operating hours for electrified technologies depend on the intermittent renewable electricity supply, combined with the variable hours of low electricity demand. These factors entail natural and social-economic characteristics and are affected by deep uncertainty.

- Baseload electrification: This electrification strategy entails a constant electricity supply for industrial processes. The baseload strategy is not attuned to the electricity system of the future. This is because it does not support the intermitted characteristics of renewable electricity supply (Albadi & El-Saadany, 2008). When available, renewable electricity is used, but at other moments conventional electricity supply will be used. There is a certain risk that using conventional electricity for electrified industrial processes emits more CO_2 due to its conversion, compared to on-site gas use for industrial processes. When baseload electrification is used as the strategy, the Coefficient of Performance of the technologies (COP) is an important factor. A higher COP indicates lower operating costs. Low operating costs are important because the baseload strategy is unable to respond to changes in electricity price (den Ouden et al., 2017).

Two application areas have been identified for electrification technologies (den Ouden et al., 2017).

- Core processes: First of all, electrification is possible in the core processes or primary process streams of the industry. This application area is often associated with baseload electrification. This is because an intermittent production of the company's main products in often undesirable. A flexible strategy can be possible for businesses that don't rely on a stable core process stream or is able to switch to other modes of energy.

- Utilities: A second application area are the utilities in the industry. This means that the systems servicing the main processes are electrified. This application area is often associated with flexible electrification, as the intermittent nature of this strategy does not directly impact the core processes.

The choice of electrification strategy and application area affects the connection within a cluster (using the cluster conceptualisation theory). Vertical actors are often dependent on the material or product delivery of the horizontal actors. The flexible electrification strategy in the core processes results in fluctuations in the production of the semi-finished products. Connected cluster partners, who are dependent on these semi-finished products, are experiencing these production fluctuations for their own processes. Therefore, the choice of the electrification strategy and application area induces uncertainty in the connection between actor partners.

3.4 Conclusion

This chapter discussed the electrified industry in its cluster environment. When analysing the industry in its cluster environment, we identified that the connections between firms in a cluster are possible sources of uncertainty. The industrial processes of individual firms are entwined with each other in a cluster. The production of a single company depends on the production of other companies. Although the system's value creation should be considered as the whole cluster, decisions are made by the individual actors using actor objectives as parameters. Therefore, changes in the system of one industrial actor, affect the systems of other actors. The dependency and entwinedness induce uncertainty among cluster partners. The cluster conceptualisation theory can be used to identify and map the uncertain connections between industrial companies. The choice of electrification strategy and application area affect these connections within a cluster. A method to support analysts with the identification and exploration of uncertain factors should be compatible with these specific uncertainty inducing system characteristics of electrified industrial systems.

4. Uncertainties in literature

Uncertain factors regarding the electrification of the industry are identified using a literature analysis. This chapter presents the findings of this literature analysis. These uncertain factors provide an indication of what types of uncertain factors are present in electrified industrial systems. Section 4.1 discusses the uncertain factors identified in the literature analysis. Thereafter, in section 4.2, the findings of the literature analysis are synthesised and concluded in the uncertainty content taxonomy.

4.1 Extracted uncertain factors

This paragraph presents the extracted uncertain factors from a combination of academic and grey literature. The extracted uncertain factors are categorised and presented based on their content. The following categories of uncertainty were identified: policy, market, technology and process. Possible driving forces for these uncertain factors were also identified during the literature analysis, to understand why and how the uncertain factors could change in the future.

The literature used during the literature analysis assumed that industrial actors are driven by financial incentives and maintaining system reliability. Some studies argued that the success of electrification depends on the relative price between using electricity compared to other fuels or modes of sustainability (Lechtenböhmer, Nilsson, Åhman & Schneider, 2016); Yilmaz et al., 2018). Other studies focussed more on the reliability risks associated with the use of particular technologies or processes in industrial systems (Dakkoune, Vernières-Hassimi, Leveneur, Lefebvre, & Estel, 2018a). Therefore, the conducted literature analysis only identified uncertain factors which could affect the costs and the reliability of electrified processes.

Policy

Table 2 presents the policy options which the government has to change the behaviour of industrial actors (rewarding or punishing certain behaviour using financial incentives). These factors are uncertain due to the dependence on the political climate in the future.

Table 2 Policy uncertain factors in literature

Uncertain factor	Argumentation	Possible driving forces
Subsidy	Government providing financial incentives to lower the relative costs of using sustainable energy compared to conventional fuel (Yilmaz et al., 2018; Lechtenböhmer et al., 2016; Weber, 2005).	- Change of political climate; e.g. amount of CO_2 reduction (van der Lugt, 2018). - Depletion of Groningen-gas (Savelkouls, 2018b)
Tax	Government providing financial incentives to increase the relative costs of using conventional fuels compared to sustainable energy (Yilmaz et al., 2018; Lechtenböhmer et al., 2016; Weber, 2005).	- Change of political climate; e.g. amount of CO_2 reduction (van der Lugt, 2018), applying CO_2 price cap (Savelkouls, 2018a). - Depletion of Groningen-gas (Savelkouls, 2018b) - Changes in CO_2 ETS; e.g. cap reduction.

Product restrictions	Government using legislation to prohibit the use of certain goods (e.g. fossil fuels). Changes in goods restrictions affect the legality of current industrial processes in the future (Lechtenböhmer et al., 2016; Weber, 2005; Yilmaz et al., 2018).	- Depletion of Groningen-gas (Savelkouls, 2018b) - Change of political climate; e.g. amount of CO_2 reduction (van der Lugt, 2018).

Market

The industry acts often on an international or local market. How the market develops over time is uncertain. Two market sides are relevant to an industrial actor: input market (materials and fuels) and output market (end-products and waste-products). The development of the markets affects the competitiveness of the electrified industrial systems. Table 3 presents the market uncertain factors.

Table 3 Market uncertain factors in literature

Uncertain factor	Argumentation	Possible driving forces
Fuel prices	The development of fuel prices in the future affects the competitiveness of electrification (Lechtenböhmer et al., 2016; van Delft & de Kler, 2017; Weber, 2005).	- Development of economy - Exploitation potential of conventional fuels (supply) - Geopolitical conflicts with oil-producing countries.
Market price input products	Changes in demand/supply influences the market price for the input products. Changes in these variable costs (input products) affect the profits earned by the company and the competitiveness of an electrified system to other possible systems (Dyer, Furr, & Lefrandt, 2014; Weber, 2005).	- Development of economy - Upcoming industrial countries (Selko, 2015). - Governments of competing industry and their policy towards sustainability (Dialga, 2018). - Substitute for products - Change in the number of players in the market.
Market price output products	Changes in demand/supply influences the market price for the output products. Products produced with an electrified system should be able to compete with the output market price (Dyer, Furr, & Lefrandt, 2014; Weber, 2005).	- Development of economy - Upcoming industrial countries (Selko, 2015). - Governments of competing industries and their policy towards sustainability (Dialga, 2018). - Substitute for products - Change in number of players in the market

Costumer perception	When the electrified processes are more expensive, are costumers willing to pay the premium for sustainability (Dyer et al., 2014; van Delft & de Kler, 2017)?	- Change in human perception of (Vincenzi et al., 2018)

Technology

The used technologies affect the production costs in a system. The development of technologies in the future could affect these costs and therefore the competitiveness towards the other technologies. How technologies develop over time is uncertain. Table 4 presents the technology uncertain factors.

Table 4 Technology uncertain factors in literature

Uncertain factor	Argumentation	Possible driving forces
Opex	Opex affects the competitiveness compared towards other technologies (den Ouden et al., 2017)	- Technological development (den Ouden et al., 2017) - Investment in R&D
Capex	Capex affects the competitiveness compared towards other technologies (den Ouden et al., 2017).	- Technological development (den Ouden et al., 2017) - Investment in R&D
Availability new substituting technologies	Choosing the technology now results in sunk costs and locked-in systems. Profits could be lost by choosing a technology now instead of an technology with (possibly) better properties later (Atrill, 2014; Dyer et al., 2014; Weber, 2005; Yilmaz et al., 2018).	- Technological development (den Ouden et al., 2017) - Investment in R&D (Shayegh, Sanchez, & Caldeira, 2017) - Introduction of Carbon Capture Storage (Billson & Pourkashanian, 2017)
Availability of new supporting technologies	Current technologies could in the future be more productive due to supporting technologies (e.g. storage capacity). This affects the competitiveness of electrification technologies (Dyer et al., 2014; Schweiger, Rantzer, Ericsson, & Lauenburg, 2017; Weber, 2005; Yilmaz et al., 2018).	- Technological development (den Ouden et al., 2017) - Investment in R&D (Shayegh et al., 2017)
System failures	Risks associated with failures in an electrified industrial system. Possibly different failures could occur with an electrified industrial system compared to other alternative systems. What these risks are and how they develop over time is uncertain (Dakkoune, Vernières-Hassimi, Leveneur, Lefebvre, & Estel, 2018b).	- Lack of experience or knowledge by operators (Dakkoune et al., 2018b). - Lack of knowledge about the reliability of the new technology.

Energy capacity management	Management regarding the flexible use of electricity and conventional energy (gas). The optimal use of different energy sources depends on e.g. the energy price and the availability. The development of these factors is uncertain. The optimal energy management (and the profits it could earn using flexible management) is therefore also uncertain (van Delft & de Kler, 2017; VEMW, n.d., 2017).	- Lack of experience or knowledge by operators (Dakkoune et al., 2018b). - Energy prices - Energy demand/supply

Process

The use of electrification technologies affects the chain of processes connected within a cluster system. This is due to the actor dependency between actors in an industrial cluster. How the chain of processes is affected by the electrification over time is uncertain. This category is developed based on the insights learned from the literature analysis in chapter 3. Table 5 presents the process uncertain factors.

Table 5 Process uncertain factors in literature

Uncertain factor	Argumentation	Possible driving forces
Cluster Product delivery	The flexible characteristics of an electrified system could affect the product delivery to other actors in the cluster. Therefore, an electrified system also affects other actors within a system. How these flexible characteristics develop over time is uncertain (Brown et al., 2007; VEMW, n.d., 2017)	- Production/investment decisions of actors within a cluster, based on; e.g. electricity price, market price.

4.2 Conclusion

Uncertain factors affecting the financial and reliability incentives were extracted from literature. These uncertain factors were categorised based on their content. The content categorisation in section 4.1 is used to develop a content taxonomy of the extracted uncertain factors. An uncertainty content taxonomy is created to provide a structured overview of the types of uncertain factors in electrified industrial systems from the literature analysis (Figure 4).

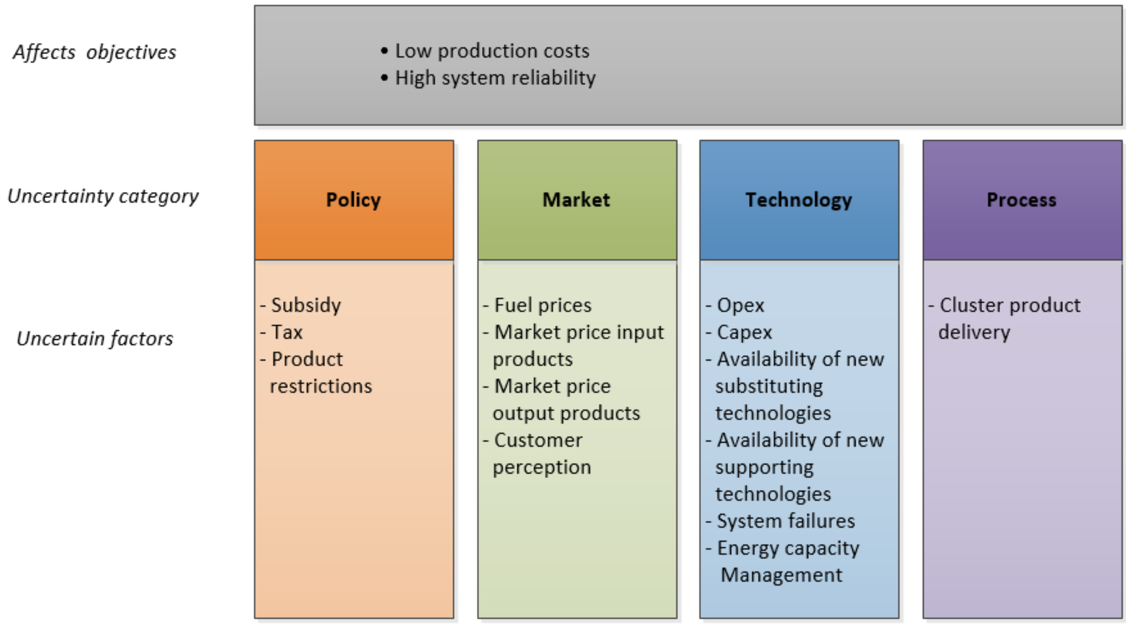


Figure 4 Uncertainty content taxonomy

This taxonomy provides an indication of the uncertain factors which are possibly present in electrified industrial systems. The categorisation in the taxonomy can be used to discuss different topics of uncertainty with industrial actors during the identification process. The identification process should handle policy, market, technology and process related uncertain factors. Also, the uncertain factors from the taxonomy can be used to discuss and compare the uncertain factors from literature and from the method (chapter 7), to assess the value of the method.

5. Theoretic framework: Uncertainty

An analysis of the current work done in the conceptualisation, identification and exploration of uncertainty is presented in this chapter. A discussion has been held about the current academic methods in uncertainty management, how these methods could contribute to the identification and exploration of uncertain factors in electrified industrial systems. Some modifications and connections between methods have been proposed. Section 5.1 explains what is meant with different types of uncertainty. In section 5.2, 'the system model perceptive' is introduced to identify uncertain factors. Thereafter, in section 5.3, the uncertainty framework is discussed which is used to explore uncertainty using three dimensions. Section 5.4. explains how insights can be gathered by modelling the future ranges of uncertain factors. Thereafter, in section 5.5 discusses how the response of the uncertainty on the system can be analysed. Finally, in section 5.6 an overall conclusion has been given.

