An ontology of Industrial Symbiosis

The design of a support tool for collaborative Industrial Symbiosis research with as test cases from Tianjin Economic Development Area and Kalundborg

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**Summary: An ontology of Industrial Symbiosis**

Industrial Symbiosis (IS) in an inter-firm collaboration that delivers both economic and environmental benefits. IS can occur when there are local opportunities for the exchange of an underutilized resource, this means that the exchanged resource is often not a standard product. A non-standard product requires technical expertise and investments in processing equipment or other physical assets. Which in turn puts additional tension on the socio-economic decision making process, because of asset specificity. Thus systems with IS are complex systems, systems with an interplay between socio-economic behaviour and the technical network (Dijkema & Basson 2009). As a consequence, IS attracts scientists from multiple different disciplines. This might explain why there is not yet a widely shared understanding of self-organizing IS (Chertow & Ehrenfeld 2012). All big challenges society phases require inter-disciplinary collaboration. Finding a way to built inter-disciplinary knowledge without reducing the level of detail, is thus not only relevant to IS-research, but ever more important for society in general.

IS-research is done by means of studying existing real world examples of IS, case studies. Cross-case comparison is an important principle for increasing the external validity of theories from case studies, and to sharpen the theories. Comparison requires the use of a shared pre-defined knowledge format, Nikolić (2009) calls this a formalism. Complex systems theory tells us that multiple formalisms are required to describe complex systems, such as IS-networks. Thus we need to connect multiple shared formalisms to come to the description of IS. Together the formalisms should cover the conceptual scope of IS. By means of a literature study, six focus points were found in the conceptual scope of IS-research. Observing the physical exchange of materials is one (1. physical network). Researching which social entities connect to whom and what type of relations they have (2. social interaction). Relating IS to policies, laws, market fluctuations and other external condition (3. institutional context). If time is considered, the focus can be on the level of decades (4. phases) or on the level of months (5. process). The value of IS-activity is also a focus point, what economic and environmental benefits does IS deliver? (6. valuation) Finding drivers and barriers for IS-activity is usually the goal of the research. A detailed analysis of four case studies shows that individually they do not cover the complete conceptual scope. The case studies do overlap in scope, but they do not use shared formalisms. Or they do not explicit the formalism used; this troubles comparison and building further on there research. An ineffectiveness in the contributing to the collective body of knowledge by individual learning processes can be resolved by the use of modern information and communication technology (ICT) tools (Davis, Nikolić & Dijkema 2010). ICT tools can process and communicate large amounts of data and ICT tools induce the need for a systematic input of data. This can shape formalisms, a secondary benefit.

To explore the use of modern ICT-tools for IS-research; the particular tool in this thesis is Enipedia. Enipedia is a semantic wiki, and wikis enable contribution. But to take advantage of a semantic wiki as an ICT tool, an ontology is required. An ontology specifies how concepts relate to each other. The main design objective of this thesis is:

**Design an ontology that can store and share IS case study data, with the possibility to evolve through the input of contributors.**

Ontologies have abstract layers that describe the typologies of things and concrete layers that describe particular objects. The facility is an abstract concept, *Asnaes power plant* is a particular facility. Facilities have properties, for example: ‘has coordinates’ and ‘has synergy with’. The coordinates are longitude and latitude. The ‘has synergy with’ property connects to another facility, in this way objects have a relation through a property. This is how an ontology is built up. The ontology in this thesis has only one abstraction layer (categories) and one concrete layer (the pages on the wiki). It is built on the Resource Description Framework (RDF), an abstract top-level ontology. The ontology in this thesis is more a domain or application ontology. Therefore a ‘fit for purpose’ approach is used for the design of the ontology.

Sub objective one: Design an ontology that can represent IS-case studies.

In the design of an ontology trade-offs have to be made. An ontology that specifies an conceptualization in detail requires ontological commitment. This high commitment means that the ontology can be used in fewer contexts and is more difficult to extend. Extendibility is important for an evolving ontology.
Sub objective two: Develop procedures and techniques to enable contribution to the ontology.

To make the ontology ‘fit for purpose’, two case study data sets are used for the design. The design is made on the basis of a data set from the Tianjin Economic Development Area (TEDA). This data set was obtained through a field study by Chang Yu. The second case, a data set of Kalundborg (Jacobsen 2006), is used to evaluate the genericness of the ontology. The result of the design process is described below, but the only way the ontology can be fully appreciated is by browsing through it on Enipedia.

For the physical network there are two important categories, the facility and the synergy link. Facilities are connected through synergy links. The facilities have properties, such as industry sector and coordinates. The exchanged product, receiver and supplier facility are stored through properties on the synergy link page. Tests show that this part of the ontology works; we can give visuals of the complete network of facilities and let the wiki calculate distances of the synergies, for instance. The data sets do not have much information about social interaction. Match making workshops are represented by instance from the category ISevent. The facilities gained a property that stores their participation in such an event. The events are organized by TEDA eco center, and this category is called coordinator. We can show all the connections and we can give simple social network metrics. Next step is to give everything a time component. Synergy links, events, they all gained a start date and an end date. This way the wiki can visualize timelines of the activities in the region, or show the network evolution. Also counts can be given of the number of events (or objects with event labels) each year. The data sets contain economic and environmental outcomes of the synergies, the value the synergy brings. The outcomes are listed as either a cost or a benefit on the synergy page, together with information about the type, quantity (unit), duration and to whom the cost/benefit is assigned. This way we can sum up cost/benefits over the region. Now that the different aspects are on the wiki we can combine them to explore drivers and barriers. We can show the time between two particular facilities meeting in a workshop, and the establishment of a synergy between those two. To explore the role of distance as an economic parameter, we can give the distance of the synergy, the exchanged amount of substance next to the economic outcome.

The ontology can represent the two data sets almost completely accurate. But during the design and testing some problems revealed itself. Also the data sets were not covering the complete conceptual scope of IS, so there are also some remarks regarding representing IS. Fluctuations in the mass flows could not be represented. Social interaction is simplified to having a connection, because of limited information. Laws and regulations were represented as events which left little room to specify their influence. Cost and benefits of the synergy could not yet be represented on a satisfactory level of detail. In summary the proposition is to solve the problems by decoupling some of the information, different pages for social entities, a separate page for the mass flows and also for events and valuations. This will make the ontology more modular and larger.

Users/contributors could already fill in data. With some knowledge of Semantic wikis, contributors could run queries and add properties. But large contributions to the structure of the ontology are not possible. Partly because contributors might not understand how everything is related within the ontology. During the design process, property matrices were developed as an artifact to maintain oversight of the structure of the ontology. These matrices can also be used to help users/contributors to understand the structure of the ontology. A category has an amount of properties (grouped into templates), in the property matrices the properties are ordered based on which conceptual part they help to represent. When you want to change a property or category, the property matrix will show if it has an effect on other parts of the ontology in regard to representing IS. The proposal is to further sub divide the ordering of properties. A sub division based on the function they fulfil in regard to a method of analysis. This way users/contributors can fill in data on the basis of a method of analysis, visualizing a network diagram, performing a social network analysis or a process analysis, for instance. New functions/methods of analysis may be added as well. The sub division based on function also reveals when a change in the ontology disrupts a function. The fact, that some properties are used for multiple functions, shows that it is not possible to make the ontology completely modular. Several contributors changing and adding things to the ontology, an evolving ontology, is therefore not yet in reach without coordination.
The ontology can store and share the data sets from TEDA and Kalundborg. The data can be visualized and analyzed in multiple ways on the wiki. Some of the applications of the ontology provide results that are similar to the main results of an entire IS research article. The wiki with the ontology is thus a tool that can support IS-research. Contributors can fill in new data on the wiki, run queries and add properties, but contributing to the structure of the ontology is challenging. A change to the ontology, to improve a function of the ontology, will probably change another function of the ontology at the same time. The contributor might not realize that. Therefore, property matrices have been developed to guide the process of contribution, and show the connections different formalism have with each other. But the ontology is not ready for this process, some concrete suggestion were made to make the ontology more modular. Meanwhile a step of expert and user validation is required before the ontology can be revised. This future research will determine if a continuous evolving ontology is possible.
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Further development of the ontology as a tool for supporting IS research.  

The ontology with the most important properties and the minimum amount of instances to show the structure.  

Systems description of IS, using the general system approach of Ashby (1957).  

Various scientific disciplines are needed to describe the complexity of industrial systems. ICT is added as a tool, so it does not bring content but helps to bring the different sciences together.  

Overview of literature and concepts in IS.  

Above Institutional hierarchy of rule sets (Holling 2001). Below impression of context of IS in terms of systems hierarchy. Right side how Institutional economics shows that all layers of the hierarchy are connected and are influencing each other (Koppenjan & Groenewegen 2005).  

At least two modeling steps are needed in industrial ecology.  

Similar aspects of the phenomena's need to be researched.  

Overlapping ontologies in regard to material and energy.  

Structure of this chapter  

Crossing product chains. Left: A relation between different product chains is considered IS. Right: Over the years, the IS becomes a product chain on itself. Which crosses the traditional product chain and thus makes differentiation between by-product and product impossible.  

Industrial Classification.  

The added-value chain extended with some activities (McPhee & Wheeler 2006), originally from Porter & Millar (1985).  

Layers of an agent. The facility represents the physical infrastructure. Then there is the process the physical transformation of the product. The formal organization is bound by contracts and laws and involved in the financial transaction, whereas the informal organization consisting of individuals and groups of individuals are involved in the information exchange.  

Layers of the IS-relation. Process refers to the manufacturing process.  

Synergy link regarding CHP.  

Hollings adaptive cycle, re-organization ($\alpha$) followed by exploitation ($r$) then conservation ($K$) and release ($\Omega$) (Holling 2001). The remember feedback can teach a smaller system an interesting organizational lesson, the revolt is where a smaller cycle can let a faster cycle go into the release phase for instance. From exploitation to conservation is typified by increased connectedness and network formation together with more accumulation of resource within the boundaries of the system.  

The process of network evolution.  

Four quadrants.  

RDF triplets. Above the concept triplet, below a practical example of Enipedia. Understandable by humans through naming and understandable for computers through the URI's. The base of all URI's on Enipedia is http://enipedia.tudelft.nl/wiki/  

Part of the ontology of IS. The abbreviations as used in the figure, are as used in SPARQL as well. SPARQL and the path of the red character are explained in section L.2.  

The property distance between facilities has the type quantity. This lets the property point to a number with a unit. The property can hold unit conversion on its page. The page holds a template that makes it easy to fill in the unit conversions.  

Query to retrieve coordinates from receiving symbiont page. ?to is the variable that the query wants to find, in this case the search pattern starts on the page where the query is run on (a:{{sparqlencode:{{PAGENAME}}}{{}}}). Every search pattern is given in the RDF triplet form, subject-predicate-object.  

Graph of a Semantic Internal Object (SIO). Without SIO there would be the need to specify at least 3 additional properties per extra type of input. The other option, specifying each input on a different page, comes at the cost of clarity, as in this case not all information would be on the same page. The principle of the blank node and SIO together with the option to query the information onto another page, satisfies the need of the computer and the human-user.
The SIO templates, the template with query and the result on the page of Unico.

Creating a category (left) and layers of a page (right). The best way of getting a feeling with using a Semantic wiki is just creating a small ontology with at least one category.

Adding a property to a page. The property Location with value TEDA is added to a page in three different ways. Only where two colons (:) are preceded by Location, the real property name is needed. In the other cases a different (but consistent) name can be used for presentation purposes.

The page on Eniepdia that explains something about using and contributing to the wiki.

A decoupled design (1) means that one of the functional requirements is dependent on two design parameters (2), when mapping to the process domain equation (3) needs to be considered. (Suh 2001).
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Dualities when describing things. The real world is described by many, when describing this real world various approaches can be taken. This table gives some of them in dualities, of which some are exclusive (only one of both approaches can be taken) and others could be complementary to each other. The chapters where those dualities are coming back are given as well. The dualities are also largely overlapping but I cannot fit them all in two, three or four paradigms.
Part I

Introduction

1 Industrial Symbiosis research

The global economic system exists of product chains that together form a network of industries. The environment functions as a source and sink for the economic system; raw materials are extracted and waste is disposed. In these networks of industries there exist local opportunities for material exchanges beyond the regular product chains. This can deliver economic gain as well as reduced material extraction from and disposal to the environment. This is called Industrial Symbiosis (IS).

Industrial Symbiosis engages traditionally separate industries in a collective approach to competitive advantage involving physical exchange of materials, energy, water, and/or by-products. The keys to industrial symbiosis are collaboration and the synergistic possibilities offered by geographic proximity (Chertow 2000).

IS is not found in every regional industrial system and there are differences in the amount of synergies per region. Also industrial networks evolve, there are thus always opportunities for new synergies and more IS. Hence, there is a clear potential benefit in understanding the coming about of IS. This requires knowledge from both the natural sciences and the social sciences, as the systems studied are an interplay between socio-economic behavior and the technical network (Dijkema & Basson 2009). Such systems are also referred to as complex systems, therefore the IE community is now opening up to complex systems theory.

Currently the understanding of IS comes from the study of existing industrial networks with IS-projects; case studies. A case study is a method for acquiring knowledge, see the lower half of figure 1. This is done by first gathering data, observations, interviews and existing data sources. Then interpreting the data, and performing an analysis. Sometimes a framework is developed for this analysis, but there are also existing methods of analysis that can be used. The understanding gained can be communicated to other researchers or used for practical implementation of new IS-projects. However, researcher are still searching for ‘a more widely shared understanding of self-organizing IS’ (Chertow & Ehrenfeld 2012). This indicates that there is room for improvement somewhere in the process of IS-research. Previous studies have formulated a possible solution:

Modern information and communication (ICT) tools can increase efficiency and the effectiveness by which individual learning contributes to the collective body of IE-knowledge (Davis et al. 2010).

Based on the work of (Davis et al. 2010) this thesis explores the usage of a modern ICT tool for IS-research. The tool is Enipedia, Enipedia is a semantic wiki. The wiki format facilitates contribution. To make use of Enipedia as an ICT tool, an ontology is required. An ontology specifies how concepts relate to each other (Gruber 1995), this makes it possible for computers to also understand the information put on the wiki. So, the main goal of this thesis is to create an ontology of IS on Enipedia.

Figure 1: The creation of knowledge by describing cases of IS.

1Industrial Ecology (IE), the field IS is part of.
2 Design objective

Part II explore the research field of IS. IS research is done by means of case studies of existing IS projects around the world. The studies all have different focus points and the studies use different formalisms for describing their results. The ontology should thus be able to connect and share multiple formalisms and also change along with the latest insights.

**Design objective** Design an ontology that can store and share IS case studies, with the possibility to evolve through the input of contributors.

This can further sub divided into two design objectives.

1. Design an ontology that can represent IS-case studies.
2. Develop procedures and techniques to enable contribution to the ontology.

2.1 Outline thesis and approach

**Part II** This part explores the IS research field and involves the principles of complexity science. This is done by studying IS literature, some articles about complex systems and doing case study research. The result is a better understanding of the problem the community of IS-researchers faces.

**Part III** This part studies the ontology engineering literature in relation to the online documentation of RDF and semantic wikis. This delivers the understanding to formulate the two sub design objectives.

**Part IV** In this part the ontology is designed and tested. The design is made on the basis of the data sets of two case studies: Tianjin Economic Development Area and Kalundborg.

**Part V** This part answers sub objective two. Existing ontology design principles, axiomatic design and the experience obtained during the design process are used to formulate the procedure for contributing to the ontology. This part also discusses which future steps need to be taken to test the contribution to the ontology.

**Part VI** Conclusion.

3 Contribution

This thesis is the final part of the Engineering and Policy Analysis (EPA) master programme at the University of Technology in Delft. EPA focusses on the understanding of socio-technical (or complex) systems, with the goal to give a policy advice or play another role in the process of policy making. IS-networks are also socio-technical systems that can be influenced by policies. This thesis is relevant to EPA, as it reveals underlying problems in achieving a shared understanding of complex problems. Building multi-disciplinary knowledge without reducing the level of detail is valuable for many policy problems, not only IS. Hence, working towards a tool that can support this process is valuable for policy analysis in general.

The scientific contribution of this thesis is in two domains. Part II helps to define the problem the IS-community as a whole faces. The thesis provides insights in the problem of acquiring collective knowledge for IS.

The remaining of the thesis contributes to ontology engineering and design principles. Three aspects led to this contribution:

- Practical insights in the process of building a web ontology. (the main objective of this thesis)
- Existing ontology design principles
- Axiomatic design and the coupling of functions to material parts

The combination of these three led to valuable insight into the design of ontologies that need to evolve through the contribution of users. These are valuable insights for any multi-disciplinary field.
Part II  
Problem description  

4 Principles of Industrial Symbiosis research

Literature has described the industrial systems studies by IE and IS as complex systems (Dijkema & Basson 2009, Chertow & Ehrenfeld 2012, Boons, Spekking & Moutzakitis 2011). Therefore this section does not only research the principles of IS-research, but also those of the study of complex systems and the relation of the two. Both IS and complexity science take a systems perspective, this is an undebated principle which requires no further discussion. In IE and IS research, a debated principle is the role of the metaphor with ecology. A metaphor is not a scientific argument, so we follow Jensen, Basson & Leach’s (2011) advice: Industrial systems need to be studies in the same manner as ecological systems, by observation and interpretation. This is in-line with the most used method in IS-research: The Case study.

IS literature does not describe the principles of case study research, so we use the most cited article (1) in ‘case study research’ (web of science) for reference.

- Eisenhardt (1989)
- Mikulecky (2001)

The principles of complexity science come from the definition of Mikulecky (2). Nikolíc (2009) provides a number of definitions of complex systems, Mikulecky’s (2001) is the only one that states principles, the others all describe elements of a complex system.

4.1 Case study research and complexity

Case studies - IS-research often takes the form of a case study. Researchers have analyzed cases of IS in industrial regions all over the world. During the data gathering and interpretation process confidence can be built by using triangulation, this can result in a strong theory within one case. But for a sharp and confirmed theory, cross-case study analysis is required (Eisenhardt 1989). From a single case study it is hard to determine if a case is representative for the (generic-)system or an outlier. Both the outlier and the representative case have there value but only if it is known which one is which. Using a special (outlier) case to design a generic policy is not advisable. Case study research thus requires replication and/or comparison between cases. This means a pre-defined knowledge format is required, a shared formalism (box A).

Complex Systems - In the introduction IS was labelled a complex system. Incomparability is almost inherent to complex systems. To understand that, we refer to Mikulecky’s (2001) definition of complexity.

Complexity is the property of a real world system that is manifest in the inability of any one formalism being adequate to capture all its properties (Mikulecky 2001).

To come to a complete system description, it is thus required to use multiple formalisms. But to compare cases, you need a shared formalism. So you need multiple but shared formalisms. This puts additional tension on the collective effort of researchers.

2see also appendix G
3Not strange as laboratory experiments are not an option.
Box A: Formalisms and incompatible axioms

A formalism can be seen as a pre-defined representational knowledge format (Nikolić 2009).

Mathematics is a formalism, it defines the numerical system and rules for usage (multiplication, subtraction etc.). Together they represent reality in some way and we have agreed upon a way to communicate about them. But there are layers of formalisms and a formalism does not need to be a complete scientific field. Consider Game theory, it uses rules of mathematics and some of psychology, at the same time it could be built into the formalisms of economics or biology. One thing that formalisms have in common is that they are built on axioms. Axioms do necessarily have the form of mathematical statements (although that eases validation or falsification), they can also refer to statements that are conceivably less hard. Assumptions or world-views are examples. Here we consider one concrete example from economics. Neo-classical (micro-)economics is built on (among others) the following two assumptions: Consumers have full information and act rationally. Keynesian economics, but also many other economic formalisms, do not agree with these two axioms. They assume bounded rationality and limited information (transaction costs). Let us consider the analyses of two different real world economic systems, one analysis with Neo-classical glasses and another with Keynesian glasses. The two resulting case studies can not be compared; they can only lead to a discussion of the respective axioms. These two formalism have at least a shared language and similar scope. The field of IE consists of researchers that due to their background use different formalisms with different languages and only partly overlapping scope (environmental economics and supply chain analysis, for instance).

Mikulecky (2001) says we need multiple formalisms to describe complex systems. For the case study approach, it is required to research multiple cases and compare them. Comparison requires a shared formalism (see also box A). So we need multiple formalisms to asses case I, lets say formalism A, B and C. Then we need those same formalisms again to asses case II, because using other formalisms, say D,E and F, would result in incomparability. Three problems arise.

1. The formalisms each use their respective (scientific) language. This either troubles the inter-disciplinary dialogue or prevents it from happening.

2. Some formalisms may have overlapping scope but incompatible axioms.

3. The combined scope of the formalisms does not comprehend the system completely, a gap in scientific knowledge. A new formalism may be developed or an existing formalism may be added to.

These three problems result in three tasks: Connecting formalisms (1), Addressing incompatible formalisms (2) and developing new formalism (3).

4.2 Working towards a shared conceptualization of IS

Connecting formalisms (1) - To understand complex systems we need to connect formalisms (Nikolić 2009). Point one states that this requires multiple knowledge domains. Each knowledge domains has developed its own vocabulary and researchers are accustomed with thought patterns of other researchers within the domain. Interactions between researchers from different domains require much more effort.

If we understand multiple formalisms as multiple knowledge domains or fields, and if we assume that most people master only one field, this means that many different researchers and stakeholders need to communicate and understand each other if we are to understand λ-systems. In order for this understanding to happen, a shared language is needed (Nikolić 2009, p.25).

Thus working towards connecting formalisms and a shared language (not domain specific) is the task at hand. A multi-disciplinary field in a relatively early stage of evolution, IE, is not easily united in a

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4Specialized jargons and terminologies (Nikolić 2009).
5Complex systems
shared language. On the other hand, the necessity is confirmed. Confirmed by the ongoing discussion about terms and vocabularies in the domain of IS, by Lombardi & Laybourn (2012) for instance.

**Incompatible formalisms (2)** - The previous paragraph pointed out that a formalism usually comes with its own language. A language uses a vocabulary. A taxonomy is a vocabulary were it is clear how words in the vocabulary relate to each other. A taxonomy, when even further formalized, results in an ontology.

IE embodies not a single ontology, but a set of complex and, in some ways, mutually exclusive ontologies (Allenby 2006).

Mutually exclusive ontologies, in other words, are incompatible formalisms. Allenby (2006) presses that IE as a field needs to learn to deal with mutual exclusive ontologies. In the domain of IS, there is a more concrete call. A call that asks for shared formalisms for comparison of IS-cases.

Thus we need to reveal, where the incompatibility of formalisms troubles the assessment of IS-cases. The next step has two options. One, propose a way of dealing with the incompatibility or two, evoke a discussion among researchers. Then the way is open for comparing cases based on shared formalisms.

**Classic gaps (3)** - A third point remains. Even with a common language and connected formalisms, complex industrial (IS-)systems may still not be understood completely. New formalisms may be developed or existing expanded. This thesis is not concerned with that task.

**Shared effort** - This paragraph recapitulates on this section. The complexity of industrial systems poses challenges for the research of IS by means of case studies. To be able to understand complex systems, multiple formalisms are required. But to compare cases, we require a shared formalism. To satisfy both criteria, two tasks need to be preformed first. One, connecting existing formalisms and work on a unifying language. Two, deal with incompatibilities between formalisms, either by evoking a discussion or by adaptation of one of the formalisms. The two tasks (and thus this thesis) are only a small step in understanding IS. The remaining steps require a shared effort. Multiple cases need to be described by researchers from multiple domains. This puts a lot of tension on the collective effort. It requires a task division that does not exactly fit the traditional knowledge domains. The next section therefore presents the conceptual scope of the study of industrial systems (industrial systems with IS).

### 5 System delineation

A research domain has a scope, the scope does not need to be exactly defined but some understanding of the central topics in a domain is required among researchers. So, a literature research is preformed. Appendix explains the literature research performed, it had two starting points. Chertow’s (2000) definition of IS is the first anchor point for the conceptualization.

IS engages traditionally separate industries in a collective approach to competitive advantage involving physical exchange of materials, energy, water, and/or by-products. The keys to industrial symbiosis are collaboration and the synergistic possibilities offered by geographic proximity (Chertow 2000).

But as Chertow’s (2000) definition is focused on the state of affairs, Boons et al. (2011) is the inspiration for looking at IS as a dynamic process. How this further results is a break down of the system, is explained in this section. In retrospect a conceptual division of the scope into three parts was observed (figure 2). One part that is focused on identifying relevant objects present in an industrial system engaged in IS, the static part. What is there? The next part is focused on the changes of the system over
time. **When was it there?** The third part is concerned with the valuation of every step or object. Information about these three parts makes it possible to say something about the drivers and barriers of IS. The valuation and extracting the drivers and barriers are associated with the why question. **Why is it there?** Where the ‘what’ and ‘when’ question are relatively descriptive, the why question necessarily requires interpretation of observers.

### 5.1 Description of the state of IS in a system

Chertow’s (2000) definition is partly focused on recognizing IS. Taking a snapshot of an industrial system, that is engaged in IS. **What** do you observe when taking a snapshot of IS? We observe a physical network, a social network together in an (institutional) context of rules and norms.