5.1 Definitions of uncertainty

Complex socio-technical systems are subject to uncertain future conditions. The uncertain future conditions are formed by local and global drivers, covering the natural, economic, technical and social trends (Gao et al., 2016). Uncertainty affects decision-makers, as the effects of the decisions on the outcomes of interests under uncertainty are not completely deterministic understood. Among scientists from different research fields, there is not a single interpretation of the term 'uncertainty'. First, in 1921, Knight distinguished uncertainty from risk in economics. A risk is defined as a situation involving a 'measurable' quantifiable uncertainty using probabilities. "It will appear that a measurable uncertainty, or 'risk' proper, as we shall use the term, is so far different from an unmeasurable one that it is not in effect an uncertainty at all" (Knight, 1921, p.20). Therefore, uncertainty involves situations with only immeasurable uncertainties.

Funtowicz and Ravetz (1990) continued by defining the term (immeasurable) uncertainty. They stated that uncertainty is a situation of inadequate information, categorised in inexactness, unreliability and ignorance of the information. They are implying that more information or knowledge about a situation reduces the level of uncertainty. This is a broadly accepted interpretation in public. Although, there are situations where lots of information is available but uncertainty is still present and obstructs decision-making (van Asselt & Rotmans, 2002). Also, new information could possibly increase the perceived uncertainty by decision-makers. This is because the presence of uncertainties that were previously unknown can be unveiled by new knowledge and information of a complex system (van der Sluijs, 1997; Bowden, Maier, & Dandy, 2012). Socrates and Plato already realised this phenomenon that the more we gain knowledge about nature, the more we are confronted with the limits of our knowledge (Pörksen, 2002). Therefore, uncertainty is not simply a lack of information or knowledge. Although, the lack of information or knowledge is a type of uncertainty. In order to cover the full facet of the term uncertainty, Walker et al. (2003, p.8) defined uncertainty as "*any departure from the unachievable ideal of complete determinism*".

When conceptualising uncertainty, the general approach considers the use of probability density functions. This results in a distribution around some 'best-guess' (Maier et al., 2016). Although, multiple future trajectories that correspond to distinct future states of the world don't have an associated probability of occurrence (Kwakkel et al., 2010), or the probabilities of the future states are not agreed on by experts and the predictions based on past data are not reliable. Finding the 'best guess' is therefore not suitable to gather insights about the future. Gao et al. (2016) defined this kind of uncertainty that is incalculable, uncontrollable with multiple different views of the future as deep uncertainty.

When considering a multi-actor socio-technical system such as an electrified industrial cluster, the different uncertainties (risk, uncertainty and deep uncertainty) are affecting the decision-making processes of industrial actors. Atrill (2014) indicated that there is a certain risk in the decision-making, as there may be an opportunity cost in the form of the benefits lost from later information. This results in actors ignoring or delaying certain investment decisions to obtain newer and better information in a later stage.

5.2 System model perspective

Decision-makers are affected by uncertainties, as they have to consider decision options in a situation with (future) unknowns. Because of the complexity in systems and the wide range of possible future outcomes to be considered, a structured analytic process is required. 'Decision support', with the use of the system model, enables decision-makers to explores the effects of alternative decision options under uncertainty (Walker & Haasnoot, 2011).

Walker et al. (2003, p.7) define a model as "an abstraction of the system of interest – either the system as it currently exists, or as it is envisioned to exist for purposes of evaluating policies in a different (e.g., future) context". A model can be broadly interpreted, from a high aggregated conceptual formulation till a specific mathematical formulation. A system model represents the causal relations within the system. The causal relations provide insights into how the system components interact and behave with each other. By placing the system model in its socio-technical context, an exploration can be made about the response of a *system* to outside *policies* during possible different future *contexts* (Figure 5). These components were synthesised in the 'system model perspective'.

When using the 'system model perspective' for addressing uncertain factors, a system model could be an appropriate tool to identify and explore contextual uncertain effects on system performance. Fluctuation in uncertain factors affects the system and its output, resulting in the achievement or failure of certain objectives or preferences stated by the actors and decision makers (outcomes of interest) (Figure 5). The achievement or failure of the objectives determine the success of the implemented *policy* or implies the need for a new *policy* (policy-cycle).

The interrelation between the uncertain contextual input, the system model and the outcomes of interests is used in this research to identify uncertain factors. When reformulating the 'system model perspective' reasoning by the author, *we can conclude that a factor is experienced as uncertain when the uncertainty affects the actor's system and objectives.* Therefore, by retrieving the information about the system, policy and outcomes of interest, an identification can be made for the uncertain factors. The 'system model perspective' allows us to get into the specific *system* and *policy* characteristics of electrified industrial systems while identifying uncertainty.

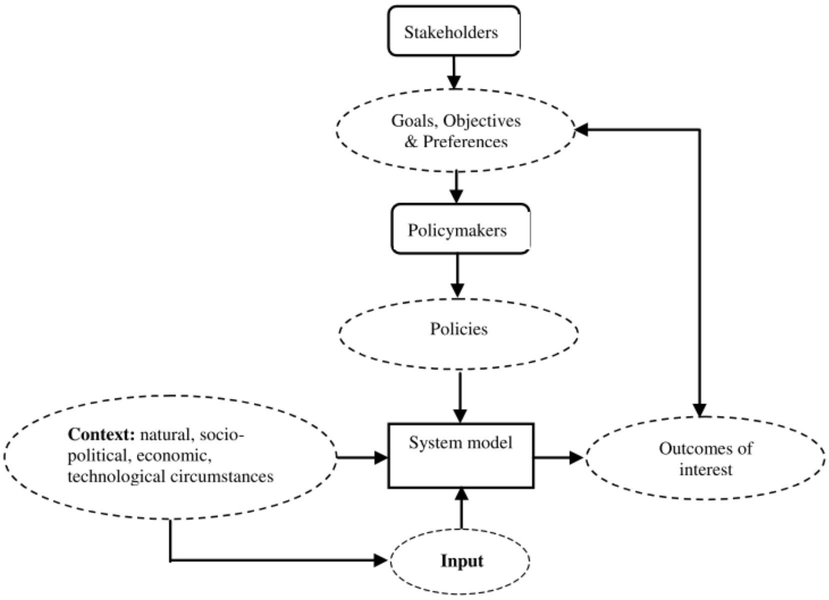


Figure 5 System model perspective (Walker et al., 2003)

5.3 Exploring the dimensions of uncertainty

How uncertainty should be managed depends on the specific characteristics of the uncertainties, indicating the need for an assessment procedure for uncertainty. Kwakkel, Walker & Marchau (2010) developed a framework for the systematic treatment of uncertainty in decision support to improve the management of uncertainty in decision-making processes. The uncertainty framework is built upon the 'system model perspective'. The framework of Kwakkel, Walker & Marchau (2010) is a revision of the work by Walker et al. (2003). A discussion about the difference between the original and revised framework, and an argumentation why the revised framework is appropriate for this research, has been provided in Appendix A. Section 5.3.1 explains the workings of the uncertainty framework. Thereafter, in section 5.3.2, a revision of the location dimension has been proposed for industrial systems.

5.3.1 Uncertainty framework

The identified uncertain factors need to be explored to provide appropriate treatment of uncertain factors. The aim of Walker et al. (2003, p.5) was to "synthesize a wide variety of contribution on uncertainty in model-based decision support in order to provide an interdisciplinary theoretical framework for systematic uncertainty analysis." This supports decision-makers in managing uncertainties and communicates these uncertainties among actors (Kwakkel et al., 2010). Walker et al. (2003) analysed and synthesised different kinds of uncertainty found in literature and mapped the concept of uncertainty using three dimensions (Figure 6): location, level and nature. The dimensions of the framework would help in exploring, articulating and prioritising uncertainties in multi-actor systems (such as industrial clusters), leading to adequate acknowledgement and treatment of uncertainty in decision-making.

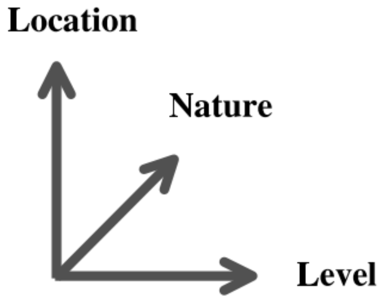


Figure 6 Dimensions of uncertainty (Walker et al., 2003)

The *location* of uncertainty describes where the uncertainty is manifested using the logic of the model formulation. This dimension makes it possible to pinpoint the possible sources of uncertainty and its (causal) effect on the outcomes of interest. The *system* model from the 'system model perspective' (section 5.2) could be used to assess the location dimension. Kwakkel, Walker & Marchau (2010) defined six locations of uncertainty:

- *System Boundary*: Uncertainty regarding the boundaries of the modelled system.
- *Conceptual model*: Uncertainty in the relationship between the variables inside the system boundary.
- *Computer model*: Uncertainty in the implementation of the conceptual model to a computer model.
- *Input data uncertainty*: Uncertainty in the data of the parameters, both within the model boundary and as inputs to the model.
- *Model implementation:* Uncertainty from the implementation of the conceptual model into computer code. This uncertainty is related to the bugs, errors and hardware errors in the computer code.
- *Processed output data:* The uncertainty that is accumulated within the model complex which is expressed in the output data of the model.

The *level* dimension of uncertainty defines where the uncertainty manifests itself along the spectrum between deterministic knowledge and total ignorance. In other words, it describes the severity of the uncertainty. The level of uncertainty provides information about how the uncertainty can be dealt with. For instance, a high level of uncertainty requires adaptive strategies due to the large variance in possible outcomes of the uncertain factor. For low-level uncertainty, less adaptive strategies are required. Kwakkel, Walker & Marchau (2010) defined four levels of uncertainty:

- Level 1 - *shallow uncertainty*: Being able to enumerate multiple alternatives and provide probabilities (subjective or objective)
- Level 2 - medium uncertainty: Being able to enumerate multiple alternatives and rank order the alternatives in terms of perceived likelihood. However, how much more likely or unlikely one alternative is compared to another cannot be specified.
- Level 3 - *deep uncertainty*: Being able to enumerate multiple alternatives without being able to rank order the alternatives in terms of how likely or plausible they are judged to be.
- Level 4 - *recognised ignorance*: Being unable to enumerate multiple alternatives, while admitting the possibility of being surprised.

The *nature* dimension describes whether the uncertainty is due to the imperfection of our knowledge or is due to the inherent variability of the phenomena. Assessing the nature dimension helps in understanding what is causing the uncertainties and how to deal with it. An epistemic uncertainty can be reduced by conducting research to increase the knowledge about a phenomenon, while this is not appropriate for ontic or ambiguous uncertainty. When an uncertain factor entails an ambiguous nature, the appropriate strategy is to aim at integrating frames and support joint sensemaking. Gaining more knowledge with the use of scientific research based on a single frame is then not an appropriate strategy (Brugnach et al., 2008). The three dimensions are synthesised in the uncertainty framework:

- *Epistemology uncertainty*: Uncertainty due to the imperfection of knowledge. New knowledge or information by research may reduce the level of uncertainty.
- *Ontology uncertainty*: Uncertainty due to the inherent variability of the factor. Inherent variability is typically found in factors regarding social, economic and technological trends. New knowledge or information by research may not result in an improvement in the quality of output.
- *Ambiguity*: Uncertainty due to the different interpretations by actors (based on their frames and values) of the same data. This implies the need to integrate frames and support joint sensemaking.

The three dimensions are combined in a framework by Kwakkel, Walker & Marchau (2010) to provide a systematic overview for the exploration of uncertainties (Figure 7).

		Level				*Nature*		
Location		*Level 1: shallow uncertainty*	*Level 2: medium uncertainty*	*Level 3: deep uncertainty*	*Level 4: recognised ignorance*	*Ambiguity*	*Epistemology*	*Ontology*
System boundary								
Conceptual model								
Computer model	Model structure							
	Parameters inside the model							
	Input parameters to the model							
Input data								
Model implementation								
Processed output data								

Figure 7 Uncertainty framework (Kwakkel, Walker & Marchau, 2010)

5.3.2 Changing the location dimension

Some specifications of the location dimension in the Kwakkel, Walker & Marchau (2010) framework are not relevant for this research. The location specification is mostly related to decisions regarding the modelling of the system (e.g. *conceptual model*, *computer model* and *model implementation* categories). The location dimension should reflect the objective of the study. The goal of this research is to support analysts in the identification and exploration of uncertain factors in electrified industrial systems. Therefore, the location dimension should reflect the perceived uncertainty space in electrified industrial systems (using industrial actors as input), not the uncertainty involved with the transformation process of the modeller's perception of the real-world system to a computer model. Therefore, a revision of the location dimension is required.

In this research, a revised location dimension is created to make the uncertainty framework compatible with industrial systems. The revised location dimension is developed based on the insights of the cluster conceptualisation theory (discussed in chapter 3). The cluster conceptualisation theory explains how industrial companies interact with its cluster and context. Using the theory, two external links of industries and their environment are identified: cluster connection and socio-economic context connection. The cluster connection can be described as the interaction and dependency (entwinedness of processes) between horizontal and vertical actors. The socio-economic context connection can be described as the interactions and dependency of the actor with a phenomenon outside the cluster environment. These links provide insights in the external relations of industrial companies. Uncertainties are often experienced due to external interactions, which induce a limited scope of control. Therefore, the revised location dimension reflects the uncertain connections of industrial actors with their environment. The following specification of the location dimension has been developed (visualised in Figure 8):

- *Internal*: Uncertainty located within the boundary of the industrial actor's system (blue box). An example can be the risk of breaking down processes within the facility.
- *Cluster*: Uncertainty located in the connection between cluster partners (red arrow). This means that the source of the uncertainty is located outside the actor's own system. This uncertainty develops due to the dependency between industrial actors within a cluster. Policy decisions (electrification strategies) taken by one actor, can affect other actors within a cluster. An example can be an unpredictable variation in product supply by a connected partner due to electrification.
- *Socio-economical context*: Uncertainty located in the connection with the socio-economical context (green arrow). This means that the source of the uncertainty is located outside the actor's own system and its cluster where it operates. Some examples are the uncertainty in the development of governmental policy or the fuel market.

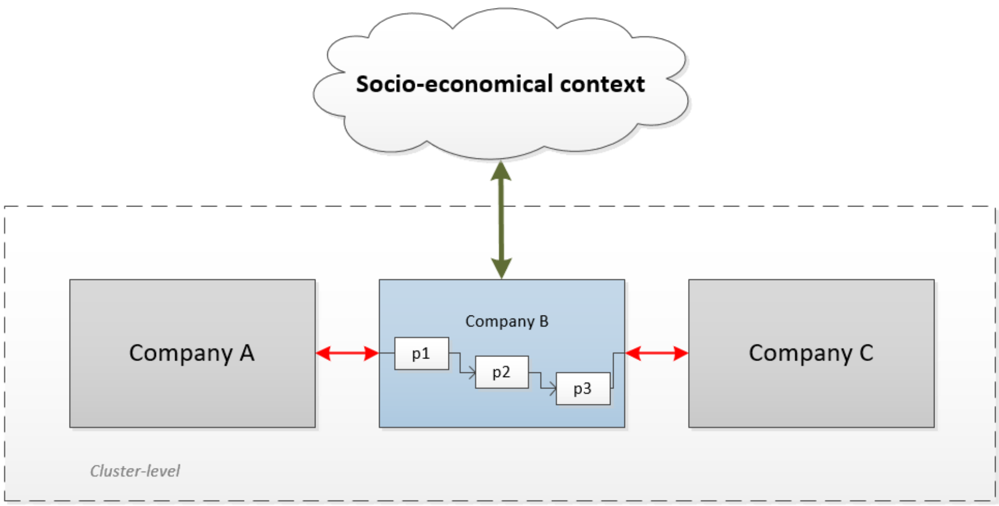


Figure 8 Revised location dimension

The new location dimension, with the specification of the level and nature dimension by Kwakkel, Walker & Marchau (2010), is synthesised in the following framework (Figure 9):

	Level				**Nature**		
Location	Level 1: shallow uncertainty	Level 2: medium uncertainty	Level 3: deep uncertainty	Level 4: recognised ignorance	Ambiguity	Epistemology	Ontology
Context							
Cluster							
Internal							

Figure 9 Revised uncertainty framework

5.4 Modelling the future

When the uncertain factors are identified and their dimensions defined, it is important to explore the impact of the uncertain factors on the system. The direction and magnitude of the development of uncertain factors affect the system's future state (the original 'system model perspective' theory, section 5.2). In order to explore the impact of uncertainties, we need to gain insights into the future development of uncertain factors. Modelling is an important tool to help us understand a complex system. Also, modelling could help us understand the future, to support planning and adaptation. Maier et al. (2016) defined paradigms for modelling the future. Using the paradigms, information can be obtained about how the future development of uncertain factors should be modelled (e.g. bandwidths or ranges). The paradigms are categorised in three approaches: *use of best available knowledge*, *quantification of future uncertainty and exploring multiple plausible futures*. The dimension information from the uncertain factors can be used to select the appropriate paradigm. The three paradigms are visualised in Figure 10.

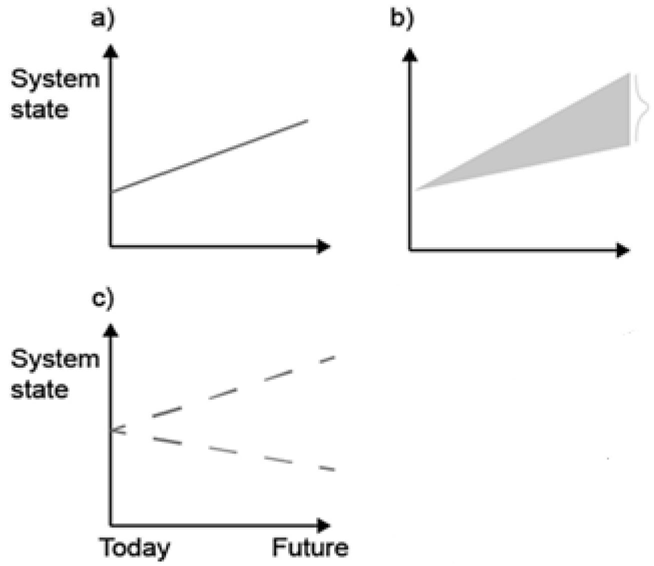


Figure 10 Paradigms for modelling the future (Maier et al., 2016)

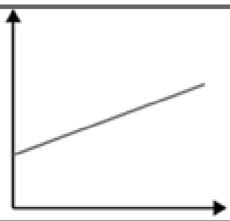
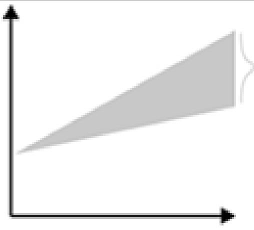
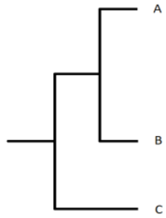
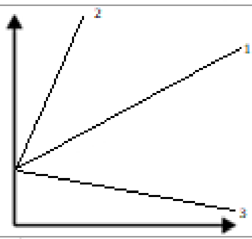
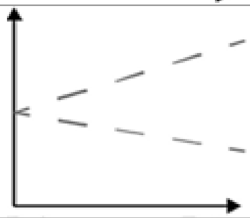
The first paradigm (Figure 10a) uses current knowledge of the system and its processes to anticipate the system's future behaviour (Bankes, 1993). Although, using knowledge to anticipate a system's future behaviour has its limitation. As discussed in section 5.1, knowledge will not always lead to more insights in a system. This paradigm corresponds to factors with a deterministic and clear enough future. Therefore, this paradigm can be used to model future developments of factors which are not noticeable uncertain, or are at least not important enough to address the uncertainty explicitly (Walker, Marchau, & Kwakkel, 2013), and where a future estimate based on current knowledge is sufficient.

The second paradigm entails the treatment of the future as quantifiable uncertainties. This paradigm deals with system processes and conditions which cannot be captured within the system because its effects are not completely understood. The system processes and conditions are subject to uncertain variability. Using this paradigm, the modeller can make predictions for input, parameters and structure using distributions to develop an estimated bandwidth of output uncertainty (Beyer & Sendhoff, 2007; Schoups & Vrugt, 2010). The statistical properties of the uncertain processes and conditions (factors) are considered constant, making the used distribution vulnerable to future changes. Although, the uncertainty modelled by distributions often increase over time (Mahmoud et al., 2009). Quantifying uncertainty using probability distribution functions allows the modeller to develop different outcomes within a plausible future (Figure 10b). Also, quantifying uncertainty makes it possible to develop multiple forecasts (bifurcation) with associated probabilities of occurrence (Walker et al., 2013). In the uncertainty framework (Figure 9), this uncertainty is defined as an uncertain factor with a 'shallow uncertainty' level, since the modeller is able to express the uncertain parameters in statistical terms.

The third paradigm treats uncertainty by exploring multiple plausible futures. This guides the modeller from the idea of a single possible future. Maier et al. (2016, p.156) conclude that this paradigm is "useful when the different processes and conditions seemingly do not easily fit within a single model, and their resulting futures cannot be harmonised within a probabilistic framework." The dynamics of the processes of the modelled system and how these processes affect the system over time are not well understood. The lack of knowledge about the system processes is so severe that developing a single possible future (best-guess) based on probabilities is not appropriate. Therefore, 'exploratory modelling' is necessary to explore the different possible future states. These uncertainties are often associated with climate, technological, socio-economic and political change (Maier et al., 2016). Figure 10c shows the paradigm. In the uncertainty framework (Figure 9), this uncertainty is conceptualised as 'medium uncertainty' and 'deep uncertainty' levels. The 'recognized ignorance' level is also treated with this paradigm in this research. This is because it is important to explore a large spread of multiple future states when almost no information is available about an uncertain factor.

An overview of the connection between the dimensions of uncertainty and the paradigms are provided in Table 6. The paradigms can be used to model the future ranges of the identified and assessed uncertain factors. The future ranges can be used to explore the impact of uncertain factors on the system.

Table 6 Paradigms characteristics

Level	Paradigm	Visual
- : Deterministic or clear enough future	*Use of best available knowledge*	
1: Shallow uncertainty	*Quantification of future uncertainty*	 
2: Medium uncertainty	*Exploring multiple plausible*	
3: Deep uncertainty & 4: Recognized ignorance	*Exploring multiple plausible*	

5.5 Exploring the response of uncertainty

To explore the impact of the uncertain factors in complex systems, global sensitivity analysis is an important approach. Sensitivity analysis measures the output behaviour of the model across the input space of uncertain factors (Liu & Homma, 2009). The future uncertain development (range or bandwidth) of uncertain factors can be used as the input space for the sensitivity analysis.

Where the 'one-at-a-time' sensitivity analysis' measures the response in the output of a model given individual input changes of uncertain factors, global sensitivity analysis evaluates the full distribution of each uncertain input across the domain of all other parameters (Jaxa-Rozen & Kwakkel, 2018a). A global sensitivity analysis has some important properties; it measures sensitivity across the whole input space, is able to deal with nonlinear response and explores the non-additive effects between model parameters (Saltelli & Annoni, 2010). Given these properties, global sensitivity analysis is an appropriate approach to analyse the uncertain response in complex multi-actor systems. The 'one-at-a-time' analysis would lead to an incomplete or misleading interpretation of model uncertainty.

Variance-based global sensitivity analysis (often referred to as the Sobol method) is a technique to analyse the global response of changes in uncertain input. The Sobol method "provides first-order and total indices, which respectively describe the fraction of output variance contributed by each factor on its own, and by the sum of first-order and all higher-order interaction for each factor" (Jaxa-Rozen & Kwakkel, 2018, p.246). Therefore, the Sobol analysis could be used to analyse how much uncertainty (variations) an uncertain factor induces to the system by using output performance indicators. The paper by Jaxa-Rozen and Kwakkel (2018) elaborates more on the mathematical background of the method. The Sobol analysis is included in the opensource Exploratory Modelling Workbench software (Kwakkel, 2017). This software can establish an input and output connection with a computer model. By controlling the input and collecting the output of the computer model, a Sobol analysis can be conducted. The outcome percentages of the analysis are directly interpretable as measures of sensitivity.

5.6 Conclusion

This chapter discussed the established academic methods in uncertainty management. The 'system model perspective' provides a systematic overview of the *system*, *policy*, *context* and *outcomes of interest* components and explains the interrelation between them. This theory can form the basis for the identification of uncertainty. In order to provide the right treatment of the identified uncertain factors, it is required to explore the uncertain factors based on the location, level and nature dimension. The uncertainty framework can be used to explore these dimensions. A revision of the location dimension by the author was necessary for studying the specific case of uncertainty in industrial systems. The paradigms for modelling the future can be used to process the dimension information of the uncertainties into future bandwidths or ranges. The future ranges of uncertain factors can be used as the input space for a Sobol analysis. The Sobol analysis is a technique to analyse the response of uncertain factors on the system. An exploration can be made how much variance an uncertain factor causes in the outcomes of interests. The established academic methods discussed in this chapter form the basis in the development of the formal method to support analysts in the identification and exploration of uncertain factors in electrified industrial systems.

6. Development of the method

The findings from the three literature analyses are combined and synthesised into a formal method to support analysts in the identification and exploration of uncertain factors in electrified industrial systems. This chapter elaborates how the method works. Also, an explanation is given how the literature analyses contributed to the development of the different method steps. Section 6.1 discusses how the findings of the three literature analyses were synthesised. In section 6.2, the method steps for identifying and exploring uncertain factors are formalised. A conclusion is provided in section 6.3.

6.1 Synthesis of the literature analyses

The conducted literature analyses were synthesised to come towards a method for the identification and exploration of uncertain factors in electrified industrial systems. The literature analyses consisted of analysing the characteristic uncertain components of electrified industrial systems (chapter 3), the types of uncertain factors identified in literature (chapter 4) and the conceptualisation of uncertainty (chapter 5).

A first step in handling uncertain factors would be to identify what is considered as uncertain. Although a cluster consists of entwined processes and the system's value creation should be considered as a whole, it is important to realise that decisions are made by the individual actors using actor objectives as parameters (section 3.2). The individual industrial actors have to make the investment decision to electrify their systems while experiencing uncertainty. Therefore, industrial actors are needed as input for the identification and exploration of uncertain factors. They have the specific knowledge about industrial systems and are experiencing the uncertainty in these systems.

To support analysts in the identification of the uncertain factors, while involving industrial actors as input, the 'system model perspective' can be used (section 5.2). When reformulating the 'system model perspective' theory, we can conclude that: *a factor is experienced as uncertain when the uncertainty affects the actor's system and objectives.* Therefore, by retrieving the information about the other components of the theory (*system*, *policy* and *outcomes of interest*), the uncertain factors can be identified. The 'system model perspective' allows us to get into the specific *system* and *policy* characteristics of electrified industrial systems while identifying uncertainties. The cluster conceptualisation theory can be used to conceptualise the *system* into a visual model (section 3.2). As uncertainty is perceived on actor level, actor level systems are leading during the identification process. By demarcating the actor *systems* within its cluster system using this theory, a systematic overview can be created which includes the characteristic (uncertainty inducing) entwined cluster processes. In order to obtain information about the *policy (*or system change) of the systems, it is important to define what electrification strategy is being used (section 3.3). The electrification strategy being used (e.g. flexible or base-load) affects the actor's *system* and its connections to their cluster partners (e.g. flexible supply). To obtain information about the *outcomes of interest* (or objectives), the analyst should identify what the industrial actors want to achieve with their business.