**Physical network** - One part observable about IS are its mass and energy flows, the physical connection between industries.

The physical exchange of materials, energy, water, and/or by-products (Chertow 2000).

Most IS-activity encompasses some form of physical exchange, sometimes making lasting footprints in the form of infrastructure. It is thus not strange that almost every single IS-case study article has a visualization of the mass flows between industries (figure 3). Figure 3 shows the physical network of three different industrial regions engaged in IS van Beers et al. (2007, Kiwiana), Shi et al. (2010, TEDA) and Chertow (2000, Kalundborg).

![Figure 3: Visualization of the physical network of three different industrial regions engaged in IS van Beers et al. (2007, Kiwiana), Shi et al. (2010, TEDA) and Chertow (2000, Kalundborg).](image)

three different industrial regions engaged in IS. Form left to right van Beers et al. (2007, Kiwiana), Shi et al. (2010, TEDA) and Chertow (2000, Kalundborg). The physical exchange (depicted by the arrows) takes place between certain entities (squared blocks). Henceforth those physical entities are called facilities. The difference in industrial nature and the geographic distance between the facilities are aspect in which IS-researchers are especially interested (Chertow 2000). The Section ?? goes into more detail about the facility and its features. An iconized image of the physical network is given in figure 4(left).
The physical network does not always run exactly parallel with the social network. Nor is it observable in the same way as the physical network. However, the social network is at least equally important for IS.

**Social interaction** - According to Chertow (2000), collaboration is one of the two keys to IS. Collaboration entails that social entities work together on a shared goal, IS. It means that next to the sought physical relationship, there is also a social relationship. Figure 3 (middle) presents the iconized image together with the technical network. A social relationship usually means that entities share information of some kind. Of interest is the degree of openness or trust with which this information exchange takes place (Gibbs & Deutz 2007, Tudor, Adam & Bates 2007). Ashton (2008) did a Social Network Analysis (SNA) of an industrial cluster on Puerto Rico. The trust between managers of facilities, that were engaged in IS, exceeded the trust between managers only engaged in supply chain relations. This confirms that social relationships play a role in the formation of IS-networks. This has been known since the study of Gertler (1995) in Kalundborg. More recent studies place individual relationships in a larger social context. This is done by using theories from the social sciences, for instance social embeddedness.

Social embeddedness formalizes how recurring social interactions among actors shape economic activities (Granovetter 1985 in Ashton & Bain (2012)).

IS, like any other economic activity, is thus a social relation as well. And IS therefore takes place in a social context. But it is not a mere social context, as is explained in the next paragraph.

**(Institutional) context** - Chertow's (2000) definition does not include a direct reference to the (institutional-)context, but it does refer to the relativity and contextuality of IS.

IS is a collective approach to competitive advantage (Chertow 2000).

Competitive advantage is a relative notion. What is considered competitive depends on the surroundings. Even in a globalizing world competitive advantage is a local phenomena (Porter 2000). The dependence on buyers and suppliers, possible substitute products and technological or institutional innovation all influences what the competitive strategy is for each individual facility as well as for an industrial region as a collective. But context goes further then external factors. Context is also about scale of observation. Any system is itself context to smaller faster systems, but also has a larger slower system as its context (Holling 2001). In complexity science this phenomena is known as: Nested systems. Economics also recognizes that some form of rules or context shapes the behavior social entities. But the influence is in both ways, the behavior of social entities also shapes the institutional context. This means there are positive or negative feedbacks in the system, amplifying or dampening system behavior (Chertow & Ehrenfeld 2012). Environmental regulations and other related policies form a directly visible example of how IS is influenced by institutional context, see figure 5. The availability of certain resources or infrastructure can also be a context for the sprouting of IS-activity. In the description of IS the focus has long been on the visible part of IS-activity, physical resource exchange. But another aspect of IS, the institutional change, or long-term culture change (Lombardi & Laybourn 2012), is a topic of increasing interest in the IS community. IS is for most a special direction in the evolution of industrial systems. This brings us to the next section, the description of the evolution of IS.

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6 The economic term is institutions, see appendix E.
5.2 The description of the evolution of IS

Analyzing IS as a snapshot (section 5.1) gives the end result of IS-activity, physical exchanges of material and energy. A snapshot also identifies which institutional conditions are present in regions engaged in IS. However, to find the drivers and barriers for IS development, information about the evolution of IS in a region is required. Information about the larger development of the region (macro, phases) and information about small scale events within projects in the region (micro, process), see figure 6. So you can observe what is there (previous section 5.1) but when it was there and for how long, is also important to know. If something (IS) takes years to develop, longitudinal analysis is a necessary step (Boons et al. 2011).

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<td>2</td>
<td>Regional learning</td>
<td>Uncovering</td>
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<td>3</td>
<td>Sustainable district</td>
<td>Embeddedness</td>
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Table 1: Three phases of IS development in an industrial region.

This division into phases helps to view IS development in context to the development of the industrial region‡ (Baas & Boons 2004) and to compare the types of activities undertaken in each phase. A phase

‡Objects or events that have something to do with IS.

§The development of an industrial region depends on far more than just IS-activity.
division enables the communication and classification (on an aggregated level) of IS developments, as is
done by Chertow & Ehrenfeld (2012). The phases are neither discrete nor linear. A region may start to
pursue IS only to fall back to common practice, due to a lack of success or changed economic conditions.

The division of IS-development into phases is a conceptual tool, useful for analyzing and comparing
IS-activity on the regional level. The regional IS-development is context for smaller IS-projects (nested
systems), those projects are the result of a sequence of events. Two parties need to connect and share
information (make a social connection [5.1], among other things. This all precedes the actual singing of
a contract. This sequence of events can be analyzed by means of process analysis (Poole, van den Ven,
Dooley & Holmes 2000).

**Process** - Process, 'a sequence of events' (Ven and Poole 1995 in Yu, De Jong & Dijkema (2014)), is
a formalism for looking at the changes of a system in time. Similar to phases, events are discretized
moments in time. Only phases have a larger time step and are labeled in retrospect by a researcher.
A smaller time step (and multiple observers) together give a (more) bottom up approach to narrative
analysis. The narrative of an individual IS-project (the establishment of a connection between two or
more facilities) can consist of different events: Performing feasibility studies; issuing a pilot; signing a
contract and/or media attention about the IS-project. Some of these events also influence the larger IS-
development in a region. For instance, the pilot may trigger the establishment of an IS-research program
in the region. The goal of the process formalism is to identify dynamics and/or patterns in system
evolution (de Valk 2011). Possibly revealing that there is even a pattern in serendipitous development
of IS (Paquin & Howard-Grenville 2012).

In this section [5.2] IS was described as an evolution over time, IS as a development of an industrial
region over phases and IS as individual projects. Projects undergo a process. A process that can be
considered successful if the result is a connection between one or more facilities. Conceptually dividing
IS-development in phases and performing process analysis are ways to research the **how**-question. How
did IS come about? At the same time drivers and barriers towards IS-evolution might be identified, the
**why**-question. For the why-question to be answered, another concept is required, the concept of value.

### 5.3 Valuation

The concept of value is used to get insight into why IS exists. Value is an evolutionary force (Jensen,
Basson & Leach 2011), a driver. So what are the drivers and barriers for the development of IS?
Valuation differs depending on place, time and observer. Differences in valuation are at the core of the
existence of IS, see also appendix [G.1] One firm has a low or negatively valued (to them) output, a
by-product or waste. To another firm this output has somehow value. The difference in perceived value
is enough to establish an exchange. IS-researchers take different approaches in the measurement of value
(Sidiropoulos, Mouzakitis & Adamides 2010, p.11). So we need to clearly establish in which context
value is measured.

- To whom does IS bring value? IS should bring value to the firms involved (Mathews & Tan 2011).
  Next to firms there are government organs, regional developments bodies and other third parties
  that have an interest in IS as an activity that brings value. Furthermore IS may have a value for
  society at large.

- In which context? Are there certain spatial or time related influences that have contributed to an
  increased or decreased value of IS. Is the value of IS assessed in regard to a historic situation or in
  regard to alternative scenarios (Jacobsen 2006). Is the value (cost/benefit) long-term or short-term.

- What type of value does IS bring and how do we measure it? Firms engage in IS because off
  economic value (Ehrenfeld & Gertler 1997), money. Other parties are also interested in the social
  and environmental benefits of IS. IS-researchers go one step further and construct performance
  indicators for measuring the structural advancement of IS in a region.

**Drivers and barriers** - Another part of the IS literature is focused on identifying drivers and barriers
for the development of IS activity, for instance Mirata (2004) or Yu et al. (2014). The prospect of
achieving a positive value (benefit) can be seen as a driver, the prospect of a negative value (cost) as a
barrier. But drivers and barriers are often difficult to quantify and therefore take the form of categorized
lists. Economic, technical, political/regulatory, informational and motivational capture some of the tags for drivers and barriers, see for instance van Beers et al. (2007), Mirata (2004) or Heeres, Vermeulen & de Walle (2004). Figure 7 gives an iconized image of drivers and barriers for the development of IS-projects. The definition of Chertow (2000) states that IS has two key drivers (besides the economic one): Collaboration. Collaboration can be tagged under motivation/informational driver. The other key is: Physical proximity, a technical driver/barrier. For drivers and barriers to be identified, information from all conceptual parts of the system are required. Social and economic interaction over time leads to an exchange (IS). The potential value of the exchange determines if an IS-project is implemented. But value is determined in an (institutional) context with available information about the physical/economic possibilities. In short, a single driver does not cause IS. One driver or barrier can not explain IS, or any form of complex socio-technical behavior (Baas 2005). A case study with a specific focus may thus deliver a wrong conclusion. This brings us back to the previous section 4, we need to develop a set of shared and connected formalisms for the description and discussion of IS. The next section illustrates that connecting and comparing case studies is not at all a trivial exercise.

6 Evaluation of four IS case study articles

A method states which steps need to be taken to come to a certain output. Because of the method, this output is a predefined knowledge format. A predefined knowledge format is a formalism (Nikolić 2009). In IS-literature, the steps of data gathering are not communicated in detail, usually interviews or an existing database form the sources for data. Therefore this section is assesses the communication of the steps of data interpretation and the resulting output. This is formulated on the basis of the two previous section 4 and 5.

The previous section gave, based on literature, a conceptual scope for the research of IS. The section before that 4, stated that multiple formalisms are required for the study of complex systems. However, that section also stated that case study analysis requires the use of shared formalisms. With these given requirements, four (IS-)case study articles are discussed. The focus of the discussion lies on two points:

1. **Scope**: The extent to which the case studies cover the parts of the conceptual scope. The conceptual scope as given in section 5.

2. **Formalisms**: The used formalisms to cover the conceptual scope. Do the formalisms allow for case study comparison?

The first two articles are the most cited IS-case study articles Heeres et al. (2004) and van Beers et al. (2007). The remaining two, Shi et al. (2010) and Jensen, Basson, Hellawel, Bailey & Leach (2011),
are selected from a more recent time period. They both discuss geographical proximity. This makes it possible to take a detailed look at the formalisms that are used for assessing the geographic aspect of the physical network. The conceptual scope can be coffered to various extents; each scope could be sub-divided into smaller scopes. So the score is given based on the extent to which the scope is covered, see Table 2. Another aspect is the extent to which a formalism is used in discussing the respective part of the scope. Furthermore, the extent to which specific data is given, as opposed to only aggregates, is a scoring criterion. And qualitative information accompanied by quantitative information is preferred above just qualitative information.

Table 2 already shows that the articles have different focuses. The sections about the articles (6.1, 6.2, 6.3 and 6.4) could be interpreted as critique on the articles, but they merely show that even good studies are in-able to cover the complete scope of the development of an industrial region. Furthermore, this section shows that different formalisms are used in the articles, even for the same conceptual scope. This makes the articles and thus the cases incomparable.

### 6.1 Case article 1: Eco-industrial park initiatives in the USA and the Netherlands: first lessons

The article of Heeres et al. (2004) studies six Eco-Industrial Parks, located in the USA and the Netherlands. The core of EIP development is realizing IS (Yu et al. 2014). Heeres et al. (2004) discuss the success or failure (drivers/barriers ++++, see Table 2) of the six projects and compares them to find underlying reasons. The main line of argumentations is as follows:

Heeres et al. (2004) gives the Dutch EIP’s on average a higher score, especially in participation and vision. This is because of company participation. Thus active company participation in the planning phase is a prerequisite for EIP development.

**Scope** - Next to active participation of companies in the planning phase, a first focus should be on utility synergies, only later to develop more company specific synergies (Heeres et al. 2004). This conclusion shows the consideration of a stepwise evolution (phases +). Furthermore, in regard to the Dutch cases, Heeres et al. (2004) states: ‘The presence of a entrepreneurs association in an industrial park is relevant’. The association plays a role as initiator and project manager. This role is in the USA cases preformed by the government. This observation shows that the researchers have considered the social network and partly the institutional context (social network ++, institutional context +). More context is given by a table, which shows that there are great differences regarding time of establishment and the size of an EIP.

**Formalisms** - Heeres et al. (2004) goes through the effort of developing criteria for a comparative score (valuation +). This means that within the study a shared formalism for comparison of case studies is developed (point 2, see introduction of this section). But the scoring is done with qualitative arguments on a high level of aggregation; this makes replication by other researchers impossible. One of the scoring criteria is the impact of the project for economy and environment. For this criterion some data is given, but even here it is not clear how the data results in a score. So we have an extensive research with interesting conclusions, but the formalisms/method of analyses and the concrete data remains hidden (discussed further in section 7). This makes it unnecessary difficult to built further on the study of Heeres et al. (2004) and comparison with other case studies can only be done on a high level of abstraction.
6.2 Case article 2: Industrial Symbiosis in the Australian Minerals Industry

van Beers et al. (2007) describes synergies in two (heavy-)industrial regions in Australia. Similar to Heeres et al. (2004), the goal is to identify drivers/barrier(++) and to compare them for the two cases (Kwinana and Gladstone).

The researchers state that the two cases compare favorable to other well-regarded cases (Rotterdam, Kalundborg). Especially because Kwinana has a high number of synergies and those synergies are quite diverse. Furthermore, both regions have an enthusiastic and involved local industry, represented in an active industry association. Fundamental research also contributed to the success. In regard to the drivers and barriers, they are placed in three broad categories[10]. But beyond the requirement that each synergy should be a sound business case, the drivers and barriers are diverse.

Scope - There is extensive information about the physical exchanges (+++) in the two areas. The diagrams in van Beers et al. (2007) show the type of industries with the exchanged substances. The social network is not specifically discussed. The existence of an active industry association depicts a formalized social network, but there is no elaboration on how the interaction takes place. The establishment of such industry associations is an indicator for an advanced state of collaborative problem solving. This is an indicator for an advanced state/phase of IS-development, but the mentioning of some dates and time periods is not systematic (therefore phases +). Next to drivers and barriers, the article discusses triggers. Researching triggers is a form of process analysis (+). van Beers et al. (2007) gives an example in which the boilers of an oil refinery were in need of replacement; this was a trigger for a co-generation project. The triggers are summarized in a table together with the drivers and barriers, another table gives generic features of the two regions (institutional context +). Heeres et al. (2004) has more or less the same tables, the two tables from van Beers et al. (2007) are more specific and explicit, a more objective comparison is therefore possible (valuation ++).

Formalisms - Phases, processes and the institutional context, as conceptual aspects of IS, are not discussed using a specific formalism. The information given about these aspects can thus not be compared with other case studies.

IS, a water, energy or by-product exchange between separate industries (Chertow 2000), van Beers et al. (2007) operationalizes this statement by giving a network diagram of the industries and their exchanged substances. Although it requires a classification system, the industry-exchange operationalization allows for an explicit comparison. This aspect of IS is completely absent in the study of Heeres et al. (2004), there is no reference to any individual synergies, only to the collective development as a whole. Their article focuses on the role of participants in the EIP development. So both articles have an internal comparison but comparison between studies is not possible because of different scopes.

6.3 Case article 3: Developing country experience with eco-industrial parks: a case study of the Tianjin Economic-Technological Development Area in China

Shi et al. (2010) discussed the evolution of Tianjin Economic-Technological Development Zone (TEDA), one of the leading EIP projects in the circular economy program of China. The article gives five conclusions. Not all conclusions automatically follow from the data given. But the extensiveness of the description of TEDA gives credibility to the statements of the researchers.

Conclusion 1 Institutional innovation is built in the DNA of the region. TEDA is responsive to business requirements and competes for FDI with other Chinese studies.

Conclusion 2 The strategy of TEDA is to provide cheap and high quality infrastructure. TEDA is heavily subsidized but leaner than other Chinese local governments. TEDA provides investments into innovation of non-core business. This requires the establishment of more partnerships to increase innovation capacity. Examples are among others the establishment of a waste water treatment plant, a waste to soil project and a desalination plant.

Conclusion 3  Cleaner production interferes with inter-firm exchange. Six instances (out of eleven) of cleaner production led to a discontinuation of IS.

Conclusion 4  The first synergies are established pure from a business perspective, not conscious of the environmental benefits. More recently firms outsource there most polluting activities to nearby industry that is not within the administrative boundary of TEDA.

Conclusion 5  Coordination has been key, also technical facilitation and financial support. Feasibility is a requirement. Incentivizing IS is better then actively pursuing IS establishment. In TEDA this takes the form of agencies with coordinating and or facilitating(technical) roles.

**Scope** - Unlike Heeres et al. (2004) and van Beers et al. (2007), the article of Shi et al. (2010) is not focused on making a systematic driver/barrier (+) analysis. But due to the rich information on the evolution of TEDA, what has happened when, it can be concluded that TEDA was mostly an institution driven development (supported by conclusion 1 and 5). The mayor points in the evolution of TEDA are listed in a time-line, ISO 14001 certification, nomination for national trial EIP, etc. For the selected case studies, this is the most complete description of the timely aspect of regional development (phases ++). Bar charts are used to show the evolution of the industrial mix and the establishment of synergies. The discussion of the evolution of TEDA coincides with the discussion of the institutional context, establishment of policy programs and infrastructure. The size and composition of the region are also described, therefore a good description of the institutional context (++). Shi et al. (2010) do not go to the level of detail in which a process analysis is possible. The article provides the environmental benefits in a summation for the collective of synergies (valuation ++).

**Formalisms** - The exchanges between industries in TEDA are in a diagram (physical network +++). A specific aspect of these exchanges is the distance. Shi et al. (2010) measure the distances of each individual synergy. It is a form of operationalizing 'geographic proximity', a key to industrial symbiosis (Chertow 2000). So where does the formalism for assessing 'geographic proximity' further consists of? A division is made between the types of exchanges; material, water and energy. And it distinguishes between an exchange inside TEDA and exchanges where one of the two is located outside TEDA (TEDA is an administrative boundary not a geographic). For different regions the 'geographic proximity' can explicitly be compared with this formalism.

### 6.4 Case article 4: Quantifying 'Geographic proximity'

Jensen, Basson, Hellawel, Bailey & Leach (2011) quantifies 'Geographic proximity' for the synergies in the National Industrial Symbiosis Program (NISP). It is the only article that explains the data gathering and interpretation steps clearly. They consider five reasons behind the found median distance: Logistic difficulties, Economic value of the synergy, Mental distance between companies, local knowledge and the spatial diversity of UK industry.

**Conclusion 1**  Statistical analysis shows that the median distance of synergies is the NISP project is 32.8 kilometers.

**Conclusion 2**  The researchers think that the key to the success of the NISP project is: Transferable knowledge, the transparent process of the NISP and its independence. This creates a willingness of companies to work with the NISP. This makes the 'geographic proximity' an unimportant variable for the establishment of the researched synergies?

**Conclusion 3**  IS does not need to be nurtured. A coordinator can be useful in operationalizing industrial knowledge.

**Conclusion 4**  The distances of a synergy follows from the spatial distribution of industrial diversity. This is the only reason than can explain the found distances.

**Scope** - The article is focused on assessing the 'geographic proximity', a specific aspect of the physical network (+++). But the NISP project is also extensively discussed. Basically the article is a case study with the UK as subject, the UK as one big industrial area. Companies/facilities ask the NISP to help them with a resource problem (main driver). The NISP's expertise and database match them with a
company or find another solution. This means that there is no need for ‘mental proximity’ or some kind of social network (Jensen, Basson, Hellawel, Bailey & Leach 2011). The NISP reduces the need for industries to build up a social network (+), as the NISP has formalized the process of finding potential symbiont’s. This is visible in the procedure the NISP used to match companies (process +). The question remains through what decision process companies go before involving the NISP. Also the development of the NISP itself is not analyzed over time. Was there a period of self-organization preceding the NISP establishment? In the context of a landfill tax (institutional context +), the main driver (drivers/barriers +) is a resource problem or expected resource opportunity. But in the process of explaining the found mean distance, the article also discusses some other drivers and barriers of IS: Logistic difficulties, Economic value of the synergy, Mental distance between companies, local knowledge. The economic and (partly) the environmental value of the synergies are specifically assessed (valuation ++), cost savings, additional sales and the CO$_2$ savings (savings versus CO$_2$ emission of the transport).

Formalisms - Heeres et al. (2004) and van Beers et al. (2007) give the surface of the area in which the synergies takes place, not the individual distances of the synergies. The individual distance between two industries/companies is the basis for assessing the ‘geographic proximity’ for Jensen, Basson, Hellawel, Bailey & Leach (2011) Shi et al. (2010), a similar formalism. If we further compare Jensen, Basson, Hellawel, Bailey & Leach (2011) and Shi et al. (2010), there are some minor differences. The NISP is a different administrative boundary then TEDA and Jensen, Basson, Hellawel, Bailey & Leach (2011) researches only material (by truck?) exchanges but has a specific resource classification for these materials. Despite the small differences the aggregate outcomes seem to be comparable 32,8 km (Jensen, Basson, Hellawel, Bailey & Leach 2011) versus 28,2 km (Shi et al. 2010). But actually the researcher use different statistical aggregates. Shi et al. (2010) uses the Mean (sum distances divided by the number of synergies). Jensen, Basson, Hellawel, Bailey & Leach (2011) uses the Median (the middle value). An argumentation can be made for both the Mean and the Median, but they can be significantly different within a dataset. So there is still an important difference which creates incomparability.

6.5 Synthesis

Figure 8 visualizes, in an abstract way, how different case studies may be incomparable because of different formalisms used. More importantly different formalisms are used to describe the same scope. This is what the current definition of complex systems predicted (section 4). However, it troubles the collective understanding of IS. It is one of the challenges IE as a field faces (Allenby 2006), to collectively learn within a multi-ontological field (a field that uses multiple formalisms). Allenby (2006) is not yet sure what this requires of methodology and the classic forms (journals and societies) of representing scientific work. Davis et al. (2010) proposes a practical step: Exploring the possibilities of modern ICT tools for the advancement of the field of IE. This section is the bridge to the second part of the thesis. First we explain the relation of a method, tools and science (section 7.1), and explain that tools have the secondary benefit of giving systematics.

7 Tools for sharing and comparing IS case study data

The previous section illustrated that IS-case are described with a different focus. More importantly different formalisms are used to describe the same scope. This is what the current definition of complex systems predicted (section 4). However, it troubles the collective understanding of IS. It is one of the challenges IE as a field faces (Allenby 2006), to collectively learn within a multi-ontological field (a field that uses multiple formalisms). Allenby (2006) is not yet sure what this requires of methodology and the classic forms (journals and societies) of representing scientific work. Davis et al. (2010) proposes a practical step: Exploring the possibilities of modern ICT tools for the advancement of the field of IE. This section is the bridge to the second part of the thesis. First we explain the relation of a method, tools and science (section 7.1), and explain that tools have the secondary benefit of giving systematics.

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11 Actually it is just quantity of transported material. Logistics is not about quantity but the timing, is there storage possibility and does the amount fit exactly in one cargo truck. Data analysis by means of factor analysis could give different insights.
Then we give examples from IS-literature, literature that either directly or indirectly calls for the use of tools (section 7.2).

7.1 Tools in science

A case study can be performed to gain more knowledge about a scientific domain or topic. A case study is an approach or method for acquiring knowledge. An important step in case study analysis is the collection of data. Some common techniques for data gathering are: Observations, surveys and interviews. In the process of data collection, tools or instruments are used. They range from pen and paper to advanced ICT tools. Especially the ICT tools induce the need to be systematic. It can be a first step in the creation of formalisms, thereby also enabling comparison.

**Tools are used in any scientific domain** - Tools can be used to gather, structure and analyse data. A biologist uses tools; a microscope to study micro-organisms and a fridge to store the labeled samples. In the same way there is the possibility for IS-researchers to benefit from the use of ICT-tools for the collecting and storing of data from an industrial system. Tools come with procedures and standards. For biologists one could think of among others: The magnification on which the sample is analyzed, the preparation steps for making the sample, the log kept during research and the storage temperature. These are all procedures and standards tied to the tools (and method) used. Theses procedures and standards allow for validation, replication and it creates the possibility for other researchers to build further on the research done.