When information about the *system*, *policy* and *outcomes of interest* has been obtained, it is possible to identify uncertain factors with industrial actors as input. A limitation in involving industrial actors lie in the difficulty for them to work with complex and abstract concepts as uncertainty. Therefore, we need some guidance mechanisms to assist industrial actors. Using the reformulated 'system model perspective' theory, industrial actors could identify uncertain factors with the following argumentation: *factor X is perceived as uncertain, as its affects process Y in my (electrified) system, which leads to (negative) variation in the parameter of objective Z.* This reformulated reasoning can be seen as an aid for industrial actors, to identify uncertain factors in a structured manner. The categorisation of the uncertainty content taxonomy could be used to guide the conversation across different types of uncertainty with the industrial actors (section 4.2). The uncertainty content taxonomy includes the specific electrified industrial characteristics.

Uncertainty is an abstract concept and open for many interpretations. A respondent could identify an abundant list of uncertain factors while some of them have a minor effect on their industrial processes or are very unlikely it will ever happen. A selection of uncertain factors is necessary to reduce the amount of identified uncertain factors. A selection of uncertain factors can be made based on their amount of impact on the system and their likelihood of occurrence (van 't Klooster & van Asselt, 2006).

After the identification, the uncertain factors can be explored. The uncertainty framework can be used to assess the uncertain factors using the dimensions of uncertainty (section 5.3.1). The dimensions of the framework would help in exploring, articulating and prioritising uncertainties in industrial (multi-actor) clusters, leading to adequate acknowledgement and treatment of uncertainty. The dimensions provide information about where the uncertainty is located, how it is caused and how severe it is. A revision of the location dimension was necessary for this framework to grasp the specific characteristics of industrial clusters (section 5.3.2).

To explore the impact of uncertain factors on the system, the 'system model perspective' theory can be used in its original formulation: *uncertainty (context) and the electrification strategy (policy) affect how the system behaves, generates its output and whether the objectives (outcomes of interests) are satisfied.* As system performance is affected by the cluster as a whole, it is important to consider the entire cluster system during the impact exploration process (section 3.3). When conceptualising the cluster *system* into a computer model and connecting the uncertainties to it, quantitative insights can be gathered how uncertainty influences the system and the industrial actor's objectives. To analyse the impact of uncertainty on the system, quantitative information about uncertain factors is required as input. Therefore, the future development (with quantitative bandwidths or ranges) of the identified uncertain factors should be modelled. By connecting the dimension information of the uncertain factors to the characteristics of the paradigms for modelling the future, insights can be gathered how the future ranges of uncertain factors should be modelled (section 5.4). To goal here is not to predict the future development of uncertain factors, but to find an acceptable range or bandwidth as input space to explore the impact of uncertainty on the system. The Sobol analysis can be used to analyse the response of the system towards the bandwidths or ranges of uncertainty (5.5). This analysis provides insights into whether the perceived uncertainties are actually affecting the system. Also, a selection could be made about what uncertain factors are the most important to focus on in future research.

When reviewing the synthesis of the literature analyses, the insights learned from literature complement each other towards the identification and exploration of uncertain factors in electrified industrial systems.

6.2 Formal method steps

The synthesis is used for the development of the formal method to support analysts in the identification and exploration of uncertain factors in electrified industrial systems. The synthesis is operationalised into formal steps. The data requirements are listed for each step.

Step 1: Demarcate the industrial cluster

First of all, a conceptualised model of the cluster system needs to be developed. This demarcates the scope of control of the industrial actors and identifies the connections between cluster partners. The cluster conceptualisation theory can be used to develop the conceptual cluster system model. Literature search (e.g. annual reports) and semi-structured interviews with industrial actors can be used to gather the data.

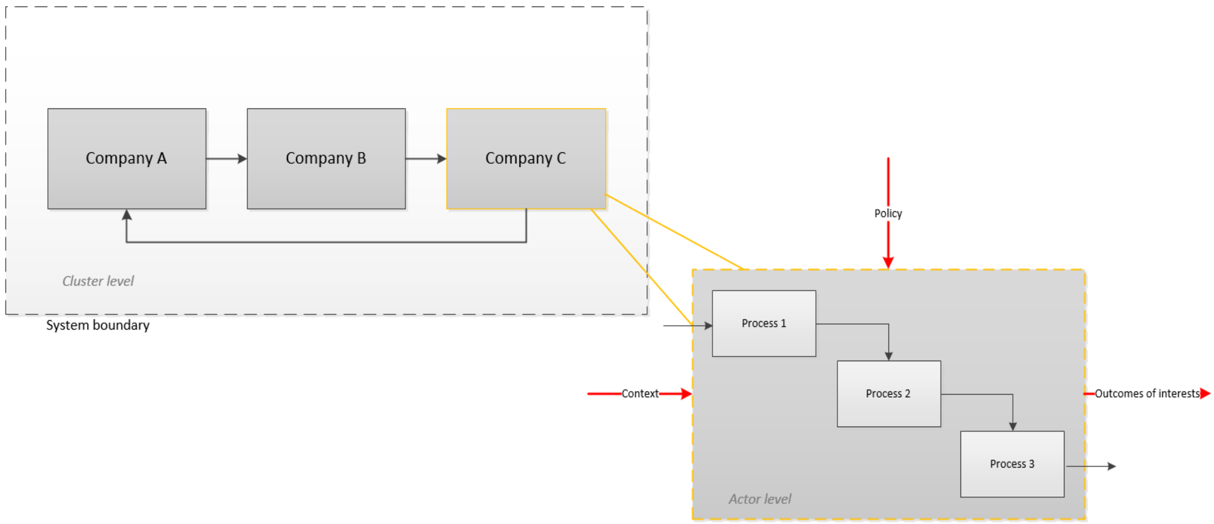


Figure 11 Cluster level and actor level

Step 2: Define system, policy and objectives of actors

When the relations of industrial actors within the cluster are demarcated, the individual actor systems can be conceptualised with their specific industrial processes. By demarcating on actor level, information about the *systems* of the individual actors can be identified (Figure 11). These systems should be visualised. Second, the actors in the cluster system need to be assessed by their preferred electrification strategy (*policy*). The categorisation in section 3.3 can be used to define the actor's electrification strategies with their respective application areas. The preferred electrification strategy should be included in the visual actor system models. Lastly, the *objectives* of the industrial actors should be retrieved. Literature search (e.g. annual reports) and semi-structured interviews with industrial actors can be used to gather the required data.

Step 3: Identify uncertain factors

Semi-structured interviews with industrial actors are used to identify the uncertain factors. During the interview, the actor system model with the individual industrial processes will be presented. Using this actor system model, the respondents will be asked to identify uncertain factors which influence their (electrified) processes and impacts their own defined objectives (Figure 12). The interviewee should be able to argue for uncertain factors in the following systematic way:

Factor X is perceived as uncertain, as its affects process Y in my (electrified) system, which leads to (negative) variation in the parameter of objective Z.

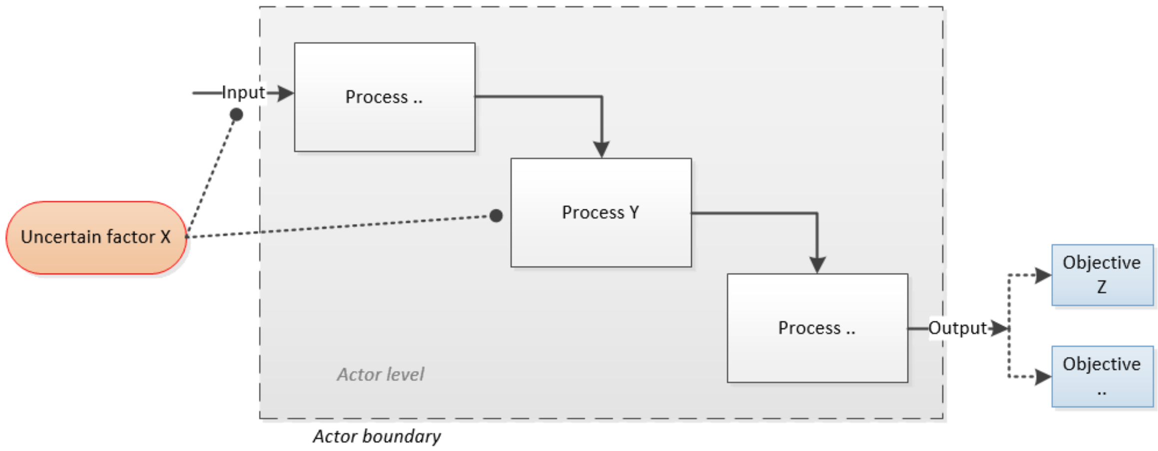


Figure 12 Uncertain factors identification

The categorisation from the uncertainty content taxonomy can be used to guide the conversation to different topics of uncertainty during the interview (Figure 4). Thereafter, a comparison will be made between the uncertain factors identified by the industrial actors and the uncertain factors extracted from literature. The interview will continue by asking if the interviewee can relate to the uncertain factors retrieved from the literature with a discussion whether it should be included in the set of uncertain factors.

Step 4: Select most important uncertain factors

The next step is to select the most important uncertain factors together with the industrial actor during the interview. The respondent will be asked to sort the uncertain factors in a grid with impact and realistic as axes using an ordinal scale (high and low) (Figure 13). The uncertain factors with a high impact and high realistic value will be selected for the next steps, while the uncertain factors with a low impact or realistic value will be discarded.

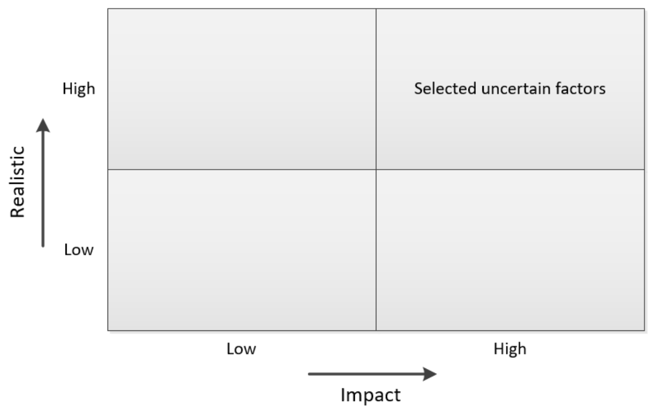


Figure 13 Selection grid

Step 5: Explore the dimensions of uncertainty

The uncertainty framework, including the revisions opted by the author, will be used to explore the different dimensions of the selected uncertain factors (Figure 9). To explore the dimensions, the perception of the industrial actors about the selected uncertain factors is required. This information can be retrieved by using a semi-structured interviewing style, by asking e.g.:

- *How do you think this factor is going to develop in the future?* Ranging from a specific value or value range till not having a clue; it provides information on how uncertain the factor is perceived.
- *What is the source of the experienced uncertainty?* Ranging from political decisions till internally not having full control over a process; it provides information on where the uncertainty comes from.
- *What is causing the uncertainty?* Ranging from a lack of knowledge till natural randomness; it provides information on how the experienced uncertainty is caused.

Step 6: Model future range
In order to analyse the impact of the selected uncertain factors on the system, the future ranges of uncertain factors should be modelled. These future ranges can be created using a combination of different information sources. First of all, the 'level' information gathered from the dimension exploration can be used. By connecting the level of uncertainty to the paradigms for modelling the future (Table 6), we know how the future ranges of uncertain factors should be modelled in order to project the experienced uncertainty of the industrial actor.

To include quantitative information to the future ranges of uncertain factors, a combination of historical data and literature/reports about future projections can be used. Historical data is used to understand how fluctuating the uncertain factors were in the past. The literature and reports about future projections can be used as a reference.

Step 7: Analyse impact on system performance
The last step is to analyse how the selected uncertain factors (quantitatively) impact the cluster system. To explore the response of the system, a Sobol analysis can be conducted. The modelled future ranges from step 6 could be used as input ranges for the analysis. The cluster system (from step 1) with the selected uncertain factors should be conceptualised into a computer model to conduct the Sobol analysis. The Exploratory Modelling Workbench computes the fraction of variance induced by uncertain factors on the outcomes of interests; using the computer model, the future ranges as input variables and the actor objectives as output variables.

6.3 Conclusion
This chapter discussed how the findings of the literature analyses could be synthesised towards a formal method. The insights learned from the uncertainty conceptualisation are combined with the uncertainty inducing characteristics of industrial cluster systems and the types of uncertain factors found in literature. The product of this synthesis is a formal method. Theoretically, his method can support analysts in:

- Identifying and arguing for a broad range of uncertain factors in electrified industrial systems using industrial actors as input
- Exploring the characteristics and effects of uncertain factors in electrified industrial systems.
- Creating support towards the use of the uncertain factors in research to multi-actor industrial clusters.

In this research, the method is referred to as the Industrial uncertainty scan. The method steps are summarised in Table 7.

Table 7 Industrial uncertainty scan steps

Step	Tool	Input	Product
1. Demarcate the industrial cluster	Cluster conceptualisation theory (section 3.2)	Literature	Cluster system model
2. Define system, policy and objectives of actors	Electrification categorisation (section 3.3)	Literature & interview data	Actor system model (incl. electrification strategy), actor objectives
3. Identify uncertain factors	'System model perspective' argumentation (Figure 12), uncertainty content taxonomy (Figure 4)	Actor system model, actor objectives, interview data	Identified uncertain factors
4. Select most important uncertain factors	Selection grid (Figure 13)	Identified uncertain factors, interview data	**Selected uncertain factors**
5. Explore the dimensions of uncertainty	Revised uncertainty framework (Figure 9)	Selected uncertain factors, interview data	**Location, level and nature information of selected uncertain factors**
6. Model future ranges	Paradigms for modelling the future (Table 6)	Selected uncertain factors, level information, literature data	Future ranges of uncertain factors
7. Analyse impact on system performance	Sobol analysis (section 5.5)	Computerised cluster system model, selected uncertain factors, actor objectives, future ranges	**Variance caused by selected uncertain factors**

When using the Industrial uncertainty scan, an argued and explored set of uncertain factors could be developed (products in bold, Table 7). The Industrial uncertainty scan is applied to a case-study to demonstrate how this method works for a real-world case. With this application, observation can be gathered about the workability of the method in practise. The application of the case-study is discussed in the third part of this research.

Part III: Case-study application

7. Industrial actors and their cluster

The first and second step of the Industrial uncertainty scan is applied to the case-study (Table 9), to observe how the method steps work in practice. The objective of the first and second step of the method is to retrieve information about the cluster system and the *system*, *policy* and *outcomes of interests* of the individual actors. The industrial actors from the case-study were involved during these steps to retrieve the required information. Section 7.1 elaborates on the demarcation of the case-study. Thereafter, in section 7.2, the system, policy and objectives of the individual actors in the case-study are identified. In section 7.3, the observations gathered from the application are concluded.

Table 8 Step 1-2 Industrial uncertainty scan

Step	Tool	Input	Product
1. Demarcate the industrial cluster	Cluster conceptualisation theory (section 3.2)	Literature	Cluster system model
2. Define system, policy and objectives of actors	Electrification categorisation (section 3.3)	Literature & interview data	Actor system model (incl. electrification strategy), actor objectives

7.1 Cluster conceptualisation

The cluster of the case-study is conceptualised in this section. The conceptualisation theory of Brown et al. (2007) (chapter 3) and literature about the case-study are used to map the connections between the industrial actors (Figure 14). The most important relations between the actors of the case-study are visualised (Kernteam Versterking Industriecluster Rotterdam/Moerdijk, 2016). The less important products, which are not supplied between the actors in the case-study, are visualised with an X (to remain a clear figure).

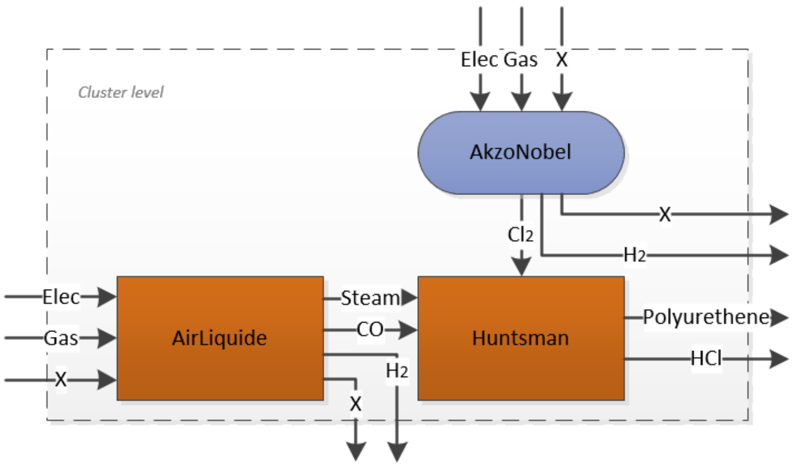


Figure 14 Cluster system case-study

The depicted case-study cluster can be seen as a value-adding web within the Botlek cluster (the Botlek cluster is also a value adding web within the complete Rotterdam industry cluster). The three actors have entwined processes which displays the dynamic characteristics of a cluster; the relation between the horizontal actor and two vertical actors. Because these processes are entwined, a certain dependency between the actors develops.

AkzoNobel, the producer of the chlorine (Cl), is the horizontal actor in this cluster. The supply and demand of chlorine is a local market. This is because chlorine is not allowed to be transported over large distances, due to the risk associated with transportations (hazardous effects on human health). Huntsman and AirLiquide are the vertical actors in this cluster. Huntsman requires the chlorine of AkzoNobel to produce their chlorine-based products, mainly for the production of polyurethane (MDI). Since the supply and demand of chlorine is a local market, Huntsman is dependent on the delivery of chlorine by the only supplying actor (AkzoNobel). Huntsman requires also steam and carbon monoxide (CO) for their polyurethane production. The steam and carbon monoxide is produced by AirLiquide and transported to the Huntsman site (Industrielinqs, 2003). Therefore, Air Liquide acts as a vertical actor in this cluster. Steam is also a local market. This results in a dependency between Huntsman and AirLiquide. The links between these companies are direct, meaning that they directly deliver their products to each other (by pipelines).

7.2 Actor system, policy and objectives

This section defines the system of the industrial actors and identifies their electrification strategy and objectives. The connections identified in the cluster conceptualisation are used to demarcate actor systems models. Actor systems models display the scope of control of the industrial actors. Block-flow diagrams are used to visualise the actor systems. The preferred electrification strategy of the industrial actors is processed in these actor systems. Thereafter, the objectives of the industrial actors were identified. Literature and interviews with industrial actors (appendix B) were used during these steps.

AkzoNobel

[redacted]

[redacted]

[redacted]

Figure 15 Actor system model AkzoNobel

[redacted]

[redacted]

[redacted]

Huntsman

[redacted]

[redacted]

[redacted]

[redacted]

Figure 16 Actor system model Huntsman

[redacted]

[redacted]

[redacted]

[redacted]

AirLiquide

[redacted]

[redacted]

[redacted]

Figure 17 Actor system model AirLiquide

[redacted]

[redacted]

[redacted]

- [redacted]

- [redacted].

The *system*, *policy* and *outcomes of interests* information learned from these three industrial actors is used during the identification step in chapter 8.

7.3 Conclusion

The first and second step of the Industrial uncertainty scan has been applied to the case-study in this chapter, to observe how the method works in practice. Following the steps of the method led to the gathering of information about the *system*, *policy* and *outcomes of interests.* Interviews (with industrial actors) and literature were used during these steps. The cluster conceptualisation provided to be a useful tool to demarcate actors within the cluster systems. This demarcation provided information about the dependency and scope of control of the industrial actors. The information is used to create actor system models in block-flow diagrams.

The industrial actors were able to specify their actor systems models (with processes and flows in the block-flow diagrams) during the interviews. The desired detailing level was achieved, including the main processes of the company which are affected by electrification. This detailing level is important to be able to identify uncertain factors in the next step. The industrial actors were also able to argue for their electrification strategy and objectives. The objectives were verified using the annual report. Verification was not possible for the actor system model conceptualisation and electrification strategy identification. Chapter 10 provides a discussion on the value of the method, given these observations.

8. The experienced uncertain factors

Step three till five of the Industrial uncertainty scan is applied to the case-study (Table 9), to observe how the method steps work in practice. The objective of these steps is to identify the uncertain factors, make a selection regarding their importance and explore their dimensions. Industrial actors from the case-study were involved during these steps to retrieve the required information. Section 8.1 discusses the process of the method steps. An explanation is given how these uncertain factors are identified, selected and dimensioned. Thereafter, in section 8.2, the identified, selected and dimensioned uncertain factors are analysed. The analysis provides an indicated what knowledge we gained from these uncertain factors with their characteristics. The differences between the interview and literature identified uncertain factors are discussed in section 8.3. Section 8.4 discusses the uncertain factors for the industrial actor who could not have been interviewed. Lastly, in section 8.5, the observations gathered from the application are concluded.

Table 9 Step 3-5 Industrial uncertainty scan

Step	Tool	Input	Product
3. Identify uncertain factors	System model perspective argumentation (Figure 12), uncertainty content taxonomy (Figure 4)	Actor system model, actor objectives, interview data	Identified uncertain factors
4. Select most important uncertain factors	Selection grid (Figure 13)	Identified uncertain factors, interview data	**Selected uncertain factors**
5. Explore the dimensions of uncertainty	Revised uncertainty framework (Figure 9)	Selected uncertain factors, interview data	**Location, level and nature information of selected uncertain factors**

8.1 Towards a list of uncertain factors

This section discusses the process of the identification, selection and dimension exploration of uncertain factors. An argumentation is provided about how the uncertain factors were identified, selected and explored. Semi-structured interviews with industrial actors were used during this process.

Identification & selection

The actor system models, the identified electrification strategies and actor objectives (chapter 7) were used during the interviews with industrial actors to identify uncertain factors. The industrial actors were able to argue for the identified uncertain factors using the reformulated 'system model perspective'. For instance; one industrial actor identified *the electricity price as uncertain, since it affected the electrolysis process in* his *system, which led to variation in the low production cost objective*. Different categories of uncertain factors were identified using the uncertainty taxonomy, ranging from policy to technological uncertainty (Figure 4). Lastly, the industrial actors were able to qualitatively assess the identified uncertain factors based on their impact and likelihood of occurrence. Therefore, a selection could be made to focus only on the most important uncertain factors.

In total, 15 relevant uncertain factors were identified and selected from three interviews. The uncertain factors are presented in Table 11. The complete interview results can be found in Appendix B. These experienced uncertain factors are presented by the author, due to the following criteria:

- Argued elaborately by the respondent: connections of uncertain factors with electrification strategy, company's system and objectives (using the system modelling perspective; Figure 12).
- Selected as a high impact on business objectives and high likelihood of occurrence by the respondent (using the selection grid; Figure 13)

Table 10 presents the experienced uncertain factor which were identified by industrial actors, but discarded in this research by the author. This was because they didn't suffice the stated criteria above. '[redacted] All these discarded factors were also not selected in the selection grid, as the respondent (who identified these factors) was unable to select the factors along the high impact and high realistic axes.

Table 10 Discarded uncertain factors

[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]

Dimension exploration

The revised uncertainty framework (Figure 9) was used to explore the dimensions of the selected uncertain factors. The framework led to the gathering of information about where the uncertainty is located, how it is caused and the severity of the uncertainty.

During the interviews, the industrial actors used the actor system model to point out the *location* of the uncertain factors: 'context' for outside the cluster system, 'cluster' for between cluster partners and 'internal' for within the actor's own system. The *level* of uncertainty is based on the respondent's expectations for the development of the factor in the future. High levels indicated that the respondent has no clear idea of how the factor develops, while low levels indicate that the respondent expects a certain development path for the factor. Despite the low level of uncertainty of some factors, the respondents were unable to provide any quantitative information. This was partly because they simply didn't have the exact numbers at hand, but also because they couldn't share strategic data. Therefore, the level dimension was assigned qualitative to maintain pragmatic. When respondents expect a distinct development of a factor while experiencing variability, the factor was assessed as 'shallow uncertainty'. When respondents were able to enumerate multiple development paths (growth, decline) and were able to rank these, the factor was assessed as 'medium uncertainty'. If the respondents were able to enumerate multiplied developments paths without ranking them, the factor was assessed as 'deep uncertain'. Lastly, if the respondents couldn't argue for an certain development and they had no idea how it could develop, the factor was assessed as recognised ignorance. The *nature* dimension has been assigned by asking the respondents how the uncertainty was caused. Most policy, market and cluster categorised factors induce uncertainty due to the differences in human perceptions of the same phenomenon, like e.g. trading (development of prices) or policy development (people's representation). Therefore, these factors were assessed as 'ambiguous'. [redacted]

Table 11 presents the list of identified and selected uncertain factors with their respective dimensions. [redacted]

Table 11 Identified, selected and dimensioned uncertain factors

[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

8.2 Analysing the uncertain factors

The identified, selected and dimensioned uncertain factors are analysed in order to understand what knowledge we gained about uncertainty in the electrified industrial cluster. An interpretation is given to the learned dimension information. As the uncertain factors are dependent on the perception of the individual actors and their unique systems, the uncertain factors are mapped within the actor system models to visualize its relations with the industrial actors (Figure 18 and Figure 19; green boxes display the uncertain factors, purple diamonds display the decisions). The selected and assessed uncertain factors are discussed per category.

Policy

[redacted]

[redacted]

Market & Process

[redacted]

[redacted]

Technology

[redacted]

[redacted]

[redacted]

Figure 18 Uncertain factors mapped AkzoNobel

[redacted]

Figure 19 Uncertain factors mapped Huntsman

8.3 Comparing literature findings with interview results

A comparison is made between the literature analysis findings (from the uncertainty context taxonomy) and the interview results in order to discuss the output of the method's identification step. When comparing the uncertain factors from literature and from the method, we see that they have a lot of similarities. The literature identified uncertain factors were generically defined while the interview identified uncertain factors were more specific. This was because the literature did not consider a specific case-study or specific industrial field for electrification, which resulted in a general overview of uncertain factors. On the other hand, the interviewed actors did consider a specific case-study; their own cluster. Despite the difference in formulation, the content of the literature identified uncertain factors and the interview identified uncertain factors are very similar. The actors from the case-study perceived uncertainty affecting their production costs and their system reliability objectives, which was also similar to the literature analysis.

All the actor identified uncertain factors are supported by literature from the literature analysis (section 4.1). Some uncertain factors identified in literature were not experienced by the respondent of the case-study (mainly related to the technology category). These differences were clearly elaborated by the industrial actors in section 8.2, why they are not uncertain for them. Therefore, the uncertain factors displayed in Table 11 is used as the definitive list of uncertain factors for the next steps, as they sufficed the criteria stated in section 8.1 while also being supported by the literature. The connection between the literature identified uncertain factors and the interview identified uncertain factors is displayed in Table 12.

Table 12 Connection literature and interview

[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
	[redacted]	[redacted]
	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]

Table 13 presents the uncertain factors which were identified by literature but were not perceived as uncertain by the respondents. These factors were discarded as the respondent were able to argue why these are not uncertain. Therefore, they will not be used for the next impact exploration step.

Table 13 Discarded uncertain factors from literature

[redacted]	[redacted]
[redacted]	[redacted]
[redacted]	[redacted]
[redacted]	[redacted]

8.4 Assigning uncertain factors for missing actor

[redacted]

[redacted]

8.5 Conclusion

Step three till five of the Industrial uncertainty scan was applied to the case-study, to observe how the method worked in practice. The steps taken led to the identification, selection and dimensioning of the most important uncertain factors. Interviews with industrial actors were used during these steps. The reformulated 'system model perspective' provided a structured process for the industrial actors to identify and argue for uncertain factors in a systematic manner. The content categorisation in the taxonomy enabled the industrial actors to identify a broad range of different uncertain factors.

The uncertainty framework was used to explore the dimensions of the uncertain factors. Assessing the level dimensions seemed to be an obstacle, due to the lack of quantitative data the respondents were having at hand. Therefore, the level dimension was assessed qualitatively. After interpreting and analysing the uncertain factors with their dimension information, we can conclude that we gained fundamental information about the perceived uncertainties; regarding the location, severity and cause. This information is important to provide the adequate treatment of uncertain factors.