Researchers rarely just use one tool; in time a researcher gathers a variety of tools to be able to comprehensively study the subject. For the sake of efficient research, the tools are grouped together in a physical place, for a biologist this can be a laboratory. An IS-researcher could also create a place were multiple tools are located in digital proximity, a platform. Then there is the process of reporting the findings, researchers are familiarized with a certain vocabulary and format for reporting. Tools can assist here as well. There are initiatives in the biology community to use ICT-tools for storing and communicating pathways of cellular metabolism (Davis et al. 2010). In a data intensive and interconnected field, such as IS, this can be especially beneficial.
7.2 Tools for IS

A call for tools from IS-literature - There are possibilities for ICT tools to assist in the IS knowledge building process, both for thorough analysis as well as for quick communication of IS initiatives. These possibilities are visible in IS-literature. Mathews & Tan (2011) try to quickly give you an insight (focus on the physical network) in the IS-initiatives all over the world. Mathews & Tan (2011) create a common graphical representation for comparison of cases. A task an ICT tool would be suited for. But ICT tools can also be useful for the more thorough analysis’s.

The comparability of different industrial systems is, in practice, constrained by the lack of agreed upon rules, methods, and indicators for the description and assessment of industrial ecosystems. It is likely that comparability between case studies of different regions can be improved with a dedicated methodology development effort (van Berkel 2009).

The indicator system for the assessment of EIPs in China’s circular Economy program is an attempt to operationalize this statement. But comprehensive assessments of IS often stumble upon the intricateness of the system. This then results in a call for tools. Geng, Zhang, Côté & Tsuyoshi (2008) states: Evaluating the eco-efficiency in EIPs, that are ever more complex, requires ‘sophisticated tools’.

Tools in regard to the analyzed case study articles - Also the case study articles described in section 6 could benefit from the use of tools for data structuring and data communication. Especially the conclusions of the articles show more knowledge than they can make explicit in the article. For the articles that study multiple cases, Heeres et al. (2004), there is simply not enough space to give all details in one article.

Jensen, Basson, Hellawel, Bailey & Leach (2011) already make use of tools, the NISP database and a geographic information system (GIS). This creates the need to work with a specific and systematic data format, a first step towards a formalism for assessing geographic proximity. Shi et al. (2010) also use a tool to assess the geographic distance, but they use a different tool and a slightly different formalism. So even thought they have almost the same conceptualization for geographic proximity, the two cases can not be compared. Aligning there formalisms is one solution, but sharing there data set on a tool that can deal with different data formats is another solution. There are many tools with specific purposes, the challenge lies in creating a tool that can assist in integrating multiple formalisms. As figure 8 (section 6) illustrated, the problem is the use of multiple different formalisms for a similar scope.

Tools already in use - When we look at the usage of ICT tools for IS, we see a focus on tools that assist in ‘Opportunity identification’. The tools are focused on engineering new instances of IS and are made for a specific region. This thesis is in the first place focused on describing IS, what Grant, Seager, Guillemme & Nies (2010) calls: Documentation review and publication. Not with a focus on regional learning but learning for the IS research community as a collective.

7.3 Outro

In summary, for the study of complex systems, such as IS-network, we need to connect multiple shared formalisms. Currently in the domain of IS, case studies are performed that cover different parts of the conceptual scope and where the scopes overlap different formalisms are used, or the formalism used is not communicated. Tools can enable the process of connecting and sharing individual case studies, meanwhile shaping formalisms.
Part III
Ontologies

The previous part explained that in the process of building a comprehensive understanding of IS, there are some problems. Mainly in the connection and communication of formalisms used in case studies. The use of tools could alleviate this problem:

Modern ICT tools can increase efficiency and the effectiveness by which individual learning contributes to the collective body of IE-knowledge (Davis et al. 2010).

So, the remainder of this thesis explores the use of tools for IS-research. A tool with potential exists, Enipedia. How to work with Enipedia is discussed in appendix L.

Enipedia is an active exploration into the applications of wikis and the semantic web for energy and industry issues. Through this we seek to create a collaborative environment for discussion, while also providing the tools that allow for data from different sources to be connected, queried, and visualized from different perspectives. http://enipedia.tudelft.nl/wiki/Main_Page (Davis, Chmieliauskas, Dijkema & Nikolic 2012)

But Enipedia needs a data structure for putting IS case study data on there in an organized way, see also appendix L. This data structure represents the concepts in the field of IS and specifies how they are related. Those data structures are called ontologies. As science is a process of continuous improvement (appendix F), researchers that have gained new insights must be able to change the ontology. In this light we formulate the main design objective of this thesis:

Design objective Design an ontology that can store and share IS case studies, with the possibility to evolve through the input of contributors.

Before the design process can start, research into ontologies and designing ontologies has to be preformed. This is done in this part. In ancient Greek philosophy they were searching for the one ontology, in modern information science they see ontologies as useful tools for structuring and communicating information (section 8). Section 9 then discusses some concepts in ontology engineering with an example. Finally the trade-offs in the design process of ontology engineering are discussed (section 10). During the research into ontologies, the main design objective is split into two sub design objectives.

1. Design an ontology that can represent IS-case studies. (answered in part V)
2. Develop procedures and techniques to enable contribution to the ontology. (answered in part V)

8 History of ontologies

The concept ontology comes from philosophy, ancient Greek philosophy, as for instance practised by Aristotle. In philosophy there is only one ontology: it should describe the being or existence of all things, its properties and how these things are interrelated. In short, the ontology describes the nature and structure of reality (Staab & Studer 2009, p.1).

Although often not explicitly stated, ontologies are in any science, as they are about categorization and differentiation. Science is also partly about categorization and how different concepts relate to each other. The extent to which this is formalized determines if it is, for instance, a shared list of terms, a taxonomy or an ontology. Formalizing all of reality is probably not possible. Therefore ontologies are nowadays used to describe only specific domains of interest. This is where the fields of Information Science and computer science play an important role. The computer science ontologies are basically built on the same concepts as the ontology in philosophy. The difference lies in the focus, less focus on the fundamental being of reality and more emphasis on making some mental models explicit for sharing and communication (also for computers) (Listor 2011, chapter 1.5).
9 Ontology concepts and example

A small example ontology of the facility is used here (figure 9) to explain the basics of ontologies. The facility is an important concept in this thesis. It represents the place where economic activity takes place, most notable activity is manufacturing. A particular facility such as Asnaes Power plant, however, is a concrete thing. These are the basic layers of an ontology. On the one hand there is the abstract concept and on the other hand the concrete real world instance, see figure 9.

Abstract and concrete “An abstract object is an object which does not exist at any particular time or place (opposed to a concrete object), but rather exists as a type of thing, i.e. an idea, or abstraction” 12

Further abstraction of the facility is possible. It would create a deeper hierarchy of concepts. This is generally how ontologies are built up. Abstraction until everything is ‘a thing’. An abstraction layer above the facility could be building or organization. All facilities are buildings. This refers more to the physical aspect of the facility, whereas organization refers to the more social aspect, the arrangement of tasks of the workers, for instance. It is thus possible to make different abstraction hierarchies, for instance, facility-building-physical construct or facility-organization-social entity. These hierarchies can becomes so abstract that they are difficult to mirror against reality. Therefore rules based on formal logic can guide the building of such ontologies (box B shortly discusses a validation technique). Because they represent such abstract concepts they are re-usable, and they can for the basis of the specification of domain or application ontologies (Guarino 1998). The Resource Description Framework (RDF, section L) can be seen as such an upper ontology.

**Box B: OntoClean**

OntoClean is a method for analyzing ontologies (Guarino & Welty 2009). This is done by assigning meta properties to classes, this is accompanied by a set of rules how these meta properties should be inherited down the hierarchy, not discussed here. The ontology in this thesis does not have many abstraction layers, but it is still interesting to take a look at the meta properties as philosophical principles. Below follows a short explanation of the meta properties, with questions they raise.

**Identity** That what determines the existence of an object. When is an amount of iron the same or a different object? What happens if it changes state to liquid?

**Unity** The amount of Iron is basically a whole that exists of smaller parts. A facility also exists of distinctive parts, does the whole facility participate in a workshop?

**Rigidity** When an object changes is it still the same object or a new object? Does the facility seem to exist if the owner changes? Or if it changes location? The object seems to exist only if the essential properties change. Is this coupled to identity?

**Dependence** Some object indicates that there is necessarily another object. The existence of a facility means that there also must be a builder. The existence of a student indicates the existence of a human being.

Enipedia, and other semantic wikis, make use of RDF. This allows for the specification of categories (an abstract layer) and its instances, pages (the concrete layer). The instances of the categories (the pages) represent real world object, this means that the abstract structure is relatively closely related to reality. Therefore we take available information as main guideline for the design of the abstract structure of the ontology, and not formal logic. More specifically, a ‘fit for purpose’ approach is followed.

**Sub objective one** Design an ontology that can represent IS-case studies. (Part IV)

Another important aspect of ontologies, are the properties of the concepts/objects. Properties are also universals, for instance the property has coordinates (see figure 9) could be a property of any object. However, as figure 9 also shows, the concrete value of these properties differs for the concrete instances

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Asnaes and UnicoTEDA. Any individual-instance of the class/category facility has the properties location and has synergy link with. This is the inheritance relation between abstract concepts and concrete object. The properties are what distinguish one category from the other, sometimes this is confused with membership, where two concepts only have one similar property. Individuals/instances within a class/category do not differ based on their properties but based on the value of the properties. Within ontologies there is also a difference in the type of property, there are relations and attributes, where relations connect individuals/objects and attributes say something about the object, section L.1 explains the equivalences in the RDF vocabulary. An attribute is more intrinsic it says something about the object itself, a relation is more extrinsic it defines how two objects are related.

Intrinsic and extrinsic Intrinsic means that something belongs to the essential nature of the thing (Merriam-Webster.com 2013). The typical example for an intrinsic property is mass, whereas weight is dependent on the gravitational force in the area, thus the exact weight can only be defined if it is known were other objects with mass are located.

Has synergy link with is an example of a property that can be considered a relation. Although not given in figure it defines a link between two concrete facilities. Multiple objects connected through relations form networks, CAS and IS are systems that consist of networks. Those networks do not necessarily consist out of objects from the same class, relations can also connect objects from different classes.

In principle an ontology is static. The abstract layer never changes; the typology of things and their relations will always be the same. However, the concrete layer can change. Objects can be created or make new connections with other objects. These changes are sometimes revered to as ‘events’ The assignment of a time component to each object is required to describe changes.

Ontological change, however, stands for the change of the abstract layer of an ontology. Somebody or something may change the abstract layer of the ontology so that it still represents the latest shared understanding of the domain. This is required for an ontology of IS, because there is not yet a shared understanding of IS. So the ontology should be able to change along with the latest insights. The next section discusses the ontology engineering issues an evolving ontology raises.

The value of has coordinates for Asnaes is 55.659 N, 11.083 E but for UnicoTEDA it is 39.049 N, 117.682 E. In part the word ‘value’ is sometimes also used for its economic meaning.

http://en.wikipedia.org/wiki/Ontology%28information_science%29
The ontology in this thesis is made for IS-researchers, but this doesn’t mean that they will all interact with it on the same level. We distinguish four levels of interaction.

1. Somebody may use the ontology to get information about the domain. (user)
2. In addition the user may fill in missing data and/or create new instances. (user/contributor)
3. The contributor may also add new properties to categories and run queries. (contributor)
4. The contributor may propose and alter the ontology so that it still represent the latest insights (structural contributor)

The latest role is required to develop new functionalities of the ontology and to create an evolving ontology. However, it requires knowledge of ontology engineering. As well as some domain knowledge.

10 Evolving ontologies

An evolving ontology requires three things. The ontology should be accessible (1) and understandable (2) by the expected contributors. Three, the ontology should be changeable. The accessibility of the ontology is provided through the wiki interface of Enipedia. But requirements two and three require design decisions, this is explained in the following two paragraphs. What is understood by contributors is explained in box C.

**Understandable** - Although ontologies can be used as computational tool, there prime is to bring together mental models. So, the ontology engineering community makes an effort to make ontologies that are a shared view of the concepts in the target domain. It is even incorporated in the definition. An ontology is a formal specification of a shared conceptualization, Borst in Staab & Studer (2009, 14)

This means that a ontology should be useful to multiple people. But useful is not the same as understandable. The ontology may be a black box for the user, with only a couple of ways to interact with it. The user is somebody with knowledge from the domain, whereas an ontology engineer is required to understand the structure and working of the ontology. Users (humans) are good at interpreting information and finding patterns, the ontology (a machine) can help them by searching and processing large amount of data at high speed, creating aggregates etc. Semantic wikis are a middle way to leverage both (Davis et al. 2010). Semantic wikis have a graphical interface that allows the users to interact with the ontology. And they can use it varying with the level of expertise they have about semantic web technology.

So semantic wikis provide users the possibility to understand the ontology, through graphically exploring it. This doesn’t mean that a user will always be able to understand the ontology. The ontology of a domain can be large and/or be quite detailed in the description of parts of the domain. An extensive ontology may be difficult to use. Hepp (2007) points to the empirical observation that large ontologies (in bytes) have fewer users. A notion to take along in the design process.

**Changeable** - The last paragraph ended with the notion that large detailed ontologies are often more difficult to understand for users/contributors. And because they are elaborate on the specification of the conceptualisation, they make many claims about the world. In ontology engineering they call this high ‘ontological commitment’. In general minimal ontological commitment is preferred (Gruber 1995). That is to leave as much room as possible to users and contributors to instantiate the ontology as wanted (extendibility). An ontology with low ontological commitment can be used in different context, re-suable. This is basically the difference between an top-level ontology and a domain or application ontology (Guarino 1998). The top-level ontology describes abstract concepts and is thus generic, it can re-used in different situations. But this means it can not provide specific functions.

In this thesis RDF is used as top-level ontology and the target is to create a domain ontology of IS (section 2). RDF used within the semantic wiki format has low ontological commitment. Creating a new instance on the wiki (a page) only requires a name space, everything else is optional. An empty
page has little value. The category from which the page was instantiated will have properties which
connect the page to other pages on the wiki. These relations between instances make up the domain
ontology. These relations create ontological commitment, if you want to represent something you need
to use this and that category with those properties. This means the ontology will only be usable for the
domain the ontology is committed to, extensibility only for the specific domain. However, what if the
conceptualisation of the domain changes? We want to be able to add new concepts to the ontology, an
evolving ontology. Adding new concepts to the ontology and changing the structure of the ontology may
have an effect on the information already there. So, if this is done in the wrong way, information in the
ontology in the form of instance will become useless. This is where understandability and changeability
connect. If you understand the ontology, you will know when a change is problematic. But it is quite
optimistic to assume that a contributor will immediately understand an ontology of a complex domain.
In the initial design the process of contribution this needs to be considered.

**Sub objective two** Develop procedures and techniques to enable contribution to the ontology. (Part

As discussed minimum ontological commitment is a general design criteria, another one is minimum
encoding bias (Gruber 1995). This means that ontology language specific symbols and notations should
be avoided. Coding the ontology only entirely on the basis of RDF would mean an encoding bias. But
with the increasing use of RDF as the standard for the semantic web, using RDF actually promote reuse
and extensibility (Hoekstra 2009, 82).

This part introduced ontologies, its basic concepts, the trade-offs in ontology engineering and the
accompanying design decisions. This resulted in the formulation of the two sub design objective and the
context to start the design of the ontology of IS.
Part IV
Designing an ontology of Industrial Symbiosis

Section 2 introduced the design objective for this thesis.

**Design objective** Design an ontology that can store and share IS case studies, with the possibility to evolve through the input of contributors.

In this part we stick to sub question one:

1. Design an ontology that can represent IS-case studies.

For designing the ontology a ‘fit for purpose’ approach is used. Therefore the data gathered during a case study is the basis for the design. This fits with the design objective, design an ontology that can represent IS-case studies. The data is from the industrial region of TEDA, information about the region is given in section 11.1. This data is gathered during a field study of Chang Yu. The ontology should be able to represent multiple cases. So a second data set is used to check if the ontology is generic enough. The second data set is from the Kalundborg district, a case study of Jacobsen (2006), section 11.2. This design method results in the following reporting format.

section x.1 The ontology should be able to represent the TEDA data set

section x.2 The ontology should be able represent the Kalundborg data set.

section x.2.1 Test the functionalities of the ontology.

This structure repeats itself for each conceptual part: The Physical network 12, the social network 13, The evolution of IS in a region 14 and the valuation of IS 15. Each section x.1 begins with giving the relevant data from the data set for the conceptual part and the corresponding properties that enable the representation of this data. The data is followed up by a graphical representation of the ontology, with instances. Section x.2 then evaluates the ontology based on the Kalundborg data. Then we test the ontology. This takes the form of a series of examples of applications of the wiki. Five types of applications of the wiki are explored:

1. Built shared vocabularies
2. Give oversight
3. Give averages or other statistics
4. Accounting (material flows or monetary values)
5. Matching (reveal matches on the basis of social or physical properties)

Section 12.2.1 will shortly introduce those applications.

The validity in regard to the design objective is automatically fulfilled by designing the ontology immediately from two existing data sets. Any issues that remain are discussed in section 16. The validity regarding representing IS is also discussed in that section.

11 Introduction two the two data sets

11.1 Tianjin Economic Development Area

Tianjin is a port city. It is the closest seaport to Beijing. Tianjin Technological Development Area (TEDA) is an industrial park in the harbor area with several locations around Tianjin. TEDA can in all ways be described as large and multi faceted (Shi et al. 2010). After TEDA’s establishment in 1984 there have been several milestones regarding its environmental performance starting with institutional
activities such as the establishment of control and coordination bodies, the ISO 14000 certification in 2000. The National Pilot Industrial Area for the Circular Economy in 2005 and one of the three first demonstration EIP’s of China in 2008 as well as tremendous ongoing growth in GDP during these years (Yu et al. 2014). TEDA is a mixed industrial area, with both local and multi-national companies in the four dominating industrial sectors: electronics; auto-mobile & machinery; biotechnology & pharmaceutical; food & beverage (Shi et al. 2010). Activities in TEDA include: Collective waste water treatment, by-product exchange, co-generation but also informational activity such as a weekly newspaper designed to communicate environmental news, such as new regulations, innovations and public opinions (Song et al. 2006 in Geng et al. (2008)). TEDA is thus in many was an example of a RIS concerned with sustainability and engaged in IS, which makes it interesting case study material for IS.

<table>
<thead>
<tr>
<th>Synergy Title</th>
<th>Herbie-Unico: Herbie sends packing waste to Unico (plastic, wooden packaging and carton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Synergy Description</td>
<td>complete, sign a contract (recycling the packaging waste)</td>
</tr>
<tr>
<td>Contract duration</td>
<td>1 year</td>
</tr>
<tr>
<td>Synergy Completion Date</td>
<td>2011</td>
</tr>
<tr>
<td>Outcome name and amount</td>
<td>Additional Private Investment 0; Additional Sales 412300; CO₂ Reduction 480; Cost Savings 6545; Diversion from landfill 187; hazardous waste 0; Raw Material Reduction 187;</td>
</tr>
</tbody>
</table>

Table 3: Data of one Synergy Link between Herbie and Unico. Outcomes are given in Yuan or tons.

<table>
<thead>
<tr>
<th>Match making workshop</th>
<th>Date</th>
<th>Number of Participants</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>15 April 2010</td>
<td>28</td>
</tr>
<tr>
<td>2</td>
<td>21 October 2010</td>
<td>33</td>
</tr>
<tr>
<td>3</td>
<td>15 December 2010</td>
<td>54</td>
</tr>
<tr>
<td>4</td>
<td>1 April 2011</td>
<td>54</td>
</tr>
<tr>
<td>5</td>
<td>8 June 2011</td>
<td>20</td>
</tr>
<tr>
<td>6</td>
<td>24 October 2011</td>
<td>20</td>
</tr>
</tbody>
</table>

Table 4: Data about the series of match making workshops organized by TEDA Eco-center.

The data of TEDA is provided by Chang Yu. The data was gathered during a field study in 2012. A fragment of the original data is give in the figures 3 and 4.

11.2 Kalundborg

Kalundborg inspired Ehrenfeld & Gertler (1997) to name a certain form of inter facility cooperation Industrial Symbiosis (IS). Kalundborg is a port city in Denmark. Its industrial area is large in regard to the cities population, but small compared to industrial regions like TEDA. The symbiotic activity already started around 1970, and increased over the years. The core of the synergies is built around water and heat cascading.

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15.a standard for environmental management, not a product but a process standard
16.China has set the objective to go from a linear towards a circular economy, key role herein are the industrial areas the EIP program run by SEPA tries to stimulate industrial areas to be sustainable, see Geng et al. (2008) for performance indicators, how EIP’s are evaluated.
Jacobsen (2006) is the most cited in depth quantitative study of Kalundborg. The study includes data from several other case studies.

<table>
<thead>
<tr>
<th>Description and date of first initiation</th>
<th>Wastewater (1992)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description of substitution</td>
<td>Wastewater substitutes groundwater and surface water</td>
</tr>
<tr>
<td>Savings from substitution 2002</td>
<td>9,000 m³</td>
</tr>
<tr>
<td>Savings from substitution 1990-2002 (cumulative)</td>
<td>1065000 m³</td>
</tr>
<tr>
<td>Alternative to symbiotic exchange (1)</td>
<td>Discharge of wastewater</td>
</tr>
<tr>
<td>Investment, by the time of initiation (in DKK)</td>
<td>+/- 2000000</td>
</tr>
<tr>
<td>Pricing principle</td>
<td>Giveaway</td>
</tr>
</tbody>
</table>

Table 5: Environmental and economic parameters from the synergy link Between Statoil and Asnaes, data from 2002 (Jacobsen 2006)). (1) More alternatives might have been considered and alternatives typically change over time.

<table>
<thead>
<tr>
<th>Year</th>
<th>Discharge fee</th>
<th>Surface water</th>
<th>Ground water</th>
</tr>
</thead>
<tbody>
<tr>
<td>1990</td>
<td>11,07</td>
<td>0.88</td>
<td>3.00</td>
</tr>
<tr>
<td>2002</td>
<td>13,13 DKK/m³</td>
<td>6.50 DKK/m³</td>
<td>15,19 DKK/m³</td>
</tr>
</tbody>
</table>

Table 6: Taxes and prices associated with water exchanges in the Kalundborg area (Jacobsen 2006).

<table>
<thead>
<tr>
<th>Year</th>
<th>Cooling water</th>
<th>Wastewater</th>
<th>Surface water</th>
<th>Gas</th>
<th>Gas</th>
<th>Steam</th>
<th>Steam</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>m³/year</td>
<td>m³/year</td>
<td>m³/year</td>
<td>tons/year</td>
<td>tons/year</td>
<td>GJ/year</td>
<td>GJ/year</td>
</tr>
<tr>
<td>1990</td>
<td>714000</td>
<td>-</td>
<td>1570000</td>
<td>3600</td>
<td>-</td>
<td>641000</td>
<td>427000</td>
</tr>
<tr>
<td>1991</td>
<td>705000</td>
<td>-</td>
<td>1590000</td>
<td>2400</td>
<td>-</td>
<td>704000</td>
<td>509000</td>
</tr>
<tr>
<td>1992</td>
<td>644000</td>
<td>1580000</td>
<td>1660000</td>
<td>1900</td>
<td>2600</td>
<td>760000</td>
<td>378000</td>
</tr>
<tr>
<td>1993</td>
<td>721000</td>
<td>1260000</td>
<td>1760000</td>
<td>2000</td>
<td>4200</td>
<td>826000</td>
<td>306000</td>
</tr>
<tr>
<td>1994</td>
<td>704000</td>
<td>1450000</td>
<td>2300000</td>
<td>2700</td>
<td>7400</td>
<td>798000</td>
<td>268000</td>
</tr>
<tr>
<td>1995</td>
<td>695000</td>
<td>1250000</td>
<td>2540000</td>
<td>80</td>
<td>3500</td>
<td>784000</td>
<td>375000</td>
</tr>
<tr>
<td>1996</td>
<td>598000</td>
<td>1550000</td>
<td>3070000</td>
<td>0</td>
<td>677</td>
<td>906000</td>
<td>303000</td>
</tr>
<tr>
<td>1997</td>
<td>533000</td>
<td>1010000</td>
<td>3141000</td>
<td>0</td>
<td>813</td>
<td>805000</td>
<td>197000</td>
</tr>
<tr>
<td>1998</td>
<td>459000</td>
<td>1210000</td>
<td>2623000</td>
<td>0</td>
<td>0</td>
<td>750000</td>
<td>220000</td>
</tr>
<tr>
<td>1999</td>
<td>505000</td>
<td>1300000</td>
<td>2550000</td>
<td>0</td>
<td>0</td>
<td>718000</td>
<td>223000</td>
</tr>
<tr>
<td>2000</td>
<td>260000</td>
<td>550000</td>
<td>2473000</td>
<td>0</td>
<td>0</td>
<td>742000</td>
<td>111000</td>
</tr>
<tr>
<td>2001</td>
<td>590000</td>
<td>570000</td>
<td>2412000</td>
<td>0</td>
<td>0</td>
<td>753000</td>
<td>192000</td>
</tr>
<tr>
<td>2002</td>
<td>483000</td>
<td>900000</td>
<td>2840000</td>
<td>0</td>
<td>0</td>
<td>829000</td>
<td>197000</td>
</tr>
</tbody>
</table>


12 Physical Network

Section 5.1 introduced the physical network as an important conceptual part of IS. The physical network basically constitutes of ‘the physical exchange of material and energy’ between facilities, according to Chertow’s (2000) definition. All other analyzed definitions also mention IS as some form of relation between agents (appendix A). This complies with the assertion of Nikolic (2009) that the representations of CAS should be agent-based. Agents and relations together form a network.
Table 8: Major input-output environmental flows from Asnaes in 2002 (Jacobsen 2006).