When comparing the uncertain factors from literature and from the method, we see that they have a lot of similarities. All the actor identified uncertain factors are supported by literature from the literature analysis. The empirical data matches the expectations from literature, except for the technology related uncertain factors. The technology related uncertain factors were identified in literature, but not experienced by the industrial actors. Chapter 10 provides a discussions on the value of the method, given these observation.

9. Uncertainty affecting the cluster system

Step six and seven of the Industrial uncertainty scan are applied to the case-study (Table 14), to observe how the method steps work in practice. The objective of these steps is to model future ranges of uncertain factors and use these ranges to analyse the response of the cluster system to uncertainty. Unfortunately, due to time limitations in this research, the author was unable to connect the uncertain factors to the Flexnet cluster model of the case-study. Therefore, no information could be retrieved about the quantitative effect of uncertain factors on the system. Nevertheless, the future ranges of uncertain factors are modelled in section 9.1. The analysis of the uncertain effects on cluster performance is executed theoretically without a cluster model in section 9.2, to demonstrate how this analysis should be conducted. Finally, in section 9.3, an overall conclusion is given.

Table 14 Step 6-7 Industrial uncertainty scan

Step	Tool	Input	Product
6. Model future ranges	Paradigms for modelling the future (Table 6)	Selected uncertain factors, level information, literature data	Future ranges of uncertain factors
7. Analyse impact on system performance	Sobol analysis (section 5.5)	Computerised cluster system model, selected uncertain factors, actor objectives, future ranges	Variance caused by selected uncertain factors

9.1 Modelling the future

The development of the future ranges is discussed in this section. These future ranges are used as a quantitative input space for the Sobol analysis, to analyse the impact of the uncertain factors on the system. The identified and selected uncertain factors from the prior steps are used to model the future ranges. Appendix C presents all the modelled future ranges. Observations were made during the modelling of the future ranges. Section 9.1.1 discusses the process of modelling future ranges of uncertain factors. Thereafter, in section 9.1.2, the future ranges for three different uncertain factors (Table 15) are presented. This section demonstrates how the process resulted in the modelled future ranges for the three uncertain factors.

Table 15 Demonstrated factors for modelling the future

Factor	Nature	level	Location	Category	Paradigm
CO_2 price (€)	Ambiguity	2	Context	*Policy*	*Exploring multiple plausible futures*
Electrify price (€)	Ambiguity/ Ontology	4	Context	*Market*	*Exploring multiple plausible futures*
Chlorine demand (V)	Ambiguity	2	Cluster	*Market/ Process*	*Exploring multiple plausible futures*

9.1.1 The process

In order to create the future ranges from the uncertain factors, the following information is used:

- Uncertain factors and their level dimension information (chapter 8).
- Historical data of the uncertain factors and the statistical properties (appendix C).
- Scenarios or reports from other research institutions as reference, when available.

First of all, the level dimension data of the uncertain factors is used to choose the appropriate paradigm to model the future. Table 6 presents the connections between the levels of uncertainty and the three paradigms. Low-level uncertainties used the *quantification of future uncertainty* paradigm (short range or bandwidth), while high-level uncertainties used the *exploring multiple plausible futures* paradigm (large range or bandwidth) to model the future.

To explore the effect on the system and actor objectives, it is needed to provide quantitative information to these future development paths. As indicated before, low-level uncertainties imply that the industrial actor expected a certain development and could argue for it with data. Although the respondents were unable to provide any quantitative information. This was partly because they simply didn't have the exact numbers at hand, but also because they couldn't share strategic data. Therefore, the qualitative expected development of industrial actors in combination with grey literature and data sources were used to assign quantitative ranges (bandwidths) to the expected future developments. Although, the availability of historical data was also extremely scarce. [redacted] When there was data available, the historical data was most of the time not suitable. Therefore, the author had to make a lot of (subjective) assumptions which largely influenced the quantitative future ranges.

The ranges were created with an upper and lower bound to model the uncertainty in numerical development. The objective was to set these bounds that the range: *projected the expected qualitative development of the industrial actors (using the paradigms), was aligned with scenario literature and historical data* (when available). To goal was not to predict the future development of uncertain factors, but to find an acceptable range or bandwidth as input space to explore the impact of uncertainty on the system. Sometimes, concessions had to be made while developing the future ranges. Overall, when an uncertain factor had a low-level of uncertainty and the respondents expect a specific development path which was supported by literature, the expectations of the respondents and literature were leading in the development. This is because developments of the past are not always aligned with developments in the future. Due to particular events (e.g. awareness sustainability), some uncertain factors are expected to have a specific development path which was not the case in previous years (e.g. CO_2 price). When an uncertain factor had a high level of uncertainty and the respondents didn't know what to expect while literature also couldn't provide an indication, the statistical properties of the historical data were leading in the development of the ranges or bandwidths.

9.1.2 Future ranges

This section present the future ranges of three uncertain factors. These future ranges are the results of the process described in 9.1.1.

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

9.2 Effect on system performance

As indicated at the start of this chapter, the exploration of the uncertain effects on the system performance could not have been conducted. Nevertheless, this section will explain how this step would have been conducted to demonstrate its use. It provides an indication where this step manifests itself within the complete method.

A Sobol analysis can be used to analyse the response of the system and the objectives (stated by the industrial actors) to the uncertain factors. The analysis indicates the fraction of variance caused by an uncertain factor on the outcomes of interests, over the full range of parameters in the model. The Exploratory Modelling Workbench can be used to conduct the Sobol analyses. To conduct the Sobol analyses using the Exploratory Modelling Workbench, the following components are required:

- A conceptualised computer model of the electrified cluster system.
- Actor objectives to analyse the system performance.
- Uncertain factors with quantitative ranges.

These components should have been identified in the previous steps of the method. Although, a transformation from the conceptualised cluster model to a computer model is still required. In this case-study, the Flexnet model (linear optimisation) would have been used. The outcomes of interests (objectives) which were affected by uncertainty were identified: *low production costs* and *system reliability*. The uncertain factors with their quantitative ranges were discussed in section 9.1. When conducting the Sobol analysis in the Exploratory Modelling Workbench, the software creates an m-dimensional space of uncertain factors with their corresponding ranges. This m-dimensional space is used as input for the computer model. Thereafter, the software gathers the output of the computer model and computes how much variance an uncertain factor induces on the selected outcomes of interests. Therefore, a statement could be made about whether the experienced uncertainty is actually affecting the system and the actor objectives. Also, a selection could be made of the most variance inducing uncertain factors to focus on in future research.

9.3 Conclusions

Step six of the Industrial uncertainty scan was applied to the case-study, to observe how the method worked in practice. The step led to the future ranges of uncertain factors. By connecting the level characteristics of uncertain factors to the paradigms, we obtained information on how the future development ranges should be created. The respondents couldn't provide any quantitative expected future developments or data. Also, the availability of data in grey literature was scarce. Therefore, the author had to make a lot of (subjective) assumptions which largely influenced the future ranges. Therefore, the ranges are not defendable. Unfortunately, due to time restrictions, the last step to measure the response of uncertain factors to the electrified industrial cluster system was not conducted. In theory, the future ranges could be used as input space to a Sobol analysis, to retrieve information about how much variance an uncertain factor causes on the cluster system and objectives. With this analysis, a statement could be made about whether the experienced uncertainty is actually affecting the system and the actor objectives. Chapter 10 provides a discussions on the value of the method, given these observation.

10. Discussing the method's value

This chapter discusses the value of the method. It is important to reflect on the workability of the method and the theoretical foundation of the method steps, to judge whether it accomplishes the objectives: supporting analysts in the identification and exploration of uncertain factors in electrified industrial systems. Section 10.1 reflects on the workability of the different method steps and their theoretical foundation. Thereafter, in section 10.2, a discussion about the fundament of this method is presented: the effectiveness of the collaborative bottom-up approach. Section 10.3 discusses possible application areas for the method. Finally, in section 10.4, a conclusion about the value of the method is provided.

10.1 Method in practice

The observations from the case-study application (chapter 7, 8 and 9) are used to reflect on the method steps and their theoretical foundation. During the discussion, the following criteria are used to test the method's value:

- The formal method should support the analyst in the identification and argumentation of a broad range of uncertain factors in electrified industrial systems.
- The formal method should support the analyst in exploring the characteristics and the effects of uncertainty in electrified industrial systems.
- The formal method should create support towards the use of the uncertain factors in research to multi-actor industrial clusters.

Step 1-2: Industrial actors and their cluster

The cluster conceptualisation theory was a useful tool to identify the scope of control of the industrial actors in the cluster. This information was used by the analyst to construct a preliminary actor system models. The actor system models was visualised as block-flow diagrams. Block-flow diagrams enabled a clear overview of the system for the analyst and the respondents. During the interviews, the respondents could indicate changes or specifications to the actor system models. After elaborating the electrification strategy by the respondents, this model overview provided aid in identifying which processes are affected by electrification technologies and strategies. The desired detailing level was achieved for the actor system model. The importance of the system model was to demarcate the processes of the industrial actors and providing a visual overview for the identification phase. The system model didn't require specificities in flows or structures. Therefore, no sensitive company information was retrieved and the involved respondents were collaborative in the development of the high-level actor system models. Although, with a more detailed system model, more system specific uncertainties (e.g. technology) could have been identified. When developing the actor system models, the analyst was dependent on the willingness to share information by the industrial actor.

Next, the company objectives of the industrial actors in the case-study were identified. Using annual reports (analysed beforehand), the stated objective could be validated during the interviews. When an objective in literature was not indicated by the respondent in the interview, a discussion has been held whether it was relevant for analysing electrified industrial systems.

The first and second method steps (with the use of interviews with industrial actors) resulted in the required information about the *system*, *policy* and *outcomes of interests (objectives)* of industrial actors in the case-study. When gathering information about the system, policy and objectives, you are dependent on the perception of the respondent. The question one could ask is if one respondent could be representative of the whole company, regarding the knowledge (about the *system* and *electrification strategy*) and what the company want to achieve (*objectives)*. As indicated before, the objectives could be validated through literature. Validation was not possible for the (partly unique) system demarcations and the (actor preferred) electrification strategies. To overcome this issue, these steps could be improved by involving more interview respondents from the same company to get a better representation of the industrial actors.

Step 3-5: The experienced uncertain factors

Interviews with industrial actors were used to identify what they experienced as uncertain in their systems. The actor system model proved to be a very useful aid in the identification of uncertain factors. The visual overview to locate uncertain factors in combination with the argumentation structure of the 'system model perspective' theory, resulted in a structured way for the industrial actors to identify what they experienced as uncertain. The respondents acknowledged the fact that each of them is having their own perception of uncertainty. Therefore, they appreciated that they had an influence on the identification and exploration of the uncertain factors (support).

The difficulty for identifying and arguing uncertain factors by the respondents differed per person. The respondent with a broader management perspective felt more at ease during the uncertain factor identification compared to the technologist. As feedback one stated that this identification process would be more appropriate at the higher hierarchal layer of the company. Employees from the management layer are more experienced with these kinds of topics and are often experiencing these uncertainties as they are the decision-makers. Involving people from the management layer in this process could improve the quality of the identified uncertain factors. Nevertheless, people from other branches in a company could be very valuable due to the specific (e.g. technical) knowledge they have. Therefore, conducting this process with e.g. a technologist is still very useful. When comparing the identified uncertain factors from the technologist and the manager in the interviews, we can see that the technologist focussed more on the technology related uncertain factors while still identifying some policy and market uncertain factors (which were similar to the manager's factors). Therefore, the uncertainty taxonomy was a useful tool to guide the conversation to different topics of uncertainty and broaden the scope of the respondents during the interviews.

The uncertainty taxonomy, developed during the literature analysis, considered only uncertainty affecting the objectives: 'production costs' and 'system reliability'. The respondents did only identify uncertain factors within the categorisation of the taxonomy. Therefore, there is a certain risk that due to the used categorisation in the taxonomy to guide the conversation, 'uncategorised uncertain factors' (which were not in the taxonomy) were not covered during the identification. Nevertheless, the respondents indicated that all topics of uncertainty were discussed. Further research should indicate whether other categories of uncertainty are relevant for electrified industrial systems and the taxonomy should be complemented. Very few technological uncertain factors were identified (with only a low-level uncertainty). Therefore, one could argue the use of this category as unnecessary, since the technology was considered predictable while e.g. the market was deeply uncertain. At this stage, with just three respondents, cancelling the technology category would be too soon, as the literature analysis did indicate it as uncertain. Also, the industrial actors in the case-study were interested in system proven electrification technologies (e.g. power to heat with a TRL level of 9). Other electrification technologies may be in an earlier and less defined phase, which can be a source of uncertainty. Future research should look more into the relevance for the technology category and possible complement the taxonomy with new categories and actor objectives.

The assessment with the use of the uncertainty framework enabled the analyst to explore the dimensions of uncertainty. This provided fundamental information about the characteristics of uncertain factors. These characteristics are important to provide the adequate treatment of uncertain factors. A revision of the location dimension was required for the uncertainty framework, as the location dimension should reflect the object of the study. The cluster conceptualisation theory was used during the development of the location revision. The revision reflects the uncertain connections of actors in a cluster. The revision was considered successful as it provides insights into the dependency of industrial actors to external relations.

Interviews with industrial actors were used to assess the dimensions of uncertainty. It was relatively easy to identify the location dimension of uncertain factors due to the use of the actor system models (visual aid). The respondents also grasped what is causing the uncertain factors (nature dimension). Assigning quantitative data to the expected values of an uncertain factor (in order to evaluate the level of uncertainty) was difficult for the respondents. Therefore, they indicated the future development of uncertain factors qualitatively. Although with low-level uncertainty (implying you know how a factor is going to develop quantitatively), they couldn't provide any quantitative indications. This was partly because they simply didn't have the exact numbers at hand, but also because they couldn't share strategic data. One respondent replied that the company has projections and specific expectations of the (low-level uncertainty) factors, but was unable to share these. Assigning specific values to expected future developments seem to be a sensitive matter, as it could compromise corporate strategy. A qualitative discussion about the level of uncertainty proved to be sufficient to identify the level of uncertainty, as the respondents were able to argue elaborately during the interview. Although, there is a certain risk that some factors are falsely assessed as a high-level uncertainty. This could be due to respondents indicating they don't know how an uncertain factor is going to develop, while actually they just don't want to share their information. As indicated before, you are dependent on the perception and willingness of the respondents.