<table>
<thead>
<tr>
<th>Input</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>Solid waste</td>
</tr>
<tr>
<td>Groundwater</td>
<td>waste recycled</td>
</tr>
<tr>
<td>Surface water</td>
<td>waste incinerated</td>
</tr>
<tr>
<td>Cooling water</td>
<td>waste landfilled</td>
</tr>
<tr>
<td>wastewater</td>
<td>By-products</td>
</tr>
<tr>
<td>Raw material</td>
<td>GJ</td>
</tr>
<tr>
<td>electricity</td>
<td>Fly ash from orimulsion</td>
</tr>
<tr>
<td>coal</td>
<td>gypsum</td>
</tr>
<tr>
<td>orimulsion</td>
<td>filter gypsum</td>
</tr>
<tr>
<td>fuel oil</td>
<td>clinker</td>
</tr>
<tr>
<td></td>
<td>Wastewater</td>
</tr>
<tr>
<td></td>
<td>salty cooling water</td>
</tr>
<tr>
<td></td>
<td>Emmissions</td>
</tr>
<tr>
<td></td>
<td>CO₂</td>
</tr>
<tr>
<td></td>
<td>SO₂</td>
</tr>
<tr>
<td></td>
<td>NOₓ</td>
</tr>
</tbody>
</table>

For IS, some aspects of the physical network are especially important. The wiki needs to be able represent the 'Geographic proximity' of facilities (distance). 'Traditional separate industries', the wiki should be able to give the industrial nature of the facilities in a relation (industrial sectors). And also the already mentioned 'physical exchange of material and energy' should be represented (physical exchange).

12.1 Design of ontology based on the data set of Tianjin Economic Development Area

Representing a physical network requires agents and relations (previous paragraph). The TEDA data set contains information about supplier and receiver companies, table (left) and information. Information that they have exchanged a product. Enough information to create a network. This is done by creating two categories. FacilityIS, representing the supplier and receiver company and the category Synergylink, representing the relation. This is shown in table (right) and figure 10. Table 9 shows

Table 9: Part of the data used to represent the physical network, units in tons or yuan (left). Categories and properties that together constitute the physical network (right).

further which properties are required for which aspect of the physical network to be represented, physi-
cal exchange, distance and industrial sector. The resource description framework (RDF) is discussed in

Figure 10: The categories SynergyLink and FacilityIS. Instantiation results in a concrete representation of a synergy.

appendix L but figure 10 recapitulates this shortly. The figure shows how the categories and some of the properties from table 9-b result in actual pages on the wiki. An instance of the category SynergyLink is created, a page named SynergyLinkVestasUnico. This synergy link has for the property FormFacility the value VestasTEDA and for the property ToFacility the value UnicoTEDA. Both Vestas and Unico also have a page and they are both an instance of the category FacilityIS. On the wiki this is the minimum amount of properties and categories for representing the smallest element of a physical network, a relation between two agents. SPARQL has a graph visualization that can represent the pages of the network graphically, an example is shown on the bottom of figure 10.

The location of each company in the data set is given by coordinates, see table 9-a. So on the wiki each facility also has coordinates, property Point. Two queries retrieve the coordinates of the two facilities to the synergylink page, the Geodistance parser then calculates the distance between the two points, see figure 11-a. For an explanation about queries, see appendix L.2. Next to coordinates, the facilities and the synergies also have a location tag. The tags allows for easy differentiation between facilities in different industrial regions. The property location is not visible in figure 11-b, because its use is further explained in section 14. Each facility also falls within an industrial sector. According to the data set Herbie falls under electronic processing and Unico falls under Solid waste recycle. Two tables together represent the exchanged product in the synergy link, see the bottom of figure 11-c. To get these tables the semantic internal objects package is used (appendix L.3). SIO lets you specify a non existing page (blank node), properties are stored on this node and retrieved to the page by a query. This way you can create tables with multiple properties in a row.

In these two paragraphs we have shown how the (physical aspect of the) TEDA data set is put in a category property structure on the wiki. The example contained only information about one synergy link, but the structure works also when all synergies from the data set are put on the wiki. The network visualization in figure 12 shows all facilities and synergies in the TEDA data set. But is the ontology on the wiki also able to represent IS-data from other industrial regions, this is discussed in the next section.

12.2 Can the ontology represent the Kalundborg data set?

As discussed in the introduction of this part [IV], data from the industrial region of Kalundborg is used to evaluate the genericness of the ontology. The physical network of the Kalundborg region can also be represented by the wiki. Figure 13 shows that. So to a large extent the ontology can represent the Kalundborg data set and thus passes the test of genericness. However, the Kalundborg data set is

17http://mapping.referata.com/wiki/Geodistance
Figure 11: (a) The parser with two SPARQL-queries for calculating the distance between two facilities. (b) The part of the ontology required to represent the physical network. (c) The table that represents the physical exchanged material on the page of the synergy.
Figure 12: The IS-linkages within the TEDA data set.

Figure 13: Physical network of IS-linkages in the Kalundborg region.
different from the TEDA data set. Some of these differences are discussed in this section, as they give valuable insight for improvements to the ontology.

The Kalundborg data contains more information about the flows of materials, inputs and outputs of facilities. Furthermore, some of the agents involved in the physical exchange are not clearly given by the data set or they exist as group of agents that may not be correctly represented by the category facility. In this section is discussed how this affects the ability of the wiki to represent the Kalundborg data. This is done with examples from the Kalundborg data set, see tables 10 and 11.

<table>
<thead>
<tr>
<th>Year</th>
<th>Heat</th>
<th>Gypsum</th>
<th>Fertilizer</th>
<th>Yeast Slurry</th>
<th>Fly Ash</th>
<th>Sludge</th>
<th>Boiler water</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>GJ/year</td>
<td>tons/year</td>
<td>m³/year</td>
<td>tons/year</td>
<td>m³/year</td>
<td>tons/year</td>
<td>m³/year</td>
</tr>
<tr>
<td>1990</td>
<td>65100</td>
<td>-</td>
<td>51400</td>
<td>7400</td>
<td>162000</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1991</td>
<td>735000</td>
<td>-</td>
<td>692000</td>
<td>14000</td>
<td>255000</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1992</td>
<td>735000</td>
<td>-</td>
<td>911000</td>
<td>23000</td>
<td>204000</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1993</td>
<td>826000</td>
<td>41000</td>
<td>1200000</td>
<td>30000</td>
<td>218000</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1994</td>
<td>793000</td>
<td>94000</td>
<td>1100000</td>
<td>28000</td>
<td>29300</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1995</td>
<td>803000</td>
<td>43000</td>
<td>1500000</td>
<td>27000</td>
<td>15400</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1996</td>
<td>868000</td>
<td>183000</td>
<td>1500000</td>
<td>29000</td>
<td>182000</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1997</td>
<td>825000</td>
<td>199000</td>
<td>874000</td>
<td>25000</td>
<td>93000</td>
<td>3500</td>
<td>-</td>
</tr>
<tr>
<td>1998</td>
<td>836000</td>
<td>185000</td>
<td>380000</td>
<td>42000</td>
<td>71000</td>
<td>4300</td>
<td>-</td>
</tr>
<tr>
<td>1999</td>
<td>829000</td>
<td>205000</td>
<td>378000</td>
<td>59000</td>
<td>91000</td>
<td>4800</td>
<td>-</td>
</tr>
<tr>
<td>2000</td>
<td>805000</td>
<td>208000</td>
<td>338000</td>
<td>72000</td>
<td>49000</td>
<td>4100</td>
<td>-</td>
</tr>
<tr>
<td>2001</td>
<td>850000</td>
<td>193000</td>
<td>276000</td>
<td>92000</td>
<td>33000</td>
<td>3500</td>
<td>-</td>
</tr>
<tr>
<td>2002</td>
<td>845000</td>
<td>154000</td>
<td>216000</td>
<td>106000</td>
<td>32000</td>
<td>3600</td>
<td>50000</td>
</tr>
</tbody>
</table>


In the Kalundborg data set there are some unclarities about the facilities involved in the synergies. An exchange may actually take place between a number of smaller geographically dispersed facilities or it is not exactly given with whom the exchange takes place. A part of the description from the data in table 10 is highlighted here to discuss this unclarity, from the work of Jacobsen (2006):

- (3) Organic fertilizer (Novogro/Novogro/30) from Novo group to local farmers
- (4) Yeast slurry from Novo Group to local farmers
- (5) Fly Ash from Asnaes Power Plant to Danish cement industry
- (6) Wastewater sludge from Kalundborg municipality to Bioteknisk Jordrens

Three and four mention an exchange with local farmers and six mentions the exchange with the municipality of Kalundborg. These are both agents that exist of smaller geographical dispersed facilities (farms and households). This is an important difference considering logistics and infrastructure development. Also it affects the assessment of the geographic distance between facilities\[18\]. The municipality can be seen as one agent in the regard to decision making processes, but for the farmers this is possibly not the case. To represent them as one facility, as done on the wiki, thus means an incorrect representation of reality. (5) five mentions the Danish cement industry. The Aalborg cement factory is the only clinker factory in Denmark, but it is not sure that the fly ash actually goes there. The fly ash with nickel and vanadium goes to a recycling plant in Great-Britain\[19\], but its exact whereabouts are unknown. This means that some information on the wiki still needs to be verified.

---

\[18\] Some sources mention that over a thousand farms are making use of the fertilizer program, see Enipedia

\[19\] saved source on Enipedia
The ontology on Enipedia is not yet able to represent the extensive information about mass flows in the Kalundborg data. The *SymbioticExchange* template (figure 11) is designed to represent only one flow. Therefore only the accumulation of the flows over the years can be given, or only the flow of the latest year. The first option is chosen on the wiki. But this means that some information is lost in regard to the physical exchange of materials or energy. Section 16 shows a design change that creates the possibility to represent each year separately. The TEDA data only contained information about materials that were symbiotically exchanged. The Kalundborg data set contains information about inputs and outputs (see table 11 for Asnaes Power Plant) that are not exchanged in a synergy, and inputs and outputs from which it is not immediately clear in which synergy they are exchanged. For the inputs and outputs two new

<table>
<thead>
<tr>
<th>input</th>
<th>output</th>
</tr>
</thead>
<tbody>
<tr>
<td>water</td>
<td>solid waste</td>
</tr>
<tr>
<td>groundwater</td>
<td>waste recycled</td>
</tr>
<tr>
<td>surface water</td>
<td>waste incinerated</td>
</tr>
<tr>
<td>cooling water</td>
<td>waste landfilled</td>
</tr>
<tr>
<td>wastewater</td>
<td>by-products</td>
</tr>
<tr>
<td>energy</td>
<td>fly ash from coal</td>
</tr>
<tr>
<td>electricity</td>
<td>Fly ash from orimulsion</td>
</tr>
<tr>
<td>raw material</td>
<td>gypsum</td>
</tr>
<tr>
<td>coal</td>
<td>filter gypsum</td>
</tr>
<tr>
<td>orimulsion</td>
<td>clinker</td>
</tr>
<tr>
<td>fuel oil</td>
<td>wastewater</td>
</tr>
<tr>
<td>wastewater</td>
<td>salty cooling water</td>
</tr>
<tr>
<td>emissions</td>
<td>tons</td>
</tr>
<tr>
<td>CO₂</td>
<td>2822000</td>
</tr>
<tr>
<td>SO₂</td>
<td>2724</td>
</tr>
<tr>
<td>NOₓ</td>
<td>3785</td>
</tr>
</tbody>
</table>

Table 11: Major input-output environmental flows from Asnaes in 2002 (Jacobsen 2006).

templates are created, *Inputs* and *Outputs* as previously inputs and outputs could not be represented. These templates enable the representation of the inputs and outputs, but is also used to try out some applications, see the next section 12.2.1. The result on the wiki is given in table 12. The templates basically use the same properties as the *SymbioticExchange* template used for the *SynergyLink* category.

So with some minor adaptations the ontology can also represent the Kalundborg data set. Therefore the next step is filling the data sets into the ontology an running tests. At the same time this reflects on the applications of the ontology and the wiki.

12.2.1 Testing and applications

The ontology is immediately put to the test by inserting the data from the two cases. This section shows the applications of the ontology, when data is inserted into the ontology. In regard to the physical network there are five types of applications:

1. Built shared vocabularies
2. Give oversight
3. Give averages or other statistics
4. Accounting (material flows or monetary values)
5. Matching (reveal matches on the basis of social or physical properties)

**Built shared vocabularies** - The idea of a wiki is to share information. Individual users add information to the wiki so that the collective of information grows. The users can discuss and improve the
<table>
<thead>
<tr>
<th>Input/Output Facility:</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>product</td>
<td>amount</td>
<td>units</td>
<td>temperature</td>
<td>hazardous</td>
<td>otherinfo</td>
<td>contains1</td>
<td>contains2</td>
</tr>
<tr>
<td>Groundwater</td>
<td>61,000.00</td>
<td>M3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surface water</td>
<td>696,000.00</td>
<td>M3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cooling water</td>
<td>483,000.00</td>
<td>M3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wastewater</td>
<td>9,000.00</td>
<td>M3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electricity</td>
<td>317,000.00</td>
<td>GJ</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coal</td>
<td>387,000.00</td>
<td>Ton</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ash</td>
<td>690,000.00</td>
<td>Ton</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuel Oil</td>
<td>21,000.00</td>
<td>Ton</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Output/Output Facility:</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>product</td>
<td>amount</td>
<td>units</td>
<td>temperature</td>
<td>hazardous</td>
<td>otherinfo</td>
<td>contains1</td>
<td>contains2</td>
</tr>
<tr>
<td>Municipal Sewage Waste</td>
<td>187.00</td>
<td>Ton</td>
<td></td>
<td></td>
<td>Incinerated</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Municipal Sewage Waste</td>
<td>72.0</td>
<td>Ton</td>
<td></td>
<td></td>
<td>Landfill</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fly ash</td>
<td>32,000.00</td>
<td>Ton</td>
<td></td>
<td></td>
<td>Firm coal</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fly ash</td>
<td>1,400.00</td>
<td>Ton</td>
<td></td>
<td></td>
<td>Nickel</td>
<td>Vanadium</td>
<td></td>
</tr>
<tr>
<td>Gypsum</td>
<td>164,000.00</td>
<td>Ton</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clinker</td>
<td>1,500.00</td>
<td>Ton</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wastewater</td>
<td>117,000.00</td>
<td>M3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Salty water</td>
<td>936,600,000.00</td>
<td>M3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO2</td>
<td>2,822,000.00</td>
<td>Ton</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SO2</td>
<td>2,734.00</td>
<td>Ton</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NOx</td>
<td>3,785.00</td>
<td>Ton</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Municipal Sewage Waste</td>
<td>324.00</td>
<td>Ton</td>
<td></td>
<td></td>
<td>Recycled</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

References and Notes:

<table>
<thead>
<tr>
<th>reference</th>
<th>notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jacobsen 2005 E-supplement</td>
<td>The input output data is from 2002.</td>
</tr>
</tbody>
</table>

Table 12: Inputs and outputs of the Asneas power plant.
information available. This philosophy already enables the building of shared vocabularies. But a user contributes in a certain vocabulary, as discussed scientific domains use different vocabularies (section 4.2). In a worst case scenario, it could mean that information about a similar concept is discussed twice under a different name, without users knowing it. This can prevent a discussion from taking place, and preventing the connection pieces of information. Furthermore, the use of different vocabularies can lead to misunderstanding or misconceptions. By formalizing relationships between concepts (an ontology), the differences and similarities in a vocabulary can be revealed. In this way the wiki together with the ontology can assist in creating a shared vocabulary, a prerequisite for comparing IS-cases.

Some terms or words used in the TEDA and Kalundborg data sets leave room for different interpretations or are based on a different logic of classification, especially for the naming of the physical exchange for material and the naming of the industrial character of the facilities involved. Table 13 shows how two different naming systems can be orthogonal to each other. IS is defined as a ‘by-product’ exchange between ‘traditional separate industries’ (Chertow 2000). A by-product is basically a product that is not further used in the supply chain but still has value, and might be usable in another supply chain. Practically to come to an actual exchange, information about the physical properties of the material is interesting not if it is classified as a by-product. Physical properties are the basis for the technical naming (classification). It would thus be helpful if the wiki could be able to relate these types of vocabularies. An example follows in the next paragraph.

In the TEDA data set the single most exchanged material is packaging waste (an economic name). Packaging waste is a mixture which contains various materials, see table 9. In figure 11 is shown that this is stored on the page of each individual SynergyLink page. SPARQL can be used to retrieve the information. For instance, we can ask SPARQL to retrieve all the substances in packaging waste with a count. The result is given in figure 14. So packaging waste most often contains plastic, but even within one data set, packaging waste is not always the same material. This is not directly a problem, but based on summaries like table 14 (a), we can decide whether or not to adjust the naming. For packaging waste it would be possible to create sub groups or labels, based on quality, composition or origin, for instance. In a later stadium of the development of the wiki we could give packaging waste certain properties, thereby defining it. The importance of consistent naming comes back when other applications of the wiki are discussed.

The TEDA data set contains information about the industrial sector of the facilities. It is unknown to which supply chain each facility belongs. So the ontology only stores information about the industrial sector. The idea is again that this information can be used to come to a consistent naming system. Table 14b shows the different industry sectors present in TEDA. Looking at the list one might merge some names or create sub-groups, food & beverage processing and food processing could clearly be grouped under food industry, for instance. To operationalize ‘Traditional separate industries’ is not possible, then you need to now exactly what the ‘traditional’ supply chains are. Kalundborg is the model case of IS, but if it fulfils the ‘traditional separate industry’ criteria is unsure. Are Power generation and District heating traditionally not related? See figure 14 for the relations between industries. The classification of industries and companies is also a topic in the (scientific) field of public administration. The IS-community and the wiki could use existing classification systems. The IE-wiki uses the Industry Sector

Table 13: (A) Different ways to classify exchanged goods and (B) different ways to classify industries.
Table 14: (a) Packaging waste contains these substances, according to the TEDA data set. (b) The industrial sectors in the TEDA data set.

<table>
<thead>
<tr>
<th>product</th>
<th>times_of_occurrence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paper</td>
<td>3</td>
</tr>
<tr>
<td>Plastic</td>
<td>6</td>
</tr>
<tr>
<td>Cotton</td>
<td>5</td>
</tr>
<tr>
<td>Iron Scrap</td>
<td>4</td>
</tr>
<tr>
<td>Wood</td>
<td>3</td>
</tr>
<tr>
<td>Copper</td>
<td>2</td>
</tr>
<tr>
<td>Iron</td>
<td>2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>industry</th>
<th>sector</th>
<th>count</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equipment</td>
<td>Manufacturing</td>
<td>1</td>
</tr>
<tr>
<td>Food</td>
<td>processing</td>
<td>2</td>
</tr>
<tr>
<td>Plate</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Adhesive</td>
<td>products</td>
<td>1</td>
</tr>
<tr>
<td>Food &amp;</td>
<td>Beverage processing</td>
<td>1</td>
</tr>
<tr>
<td>Steel plate</td>
<td>manufacture</td>
<td>1</td>
</tr>
<tr>
<td>Battery</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Electronic</td>
<td>waste recycle</td>
<td>1</td>
</tr>
<tr>
<td>Scrap metal</td>
<td>processing</td>
<td>1</td>
</tr>
<tr>
<td>Plant extracts</td>
<td>R&amp;D and production</td>
<td>1</td>
</tr>
<tr>
<td>Automobile</td>
<td>electrical equipment</td>
<td>1</td>
</tr>
<tr>
<td>Electronic</td>
<td>processing</td>
<td>3</td>
</tr>
<tr>
<td>Logistics</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Medical</td>
<td>appliance manufacturing</td>
<td>1</td>
</tr>
<tr>
<td>Pharmaceutical</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Rare earth</td>
<td>and permanent magnet materials</td>
<td>1</td>
</tr>
<tr>
<td>Chemical</td>
<td>material and products manufacturing</td>
<td>1</td>
</tr>
<tr>
<td>Digital</td>
<td>product manufacture</td>
<td>1</td>
</tr>
<tr>
<td>Air-laid</td>
<td>paper production</td>
<td>1</td>
</tr>
<tr>
<td>Biological</td>
<td>medicine</td>
<td>1</td>
</tr>
<tr>
<td>Waste metal</td>
<td>recycle and recycle</td>
<td>1</td>
</tr>
<tr>
<td>Auto parts</td>
<td>and components manufacture</td>
<td>4</td>
</tr>
<tr>
<td>Hazardous</td>
<td>Waste Treatment</td>
<td>1</td>
</tr>
<tr>
<td>Power</td>
<td>generation</td>
<td>1</td>
</tr>
<tr>
<td>Recycled</td>
<td>water production</td>
<td>1</td>
</tr>
<tr>
<td>Waste</td>
<td>recycling</td>
<td>3</td>
</tr>
<tr>
<td>Semiconductor</td>
<td>manufacturing</td>
<td>1</td>
</tr>
</tbody>
</table>
overview of the European Union. Ashton (2008) uses the North American Industry Classification System. In regard to the classification and naming of materials, the field of chemistry has some experience which might be useful.

Figure 14: Industrial sectors in the Kalundborg network. Whether these are ‘traditionally separate’, is unsure.

The ability of the wiki to assist in building shared vocabularies was discussed in the preceding four paragraphs. A shared vocabulary is a prerequisite for comparison of IS-cases. Currently the IS-community uses different vocabularies for concepts that are at the core of defining IS (‘by-products’ and ‘traditional separate industries’). Practically the ontology makes it possible to compile lists that show inconsistencies within and between vocabularies.

**Oversight** - An ontology stores information in a way that resembles reality (simplified), from a bottom up approach. For example, facilities are modeled as a group of things, but each facility has different values for its properties. Other modeling approaches model something only as a group of things, where their properties are averaged in advance. With ontologies it is therefore sometimes difficult for users to see the bigger picture, when browsing through the instances of an ontology. Fortunately, oversight can be created with SPARQL and some Semantic wiki functions. The lists from table 14 are already a simple example. But the wiki can also create visualizations. The visualizations of the physical network (figures 12 and 13) are examples. By using stored properties the oversights can be enriched or altered to give related insight. For example in figure 12 the linewidth is determined by the amount of material exchanged. Using the distance between facilities or the Cost savings for the linewidth, are other options. Figure 14 shows that the names of the nodes can also be altered to represent for instance the industrial sector of the facility. Another functional visualization is given in figure 15, it shows all facilities in the TEDA data set. Both the map and the graph visual also help the user navigate through the different pages on the wiki.

An oversight helps in the communication of complex systems. For IS the network diagram is important in the scientific communication, see for instance (Mathews & Tan 2011). If data about the synergies in a region are on the wiki, the wiki can automatically generate oversights, such as the network diagram. In general, oversight is the ability to summarize a specific aspect of the ontology onto a single page, instead of dispersed over many pages (layers).

**Statistics** Science is an iterative process between practical observations and motivated theory (Box 1976). Each new iteration is confronted with the previous and will be confronted with the next. A feedback loop between practice and theory, see figure 1 in part II. Statistics is a tool for the comparison or confrontation of iterations. In this thesis statistics therefore means: The creation of quantitative or semi-quantitative indicators for the comparison of data.

The example for showing the application of statistics, concerns the concept of geographic proximity. As explained in section 12.1 the wiki is able to store the coordinates of each facility engaged in a

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21 http://www.census.gov/eos/www/naics/
synergy. The distance between two coordinates is calculated by the Geodistance parser and queried onto the respective synergy page. We can now use this to quantify geographic proximity.

In part II (section 6) is discussed that researchers use different formalisms for giving an indicator for geographic proximity; total surface area in which the synergies take place; just the length/width of the area or the distance each resource travels is measured separately. The last option is used in the articles that have a specific focus on geographic proximity (Shi et al. 2010, Jensen, Basson, Hellawel, Bailey & Leach 2011). Figure 15 shows the distances of the synergies in the Kalundborg data set. For communicating the results Shi et al. (2010) use the mean (average), Jensen, Basson, Hellawel, Bailey & Leach (2011) use the median (middle value). SPARQL has a command to calculate the mean, AVG(variable), and the middle value can be picked out of the list or a query can be made to order the distances and then offset half. The mean and median of the TEDA and Kalundborg data set are given in table 16. The table shows that comparing the mean (Shi et al. 2010) and the median (Jensen, Basson, Hellawel, Bailey & Leach 2011) of two regions is useless. Figure 15 shows that this is because of the spread, one large distance influences the mean a lot, whereas the median is not influenced by one

<table>
<thead>
<tr>
<th>synergy/link</th>
<th>distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Synergy Link: Aarsaas:Fish Farm</td>
<td>6.01</td>
</tr>
<tr>
<td>Synergy Link: Statoil:Aarsaas:Tech Water</td>
<td>2.33</td>
</tr>
<tr>
<td>Synergy Link: Aarsaas-Statoil-Deionized Water</td>
<td>1.6</td>
</tr>
<tr>
<td>Synergy Link: Aarsaas-Statoil</td>
<td>1.6</td>
</tr>
<tr>
<td>Synergy Link: Statoil:Aarsaas:Cooling Water</td>
<td>1.6</td>
</tr>
<tr>
<td>Synergy Link: Foresyning:Nova Nordisk</td>
<td>1.2</td>
</tr>
<tr>
<td>Synergy Link: Nova Nordisk:Foresyning</td>
<td>1.2</td>
</tr>
<tr>
<td>Synergy Link: Aarsaas:Foresyning</td>
<td>1.2</td>
</tr>
<tr>
<td>Synergy Link: Aarsaas:Gyproc</td>
<td>1.2</td>
</tr>
<tr>
<td>Synergy Link: Statoil:Gyproc</td>
<td>2.01</td>
</tr>
<tr>
<td>Synergy Link: Foresyning:GSS90</td>
<td>2.33</td>
</tr>
<tr>
<td>Synergy Link: Aarsaas:Glycol</td>
<td>2.1</td>
</tr>
<tr>
<td>Synergy Link: Nova Nordisk:Glycol</td>
<td>2.7</td>
</tr>
<tr>
<td>Synergy Link: Nova Nordisk:Famas</td>
<td>13.2</td>
</tr>
<tr>
<td>Synergy Link: Nova Nordisk:Famas-Yaast</td>
<td>13.2</td>
</tr>
<tr>
<td>Synergy Link: Tase:Foresyning</td>
<td>14.15</td>
</tr>
<tr>
<td>Synergy Link: Statoil:Fertilizer Industry</td>
<td>84.27</td>
</tr>
<tr>
<td>Synergy Link: Aarsaas:Cement Industry</td>
<td>170.35</td>
</tr>
<tr>
<td>Synergy Link: Aarsaas-Ni Vanadium Industry</td>
<td>766.91</td>
</tr>
</tbody>
</table>

Table 15: Distances of the Kalundborg synergies.

Bailey & Leach (2011) use the median (middle value). SPARQL has a command to calculate the mean, AVG(variable), and the middle value can be picked out of the list or a query can be made to order the distances and then offset half. The mean and median of the TEDA and Kalundborg data set are given in table 16. The table shows that comparing the mean (Shi et al. 2010) and the median (Jensen, Basson, Hellawel, Bailey & Leach 2011) of two regions is useless. Figure 15 shows that this is because of the spread, one large distance influences the mean a lot, whereas the median is not influenced by one
Table 16: Mean and median of the synergy distances (km) in the TEDA and Kalundborg data set.

<table>
<thead>
<tr>
<th></th>
<th>In Kilometres</th>
<th>Mean</th>
<th>Median</th>
</tr>
</thead>
<tbody>
<tr>
<td>TEDA</td>
<td>16.9</td>
<td>3.79</td>
<td></td>
</tr>
<tr>
<td>Kalundborg</td>
<td>56.9</td>
<td>1.9</td>
<td></td>
</tr>
</tbody>
</table>

large distance. The wiki makes it possible to generate different indicators from the data sets, this allows researchers to compare there viewpoints. In section 5.3 the distances between facilities are discussed further, distance as economic parameter.

Statistic is the name of the wiki function that allows for the creation of indicators for the comparison of cases. The example was geographic proximity. The stored data combined with SPARQL made it possible to show indicators of geographic proximity. The two cases (TEDA and Kalundborg) were compared on two statistical averages. Geographic distance calculations are brought forward as a mayor result in some IS research articles. This reflects well on the ontology as it can create similar results.

**Accounting**
The idea of a wiki is that it can host data from several sources, put there by different users. The ontology guards the systematics of this process. Still the checking of the consistency of quantitative data is functional. Not just for errors or inconsistencies, but also to learn about the structure of the ontology and how to improve it. Thus, accounting does not only refer to the counting of quantitative values (section 15), but also to a process of sense-making. Checking the consistency of quantitative data is what precedes the creation of indicators for comparison, accounting thus precedes statistics (for the wiki). For instance, under synergy outcomes the TEDA data set lists *Raw resource reduction* and *water savings*, whereas the Kalundborg data set mentions *substitution*. Those are all important when making an indicator for the resource reduction or de-materialization through IS. But it is unclear how these are interrelated. Does raw refer to mining, virgin materials? Is the complete amount substituted considered a reduction of material use? How does water savings relate to this? We can count each of them separately and list them for communication purposes, but we cannot make a comparable indicator yet.

In the following paragraph we investigate the material streams of *Asneas Power Plant*. The Kalundborg data set contains information about inputs and outputs, next to data about the exchanged material, see the previous section (figure 12). A query is made to check if this is consistently transferred onto the wiki (table 16). A query is run that asks (in human language):

> Show all outputs (products) of this facility, with their quantity and unit. But only if that product is exchanged in some synergy. Give the synergy and the quantity and unit exchanged as well.

The result is in table 16. Although water and steam exchanges are the most important synergies regarding the Asneas power plant, they are not found in the balance check. Steam is not reported as output while it is mentioned as exchanged material. Various kinds of water are mentioned as output, but different names make that they don’t have a semantic match (salty water, cooling water, waste water, deionized water, tech-water, boiling water, ground water and surface water). Matches for fly ash and gypsum are found. Fly ash is exchanged with two different facilities, the fly ash from the power unit that burns Orimulsion is send back to retrieve vanadium and nickel. The output of 1400 ton matches the exchanged amount. The second stream of Fly ash is from coal burning, it shared for the making of cement. The quantities don’t match because the output data is from 2002 only, while the exchange fly ash is the accumulated amount over the time period 1990-2002. The Gypsum flow (from 2002) matches in quantity as well, the other quantity mentioned for the Gypsum flow is the amount of Gypsum exchanged when the synergy was first established. The experiment shows that many errors can be made by the users filling in the data. But mainly does it show that small differences in data sets causes errors as a semantic match needs to be precise. Therefore the idea is to store the quantities of materials only on one place and then query the amount onto the other pages. This also prevents double counting by users that are not familiar with the structure of the ontology. Section 20 discusses the suggested changes to the ontology.

This example showed how the wiki can be used to check the consistency of the data on the wiki. Other examples (section 13) will follow that show the more obvious functions that falls under the accounting.

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22 for the actual query edit *Asneas power plant* page.
application, the summing up of quantities such as financial results.

Matching - The focus of current ICT tools developed for IS lies on prescribing IS, opportunity identification (Grant et al. 2010). Therefore the ability of the wiki to match facilities is explored. A facility with an output that matches another’s facilities input.

Figure 17-A shows that matching input and output can be done directly. But as soon as there are process steps required before use (figure 17-B and C), human interpretation is needed to come to the right match (figure 17-D).

The property product is purposefully re-used as this makes it possible to make use of a whole existing structure on the wiki. To explain how you can draw on structures made by other wiki contributors but also to show the power of connecting data, an example with facility Gyproc is used. Gyproc a plasterboard manufacturer in Kalundborg, it is already engaged in synergies but for the sake of the example that is ignored. Gyproc needs gypsum as input, if facilities in the area have there outputs specified it is an easy search for SPARQL, 17-A gives all facilities with output gypsum. But what if there were no facilities in the area that produced gypsum, maybe Gyproc would consider products that only need one process step to become gypsum. Here the data about generic process chains is used. The wiki hosts information about known/used chemical processes, another project on Enipedia (Davis et al. 2012). So, you could search for products that are one or two steps away of becoming gypsum, see figure 17-B and C. Then couple the result to facilities in the area again, figure 17-D. This example shows future practical use of the wiki. It is possible to automatically query part of this example on every facilities page for each input. There are some small complications though. Currently the ontology does not see any difference in importance between CaSO$_3$ and water. But water is a quite common product used in many reactions. To further develop the matching application would require the assignment of meta-properties such as, availability, value or priority).

The ontology of IS on the wiki is designed to describe IS (specifically the TEDA and Kalundborg data sets). By using the description combined with certain aspects of the wiki, the wiki can assist in creating a shared understanding of IS. These aspects were grouped into five applications, building shared vocabularies, creating oversight, statistics, accounting and matching. The applications fit into the process of collective learning (figure 18), or sense-making (Davis 2012). Although this thesis is focussed on the description, the wiki can develop also into a prescriptive tool. This would complete the feedback loop.

This last application showed that description and prescription go hand in hand for the conceptual part about the physical network.
13 Social interaction

According to Chertow (2000), collaboration is one of the two keys to IS. Collaboration entails that social entities work together on a shared goal, IS. It means that next to the sought physical relationship, there is also a social relationship. The social relationships do not always leave a physical trace and are thus more difficult to observe explicitly. A conceptual difference is made between a direct social relation and an indirect social relation, see also figure 19. Direct means there is a direct observable relation, or in a survey the facilities have stated that they have a social relation. Indirect means this is still somewhat unclear, facilities take part in the same research program, are in an industry association together or another binding factor that might imply a social relation.

The ontology is constructed on the basis of the TEDA data (section 13.1). Then the Kalundborg data is discussed in regard to the ontology. Afterwards practical examples from the wiki will follow, that show the applications of the representation of the social interaction (section 13.2.1).

13.1 Design of ontology based on Tianjin Economic Development Area data set

The TEDA data set contains information about a series of workshops; those workshops are organized by TEDA Eco center. TEDA eco center is a NGO supported by the TEDA administration. The workshops are match making workshops (figure 19-a). The information about the facilities lists in which workshop the faculty participated (also figure 19-a). To represent the workshops and TEDA eco center, two new categories are created: ISeven and Coordinator. A coordinating body can be an important entity in the establishment of IS-linkages (Mirata 2004). Information sharing, matching facilities and the reporting of environmental performance are some of the functions a coordinator could have. Literature also refers to facilitators or anchor tenants, these have similar functions. The event represents a moment in time, such as a workshop or another moment worth representing. In section 14 the time aspect of events is discussed.

Figure 19-b shows the categories and properties required for the representation of the social network, 19-c shows how this looks graphically for the two facilities Herbie and Unico. The property StartDate is not given in the table, the assignment of time related properties is discussed in section 14. The social network representation partly uses the same properties as the physical network, ToFacility and FromFacility. The reasoning behind this is that a physical relationship also denotes a social one. At least one individual should have shared information with an individual from the other facility to come to the exchange. This is considered a directly observable relation. An indirect social relation is the shared connection to TEDA eco center. Even if the facilities participated in the same workshop, it does not necessarily mean that they have a social relation.

The ontology can represent the direct and indirect relations in the TEDA data set.
Figure 19: (a) The relevant TEDA data, (b) the property table, and (c) the ontology.
13.2 Can the ontology represent the Kalundborg data set?

The study of (Jacobsen & Anderberg 2004) focuses on the assessment of economic and environmental aspects. It contains no data about possible information exchanges taking place. The physical synergies were already on the wiki, thus only the coordinator, Symbiosis Center Kalundborg, was added to the wiki. This means that the ontology can represent the social network of the Kalundborg data set. It also means that the ontology requires another test. Testing with data sets focused on the social interactions of facilities or individuals.

13.2.1 Testing and applications

For the following two types of applications an example follows below:

- Oversight
- Statistics (with some side notes in regard to accounting)

**Oversight** - Similar to the physical network, SPARQL’s graph visualization can be used. Figure A shows that TEDA eco center is (indirectly) connected to all facilities in the TEDA data set. The edges are match making workshops from the category ISevent. It shows the common denominator of the data set, suggesting that this is the basis for the scope of the data set. Figure B shows how a graph visualization can be made on each facilities page, giving all direct connections of that facility. The facility is Asnaes power plant from the Kalundborg data set. The connections are all physical exchanges. This visual also helps the user navigate over the wiki.

With the graph visual it is currently possible to query one type of relation at the time as the properties that connect facilities and the properties that connect events are different. Literature about social networks usually specifies multiple types of social relation. For instance Ashton & Bain (2012):

- Any relation: having any business or non-business relationship with another in the network.
- Informal exchange: providing or receiving technical advice or raw materials at no cost.
- Product sale: selling products to another company.
- By-product synergy: selling or donating by-products to another.

Information about the types of social relations is usually obtained by interviews of central individuals in the respective facilities. As, some relations are otherwise hard to identify. The ontology is not ready...
to host data from interviews (section 20), as the data sets did not contain such information. Making this possible would be a valuable step in the development of the ontology. As information about social relations is the basis for Social Network Analysis (SNA), a way to measure a node's importance in a network. SNA as a possible application is discussed in the next paragraph.

Statistics - Social network analysis (SNA) is a way to quantify social relations. This makes it possible to compare social networks in a universal way. Therefore we examine how it could be incorporated on the wiki.

As discussed in the previous section, we do not have data about various social relations. But in IS-literature SNA studies often take synergies as one of the relations (Ashton 2008) or even as basis for the analysis (Domenech & Davies 2011). This means the synergy data can be used to explore the incorporation of SNA on the wiki. This is done by calculating the degree (number of ties) and degree centrality (normalized degree) of each facility, a simple network metric for the importance of the node in the network.

\[
C'(n) = \frac{d(n)}{g-1}
\]

C'(n) = degree centrality
\(n\) = node (a facility)
\(d\) = degree (number of synergy links)
\(g\) = total nodes in the graph

On the wiki a node is an instance in the category FacilityIS, the degree is the number of ties, SynergyLinks a facility has. The total nodes in the graph is a count of the facilities, this count is stored as a new property on the page of the Regional Industrial System, TEDA or Kalundborg. Figure 21 shows the results for Kalundborg (a) and TEDA (b). The TEDA data set contains thirty-one facilities, so not all are given in figure 21. These facilities all have a degree of one. Comparing the two data sets shows that both have a couple of central facilities, these structures are different however. TEDA are a couple of star shaped graphs, not even all connected. Kalundborg evolves around four connected central facilities that have the connection to facilities in the 'periphery'. There is an error in the calculations for the degree centrality of the Kalundborg facilities. This is visible as Asnaes has a normalized degree centrality of one. The reason is that Asnaes has multiple synergies with other facilities, they are counted double in this calculation. Therefore the findings do not correspond exactly with the findings of Domenech & Davies (2011), who also did a network analysis on Kalundborg. This is solvable with SPARQL, but it represents also the conceptual problem; one connection and multiple mass flows. In section 20 is discussed how this could be resolved by a change to the ontology.

There is software that can do more advanced network analyses, not only degree centrality. For example: UCINET, used by (Ashton 2008). IS-research could benefit from either building similar tools.

Figures 21: (a) Structural network analysis of the Kalundborg and (b) TEDA region.
into the wiki or create exchange formats, as this would commit researchers to a certain conceptualization of IS.

14 IS as evolution over time

IS as a special type of inter-firm relation is in literature defined in two ways (see also the introduction of section 5):

1. By observing established IS-linkages, then highlighting the key characteristics (type of industries involved, type of materials exchanged, the intensity of the relationship between facilities.)

2. By observing the steps taken during the development of individual IS-linkages and the surrounding region. Describing IS as a special business process.

So far IS was described as a situation in an industrial region where facilities have physical and social connections (section 12 and 13), IS from the perspective of point one. Here the focus lies on describing the evolution of IS, IS as sequence of events. So, basically this section is about assigning a time component to each category.

14.1 Design of ontology based on the data set of Tianjin Economic Development Area

The synergies in the TEDA data set all have contract durations and a synergy completion date. The matchmaking workshops also have a date, see figure 17a. So all categories (FacilityIS, SynergyLink, ISevent and Coordinator) have gained the properties StartDate and EndDate, see figure 17b. This means they have a time component. Figure 22a shows the ontology in a graphical form, you can see that various instances from the categories are queried onto a timeline through the StartDate and EndDate properties (figure 17c). The Location of these instance determines if they are queried in this timeline, otherwise also events and synergies from other regions would have been queried in the same timeline. The properties required to represent the time component are all grouped under the template ISevent, this template is embedded on all four categories.

On of the important conceptual scopes of IS literature is the (institutional) context (section 5.1). But (institutional) context is not discussed as a separate section in the design of the ontology. This decision was made because it coincides with the phase typology of IS [5.2], so context is operationalized by instances in the category ISevent. For instance, TEDA was awarded as one of the three national demonstration pilots for the circular economy (Yu et al. 2014, Shi et al. 2010), figure 22a shows that this was represented as an event. New regulations, subsidies, resource crises all can be represented as an event to give context to the establishment of synergies in the region. On the top of figure 22c is shown that also these events appear in the timeline, as it has a start date. The matchmaking workshops are also represented as an ISevent. So context and events stands for the ability of the wiki to represent...
Figure 22: (a) The graphical representation of the properties and classes required to represent the time aspect of IS. (b) The table with event labels. (c) The time line of TEDA (c).
everything that happens around the establishment of the synergy links. Figure 22-b shows a labeling for the counting and interpreting the sequence of events, this corresponds with the third column (process analysis) in table 22-b. But this is further discussed under applications (14.2.1).

The aspect of time in the TEDA data set was represented by the ontology. Basically by giving each instance from the four categories a StartDate and an EndDate. The context to IS development is given through representing important happenings as instances in the category I$event$.

### 14.2 Can the ontology represent the Kalundborg data set?

Tables 5 and 7 (section 11.2) gives the data of the synergies in Kalundborg. The focus of the data set is on the period from 1990 to 2002, but the first date of initiation is always given. The synergies do not have a clear contract duration as in the TEDA data set, some are indefinitely ongoing or paused. But as the StartDate is the most important for representing the time component, this does not pose as a problem.

The Kalundborg data set does not contain information about contextual events, so the timeline basically contains only the data about the establishment of the synergies (figure 23). The Kalundborg data contains information from a time period of fifty years, whereas the TEDA data set is about a three year period. This is not a structural difference, only a difference in magnitude. It does give rise to a whole new set of events. Ehrenfeld & Gertler (1997) describe that Gyproc was relocated to Kalundborg because of the presence of cheap gas from Statoil refinery. Furthermore the need for replacement of the boilers of Novo Nordisk was a prerequisite for the synergy with the power station. Another example that could be listed as a possibly important contextual event are the ownership changes of Asnaes. Asnaes changed ownership two times since the start of the synergy. The data set does not give information about these events. Therefore there is no indication that the ontology needs to change, to be able to represent such events.

The ontology is able to represent the aspect of time in the Kalundborg data set. As discussed in section 12.2, the ontology is not yet able to give differences in exchanged quantities during time periods. A solution is proposed in section 20. A richer representation of IS evolution requires more information about events that could have influenced the development of IS.
14.2.1 Applications

Now that the aspect of time is incorporated in the ontology, some new functionalities of the ontology can be explored. Overview and statistics are the tags used to list the applications under.

**Overview** - IS-case study articles often incorporate a timeline of important events, see for instance Ehrenfeld & Gertler (1997), Shi et al. (2010). A quick way for a reader to get an oversight of the evolution of IS in a region. The wiki can dynamically generate this from the data put on the wiki, through the timeline format of ASK. Mandatory is a start date, optional an end date and one or multiple selection criteria. The property *Location* is the selection criteria in our case. Figure 17 shows the result for `Location::TEDA`, and figure 23 for `Location::Kalundborg`.

Identifying typical evolution patterns of IS is a subject in literature (Baas & Boons 2004, Chertow & Ehrenfeld 2012, Ashton 2009). The timeline can assist here, increased IS activity or an institutionalization of IS development might be visible in the timeline. Another way to make sense out of the sequence of events, is by counting them. This is measurable and a start in the direction of comparison. Figure 24 shows how this results in an oversight. The next paragraphs will further discuss the counting of events.

**Statistics** - So how do we make sense out of a sequence of events? A method called process analysis. The two variants that are discussed in this section are both based on history event analysis as described by for instance Poole et al. (2000).

![Figure 24](image)

Figure 24: (a) The number of events over the years in TEDA and (b) Kalundborg.

- Process analysis for EIP’s and IS (Yu et al. 2014)
- Functions of Innovations Systems (FIS) method (Suurs 2009), adapted for EIP analysis by de Valk (2011).

The events are labeled (see table 18) for keeping track of the type of events. The possibility for labeling is built into the ontology through the template `ISeventSetSIO`, see table [17] and table [23] for the result. It is a semi-quantitative method, the events are only assessed positive or negative (and labeled). The idea is to search for patterns, certain type of events following up on each other. How to label events and more about the collection of event data can be found in appendix 1.2. The point here is that the wiki can host this data and sum up the events, as in figure 24. The bar chart shows the count of the events in the different years. Ideally the bar chart would give different colors for the different types of events. Another small problem is the sorting based on date, therefore the property *year* has property `type` `number` and not date.

15 Valuation

IS, like any other economic activity, exists because it adds value somehow. But value is not an absolute thing, therefore we need to know to whom IS brings value, in which context and what type of value.

24 ASK is a command that queries data from other pages on this page, similar to SPARQL.
Yu et al. (2014)  de Valk (2011)

<table>
<thead>
<tr>
<th>Company Activity</th>
<th>Entrepreneurial Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technical Facilitation</td>
<td>Knowledge development</td>
</tr>
<tr>
<td>Informational Activity</td>
<td>Knowledge Diffusion</td>
</tr>
<tr>
<td>Institutional activity</td>
<td>Guidance of Search</td>
</tr>
<tr>
<td>Economic and Financial enabler</td>
<td>Facilitating IS</td>
</tr>
<tr>
<td>Support from advocacy coalitions</td>
<td></td>
</tr>
</tbody>
</table>

Table 18: Two different sets of event labels for history event analyses

Section 5.3. This means there are many ways IS can be assessed, as an individual business transaction (Chertow & Lombardi 2005), as a regional strategy (Korhonen & Snakin 2005) or as an national economic program (Geng et al. 2008). The TEDA-data set is used to design this aspect of the ontology (section 15.1), this design is evaluated with the data from Kalundborg (section 15.2).

Section 12 represented IS as a physical network, section 13 as a social network. Then IS was described as a series of steps in time (section 14). Combined with the valuation of IS, we can now try to identify drivers and barriers behind IS, the wiki can assist us in this (section 15.2.1).

15.1 Design of the ontology based on the data set of the Tianjin Economic Development area

The TEDA data set contains information about the outcomes of the synergies (figure 25-a). This is a typical way to value IS, give the economic and environmental benefits of IS. Next to benefits there are always costs for participants. So the data about the outcomes of the synergies is put into two almost identical tables, one containing the benefits and the costs (figure 26-b).

![Figure 25: (a) The TEDA data about outcomes of the synergies and (b) the properties required to represent this.](image-url)
The first property in the template (figure 25-b) is to list the cost or benefit by a name. For instance, *Additional Sales* and *CO2 reduction* (figure 26-a). The second property is there to specify how the benefit or cost comes about. The *CO2 reduction* may actually be the result of *raw material reduction*, one of the other benefits listed. Then you can specify the monetary value of the benefit. For *additional sales* this is: 412300 Yuan. In the table (figure 26-b) this is given as euro 50685, using SIO in combination with the special property type *quantity*. Because most benefits come in the form of a saved resource, the ontology allows for the storing of an *amount* and a *unit*. The outcome *additional private investment* confirms that it is important to now who will incur the cost or benefit. The data states zero private investment, meaning Unico and Herbie did not invest to make this synergy happen, possibly public investment though. Three properties are put in place to represent this, *assignedtoparticipant1*, *assignedtoparticipant2* and *assignedtothirdparty*. The first refers to the supplier facility, the second to the receiver. A third party can be a public organization. Zero additional private investment is thus represented as two zeros for participant one and two and an unknown amount for the third party, see figure 26-b. The number of years the benefit or cost occurs is given in the last column, for the TEDA data this is all one, because of the one year contract duration. But in other cases, Kalundborg for instance, there might be an investment (*number of years*: 1) and a benefit that occurs for ten years (*number of years*: 10). This means the present and future value of the cost or benefits starts to play a role. This means a certain decree of uncertainty in future value added. These fluctuations in value make it difficult to objectively list benefits and values. Transaction cost ([2]) is also a notion that illustrates the difficulty to give an exact value to costs and benefits. And then there is the social value of IS, which is by definition based on perspective. In research the assessment of IS is therefore often a survey based assessment, see for instance Kurup (2007). The people involved are asked to rate the IS-project on economic, environmental and social factors. This is not something the wiki can enable yet, but an interesting future in parallel with the list of measurable costs and benefits.

Finding drivers and barriers for IS is often the end goal of IS-research (section 5.3). Drivers and barriers are even more difficult to measure objectively and are therefore often the result of interpretations

![Ontology](image.png)

**Figure 26:** (a) The part of the ontology required to represent the added value of IS and (b) how this is represented on the page of the synergy between Herbie and Unico.
of interviews with the people involved. As visible in figure 25b, there are no properties in place for representing drivers and barriers. This is because drivers or barriers are extracted from the representation of the other conceptual parts, in combination with the valuation and the interpretation of the user. Examples come back in section 15.2.1.

The value of IS is in the ontology represented as a list of cost and benefits. It is possible to specify various types of costs and benefits and to whom they are assigned.