Coincidentally, the uncertain factors identified by multiple actors were assessed with the same dimension values. It is possible that actors experience the same factors differently with e.g. a different expected development (degree of uncertainty). Therefore, when applying the method to a multi-actor system, a workshop with the relevant actors could be organised to improve this phase. A workshop could enable a collaborative discussion between the actors about what uncertain factors are important and how these should be assessed. The characteristics of the Delphi method can be used to guide the workshop with industrial actors (instead of experts) (Renzi & Freitas, 2015). First of all, the actors should be able to express their own thoughts about the uncertain factors. This could form the first round in the workshop, where the actors provide their input anonymously. Thereafter, a discussion can be held about the results from the first round. The discussion about the results can encourage the actors to revise their earlier answers. Repeating this process in multiple rounds can lead to consensus of the uncertain factors with their characteristics. Further research should look more into the use of a workshop.

Step 6-7: Uncertainty affecting the cluster system
Unfortunately, the last step of the Industrial uncertainty scan could not be completely executed. Therefore, a discussion is only provided for the modelling of the future ranges (step 6). The future ranges of uncertain factors were developed by the analyst and not during the interviews with the respondents. The dimension characteristics learned from the assessment process was an important fundament for the development of supported future ranges of uncertain factors. But due to the lack of quantitative indications by respondents, the actor data couldn't be modelled into the future ranges. Therefore, the quantitative development of the future ranges relied on the grey data sources (historical data and reports about future development). Although, the availability of the specific industrial and energy-related data was scarce. Therefore, the author had to make lots of assumption when developing the future ranges. This could affect the support towards the exploration of uncertain factors (use of uncertain factors in research). A feedback session should be held in order to check whether the developed future ranges are still representing the respondent's perception about the uncertainty. Further research should also look to a more efficient way to retrieve the specific data for modelling future ranges. Data experts are often involved when "there is scarce or insufficient empirical material for a direct quantification of uncertainty" (Refsgaard et al., p.1549, 2007). By involving data experts, more quantitative insights into future developments of uncertain factors could have been gathered.

10.2 Collaborative approach

The Industrial uncertainty scan embraced the concept of collaboration, by using industrial actors as input for the identification and exploration of uncertain factors. The industrial actors are the experts about their (unique) systems and are also experiencing the uncertainty during investment decisions. The input of the industrial actors was important since they were able to identify the specific industrial uncertainties within the entwined cluster. Also, by involving stakeholders, support can be created towards the use of the identified and explored uncertain factors in research by the analysts.

Uncertainty is dependent on the perceptions of humans. When thinking about the future, people often predict future developments using past experience as reference. Although, a past trend may not be appropriate to project the future (as we have seen in section 9.1). Describing in other words; an expert of the past experience (industrial actors) may not be an expert of the future. Therefore, one could argue that using the industrial actors as input would not be appropriate for the identification and exploration of uncertainty. In this research, we value the idea of collaborative uncertainty exploration. The involvement of multiple actors with different perceptions contributed to diverse uncertain factor identification and exploration. When applying a diverse range of uncertain factors to an electrified industrial system, the robustness of the system under different contexts can be tested. Also, ambiguous uncertainty can be identified when using diverse stakeholders as input. The author opted the unachievable idea of predicting the future. Stating that experts are better in identifying and exploring uncertainty may not be true. The collaborative concept of this method connects well to the robust decision-making approach, in which one wants to test the robustness of their decisions under a broad range of different futures (Lempert, Groves, Popper, & Bankes, 2006). The development of a broad range of plausible futures benefits from the involvement of a diverse group of actors.

10.3 Applicability of method

This section discusses the possible application areas of the Industrial uncertainty scan. The discussion provides insights into which situation the method could contribute to the identification and exploration of uncertain factors.

Using the method for research to industrial clusters
The Industrial uncertainty scan is developed specifically for research to the electrification in industrial clusters. Although, the method could also be used for other researches in industrial clusters. When using the method, it is important that the system of interest include a multi-actor industrial cluster, which benefits from using industrial actors as input. The revision of the location dimensions in the uncertainty framework is relevant for other researches in multi-actor industrial clusters. The *system* component of the 'system model perspective' theory can be specified according to the focus of the study. Although, some changes are necessary to use the method for other researches in multi-actor industrial clusters. First of all, the *policy* component of the 'system model perspective' should be changed. The *policy* components should reflect the 'system change' of the study (e.g. electrification). Also, a different uncertainty content taxonomy should be created, to guide the identification process across the categories of uncertainty for the specific study.

Using the method in established uncertainty studies
The Industrial uncertainty scan has the potential to be used in combination with established uncertainty studies like Scenario Discovery. Scenario discovery characterises sets of uncertain factors, by applying statistical of data mining algorithms to databases of model generated results, into scenarios (Bryant & Lempert, 2010). The information learned from the Industrial uncertainty scan (identified and explored uncertain factors) could be used as a basis for the scenario development in a Scenario Discovery study.

Using the method by policy-makers
Many governments in the world are taking actions to reduce CO_2 emissions. With this method, policy-makers could identify and explore what the industry experiences as uncertain when investing in electrification technologies. Policy-makers have instruments to reduce uncertainties (e.g. flexible subsidy) or incentives certain behaviour (taxing CO_2) to overcome these uncertainties. Policy analysts could identify what policy measures are needed to overcome these uncertainty barriers for industrial actors, in order to achieve the societal goals of CO_2 reduction.

Also, when using the uncertain factors for developing scenarios, an exploration can be made how future policy responds to the uncertain future contexts. A collaborative approach for developing scenarios is tested in public domains before (Bryant & Lempert, 2010). The application in the public domain was considered as successful and an improvement over the traditional expert scenario development (regarding support). The Industrial uncertainty scan could contribute to the development of public scenarios, by delivering identified and explored uncertain factors.

Using the method by the private sector
The Industrial uncertainty scan with its collaborative approach was developed for scientific use, to support analysts. The method to identify and explore uncertain factors could also be used by the private sector for the development of e.g. business cases. Business cases often use scenarios to project how the investment pays out in the future. Although, when business cases are made between multiple actors (multi-actor systems), there is not always support toward the use of these scenarios due to the different perceptions of the future. An important private cooperation for electrifying industrial systems is between electricity

utility providers and the industry. During the application of the method to the case-study, it became evident that the industry has a very different perception about the uncertain future compared to an electricity utility provider. The decision-making between these parties could be improved by collaboratively developing scenarios. The Industrial uncertainty scan can contribute to the collaborative scenario development by identifying and exploring uncertain factors with the actors. The method can improve the joint sensemaking of each other's perceptions of uncertainty. The specific knowledge about energy markets and industrial systems could complement each other in the Industrial uncertainty scan.

A collaborative approach has not been used before in the private sector with private interests. The success of the collaborative approach taken in this method is debatable in the private sector. Actors may not be willing to share strategic information with others. There could also be an incentive to act strategically in the identification and exploration of uncertainty with private interests. By influencing the process, one could provoke other actors to e.g. act or invest in a certain way which could be beneficial for the strategic actor. For example, by stating that a market factor is not uncertain and is developing to a specific value, one could provoke other actors to change their system which is beneficial for the strategic actor.

10.4 Conclusion

This chapter provided a discussion to the value on the Industrial uncertainty scan. The discussion criteria have been mostly met.

- The method enabled the analyst to identify a broad set of argued uncertain factors, using the visual system overview, the systematic 'system model perspective' argumentation and the uncertain content taxonomy.
- The revised uncertainty framework in the method helped the analyst in exploring the characteristics of uncertainty in industrial environments.
- The criterium for creating support towards the use of the uncertain factors was partly met. The respondents valued the idea that they had influence on the identification and explorations of the uncertain factors.

Some improvement for the method were identified:

- The uncertainty content taxonomy could be improved by including new categories of uncertainty, which were not covered. By including new categories, the analyst is able to discuss more diverse topics of uncertainty during the identification process with industrial actors.
- Industrial actor could assess the characteristics of uncertainty differently in the framework. To overcome this problem, a workshop could be organised to enable a collaborative discussion between the actors for assessing the characteristics of uncertainty.
- The modelled future ranges of uncertainty factors were heavily influenced by grey literature and assumptions of the author. Also, the data in grey literature was scarce. Involvement of data experts could improve the data collection. To improve supports, the modelled future ranges require feedback from the industrial actors.

The method has the potential to be used for other researches in industrial cluster systems, with established uncertainty studies, by policy makers in public organisations and by companies in the private sector.

11. Conclusions and recommendations

The focus of this research was to support analysts in the identification and exploration of uncertain factors in electrified industrial systems. The product is the Industrial uncertainty scan. This chapter summarises the main findings of this research. Section 11.2 discusses the conclusions. An answer has been given to the main research question and the sub-questions. Thereafter, in section 11.3, recommendations for further research are discussed.

11.2 Conclusions

The conclusions for this research are discussed in this section. First, an answer is given to the sub-questions in this research. Thereafter, an overall conclusion is provided to the main research question.

Answering the sub-questions

S1: What specific characteristics in electrified industrial systems are inducing uncertainty?

The processes of industrial actors are entwined with each other in a cluster. The production of a single firm depends on the supply (e.g. semi-finished products) of other industries. Although the system's value creation should be considered as the whole cluster, decisions are made by the individual actors using actor objectives as parameters. Therefore, changes in the system of one industrial actor affect the systems of other actors. These changes can cause uncertainty. The cluster conceptualisation theory is introduced to map these connections between industries. A system change like electrification affects these connections within an industrial cluster. Depending on the strategy and application area, electrification causes uncertainty within a cluster. The connection between industrial actors in their cluster and the chosen electrification strategy by individual industrial actors are the specific characteristics of electrified industrial systems that are inducing uncertainty.

S2: What types of uncertainty are present in electrified industrial systems?

A literature analysis was conducted about the types of uncertain factors in electrified industrial systems. The literature analysis indicated that factors affecting the financial and reliability objectives of the industry were considered as uncertain. When categorising these factors on their content, the industry perceives uncertainty regarding policy, market, technology and process trends. These categories were synthesised into the uncertainty content taxonomy (Figure 4).

S3: What is the state of knowledge regarding uncertainty conceptualisation, identification and exploration for decision-making?

The 'system model perspective' provides a systematic overview of the *system*, *policy*, *context* and *outcomes of interest* components and explains the interrelation between them. This theory forms the basis for the identification of uncertainty. To provide the right treatment of the identified uncertain factors, uncertain factors should be explored based on the location, level and nature dimensions. The uncertainty framework of Kwakkel, Walker and Marchau (2010) is used to explore these dimensions or characteristics of uncertain factors. The characteristics of the explored uncertain factors provide fundamental information about; where the uncertainty is located (location), how severe the uncertainty is experienced (level) and how the uncertainty is caused (nature). The paradigm by Maier et al. (2016) describes how future ranges of uncertain factors can be modelled given their characteristics. The future ranges can be used to explore the impact of uncertain factors on the system. An important technique to analyse the response of uncertain factors on the system is the Sobol analysis. Using this analysis, an exploration can be made how much variance an uncertain factor causes in the outcomes of interests of a system.

> *S4: How to come towards a synthesis in the conceptualisation, identification and exploration of uncertainty for electrified industrial system?*

The synthesis consisted of connecting the established methods, frameworks and theories in uncertainty management. Some modification for the established methods, frameworks and theories were required to study the uncertainty specific for electrified industrial systems and to enable the involvement of industrial actors in the process.

The *system* and *policy* components in the 'system model perspective' theory were specified for electrified industrial systems. The cluster conceptualisation theory was used to develop the *system* component. Literature about electrification strategies was used to define the *policy* component. An argumentation line was derived from the 'system model perspective' by the author to provide a structured process for the identification of uncertain factors with industrial actors. The uncertainty content taxonomy was created to guide the identification process along different topics of uncertainty with industrial actors. The identified uncertain factors from the 'system model perspective' are used as input in the uncertainty framework to explore the dimensions of uncertainty. A revised location dimension of the framework was needed to assess the uncertainty in the industrial cluster environments. The cluster conceptualisation theory was used to develop the revised location dimension. The revised location dimension reflect the uncertain connections of industrial actors with their environment. To model future ranges of uncertain factors, a connection was made between the assessed level dimension of uncertain factors and the paradigms for modelling the future. These future development paths can be used as input to a Sobol analysis, to explore the effect of uncertainty on the *system* and *outcomes of interests* components from the 'system model perspective'.

> *S5: What is the value of using a formal method to identify and explore uncertainty in practice by analysts?*

Overall, the used method satisfied the stated criteria to support analysts in identifying and exploring uncertain factors. The visualisation of the system and the reformulated 'system model perspective' theory enabled the analyst to *identify* uncertain factors and *argue* why these are uncertain, using industrial actors as input. The taxonomy helped the respondents during the interview to *broaden* their scope about different types of uncertainty.

With the use of the revised uncertainty framework, the analyst gained insights about what the characteristics are of the uncertain factors. It should be noted that the last step, measuring the quantitative effect of uncertain factors on the system, could not be conducted. In theory, this should provide quantitative insights into the response of the cluster system to uncertainty.

The respondents acknowledged the fact that each of them is having their own perception of uncertainty. The involvement of the industrial actors in the identification and exploration of uncertainty was therefore appreciated. Although, it should be noted that the criterium about creating *support* towards to use of the uncertain factors could not be satisfied completely in this case-study. The analyst was unable to develop defendable future ranges. The analyst had to make a lot of subjective assumptions during the development, due to the lack of data in literature and quantitative indications by the respondents. These undefendable future ranges could reduce the support towards the results of the impact exploration step.