15.2 Can the ontology represent the Kalundborg data set?

The article of (Jacobsen & Anderberg 2004) is an assessment of economic and environmental benefits, thus a good test to see if the ontology is able to represent this. Table 19 shows the savings of one synergy link in the Kalundborg data set. Figure 21 shows how the wiki represents this. The environmental can be extracted from table 19; for the economic benefits table 6 is required. Jacobsen (2006) states that the Statoil gets 50% of the surface water price for the cooling water, a total of 1,8 million DKK. This means Asnaes has a 50% cost reduction for the intake of 7,6 million m³ water. These are the first two columns in table 21. Additionally Asnaes does not have to invest in a preheating facility as the cooling water has a temperature of thirty degrees. A benefit not mentioned by Jacobsen (2006) is visible in the data; Statoil avoids the discharge fee, possibly worth 90 million DKK. The two facilities together invested in the pipeline for 2 million DKK, Asnaes had to build a pretreatment facility to treat the water to boiler quality (40 million DKK). The costs and benefits are all given for one year, as they are either investments or a cumulative of the benefits over a period of time. The time period is given on another part of the page of the synergy link.

### Table 19: Environmental and economic parameters from the synergy link Between Statoil and Asnaes, data from 2002 (Jacobsen 2006). (1) More alternatives might have been considered and alternatives typically change over time. (2) The 40 million investment is for a pretreatment facility at Asneas for cooling and surface water.

<table>
<thead>
<tr>
<th>Description and date of first initiation</th>
<th>Cooling waster (1988)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description of substitution</td>
<td>Cooling water substitutes surface water</td>
</tr>
<tr>
<td>Savings from substitution 2002</td>
<td>483000 m³</td>
</tr>
<tr>
<td>Savings from substitution 1990-2002 (cumulative)</td>
<td>7611000 m³</td>
</tr>
<tr>
<td>Alternative to symbiotic exchange (1)</td>
<td>Discharge of cooling water</td>
</tr>
<tr>
<td>Investment, by the time of initiation (in DKK)</td>
<td>2000000 / 400000000 (2)</td>
</tr>
<tr>
<td>Pricing principle</td>
<td>Price linked to surface water</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>1990</th>
<th>...</th>
<th>2002</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discharge fee</td>
<td>11,07</td>
<td>13,13 DKK/m³</td>
</tr>
<tr>
<td>Surface water</td>
<td>0,88</td>
<td>6,50 DKK/m³</td>
</tr>
<tr>
<td>Ground water</td>
<td>3,00</td>
<td>15,19 DKK/m³</td>
</tr>
</tbody>
</table>

### Table 20: Taxes and prices associated with water exchanges in the Kalundborg area (Jacobsen 2006).

<table>
<thead>
<tr>
<th>Benefits</th>
<th>costs</th>
<th>mechanism</th>
<th>specification</th>
<th>monetary value</th>
<th>amount</th>
<th>units</th>
<th>assignedparticipant</th>
<th>assignedparticipant2</th>
<th>assigneddistributionparty</th>
<th>numberofyears</th>
</tr>
</thead>
<tbody>
<tr>
<td>Additional Saline</td>
<td>Cooling water</td>
<td>341,234.30</td>
<td>7,611,000.00</td>
<td>510</td>
<td>341,234.30</td>
<td>8</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost reduction</td>
<td>Reduced intake of surface water</td>
<td>341,234.30</td>
<td>7,611,000.00</td>
<td>510</td>
<td>341,234.30</td>
<td>8</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reduction of thermal pollution Avoid discharge fee</td>
<td>12,056,230.00</td>
<td>7,611,000.00</td>
<td>510</td>
<td>12,056,230.00</td>
<td>8</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Avoid investment</td>
<td>Preheating installation</td>
<td>13,404.70</td>
<td>13,404.70</td>
<td>13,404.70</td>
<td>8</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Costs</th>
<th>costs</th>
<th>mechanism</th>
<th>specification</th>
<th>monetary value</th>
<th>amount</th>
<th>units</th>
<th>assignedparticipant</th>
<th>assignedparticipant2</th>
<th>assigneddistributionparty</th>
<th>numberofyears</th>
</tr>
</thead>
<tbody>
<tr>
<td>Investment Pipeline Statoil Asnaes Cooling Water</td>
<td>300,000.00</td>
<td>134,047.00</td>
<td>134,047.00</td>
<td>0</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Investment Preheating facility</td>
<td>1,367,873.00</td>
<td>0</td>
<td>1,367,873.00</td>
<td>0</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The costs and benefits of a typical synergy in the Kalundborg area can be represented by the ontology. The ontology does not yet represent two things in enough detail:

1. Similar to the physical exchange the costs and benefits differ per year. Representing the costs and benefits per year means a more detailed representation.
2. There is data about market prices and fees, representing this together with savings every year shows the mechanism behind the costs and benefits.

Point one and two combined could reveal drivers and barriers. Searching for drivers and barriers is also central in the next section (15.2.1), where applications of the wiki are given.

15.2.1 Applications

Each conceptual part has a section about the application of the wiki. Through examples the functionality of the wiki together with the ontology are discussed for this conceptual part. The functionalities of the following types are discussed for the conceptual part valuation:

- Building shared vocabularies
- Oversight
- Accounting
- Statistics

Building shared vocabularies - In this ontology the minimum for representing the value of a symbiosis is listing the cost or benefit by a name. This is a first inventarization of costs and benefits a step to a more sophisticated data structure for storing costs and benefits of IS (further discussed under accounting). Figure 27 shows all costs and benefits listed on the wiki. The environmental benefits are in the form of reduced resource use or lower emissions. They are possibly interrelated, raw resource reduction may cause CO₂ reduction and water savings. Sometimes the environmental benefit may also be coupled to an economic one, diversion from landfill may be couple to tax avoidance and raw material reduction may be couples to cost savings. If the table cannot hold all information about the cost or benefit or the mechanism behind its occurrence, the page of the benefit itself can be used to give information. Especially less tangible costs and benefits could be given there, consider social benefits, or costs/benefits that reduce or increase risk. Consider increased or decreased dependence on buyers or suppliers. The physical exchange may also be coupled to other collaborative projects, the exchange of information or sharing assets and services.

The idea is that the list of various costs and benefits can be reduced to a limited set of costs benefits and a limited set of mechanisms. This makes it possible to create a more specific data structure for representing costs-benefits and there mechanisms, thereby giving better insight the drivers/barriers behind IS.

Oversight - The list with cost and benefits is already a way to compose an oversight. In this paragraph data from different aspects of the conceptual parts are integrated to give an indication of drivers and barriers for IS.

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25Information about environmental regulations and procedures and/or combined use of safety and cleaning services.
Information exchange and collaboration are key to IS (Chertow 2000). A series of match making workshops could be a way to exchange information, the TEDA data set contains these as discussed in the part about the social network (13.1). A query is composed to see if these workshops possibly yield result. Basically the query asks: Which two facilities were in the same workshop and established a synergy link afterwards. It returns the two facilities, their link, the workshop and the number of years between the workshop and the establishment of the link. The zeros in table 22 thus mean that those facilities established a link within the same year as going to the workshop. TEDA-eco-center has a direct influence at the establishment of the synergy links, as it organized the workshops (section 13.1). The query results indicate that the workshops contributed to the establishment of the synergies. However, a claim can not be made. Firstly, the data set envelops around the match making workshops, a bias. Secondly, only thirteen out of thirty-one synergies are established after two facilities met in a workshop. The example might not be conclusive, but it shows how the time component together with the existence of a social and physical relationship is used to explore possible drivers and barriers behind IS.

Another key to IS is geographic proximity (Chertow 2000). Geographic proximity was operational as the distance between facilities (section 12.1). The causality behind geographic proximity as key to IS remains somewhat unclear. Therefore the wiki queries the distance as one of many parameters, table 23. Distance is framed here as an economic parameter, coming down to transportation cost and logistic difficulties. This means that other factors may be more important then distance. Here are some explanations created on the basis of the synergies on the top of the table (23). There is often an obligation (regulations) to treat hazardous material. Treating hazardous material is sometimes a quite specific job. So whatever the distance to the nearest treatment, from an economic perspective it may still be better then treating it yourself. Scale, if the exchanged quantity is large there may be a scale advantage in the transportation, making the transportation cost a minor influence. Some products can quite specifically be recycled, or maybe even be re-used, this reduce the number of processing steps. A reduction in processing cost may outweigh transportation cost. Advanced statistical calculation is not yet possible with the wiki, but it would be interesting to see how the results of table 23 could be incorporated in a factor analysis.

The point here is that the establishment of a synergy is preceded by a complex decision, to single out one or two factors as the main decision criteria is to simple. The wiki can assist in revealing multiple factors (drivers/barriers) that are important for the establishment of a synergy. Especially when properties from different conceptual parts are combined new insights might be gained.

**Accounting -** In section 15 was presented how the wiki represents costs and benefits of a synergy. One synergy is taken as an example to look closer at the costs and benefits and their quantitative values. The costs and benefits of the exchange of cooling water between Statoil and Asnaes was represented in table 21. From the table it is already clear that the benefit is largely for Statoil, while Asnaes has to endure a large investment in a pre-treatment facility. But studying the article of Jacobsen (2006) reveals that this investment was required regardless of the exchange. Furthermore there was a change that Lake Tisso would not be able to provide enough surface water (exceeded carrying capacity). Using the wiki to sum

<table>
<thead>
<tr>
<th>facility1</th>
<th>facility2</th>
<th>synergy/link</th>
<th>invention</th>
<th>year3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cargill Food</td>
<td>TEDA New Water Technology</td>
<td>Synergy Link New Water Technology Cargill Food</td>
<td>IS Matchmaking Workshop 15-April-2010</td>
<td>3-9</td>
</tr>
<tr>
<td>Tianjin Samsung Opto-Electronics</td>
<td>Tailing Environment Technology Tianjin</td>
<td>Synergy Link Samsung Opto-Electronics Tailing</td>
<td>IS Matchmaking Workshop 15-April-2010</td>
<td>3-9</td>
</tr>
<tr>
<td>Finochina China</td>
<td>Tianjin Tystau Resource Management</td>
<td>Synergy Link Finochina Tystau</td>
<td>IS Matchmaking Workshop 15-April-2010</td>
<td>3-9</td>
</tr>
<tr>
<td>Tianjin Jieping-Huaxiu Plate Making</td>
<td>Golden Dragon Recycle Center TEDA</td>
<td>Synergy Link Tianjin Jieping-Huaxiu Golden Dragon Recycle Center TEDA</td>
<td>IS Matchmaking Workshop 4-April-2011</td>
<td>3-9</td>
</tr>
<tr>
<td>Vedas TEDA</td>
<td>Tianjin Haoting Metal Products</td>
<td>Synergy Link Vedas Haoting</td>
<td>IS Matchmaking Workshop 8-June-2011</td>
<td>3-9</td>
</tr>
<tr>
<td>Dentsply</td>
<td>Unico TEDA</td>
<td>Synergy Link Dentsply Unico</td>
<td>IS Matchmaking Workshop 8-June-2011</td>
<td>3-9</td>
</tr>
<tr>
<td>Tianjin Four Pillars</td>
<td>Golden Dragon Recycle Center TEDA</td>
<td>Synergy Link Tianjin Four Pillars Golden Dragon Recycle Center TEDA</td>
<td>IS Matchmaking Workshop 8-June-2011</td>
<td>3-9</td>
</tr>
<tr>
<td>Tianjin Sanhehu Lucky New Materials</td>
<td>Golden Dragon Recycle Center TEDA</td>
<td>Synergy Link Tianjin Sanhehu Lucky New Materials Golden Dragon Recycle Center TEDA</td>
<td>IS Matchmaking Workshop 8-June-2011</td>
<td>3-9</td>
</tr>
<tr>
<td>Asian Tianjin Auto Parts</td>
<td>Lirui Tianjin Industrial Waste Treatment</td>
<td>Synergy Link Asian Lirui</td>
<td>IS Matchmaking Workshop 8-June-2011</td>
<td>3-9</td>
</tr>
<tr>
<td>Vedas TEDA</td>
<td>Unico TEDA</td>
<td>Synergy Link Vedas Unico</td>
<td>IS Matchmaking Workshop 8-June-2011</td>
<td>3-9</td>
</tr>
<tr>
<td>Tianjin Alpe TEDA Logistique</td>
<td>Golden Dragon Recycle Center TEDA</td>
<td>Synergy Link Alpe TEDA Logistique Golden Dragon Recycle</td>
<td>IS Matchmaking Workshop 8-June-2011</td>
<td>3-9</td>
</tr>
<tr>
<td>Tianjin Tinghuan Food</td>
<td>Golden Dragon Recycle Center TEDA</td>
<td>Synergy Link Tianjin Tinghuan Food Golden Dragon Recycle Center TEDA</td>
<td>IS Matchmaking Workshop 8-June-2011</td>
<td>3-9</td>
</tr>
<tr>
<td>Tianjin Nestle</td>
<td>Lirui Tianjin Industrial Waste Treatment</td>
<td>Synergy Link Nestle Lirui</td>
<td>IS Matchmaking Workshop 8-June-2011</td>
<td>3-9</td>
</tr>
<tr>
<td>Tianjin Stanley Electric</td>
<td>Golden Dragon Recycle Center TEDA</td>
<td>Synergy Link Tianjin Stanley Electric Golden Dragon Recycle Center TEDA</td>
<td>IS Matchmaking Workshop 8-June-2011</td>
<td>3-9</td>
</tr>
<tr>
<td>Vedas TEDA</td>
<td>Lirui Tianjin Industrial Waste Treatment</td>
<td>Synergy Link Vedas Lirui</td>
<td>IS Matchmaking Workshop 8-June-2011</td>
<td>3-9</td>
</tr>
</tbody>
</table>

Table 22: Facilities that met in a workshop and established a synergy afterwards. Year3 indicates within how many years after the workshop the synergy was established.
Table 23: Distances of the synergy links. Last column is the monetary benefit of the synergy link in Yuan.

<table>
<thead>
<tr>
<th>synergy link</th>
<th>distance</th>
<th>transport</th>
<th>product</th>
<th>amount</th>
<th>units</th>
<th>info</th>
<th>total_benefit_in_Yuan</th>
</tr>
</thead>
<tbody>
<tr>
<td>Synergy Link: Nestle Lusui</td>
<td>62.05</td>
<td>Truck</td>
<td>Waste Oil</td>
<td>20.09</td>
<td>Ton</td>
<td>Hazardous</td>
<td>40,000.00</td>
</tr>
<tr>
<td>Synergy Link: Tianjin Lishen Blattay Unico</td>
<td>54.44</td>
<td>Truck</td>
<td>Packaging/Waste</td>
<td>15.00</td>
<td>Ton</td>
<td>14,556,500.00</td>
<td></td>
</tr>
<tr>
<td>Synergy Link: Tianjin Four Pillars Golden Dragon Recycle Center</td>
<td>54.42</td>
<td>Truck</td>
<td>Packaging/Waste</td>
<td>120.00</td>
<td>Ton</td>
<td>956,400.00</td>
<td></td>
</tr>
<tr>
<td>Synergy Link: Samsung Opto-Electronics Testing</td>
<td>52.1</td>
<td>Truck</td>
<td>Mobile Phone Casing</td>
<td>8.0</td>
<td>Ton</td>
<td>29,700.00</td>
<td></td>
</tr>
<tr>
<td>Synergy Link: Vinhay Liheing</td>
<td>49.46</td>
<td>Truck</td>
<td>Packaging/Waste</td>
<td>14.0</td>
<td>Ton</td>
<td>44,920.00</td>
<td></td>
</tr>
<tr>
<td>Synergy Link: Vistias Lusui</td>
<td>49.17</td>
<td>Truck</td>
<td>Oil Water mixture</td>
<td>48.0</td>
<td>Ton</td>
<td>Hazardous</td>
<td>288,000.00</td>
</tr>
<tr>
<td>Synergy Link: Vistias Lusui</td>
<td>36.83</td>
<td>Truck</td>
<td>Cutting Fluid</td>
<td>240.00</td>
<td>Ton</td>
<td>Hazardous</td>
<td>1,200,000.00</td>
</tr>
<tr>
<td>Synergy Link: Vistias Huating</td>
<td>32.7</td>
<td>Truck</td>
<td>Scrap Metal</td>
<td>4.2</td>
<td>Ton</td>
<td>33,600.00</td>
<td></td>
</tr>
<tr>
<td>Synergy Link: Yixuan Unico</td>
<td>24.55</td>
<td>Truck</td>
<td>Cardboard</td>
<td>0.7</td>
<td>Ton</td>
<td></td>
<td>37,250.00</td>
</tr>
<tr>
<td>Synergy Link: Cargill Food Unico</td>
<td>20.4</td>
<td>Truck</td>
<td>Packaging/Waste</td>
<td>9.0</td>
<td>Ton</td>
<td>180,000.00</td>
<td></td>
</tr>
<tr>
<td>Synergy Link: New Water Technology Cargill Food</td>
<td>17.17</td>
<td>Truck</td>
<td>Sugar and Starch</td>
<td>13.0</td>
<td>Ton</td>
<td>1,620.00</td>
<td></td>
</tr>
<tr>
<td>Synergy Link: Vistias Unico</td>
<td>11.84</td>
<td>Truck</td>
<td>Packaging/Waste</td>
<td>11.3</td>
<td>Ton</td>
<td></td>
<td>1,200,240.00</td>
</tr>
<tr>
<td>Synergy Link: Fujitsu Ten Foqiang</td>
<td>4.52</td>
<td>Truck</td>
<td>Polystyrene</td>
<td>72.0</td>
<td>Ton</td>
<td>1,200,240.00</td>
<td></td>
</tr>
<tr>
<td>Synergy Link: Toyota Motor Foqiang</td>
<td>3.84</td>
<td>Truck</td>
<td>Polystyrene</td>
<td>72.0</td>
<td>Ton</td>
<td>1,200,240.00</td>
<td></td>
</tr>
<tr>
<td>Synergy Link: JF Natural Unico</td>
<td>3.70</td>
<td>Truck</td>
<td>Packaging/Waste</td>
<td>1.5</td>
<td>Ton</td>
<td>600</td>
<td></td>
</tr>
<tr>
<td>Synergy Link: Yingli Foqiang</td>
<td>3.77</td>
<td>Truck</td>
<td>Packaging/Waste</td>
<td>72.0</td>
<td>Ton</td>
<td>102,400.00</td>
<td></td>
</tr>
<tr>
<td>Synergy Link: Dentsply Unico</td>
<td>5.6</td>
<td>Truck</td>
<td>Packaging/Waste</td>
<td>66.0</td>
<td>Ton</td>
<td></td>
<td>134,700.00</td>
</tr>
<tr>
<td>Synergy Link: ArcelorMittal Unico</td>
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<td>Truck</td>
<td>Packaging/Waste</td>
<td>10.0</td>
<td>Ton</td>
<td></td>
<td>886,250.00</td>
</tr>
<tr>
<td>Synergy Link: Tianjin Jinggang Huabei Golden Dragon Recycle Center</td>
<td>2.73</td>
<td>Truck</td>
<td>Iron Scrap</td>
<td>75.0</td>
<td>Ton</td>
<td>384,490.00</td>
<td></td>
</tr>
<tr>
<td>Synergy Link: Tianjin Stanley Electric Golden Dragon Recycle Center</td>
<td>2.51</td>
<td>Truck</td>
<td>Packaging/Waste</td>
<td>64.0</td>
<td>Ton</td>
<td>384,490.00</td>
<td></td>
</tr>
<tr>
<td>Synergy Link: Novozymes Unico</td>
<td>2.42</td>
<td>Truck</td>
<td>Waste Bags</td>
<td>0.6</td>
<td>Ton</td>
<td>8400</td>
<td></td>
</tr>
<tr>
<td>Synergy Link: Ferribi Toyota</td>
<td>2.33</td>
<td>Truck</td>
<td>Iron Scrap</td>
<td>13.0</td>
<td>Ton</td>
<td>82,800.00</td>
<td></td>
</tr>
<tr>
<td>Synergy Link: Harbie Unico</td>
<td>1.94</td>
<td>Truck</td>
<td>Packaging/Waste</td>
<td>187.00</td>
<td>Ton</td>
<td>807,490.00</td>
<td></td>
</tr>
<tr>
<td>Synergy Link: Samsung Electronics Foqiang</td>
<td>1.73</td>
<td>Truck</td>
<td>Polystyrene</td>
<td>180.00</td>
<td>Ton</td>
<td>3,000,500.00</td>
<td></td>
</tr>
<tr>
<td>Synergy Link: Tianjin Tongxiang Food Golden Dragon Recycle Center TEDA</td>
<td>1.31</td>
<td>Truck</td>
<td>Packaging/Waste</td>
<td>222.00</td>
<td>Ton</td>
<td>1,049,540.00</td>
<td></td>
</tr>
<tr>
<td>Synergy Link: Alico TEDA Logistics Golden Dragon Recycle</td>
<td>1.21</td>
<td>Truck</td>
<td>Packaging/Waste</td>
<td>19.0</td>
<td>Ton</td>
<td>122,900.00</td>
<td></td>
</tr>
<tr>
<td>Synergy Link: Tianjin Baoan-Lucky New Materials Golden Dragon Recycle Center</td>
<td>1.07</td>
<td>Truck</td>
<td>Packaging/Waste</td>
<td>30.0</td>
<td>Ton</td>
<td>210,100.00</td>
<td></td>
</tr>
<tr>
<td>Synergy Link: Chiyoda Integre Unico</td>
<td>0.92</td>
<td>Truck</td>
<td>Packaging/Waste</td>
<td>48.0</td>
<td>Ton</td>
<td>435,250.00</td>
<td></td>
</tr>
<tr>
<td>Synergy Link: Chiyoda Integre Unico 2011</td>
<td>0.92</td>
<td>Truck</td>
<td>Packaging/Waste</td>
<td>120.00</td>
<td>Ton</td>
<td>511,360.00</td>
<td></td>
</tr>
<tr>
<td>Synergy Link: New Water Technology No 5 Cogeneration Power Plant</td>
<td>0.3</td>
<td>Pipeline</td>
<td>Recycled water</td>
<td>365,000.00</td>
<td>Ton</td>
<td>0.00</td>
<td></td>
</tr>
</tbody>
</table>

63
up the costs and benefits (table 24) delivers us a strange error. The sum of the benefits is multiplied by two, while the sum of the costs is multiplied by four, unexplainable as of yet.

<table>
<thead>
<tr>
<th>addedvalue1</th>
<th>addedvalue2</th>
</tr>
</thead>
<tbody>
<tr>
<td>24,074,786.00</td>
<td>-21,474,396.60</td>
</tr>
</tbody>
</table>

Table 24: The added value of the synergy link for Statoil (addedvalue1) and Asnaes (addedvalue2).

Because different costs and benefits are caused by the same environmental saving (reduced surface water intake) we cannot use SPARQL to sum up environmental savings, as this means double counting. For this we first need a list of standardized types of environmental benefits. Next to summing up costs and benefits it is also interesting to take a look at the mechanism behind benefits or costs. Table 21 gives additional sale for the supplier and cost savings for the receiver. This is caused by the same mechanism, the Cooling water page stores the information about this mechanism. Statoil sells the cooling water for 50% of the surface water price. This is a cost reduction for Asnaes, thus they both achieve the same benefit of a quarter million euro over 12 years. Statoil also benefits through an avoided discharge fee. The discharge fee is represented as an event, the tariffs for each year are given there. The page Avoid discharge fee then queries the mass flow and the fees for the different years and calculates the benefit, see figure 28. The intend is to give all costs and benefits in this way, combining different pieces of data and letting the wiki calculating the cost or benefit. However, so far we have not found a generic ontology for representing costs and benefits on this level of detail. Especially regarding environmental benefits calculations can be quite difficult. The pipeline between Statoil and Asnaes reduces surface water usage, but creating the pipeline and putting the pipeline there causes emissions as well. These are one time emissions, but in case of emissions because of transportation or processing this may be worth considering. Making a complete assessment of the environmental impact of an IS-project also crosses wit life cycle calculations of product; both are studies on its own. They are not always incorporated in IS research. Another remark is that the economic and environmental savings are usually calculated in regard to an alternative scenario. The alternative scenario is basically the old situation. But the question is were there other possibilities, or would another opportunity have manifested itself after a couple of years?

26The introduction of an environmental fee can be an event in the process of increased symbiotic activity.
These are difficult calculations, it is questionable if a generic ontology can be created for that, but the wiki can also just link to other studies.

**Statistics** - The wiki can list and sum up costs and benefits. A generic ontology for automatic calculation of cost and benefits from the detailed data is not yet in reach, as discussed in the previous paragraph. This means that using statistics to compare the outcome of IS projects is also not possible. So this paragraph is focused on looking at the possible role for the wiki to assist current value measurement methods.

In literature we also see that measuring the value of IE-projects is done in very different ways. Sidiropoulos et al. (2010) compares five methods. Some evaluate structural aspects of the IS-network, the diversity and connectance. On the wiki this falls under the physical and social network, giving network statistics and the variety of industrial sectors involved and sees how this evolves over time. Geng et al. (2008) discusses the EIP performance evaluation of the Chinese circular economy program. From the five, this is the one that most closely resembles the framework of the wiki as it is also based on added value. Namely, industrial added value per capita and then environmental benefits per added industrial value. As the EIP performance measurement is an evaluative method over the region as a whole, it is difficult to distil drivers and barriers from the results.

The combination of measuring value and finding drivers and barriers is often done through surveys or interviews. Creating a good interview method or survey is a science in itself. As there are two interpretation steps (observer and interviewer), there is a double error margin. But interviews open up a tremendous amount of quantitative and qualitative data; therefore it is interesting to see how it combines with the wiki. In principle the wiki is in itself an interview tool; users can insert data onto the wiki. The forms for the insertion of data are already in place, but different interviewees perhaps require different instructions because they have different pieces of information. A first test with a couple of people might be enough to be sure about this. However, the wiki is now focused on representing observable things, but the opinion of people is also interesting. People can leave there opinion on the discussion page, but it is also possible to make a data structure where people give there opinion in a special format, a score on some questions. This enables future use of statistics.

16 **Can the ontology represent IS?**

In this section the nuances and remarks regarding representing IS with the ontology are stated. The ontology can now represent two case studies but that doesn’t mean that the ontology is finished. Some aspects of the data sets are still not satisfiable represented. Furthermore, some aspect from literature are under represented in the data sets and thus in the ontology. Personal insight during the construction are also a reason to discuss the representability of IS by the ontology.

**Physical network** - The SynergyLink can only represent one physical exchange, while there may in fact be multiple over multiple years. This was revealed when discussing the Kalundborg data set (section 12.2), also the inputs and outputs are not systematically enough represented. The same material is multiple times represented on the wiki. This means mass flows and their relation to the SynergyLink category should be re-evaluated.

31-b shows the suggestion to store the physical exchange as a separate page. The idea is to create a page for each year, this allows for more details to be given and more accurate representation of the fluctuations. Section 13.2.1 showed that there was a problem representing network statistics, because some facilities had multiple synergies with one other facility, this problem is also fixed by representing the mass flows on a different page. The inputs and outputs will not be stored on the page of the facility any more, they will only be queried on there. If it is unknown were an input/output comes from or is going to, the mass flow will specify unknown facility. For emissions the mass flow will specify that the receiving facility is the atmosphere, see also figure 31-b.

Infrastructure is in literature described as an important factor for IS-development, so we added the properties InfrastructureUsage and TransportationMethod to the SynergyLink page. But assets such as equipment and machinery are not yet a part of the ontology, and also there is not yet a general category for infrastructure or physical assets. And thus they are also not coupled to the valuation scheme.
**Social Interaction** - This probably the aspect least represented in the data sets. The physical relationship is represented by the synergy; the ontology is only able to give one other relationship: The meeting of facilities in a workshop. Literature describes many more types of relation: various informal relations (regarding receiving information), supply chain relation and then we are not talking about relations of individuals yet. The role individuals play (the analyst planner, the change broker, the firm decision maker (Gertler 1995)) in the establishing of a synergy and the organizational structure of facilities remains are not yet described in IS-literature. It is possible to create a category for representing individuals, and then define relations between them (figure 31). But studies that do this, Ashton & Bain (2012), usually hide the identity of the persons. So future research has to explore how social interactions can best be represented by the ontology.

**Time** - You could see the different conceptual parts as dimensions, physical, social and then time (and value, next paragraph). The time aspect is coupled to both physical and social events, this creates an intricate coupling. This is especially an intricate coupling when meaning is assigned to the time component through the event labeling. Which social and physical changes are important enough to represent as event and how do you couple them to the FacilityIS and SynergyLink pages? Certain events are clearly important to IS, regulations and laws regarding pollution for instance (institutional context). Section 15.2.1 researched the interaction of taxes and fees on the cost and benefits of IS. The idea is that laws and regulations or subsidy programs will get an separate category, see 31-b. This way it will more accurately represent the tax or law, instead of just being an event. Objects such as taxes will still be labeled as an event, but events will have there own page. This way we can better show if something really changes (ownership change) or that it is more a temporary thing (participation). It also prevents double counting of events.

Although the event labeling scheme is set in place and some event counts are shown on the wiki, a full process analysis is not preformed yet. This requires detailed and extensive data regarding happenings related to IS in the region. Doing a full process analysis may reveal the need for certain changes. It is expected, that at least an additional ordering property is required. So far we only have ordering per region (property Location), a region may have several relatively separate IS-projects. It is expected that representing an event as a separate page will enable this.

**Valuation** - Although the data sets contained quiet some information about economic and environmental benefits, a generic ontology for representing costs and benefits could not be established. The costs and benefits of IS linkages have various reasons, this makes it hard to represent the mechanisms behind them (section 15.2.1). Often it is interesting to calculate cost and benefits in regard to an alternative scenario or an historic scenario, but then it is even more challenging to come to a generic ontology.

Research into Life Cycle Analysis (LCA) may give insight for representing value, LCA uses databases with standard values for products and process steps. Another way of determining value; is by directly asking (surveys) the people involved. But for now, the idea is to also make a separate category for valuation. This will become the connection between a physical object or an event and the to which it brings value. For instance, a particular pipeline may be connected to the value ‘investment into pipeline A-B’. Which is in turn queried on the page of a facility. Or the mass flow ‘$CO_2_{facilityA} – Atmosphere$’ may connected to a cost, the cost may be queried on the page of a facility (if there is a $CO_2$-tax) or on the page ‘the society’ (if there is no tax).

**Synthesis** - Above the problems regarding representing IS with an ontology were discussed. For a large part the problems were caused because the ontology of IS is a simplified version of reality (low ontological commitment). Some solutions were also proposed. This paragraph explains the core of the problems.

The category FacilityIS on the wiki tries to encompass the entity that engages in IS. But it is not really clear which entity engages in IS. The facility (the physical building) has an owner and within the facilities there are individuals with jobs (figure 29). The contract may be between companies or organizations but the communication is between individuals, and the actual physical exchange between facilities (figure 45). To reduce this to two categories (FacilityIS, SynergyLink) creates a coupling that makes correct representation difficult. Especially, because the time component is also coupled to the same page, the social connection may have an entirely different duration than the physical connection. Some solutions were discussed and represented by figure 31-b. But further research and testing is require to sort this all out. Section 20 discusses further research.
Figure 29: Layers of an IS-entity. The facility represents the physical infrastructure. Then there is the process the physical transformation of the product. The formal organization is bound by contracts and laws and involved in the financial transaction, whereas the informal organization consisting of individuals and groups of individuals that are involved in the information exchange.

Figure 30: Layers of the IS-relation. Process refers to the manufacturing process.
Figure 31: (a) Impression of the basic structure of the ontology as is and (b) the ontology after future adaptations.
Part V
Collectively building further on an ontology of Industrial Symbiosis

Part [IV] has provided an ontology of IS. The ontology can still be improved and as science is a continuous process of learning, the ontology should be able to evolve along. Continuous contribution of users should eventually ensure this. The wiki format facilitates contribution, but section [10] explained that more then just a wiki format is required.

Sub objective two Develop procedures and techniques to enable contribution to the ontology.

- How is the ontology made understandable for user/contributors? (section [17])
- What do we need to consider when changing the ontology? (section [18])
- How does this fit into process of building collective knowledge? (section [19])
- What are the concrete steps that still need to be taken? (section [20])

17 Understanding the ontology structure

The user/contributor should at least have a grasp of the part of the ontology he/she is contributing to. This might require additional documentation, documentation about the structure of the ontology and the properties and categories used. In principle this can all be found on the wiki. When you edit a page, you see which templates are embedded on that page. Editing the template shows the properties. You can also reveal the properties by inserting the _SHOWFACTBOX_-command on the page. Through clicking on the properties you can go to the page of the property, here you will find the pages that have this property. However, this is a process of opening and editing multiple pages, oversight is lost. So, in this thesis oversights were given in graph form, much like the World Wide Web consortium (W3C) also uses to communicate RDF triplets. Another way to make the ontology more understandable is the compiled list of properties (figure [25]), this list of properties is ordered based on which conceptual part they help to represent. This way you can also see the minimal amount of data you require to represent the conceptual part, the properties colored essential. This is a form of ontological commitment (section [10]). The wiki allows you to put fragmented data on there with little ontological commitment, but representing one of conceptual parts of IS can only be done with a certain set of properties. The list with properties helps you to understand the ontology, but it also advices you what data to collect if you want to represent IS. But the method of keeping track of the role of properties can be further refined.

How to order properties - The properties required to represent a conceptual part of IS are usually ordered in one template, modular design. This template can be re-used in other categories, as done for ISevent and ISeventSetSIO. The ordering of properties by which part they conceptually represent fitted the with the design process. Ordering the properties by method of measurement or analysis is another option. During the design of and experimentation with the ontology, properties were usually added with some function or application in mind. For instance, giving network visualizations, calculating distance aggregates etc. Here follow two examples in more detail:

Process Analysis Process analysis requires the labeling of events. So properties were created to represent these labels. These labels do not really represent an observable aspect of reality but they are needed to make sense out of a sequence of events.

Social Network Analysis (SNA) Social network analysis (SNA) is another example. SNA is a way of analyzing connection between social entities and calculating an indicator for the importance of the entity in the network. For facilities this means researching a couple of connections types (section [13.2.1]). Therefore the data gathering process may involve asking the people to judge a relationship. This may induce the adding of new properties or even categories to the ontology.
Table 25: The category SynergyLink has these properties. They are ordered by which conceptual part of IS they help to represent.
Ordering the properties under the method of analysis, the function, is beneficial in two ways. One, a researcher collecting information knows which data is required to perform the analysis on the wiki. Secondly, during the analysis the researcher knows which properties are required for running the queries etc.

In section 7 was discussed that tools and methods can formalize a domain, basically this is done by coupling the properties to a method of analysis. But the methods of analysis needs to fit with the overall conceptualization, the formalism for SNA may not be mutually exclusive with the formalism for process analysis.

The new ordering of properties should thus be: First conceptual part and then method of analysis, or function. An example is given (table 25), the functions are Process Analysis, SNA and the Network diagram. The functions were chosen as they have an overlap in property use. FromFacility and ToFacility are required for SNA and the network diagram, Location is required for all functions. This means the formalisms for these functions are connected through some of the properties. The coupling between functions and material parts is an important concept for complex systems (appendix G.1).

Figure 32: Property table for three methods of analysis. Categories shown are SynergyLink and FacilityIS.

18 Changeability

The ontology is not a definitive thing, it will change and evolve. For instance, refinement in one of the methods of analysis may induce the need to change the ontology for that function. However, because there is an overlap in property usage it means that you automatically alter something for one of the other functions. In axiomatic design (Suh 2001) they call this a coupled design (figure 33-b). An ideal design is were each function is only fulfilled by one physical object (figure 33-a). More details about Axiomatic design can be found in appendix F. To be able to evolve, the ontology should thus ideally be designed completely modular. Each function should be preformed by a set of properties that is not used for any other function. But we want to connect multiple formalisms (section 4). With a complete modular design the parts of the ontology could evolve in isolation, reality evolves in relation to its surroundings. If you want to represent reality an ideally designed ontology is thus not possible. Reality is complex.

27Physical does not refer to the conceptual part of IS. It refers to some physical object in the design, a property or a set of properties, a template
physical objects can have multiple functions, and thus can an ontology that represents reality never be completely modular. This is the trade-off between extensibility and representing reality in as much detail as possible (high ontological commitment), see section 10. An ontology can thus not continuously evolve at the hand of multiple contributors. Now and then this process needs a discrete step of large revisions, by one person or a coordinated group.

The usage of one property for multiple methods of analysis (functions) is thus inevitable. But making the ontology more modular is possible. As already mentioned in section 16, to much information is integrated on pages from two categories (FacilityIS, SynergyLink). The physical network and the social interaction need to be decoupled. Concretely this also means that templates should only contain properties that are used for the same function.

19 Shaping formalisms and communicating knowledge

The ontology is built on a wiki, wikis allow contribution. So, why put such emphasis on the procedures of contribution? (1) And why are the property matrices not already ordered on the method of analysis? (2) Because we are only at the start of the development of the tool for assisting IS-case study research. First, question two is answered.

Using the ontology as a tool for the analysis of data requires two things: One, a clearly formulated method of analysis. Two, data for perform the analysis. The combination of the two gives enough information to construct the ontology in such a way that it can perform the analysis. In part [V] some applications of the ontology are shown, but these are not yet formalized methods of analysis. So it does not make sense to already order the properties based on method of analysis. First an iterative process of gathering data, formalizing the method and changing the ontology is required. But as explained in the previous section [17], it is not possible to change the ontology without altering other functions of the ontology. Therefore procedures for contributing to the ontology are required. Because the goal is to develop an ontology, that can perform multiple different methods of analysis.

This brings us back to the first question. You can not just change something about the ontology and expect that still all functions can be performed. This is why you need to be careful with the process of contributing to the ontology if you want the ontology to perform multiple functions (methods of analysis). A formalized method leads to a pre-defined knowledge format (section [6], this means we are already busy shaping formalisms. The ontology forms the basis for connecting those formalisms. Which was the task formulated at the end of part [1]. Where the ontology provides comparability and guards the logic of information, data gathered during case studies should provide checks with reality. The combination of the two can make case study research stronger. The idea was never to replace the role of the researcher for an ontology, the ontology is a mere support tool. Some data gathering and analysis can be preformed by the ontology, giving the researcher more time to search for the special case, the anecdote and other innovative insights. So, the ontology fits within the current scientific paradigm. The researcher may still deliver a scientific article with the mayor conclusions, and he/she can refer to the wiki for the data needed to back up his or her claims.

This section was quite abstract about the use of the ontology now and in the future. The next section provides more concretely which steps need to be taken for further development.
20 Future developments

One of the main underlying goals of this thesis is to work towards a shared conceptualization. A conceptualization can be formalized in the form of an ontology. The wiki was seen as software to build an ontology, software that makes it possible for multiple researchers to collectively build an ontology. The process of building this ontology would not need coordination, as the graphical interface and the ease of contribution makes self-organization possible. This was my understanding at the beginning of this thesis, this is too optimistic.

Contributors can fill in data and add properties to the ontology. With knowledge about SPARQL users could run some queries. But contributing to the structure of the ontology requires quite some knowledge about the ontology and how to construct it. The ontology has a main structure that cannot be changed easily, as a change would have effect on the whole ontology. This means there needs to be a core conceptualization already. So, without coordination it is not possible to collectively build an ontology, from scrap, on the wiki. Even when the core structure is there, it is still challenging to build the ontology further.

Representing reality in all its features is quite challenging. An ontology that tries to represent reality can therefore become quite extensive. New users and contributors will then have trouble understanding the complete ontology, which may hinder contribution. Is this a trade-off between the exactness and usability of an ontology? Hepp (2007) thinks so and formulates it as the trade-off: degree of detail and exactness vs community size. This was all discussed in this thesis, but what are the future steps to come closer to an evolving ontology for IS-research. Some steps can be done in parallel, figure 34 gives an oversight.

The ontology - The ontology is not finished. The point is not to finish the ontology, but make it ready for a larger group of contributors. This requires a revision of the ontology, but first some steps have to be taken. Section 16 discussed some parts of the ontology that require a change, some concrete changes have been proposed. The conceptual part that requires some additional research is social interaction. For instance, the part of social interaction that links to transaction costs, searching costs, recurring transactions and trust (section 13). It is difficult to put a value on those costs. Furthermore, the formalized ways of studying social interaction usually involves asking people about their relationship with others, see for instance Ashton & Bain (2012). The studies hide the identity of the interviewed people. This requires some thought about how to incorporate that on the wiki. This is also a good moment to research the possibility of performing surveys directly through the wiki. The next step is walking through the ontology with an expert in the field of IS (figure 34). The expert may indicate which parts of the ontology require further development or modification and the level of detail the ontology should attain (appendix O). The expert may also be consulted on representing the social interaction.

Functional design - The property matrices were introduced (section 17) as assistant for understanding and contributing to the ontology. The contributors should be able to change the property matrix if they change something in the ontology. Therefore the wiki should be able to dynamically represent the property matrices. How can this be done?

The wiki - A parallel future step is testing how users/contributors experience the ontology (figure 34). Are they able to create instance and fill in data quickly? Can they understand the ontology in such manner that they can run queries themselves? Appendix N gives an instruction for users/contributors. Feedback of the users can be valuable in further developing the ontology.

Revising the ontology - After the steps mentioned above, the ontology can be revised. The revised ontology can start to support case studies. Because the average IS-researcher does not have knowledge about ontologies, it is probably good to work closely with an ontology engineer for the first case studies. The choice for data gathering techniques and methods of analysis should be made collectively. But the decision should be made on the basis of what good IS-case study research is. The ontology should be adapted to that. Slowly the ontology will develop a larger set of methods for analysis. Keep in mind that the ontology can not help in all aspect of a case study. It may not always be possible to formalize anecdotal stories and qualitative parts of the research.
Long term vision - The first cases may give rise to additions and changes to the ontology. This also means that there is a need for ongoing research in regard to the process of contributing to the ontology. In the process of contribution, the idea is that (new) functions (methods of analysis) will be added to the ontology or existing will be developed. If the ontology can perform analysis's for IS researchers, there is a direct incentive to use the ontology. While an active push may be required in the beginning, later on researchers start to use the ontology because they realize what it has to offer.

In the introduction figure [1] described the cyclic process of science through case studies. At a certain point the ontology may also play a role in the prescription of IS. This requires a certain level of detail and openness of data on the ontology. This is in itself a discussion that needs to take place for optimal use of an open source platform. Section [2.2] already showed that resource matching is possible with the wiki. It requires up to date data about inputs and outputs of facilities and a clear resource classification. If the ontology is used to support the prescription of IS, it would be good to try document the process at the same time. This will be an input for doing process analysis on hindsight. A full loop of science, but this is all speculation at this point. A lot of effort and research will need to precede before this can be achieved.
Part VI

Conclusion

The establishment of IS-linkages require technical expertise within a social-economic decision making process, this happens in relation to the larger local and global context of the economy and the natural environment. IS-research is a multi-disciplinary effort. This may indicate why there is not yet a shared understanding about IS among its researchers. Studying the research done in the field of IS delivers us the basis for this thesis (part II):

For the study of IS we need to connect multiple shared formalisms. Currently in the domain of IS, case studies are performed that cover different parts of the conceptual scope and where the scopes overlap different formalisms are used, or the formalism used is not communicated. Tools can enable the process of connecting and sharing individual case studies, meanwhile shaping formalisms.

In this thesis Enipedia is used as basis for such a tool. Enipedia is a semantic wiki. wikis enable participation, but semantic wikis make use of data structures to leverage the power of machines. These data structures are called ontologies.

**Design objective** Design an ontology that can store and share IS case studies, with the possibility to evolve through the input of contributors.

1. Design an ontology that can represent IS-case studies.
2. Develop procedures and techniques to enable contribution to the ontology.

21 Design of the ontology

Ontologies are specifications of conceptualizations (Gruber 1995), by means of making concrete instantiations of abstract typologies. Ontologies can range from very abstract general ontologies to specific domain ontologies. On semantic wikis the abstraction layers are already specified within RDF. This thesis is thus concerned with designing the more concrete layers of the ontology. A ‘fit for purpose’ approach suits this. The first case study forms the basis for the design, the second evaluates the design.

1. Tianjin Economic Development Area (TEDA), data set obtained through a field study by Chang Yu.
2. Kalundborg, the data set from Jacobsen (2006)

The two cases can be found on Enipedia, showing that the ontology can represent them. Thereby fulfilling design objective one. Below we discuss the ontology for the four conceptual parts. Briefly the categories and properties required to represent the conceptual part are stated. Figure 35 gives the minimal visual support to understand the relations between the categories. The applications that were found during the testing of the ontology are represented next. Concluding with some remarks regarding the ontology.

**Physical network** - Both data sets contained information about which facility was connected to who and what resource they exchanged. This made a quite straight forward mapping to the ontology.

**Categories** FacilityIS, SynergyLink

**Properties** IndustrySector, Location, Point, FromFacility, ToFacility, Distance between facilities and the SymbioticExchange template with properties to represent the exchanged substance.

Through FromFacility or ToFacility the facilities are connected to the synergy link and in this way connected to each other. Various applications can be performed with this structure.
Figure 35: The ontology with the most important properties and the minimum amount of instances to show the structure.

- Creating a resource classification: The exchanged resources are stored on the pages of the synergies. Querying these resources into one big list reveals different naming systems and inconsistencies within the naming systems. The wiki can assign properties to determine sub-divisions in resources and separate between mixtures and pure substances. This enables IS-researchers to slowly built towards a shared resource classification.

- Creating an industry classification: The industry sector of each facility is stored. But there is not an overarching industry classification for IS. The wiki can help to identify the different logic systems behind classifications and assist in building a shared classification. This can then assist in identifying dependencies between industries.

- Network diagram: The connections between facilities together constitute a network. SPARQL has a graph visualization which can show this network, giving an oversight of all synergies in the region.

- Geographic proximity: For each facility the coordinates (Point) are stored. The synergy between two facilities contains a query that calculates the distance between the coordinates. We can give the distance of all the synergies in the data set, and also calculate averages. This can fuel the discussion about geographic proximity and resource movement.

- Mass balances: We can sum up the amounts of resources exchanged over the whole of the region. And the structure also allows checking of mass balances. But a mistake is quickly made here, because off non-standardized names of mixtures and resources, incomplete data and different time frames.

- Resource matching: Queries can identify which facilities in a certain location produce a certain resource. Enipedia also provides information about generic (chemical) processes. The two combined can support resource identification. But this again requires a consistent resource classification.

There were two point that were not represented that well. The Kalundborg data set contained more information about fluctuations of mass flows over the years; the ontology could only give the accumulation over the duration of the whole synergy. Also there were entities that were not really a facility or actually a collective of smaller facilities, those were represented as a facility anyway.
Social interaction - The data about the physical network was much richer then the data about the social interaction. So far, social interaction is thus represented by having an actual connection or by having participated in the same match making workshop.

Categories FacilityIS, SynergyLink, ISevent, Coordinator

Properties ISeventParticipatedIn, FromFacility, ToFacility, OrganizedBy

- Show connections: The ontology can show in various ways how the facilities connect. And the ontology can also show the connection to the coordinator through the match making workshops.
- Network metrics: With SPARQL we can create a query that counts the number of synergies each facility has and then transform this into a network metric. It shows that with some more data the ontology can perform social network analysis, similar to the ones presented in literature.

The social interaction is clearly a conceptual part that requires development on the basis of other case studies. A central question is which entity engages in social interaction, and how can we represent this entity.

Time component - Basically all pages need a time component. This way we can place the pieces of data in their chronological order.

Categories FacilityIS, SynergyLink, ISevent, Coordinator

Properties StartDate, EndDate, Location and the ISeventSetSIO template for event labeling

The (institutional) context is represented by instances from the category ISevent. All things of importance that do not yet have a specific category, can first be inserted as an event. All pages can also get an event label, this allows for process analysis.

- Timeline: The wiki makes a timeline visualization possible. All pages have a start and end date, the timeline can thus give an oversight of the happenings per location. Taxes and policies represented as events also show up.
- Process analysis: The labeling of events is a step in process analysis. The wiki can count the number of events (everything with an event label) per year and give them in a bar chart. This gives an indication for the symbiotic activity taking place in the region.

Some things change in reality only partly. This is the main problem in regard to representing the time component. How do you represent such a partial change? The thing still exist thus you cannot state that this was its end date. An example is the fluctuation in mass flow. Another example is a facility getting another owner or manager.

Valuation - The data sets contain various economic and environmental outcomes of the synergies. They are represented as cost and benefits on the synergy link pages.

Categories SynergyLink

Properties The Costs and Benefits templates, containing properties for representing the type of cost/benefit, mechanism, monetary value, to whom it is assigned and the time period.

Because valuation is an important (and last) part of the ontology, drivers and barriers can now also be explored.

- Typologies of costs/benefits: A list with all costs and benefits and their count can be made. The goal is to find patterns in the occurrence of costs and benefits and maybe work on finding the generic mechanism behind them. Similar exchanges of resource may list different costs and benefits, for instance.
- Match making workshops: The TEDA data set contains match making workshops, the wiki can show which facilities participated in the same workshops. Because of the time component we can then show if and when they engaged in a synergy. Revealing that the match making workshops have possibly contributed to the establishment of synergies.
• Distance as an economic parameter: Earlier we gave some statistics about the distances of the synergies. But it is quite strange to research distance in isolation of other parameters. A synergy over a large distance may be explained by a large economic benefit or a special product. We can query distance next to economic benefits, transportation method and the amount of physical exchange, this way we can speculate about factors (a combination of different parameters) behind the establishment of IS-linkages.

• Detailed calculations of costs and benefits: An example follows, it shows that making a generic structure for calculating costs and benefits is challenging. The exchange of cooling water between Statoil and Asnaes is beneficial. Statoil avoids a discharge fee and Asnaes has fewer expenses because the cooling water is sold cheaper then the surface water. The fee is represented as an event; in combination with the exchanged amount we can calculate the benefits. This requires adding a lot of information to the wiki that does not yet fit into the ontology.

• Summing up costs and benefits: The wiki can sum up various costs and benefits, environmental as well as economic.