Answering the main research question

> *RQ: How can analysts be supported in the identification and exploration of uncertain factors in electrified industrial systems?*

We can conclude that the Industrial uncertainty scan supports analysts in the identification and exploration of uncertain factors in electrified industrial systems. The method consists of the following actions:

1. Demarcate the industrial cluster
2. Define system, policy and objectives of actors
3. Identify uncertain factors
4. Select most important uncertain factors
5. Explore the dimensions of uncertainty
6. Model future range
7. Analyse the impact on system performance

When using this method in an industrial cluster, you can retrieve the most important uncertain factors, including their explored location, level and nature dimension characteristics. The method also explores the impact of the uncertainties on the cluster system.

The Industrial uncertainty scan grasped the essential theories in the field of uncertainty research, synthesised it with the specific characteristics of electrified industrial systems and operationalised it in steps. During the application of the method to the case-study, it provided to be a valuable tool to identify and explore uncertain factors. This method could be the first step towards scientific research to electrified industrial systems in their uncertain future environment.

11.2 Recommendations

This research encountered limitations during the literature analyses and the application of the Industrial uncertainty scan to the case-study. This section discusses these limitations and provides suggestions for further research. First of all, the recommendations for science are discussed. Thereafter, recommendations for practice are elaborated.

11.2.1 Recommendations for science

Expanding the uncertainty taxonomy

A taxonomy of uncertainty was created to provide a structured overview of the industrial uncertain factors from the literature analysis. It is used in the method to expand the scope of the respondents during the identification step by discussing different types of uncertainty. The literature analysis indicated uncertain factors that only affect the *productions costs* and *system reliability* objectives of the industry. Therefore, the categorisation of the taxonomy was based on these objectives. The respondents did only identify uncertain factors within the categorisation of the taxonomy. Therefore, there is a certain risk that due to the used categorisation in the taxonomy to guide the identification process, 'uncategorised' uncertain factors sectors were not covered. Further research should look if the industry has other objectives that are affected by uncertainty, as it could lead to a better specification of the categories or even new categories. This could be done by interviewing a large and diverse group of industrial actors. Also, a large literature analysis could be conducted.

Enlargement and diversification of respondents group

The method can be improved by changes in the selection of respondents. First of all, a better representation for the industrial actors is required. During the application on the case-study in this research, the industrial actors were represented by one or two respondents. One or two respondents may not be representative for the whole company. A more complete overview of the *system*, *policy*, *objectives* and *identified uncertain factors* could have been created when more people were involved to represent the same industrial actor. Also, a more diverse group of respondents should have been selected to represent an industrial actor, ranging from management till the technologist levels of the company. A diverse group could have led to a broader exploration of uncertainty due to the specific knowledge different people have.

Improving the 'model future development' step

The author had to make a lot of assumptions regarding the modelling of the future ranges of uncertain factors. This was due to the lack of quantitative indications by the industrial actors and the scarce availability of data in literature. First of all, further research should be done regarding the data gathering process. Data collection could be improved by involving data experts. Second, further research should be done about how the support towards the use of the future ranges can be secured. A second meeting with the respondents to discuss the modelled future ranges (and when needed, revising it) could improve the support.

Dealing with multiple frames of the same uncertain factors

Coincidentally, the identified uncertain factors in this research were assessed with the same dimension values by the multiple actors. It is possible that actors experience the same factors differently (e.g. the degree of uncertainty). Future research should indicate what the appropriate manner would be for the joint sensemaking of different uncertainty perceptions by different actors. Workshops could facilitate those needs.

Testing the method on more case-studies

The method should be tested on more real-world systems, to evaluate the value of the method. The last step (exploring the uncertain effects on system performance) was not conducted in this research. Further tests should indicate the value of this step. Although the workability criteria were met, it should be noted that the method was tested by using one system and three respondents. Therefore, more tests should be conducted to confirm the value of the method and reflect whether some steps of the method should be changed. Also, tests can be conducted for other research purposes in multi-actor industrial cluster systems, to explore the applicability of the method.

Understanding the uncertainty in electrified industrial systems
With the use of this method, analysts could develop a scientific overview of the uncertain factors in electrified industrial systems. Further research should identify these and explore their characteristics. Thereafter, research could be done regarding the future of the electrification pathway, given the identified and explored uncertain factors. This could provide insights into how uncertainty affects the electrification pathway in the industry. How should one deal with the uncertain factors in order to enable a renewable future?

Using the method in established uncertainty studies
The Industrial uncertainty scan has the potential to be used in combination with established uncertainty studies like Scenario Discovery. Scenario Discovery characterises sets of uncertain factors into scenarios, by applying statistical or data mining algorithms to databases of model generated results. The information learned from the Industrial uncertainty scan (uncertain factors with their future ranges) could be used as a basis for a Scenario Discovery study. Further research could look into using this method in established uncertainty studies.

11.2.2 Recommendations for practice

Using the method by the private sector
The method to identify and explore uncertain factors could be used in practice by the private sector for the development of e.g. business cases. Business cases often use scenarios to project how the investment pays out in the future. Although, when business cases are made between multiple actors, there is not always support toward the use of these scenarios due to the different perceptions of the future. The decision-making between parties could be improved by collaboratively developing scenarios for the joint sensemaking of each other's perceptions about uncertainty. The method could contribute to this by identifying and exploring the perceived uncertain factors. Although, strategic behaviour could influence the results of the method due to the private incentives. Further research should look into the value of using this method for the private sector.

Using the method by policy-makers
Many governments in the world are taking action to reduce CO_2 emissions. With the use of this method, policy-makers could identify and explore what the industry experiences as uncertain when investing in electrification technologies. Policy-makers have the instruments to reduce uncertainty (e.g. flexible subsidy) or to encourage certain behaviour (taxing CO_2). By using the method, they could identify what policy measures are needed to overcome these uncertainty barriers for industrial actors. Also, when using the uncertain factors for the development of scenarios, an exploration can be made how future policy responds to the uncertain future contexts.

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Appendices

Read Guide:

- Appendix A: Discussion revised framework uncertainty
- Appendix B: Interview results
- Appendix C: Future development uncertain factors

Appendix A: Discussion revised uncertainty framework.

This research used the uncertainty framework by Kwakkel, Walker & Marchau (2010) as a foundation for the assessment of uncertainty factors. The uncertainty framework of Kwakkel, Walker & Marchau (2010) is a revision of the original work by Walker et al. (2003). This appendix discusses the problems of the original framework by Walker et al. (2003) and explains how Kwakkel, Walker & Marchau tackled these problems in their revised framework. Also, an explanation is given why the revisions of Kwakkel, Walker & Marchau were used for this research.

Kwakkel, Walker & Marchau (2010) conducted a literature review to analyse how Walker's uncertainty framework has been used in different researches and which problems occurred during the use of the framework. A synthesis of the proposed changes in literature has been presented in the revised framework by Kwakkel, Walker & Marchau (2010). As indicated in their literature review, two problems became event during the use of the Walker framework:

- The perception of uncertainties by actors and the role of frames
- Interpretation of the level dimensions in different fields of research

Nature dimension

The Walker framework focused explicitly on the modeller's perception of uncertainty. Different stakeholders have different backgrounds and perceptions on the uncertainties perceived in the system. Brugnach et al. (2008) argued that assessing uncertainty using the framework with multiple stakeholders can lead to different perceptions, frames and interpretation using the same data. The plurality of perceptions and frames can result in unclarity, misunderstanding and value conflicts (Dewulf et al., 2009). Kwakkel, Walker & Marchau (2010) added ambiguity as a new category in the nature dimension. This category has been added in order to highlight the importance of the different interpretations by actors (based on their frames and values) of the same data. As Walker et al. (2003) already argued, the strategy for coping with uncertainty depends on the nature dimensions. When an uncertain factor entailed an ambiguous nature, the appropriate strategy is to aim at integrating frames and support joint sensemaking. Gaining more knowledge with the use of scientific research based on a single frame is not an appropriate strategy (Brugnach et al., 2008).

Level Dimension

A second problem with the Walker framework was the diversity of meanings associated with uncertainty and the situation in which it occurred. The term uncertainty has different meanings and connotations in different fields of research and actor backgrounds. Walker's framework didn't make the level dimension explicit, resulting in difficulties regarding the communication of uncertainties with actors of different backgrounds (Kwakkel & Cunningham, 2009). Therefore, Kwakkel, Walker & Marchau (2010) reconceptualised the level dimension in order to develop a uniform typology for uncertainty. The reconceptualised level dimension tried to capture the differences in the types of measurement scales. Different types of scales are used across different research fields when assigning a likelihood to certain events. The theory of scales of measurement entails the recognition of the various forms of measurements by specifying their formal mathematical properties of the different scales. The properties of the measurement scale indicate which statistical methods were appropriate to interpret the data (Stevens, 1946). Table 16 displays the various scales of measurement.

Table 16 Scales of measurement (Kwakkel, Walker & Marchau, 2010)

Level of measurement	*Mathematical structure*	*Basic empirical operation*	*Characteristics*
Nominal/categorical	Unordered set	Determination of equality	Classification into categories, no relations between categories
Ordinal	Totally ordered set	Determination of greater or less	In addition to the above, ordering of categories based on degree to which they possess some characteristic. No information on magnitude of difference
Interval	Affine line	Determination of equality of intervals or differences	In addition to the above, ordering of categories, but with information on magnitude of difference, but no absolute zero
Ratio	Field	Determination of equality of ratios	In addition to the above, absolute zero

Kwakkel, Walker & Marchau (2010, p.308) argued that the scale of measurements can be used to categorise the level dimension of uncertainty, since "the scale to be used depends on the uncertainty and procedural and methodological choices". The revised level dimension consists of four categories, displayed in Table 17. The first scale of measurement was the nominal scale. The nominal scale doesn't have a ranking order property in their measurement. This scale is associated with level 3 uncertainty (deep uncertainty), which implies that one is able to enumerate multiple possible futures without being able to rank the likelihood of those futures. The second scale is the ordinal scale. The ordinal scale has a ranking order in the property of their measurement. This scale is associated with level 2 uncertainty (medium uncertainty), which implies that one is able to enumerate multiple possible futures and rank them based on their likelihood without numerical argumentation. The third scale is the interval scale, which is not applicable to assess the level of uncertainty. When the ranking order of the measurement can be specified with numbers and intervals, probabilities (ratio scale) are more suitable. The ratio scale has an absolute zero point. This scale is used to define probabilities of future states and could be associated with level 1 uncertainty (shallow uncertainty).

Table 17 Levels of uncertainty (Kwakkel, Walker & Marchau, 2010)

Level of uncertainty	*Description*	*Examples*
Level 1 (shallow uncertainty)	Being able to enumerate multiple alternatives and provide probabilities (subjective or objective)	Being able to enumerate multiple possible futures or alternative model structures and specify their probability of occurring
Level 2 (medium uncertainty)	Being able to enumerate multiple alternatives and rank order the alternatives in terms of perceived likelihood. However, how much more likely or unlikely one alternative is compared to another cannot be specified	Being able to enumerate multiple possible futures or alternative model structures and to judge them in terms of perceived likelihood
Level 3 (deep uncertainty)	Being able to enumerate multiple alternatives without being able to rank order the alternatives in terms of how likely or plausible they are judged to be	Being able to enumerate multiple possible futures or specify multiple alternative model structures, without being able to specify their likelihood
Level 4 (recognised ignorance)	Being unable to enumerate multiple alternatives, while admitting the possibility of being surprised	Keeping open the possibility of being wrong or surprised

Location dimension

Lastly, the revised framework considers a specified location dimension as proposed by Petersen (2006). Petersen focused on applying the framework with simulation models, without considering the specific model-based decision support focus. Peterson proposed a new location dimension to improve the interpretation of its categories by using a more commonly known terminology. Kwakkel, Walker & Marchau modified the specification of the proposed location dimension of Petersen in order to bring back the decision-oriented focus. Compared to Walker et al. (2003) framework, the main difference is the terminology of the categorisation. The synthesised dimensions of Kwakkel, Walker Marchau (2010) are displayed in their framework (Figure 24)

		Level				*Nature*		
Location		*Level 1: shallow uncertainty*	*Level 2: medium uncertainty*	*Level 3: deep uncertainty*	*Level 4: recognised ignorance*	*Ambiguity*	*Epistemology*	*Ontology*
System boundary								
Conceptual model								
Computer model	Model structure							
	Parameters inside the model							
	Input parameters to the model							
Input data								
Model implementation								
Processed output data								

Figure 24 Uncertainty framework (Kwakkel, Walker & Marchau, 2010)

Conclusion
The reconceptualization of the nature and level dimension of uncertainty has been synthesised by Kwakkel, Walker & Marchau (2010) in a revision of the uncertainty framework. The reworking of the nature dimension was necessary to grasp the plurality of perceptions and frames for different actors when assessing uncertainty in multi-actor systems. The measurements of scale are well-known across different scientific disciplines. The scales are also free of methodological connotations (Stevens, 1946). The reconceptualization of the level dimension by the use of measurements of scale resulted in an explicit typology of the level dimension which helps in the communication of uncertainty across different field of research. Therefore, the revisions by Kwakkel, Walker & Marchau were essential to assess uncertain factors in multi-actor systems like electrified industrial systems.

Appendix B: Interview results

This appendix presents the results from the interviews with industrial actors in the case-study. Appendix B1 presents the actor objectives from the interviews. In B.2 are the uncertain factors displayed which were identified by the respondents of the case-study. Appendix B.3 presents the interview scheme, used during the interview to guide the conversation. Finally in Appendix B.3, the interview summary reports are presented per respondent.

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Appendix C: Future development uncertain factors

This appendix presents the future ranges of the uncertain factors. Table 22 presents the information about how the future ranges were created. The level column presents how the uncertainty was experienced by the respondents. The arrow in the same column presents the (qualitative) expected development direction of the respondents (up=growth, down=decrease, right=maintain current level). The paradigm column presents which paradigm was used to model the level of uncertainty. The historical data and literature column presents which external information sources were used. The upper bound and lower bound column presents the range of the uncertain factors.

Table 22 Future ranges

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