The costs and benefits of the synergies can be represented. But it remains the question if an (generic) ontology can be created to represent the cost benefits on a greater level of detail, revealing the mechanisms behind them.

Overall, the ontology can represent the data sets of TEDA and Kalundborg. In combination with the features of Enipedia, the ontology also proves to be functional in the analysis of the data sets. This is a positive starting point for developing these functionalities further.

22 Enabling contribution

An important trade-off in the designing of ontologies is the one between ontological commitment and extendibility (Gruber 1995). A very specific description of a conceptualization can be used in fewer contexts and can thus less freely be instantiated. Also a large ontology is more difficult to understand for users/contributors. This was a practical observation during the design. Property matrices were developed to quickly get an oversight of the ontology, these property matrices show which properties are required to represent which conceptual part. The property matrices will also show for which method of analysis (function) the property is required. This basically creates a higher ontological commitment. If you want a certain function to be performed, you have to use this property. The idea is that contributors are going to add more functions and develop functions further; this will give the ontology more value. However, the development of functions means also that properties may be changed or altered. This would not be a problem if the properties were only used for a single function. But often properties are used for multiple functions. This is the problem of a coupled design, table 26-a. Suh (2001) states that in an ideal design each physical object only full fills one function (table 26-b). Basically an ideal design is a complete modular design. But, this would also mean that a simple system is described, while the description of reality is the goal. Reality is complex, material parts can have multiple functions (appendix P and G.1).

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<table>
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<th>(b)</th>
<th>Methods of analysis</th>
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Table 26: (a) A coupled design, one property is required for multiple function. (b) A modular (ideal) design, none of the properties is required for multiple functions.
The combination of insights about existing ontology design principles, experience in the process of building a web ontology and axiomatic design have led to the formulation of procedures for contribution to the ontology, with the property matrices as artifact to guide the process. This means sub design objective two is fulfilled.

Developing the different functionalities (methods of analysis) further and using them to support case studies, fits within the current research paradigm. However, using the ontology in case studies beyond these first two has not been tested yet. Which means the process of contributing to the ontology has not been tested either. The next section contains steps that need to be taken before the ontology can be put to the contribution test. For now, this means that the main design objective, an evolving ontology of IS, has not been produced. It is expected that a continuous evolving ontology by contribution of users may at least be challenging to keep functional. Practical testing is the only way to evaluate this.

23 Future research

Currently users/contributors can fill in data, run queries and add some properties. But a revision of the ontology is required before contribution to the structure of the ontology can be considered.

- Get feedback about the usability of the ontology, from users that fill in data and run queries.
- Put properties that are used for the same function into one template. Research how the property matrices can be dynamically represented on the wiki.
- Research how to develop the part about social interaction on the ontology, at the same time researching the possibility to do surveys directly through the wiki.
- Walk an expert of IS through the ontology. The expert may determine the level of detail suitable for the ontology. Furthermore he/she can indicate which parts further to develop.
- Section [16] suggest some concrete changes to the ontology that will also make the ontology more modular. These would need to be implemented.

After revision of the ontology, case studies can benefit even more from the ontology as support tool. In the beginning this will require close cooperation of IS-researchers and ontology engineers. But more and more researchers may be able to

In a later stadium the prescriptive possibilities of the ontology may be further explored.
References


Hoekstra, R. (2009), *Ontology Representation: Design Patterns and Ontologies that make Sense*, IOS Press.


Part VII
Appendixes

A Definitions of IS

No in depth analysis of these definitions will follow, only the differences and focus will be addressed. Every single definitions talks about some form of relation between agents. Chertow (2000) is the most cited article about IS.

Industrial symbiosis engages traditionally separate industries in a collective approach to competitive advantage involving physical exchange of materials, energy, water, and/or by-products. The keys to industrial symbiosis are collaboration and the synergistic possibilities offered by geographic proximity (Chertow 2000).

As key prerequisites are mentioned; collaboration and geographic proximity. Mentioning physical exchange and traditional separate industries is fuel for some of the discussions in IS literature.

Highly inter-dependent relationship between two firms, exchanging materials and energy in a mutually advantageous manner, each contributing to the welfare of the other. (Manahan (1999) in Mirata (2004))

Manahan uses firms as entity and welfare as assessment of benefits, welfare is associated with more than just profit. Further the degree of inter-dependence is emphasized, ‘highly’.

IS engages diverse organizations in a network to foster eco-innovation and long-term culture change. Creating and sharing knowledge through the network yields mutually profitable transactions for novel sourcing of required inputs, value-added destinations for non-product outputs, and improved business and technical processes. (Lombardi & Laybourn 2012)

Lombardi and Laybourn made it as an update for the field of IS. It focusses more on innovation, which is a much debated concept of its own. Less emphasis is put on physical resources and they acknowledge that is about change so a process. They put kind of a weight on IS by stating that it is not just a change but long-term cultural change, is this change also recognized by the field of IE?

Industrial symbiosis brings together traditionally separate industries and organisations from all business sectors with the aim of improving cross industry resource efficiency and sustainability; involving the physical exchange of materials, energy and/or by-products together with the shared use of assets, logistics and expertise. http://www.nisp.org.uk/

An variation on Chertow. Perhaps to prevent exclusion of businesses that are not typical industrial, they mention organizations as well. Further they expanded the exchange to include shared assets and expertise. Similar to Lombardi and Laybourn they have discarded geographic proximity as key. Heeres et al. (2004) also have a definition of IS without explicitly mentioning IS, they bring it up when discussing EIP’s. It might be incomplete because it was not mend to be a definition however it contains most of the key topics.

New unexpected connections between heterogeneous classes of industries or even outside industrial production can occur, just because they are located close to each other.

New unexpected connections is closely related to innovation. As the focus of Heeres et al. (2004) is on EIP’s it is not strange that they involve proximity of industries.

The industrial symbiosis concept is that waste and by-products created by some enterprise during the production as well as various idle resources within the enterprise can be used by other enterprises in order to make more effective use of resources and reduce the discharge of waste.

B  The systems view of IS

IS can be described as a system, a set of elements undergoes a transformation (see figure [B6] for visual support) towards a next state. This is Ashby’s (1957) general concept of systems, what the elements represent and how the transformation occurs is to the field of IS to describe. In systems with a limited set of elements and a limited set of (closed) transitions the transformation is computable and thus predictable, those systems are sometimes revered to as simple systems (or deterministic machines). IS belongs to a different class of systems that encompass a great number of elements/agents/actors/entities/components or however you want to name it. More importantly those elements interact and adapt creating an endless amount of transitions possible for every transformation. This also creates an increasing amount of future states that is not computable, this is called the intractability of evolution (see for a more complete explanation Nikolic (2009, p.38)). Especially difficult is that in systems such as IS, it comprises not a mere technical or social system. But an interplay between socio-economic behaviour and the technical network (Dijkema & Basson 2009, p. 159). Furthermore the system is embedded within other larger systems and is itself context to smaller systems (Holling 2001), see also section [E] and [I.1]. Systems as described in this paragraph are called complex systems, or complex adaptive systems (CAS). This whole notion of CAS doesn’t mean that regional industrial systems (RIS) cannot be guided towards a state of IS, it just shows that the control in such systems is dispersed over many elements and transitions. The next transformation depends on the decisions of individual facilities, the (new) connections between facilities and the opportunity set. This process may cause path dependence of regional industrial systems and IS, the establishment of specific industries, infrastructure, environmental laws or even seemingly minor events can determine how the further evolution of a region takes place. To express this in the state-process way, the state of IS exists in many instances who have been developed over different IS processes. Similarities and differences are worthwhile to collect but need to be valued in context of both the state

29Holland (2006) is able to describe the essence of CAS in one phrase; Systems that involve many components that adapt or learn as they interact.

30RIS is proposed by Boons et al. (2011) as it is more flexible then geographic oriented terms like Eco-industrial park (EIP). This term will be used interchangeable with; industrial region, industrial cluster, industrial area and EIP
of the system and the process the system went through. In CAS and this thesis the idea is to develop a more holistic view of the world from the bottom up, this way preventing the classical macro-micro gap. System boundaries are artificial but are useful because they can give as task division for researchers to work on a topic. However sometimes researcher forget that by reducing a CAS into parts means that you probably lose some information about the system as a whole (Corning 2002), in the extreme case resulting in invalid conclusions about system behaviour.

C Multi disciplinary field

IS is part of the field of Industrial Ecology (IE) whose essence is the analogy between eco-systems and industrial systems. The analogy between nature and the human-world is not new. Humankind has taken nature as inspiration in many cases, parts of nature were translated into technologies for the benefit of society. The difference is that IE and IS do not take a part of nature as an example but they take over a general rule in nature; life is part of an integrated circular system on planet earth. This means nothing can be observed in isolation and linear production is ultimately dependant on natural cycles. The IE research community has various backgrounds as shown in figure 37 and therefore, in Allenby’s (2006) words, IE;

Unlike traditional disciplines or fields of study, integrates multiple, mutually exclusive ontologies.

So not only different field but also different conceptualizations of their respective domains. Those conceptualization sometimes overlap or leave gaps, more importantly they are not always in accordance with each other. So if rephrased there is currently not one scientific discipline that can fully conceptualize IS systems, multiple disciplines need to bring in their expertise to come to a system description. This is exactly how Mikulecky (2001) defines complex systems;

Complexity is the property of a real world system that is manifest in the inability of any one formalism being adequate to capture all its properties.

Although the coming together of scientific fields can be a great potential learning experience (Allenby 2006), different theories and models would be more valuable if it is clear how they connect in a broader ontology of a field (Moulaert & Sekia 2003), in this case the field of IS. Also practical contribution benefits from clarity whether researcher agree and disagree about concepts, theories and the comparability of models or cases. The danger of a diminishing returns on the effort to solve problems (Allen, Tainter & Hoekstra 1999), is what society is phasing. The key of these problems is the communication of individuals (about complex systems) for the collective learning of groups or society as a whole.

In this communication language is important, language here is a metaphor for the method of describing systems or fields. Allenby (2006) for one, doubts if the current methods or languages are correct and sufficient for describing IE. This is not surprising, as in the field of economics similar calls are made to address the languages of science. Dopfer, Foster & Potts (2004) points to the critiques on algebraicism and historicism, both of them cannot describe economics and this holds for all social sciences. Which leaves us all the more dependant on words but human language is multi-interpretable, people use words to frame concepts (de Bruijn & ten Heuvelhof 2008). A good rhetorician can be convincing even if is his/her arguments do not follow logic. Metaphors are also powerful but they do not necessarily have any meaning (Brands 2013).

D IS literature

IE and IS transcend different scientific disciplines. Scientific disciplines use different vocabularies. This makes a literature search based on keywords alone incomprehensive. The literature research is thus a

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31Disciplines, fields or formalism, they are all describing a bunch of knowledge. Where disciplines are arrived fields of study (physics, chemistry, biology, economics etc.), which at least have a core of accepted theory and well established common vocabulary, fields can be less well defined and be a part of a disciplines or overlapping between disciplines. Formalisms and domains are often associated with some ontology, the conceptualization of the domain or formalism.

32This due to the complicatedness, complexity and interconnectivity of problems of societies in regard to their resource base, see for elaboration (Allen et al. 1999)
Various scientific disciplines are needed to describe the complexity of industrial systems. ICT is added as a tool, so it does not bring content but helps to bring the different sciences together.

A combination of keyword search, tracing references and using different search terms to find literature about the same topic. The literature study resulted in a conceptual division (section 5), a conceptual division of the focus of IS researchers. Figure 38 shows how this conceptual division was obtained. Starting points were the articles of (Chertow 2000)(up) and (Boons et al. 2011)(down).

**E  Context of IS**

In the problem description (II) was described that systems are embedded and that a holistic perspective cannot easily be given from the background of one discipline. This is a pre-cursor for difficulties in theory building, as might be apparent from the previous sections. In this section the goal is to give a glimpse of the extendedness of systems in general and IS-systems specially. Giving an idea of the complexity of planning and creating IS within a RIS.

**E.1 Systems**

Holling (2001) is able to derive a highly aggregated model of all complex systems, natural, social and economic (see also section I.1 for the phases of the system). The model states that there is a hierarchy of systems, every system itself is also context to a smaller faster system or has a context which is a bigger slower system. As the climate and landscape determine which vegetation and furthermore which animals are present in an eco-system, this is similar for social systems. Figure 39 tries to explains this hierarchy of systems. In economics, institution is the term used when explaining that law, rules or norms and values shape the behaviour or decisions of entities lower in the hierarchy of systems. When explaining the four layered model (figure 39 right side) Koppenjan & Groenewegen (2005) state that in socio-technical systems (such as IS) there is a need for coordination due to large variety in actors, this is not actively telling actors what to do it is in the form of laws, rules or norms. Without any rules of the game the transaction costs will be high, then the rules of the game first have to be negotiated before you can actually start thinking about the transaction itself. On different layers of the model one often finds different entities/agents who coordinate the rule set; National government and European union around
layer three and Regional board or trade unions around layer two for instance. To relate this to IS-linkages a similar hierarchy based on time and scale is made for IS in figure 39(below). IS is for instance influenced by national policies and or specific subsidies form regional boards. A faster system is the routines that are in place in specific facilities, also the firm strategy could play a vital role, these strategies can be very different depending of the size and structure of the firm/organization, multinationals organization sometimes have a strict strategy without possibilities for regional opportunities. The comparison between IS to EIP’s in regard to time and space their is also visible. IS can already take place between two companies, EIP development is necessarily multiple companies. The time span of and the existence of contracts within an EIP as a whole is therefore necessary long. IS-linkages are however less specifically defined regarding time an space, the usage of excess heat for instance is very bound by distance and infrastructure, but some by-products can be exchanged by truck over long distances and therefore do not depend on long-therm fixed contracts. Figure 39(below) also shows around where evolutionary economics puts a divisions in scale, micro, meso and macro (Dopfer et al. 2004), industrial symbiosis falls exactly in the meso level as it comes fort out of the micro level decisions of facilities or individuals and their contracts. In turn the collective of synergy links generates macro level material and energy flows and defines together with normal facility exchanges the economic activity of regions and nations.

**E.2 Cultural dimensions**

Institutional context is hard to measure, in the previous section and [1] respectively the institutional layers of Koppenjan & Groenewegen (2005) and the notion of a panarchy of cycles (Holling 2001) are discussed. This shows that there is not just one institutional context but different layers of institutional context. Interesting is to go to one of the highest layers of institutional context, culture. When you have enough data you can even find patterns in culture, this is what Hofstede & Hofstede (2005) did, they formulated five dimensions which together give an indication of national cultures:

**Power distance (PDI)** The degree to which people accept that power is distributed unequally. High power index is often associated with hierarchic countries.
Figure 39: Above Institutional hierarchy of rule sets (Holling 2001). Below impression of context of IS in terms of systems hierarchy. Right side how Institutional economics shows that all layers of the hierarchy are connected and are influencing each other (Koppenjan & Groenewegen 2005).
Individualism (IDV) vs Collectivism  In individualistic societies everyone stands up for his own rights and there is a drive to achieve personal heights. Opposing to collective societies were the benefit of the group to which you belong is more important, this group serves as an extended family.

Uncertainty Avoidance Index (UAI)  Uncertainty avoidance is associated with incremental change and steady rules and regulations, leaving things to chance is something uncomfortable to countries with high UAI.

Masculinity (MAS) vs Femeninity  Where masculine cultures are more competitive and materialistic, feminine cultures are more interested in the relation and quality of life. Although there is correlation within individuals concerning gender no such implications can be made over nation wide aggregation.

Long therm orientation (LTO)  Persistence and the future play an important role in LTO cultures, but also getting reward as opposed to social obligation and absolute truth. Furthermore in low LTO cultures phenomena like returning the favour and direct reaction to harm are observed phenomena.

Comparing social behaviour and for instance environmental concern is note new (Dietz, Stern & Guagnano 1998), but to apply dimensions of cultures to IS is. To apply Hofstede & Hofstede (2005) you need to be able to make aggregations and thus large data sets, still it is interesting to make some comparisons with global status of IS projects. If masculinity, individualism and power distance are relatively high cooperation that has to grow from a trust basis might be difficult, an example is the USA. Heerres et al. (2004) finds that planning is the cause of why USA projects are less successful in regard to IS. But maybe government agencies where more or less forced to plan or influence EIP development as it did not arise from the collective of firms. Opposing in some sense is Denmark with low power distance and low masculinity scores, probably more oriented towards cooperation. There are some masculine countries that have highly developed sustainability programs, however often differently organized by a clear rule set and incentive system, Germany and Japan (Mathews & Tan 2011). The high uncertainty avoidance that those countries have can explain that. The long therm circular economy programme with an incentive system for clusters of industries fits with the observed Chinese culture of high LTO and collectivism. As already said, to make any scientific claims you need to have a large data set of industrial areas, data about government involvement and attempts to engage in IS, when plotted against success rate and cultural dimensions this might deliver some insights. Types of processes that can bring forth IS or EIP’s could be constructed, this falls out of the scope of this thesis. The IE wiki constructed by Davis et al. (2010) and colleagues could form the basis for such research.

F  Co-evolutionary modelling

To describe IS the research method ideally would conform to two general principles; it should be generic and leave room for describing differences and the method should be compatible with complexity thinking, as the system has the characteristics of a CAS. Recently Nikolic (2009) has provided us with guiding principles for co-evolutionary modelling of infrastructure, these principles are conform the complexity framework and IS fits within the description of the systems that can be modelled with these guidelines. An interpretation of these guidelines is given below:

1. Local optimization, evolution as the main mechanism of CAS does not search for 'the optimum' but for a good solution given the environment.

2. No termination criteria, there is no definite end state of research and modelling. This means we need to be open to new ideas and theories. And research methods and systems description need to open for changes.

3. Path dependency, recognizing path dependence within you own work and that from others helps finding mistakes and on the other hand improves through building on previous success.

IS is correlated with trusting each other supply chain linkages are not (Ashton & Bain 2012)
4. No sunk cost, connected to path dependence is: To accept that sometimes sunk time and money has been for nothing and switching to another route is better.

5. Modularity, if you can build in blocks, you can make a task divisions and draw on re-use, furthermore unexpected combinations of blocks can be made. Nikolic (2009) emphasizes that these block should be the agents and the interfaces.

6. Shared effort, not only are CAS often to big to encompass alone, also different perspectives can make the system or modelling effort more complete.

Collective modelling takes time, this thesis is not about the whole process, it is about the first design that will function as the basis on which collective theory building and further modelling could take place.

G Philosophy of science, Industrial Ecology and systems science

Science is modelling and simulation. Traditionally by observing what happens around you, fit this in a model, experiment and check if it performs similar to the natural world. These models are only valid in a certain space and within a certain time frame, this results in the system approach. Some models are valid in very large spaces and over very long times, some laws of physics are believed to be universal. Other models are only valid for a few decades and within a small part of the earth. This is especially true for anthropogenic systems, they are subject to static and dynamic complexity unlike Newtonian mechanisms (Allenby 2006). This brings us to the question whether or not any model of an anthropogenic system can be a representation of a part of the real world, due to notion of it being a CAS and thus evolutionary which makes it possible for small events to amplify into major influences, resulting in the model being only a snapshot. But also due to the more fundamental fact that coining something a (anthropogenic) system already builds on either of the following two philosophies of science; namely realism or constructivism (see for instance Klir (1991, Chapter 2.3)). Where either a system is a real world representation (realism) or a system is something we have constructed in our heads to represent the world (constructivism). Industrial Ecology (IE) uses nature as an analogy for industrial systems, from a modelling perspective this means you make two models. First you make a model of nature/ecology, the model you derive says something about nature/ecology, but insights gained might as well say something about industrial and/or anthropogenic systems (see as example Ashton (2009)), but you still need to model the industrial system too. IE is thus undoubtedly a constructive view on systems as it is based on an analogy or metaphor, as also explained by Boons & Roome (2008, p.51). Why would you do that? Why go through the effort of modelling two systems to explain one (see also figure 40), why not immediately model the industrial system? Besides the fact that we have more experience in studying eco-systems opposed to anthropogenic systems, the reason might be threefold:

Figure 40: At least two modeling steps are needed in industrial ecology.

34Note that constructivism is what in CAS terminology is called observer dependence.
**Time frame** Evolution in nature is much slower than evolution in the human world, technologies, norms, values and political regimes change over decades where eco-systems change only very slowly if not influenced by the external world. Which gives us plenty of time to built upon the static complexity in unravelling the dynamic complexity. Micro-organisms can form a fast evolving set, but they have low cognitive abilities and co-evolve together with other slower species.

**Experience** Nature has much more experience in evolution then we have and thus forms a large source of data.

**Data problems** Data collection is more difficult in anthropogenic systems, secrecy, privacy and other ethical constraints limit the possibility of scientific experiments. Furthermore the survival of elements in anthropogenic systems is more complex than in nature, so it is difficult to conclude anything based on pure observation in the present.

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**Box D: Analogy with crime investigation and the use of observations by individuals.**

IE and IS come fort out of an analogy with nature. Here another analogy is discussed. The analogy of doing a crime investigation. This is useful because in an crime investigation the type I and II errors are more seriously dealt with. And the process of 'falsification' (Popper 1957) is more strict. A crime investigation and the case study of IS in a region are not so different. Both require a reconstruction of what has happened and why, see also figure 41.

You start with the crime scene, you observe **what has happened.** This is comparable with observing the state of an IS-network, the physical evidence that is there. Another part is the social relations of the victim and any possible subject, do they know each other or is there another connection. Then there are the laws and circumstances, was it self-defence or an accident, is the crime even considered a crime according to the law. The institutional context goes over in the investigation of the history of the offender, did the offender commit any previous crimes, did he/she have a difficult life. This is similar to tracing the history of industrial activity, **how.** Possibly the crime is explainable through a sequence of small events in recent history.

A shortcut is the use of surveys/witnesses

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In all sciences there is some gap between reality and the human construct of that reality. This might be the most difficult when dealing with science of the human mind and social behaviour. When trying to explain the reality we come up with evolving explanations for a certain phenomena according to Verhaeghe (2011) a Flemish clinical psychiatrist and professor in the psychology

Wetenschappelijk gezien is dit het probleem van de validiteit: een concept valt nooit samen met de realiteit die het verondersteld wordt aan te duiden. De realiteit blijft onveranderd, de betekenners evolueren.

So there is always some gap between the conceptualization and the reality. Having said that, below a table of different perspectives in modelling the real world. Some are not really perspectives but methods.
Some of the dualities are exclusive, other can be used simultaneously (so they are not really dualities). Modelling complex systems cannot be decoupled from the world-views or values of the people involved.

<table>
<thead>
<tr>
<th>1</th>
<th>2</th>
<th>exclusive</th>
<th>chapter</th>
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<tbody>
<tr>
<td>Objective</td>
<td>Normative/Subjective</td>
<td>no</td>
<td>8</td>
</tr>
<tr>
<td>Quantitative</td>
<td>Qualitative</td>
<td>no</td>
<td>15.2.1</td>
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<tr>
<td>Explicit</td>
<td>Tacit</td>
<td>yes</td>
<td>??</td>
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<tr>
<td>Physical description</td>
<td>Functional description</td>
<td>no</td>
<td>4.1</td>
</tr>
<tr>
<td>Exact science</td>
<td>socio-economic science</td>
<td>no</td>
<td>everywhere</td>
</tr>
<tr>
<td>Realism</td>
<td>Constructivism</td>
<td>no</td>
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<tr>
<td>Reductionistic</td>
<td>Holistic</td>
<td>yes</td>
<td>??</td>
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<tr>
<td>Inductive</td>
<td>Deductive</td>
<td>no</td>
<td>case studies are inductive</td>
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<tr>
<td>Deterministic</td>
<td>Indeterministic</td>
<td>yes</td>
<td>III</td>
</tr>
<tr>
<td>Discrete (states)</td>
<td>Continuous (flows)</td>
<td>no</td>
<td>not really in this thesis</td>
</tr>
<tr>
<td>Algorithmic</td>
<td>Differential equations</td>
<td>no</td>
<td>similar to above</td>
</tr>
<tr>
<td>Bottom up</td>
<td>top down</td>
<td>no</td>
<td></td>
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<tr>
<td>Describing specific cases</td>
<td>Describing aggregations</td>
<td>no</td>
<td>ontologies do both</td>
</tr>
</tbody>
</table>

Table 27: Dualities when describing things. The real world is described by many, when describing this real world various approaches can be taken. This table gives some of them in dualities, of which some are exclusive (only one of both approaches can be taken) and others could be complementary to each other. The chapters where those dualities are coming back are given as well. The dualities are also largely overlapping but I cannot fit them all in two, three or four paradigms.

(de Vries & Petersen 2009), this results in the problem that hard science cannot suffice. Describing IS actually faces similar problems as other sustainable sciences and the struggle of formalizing or describing IS is thus illustrative for many sub-fields.

G.1 A functional or physical description of the world

In the study of complex systems there is the need to describe an object in terms of its physical parts and its functions. Otherwise it is not possible to explain the system behaviour resulting from the interactions of objects. This section explains why.

Aristotle, in the early days of philosophy, formulated that there are four causes for the existence of things. Considering these four causes, the material, formal, efficient and final cause, results in a more complete description of reality. In the modern science of complex systems this distinction is important to consider as well (Mikulecky 2001).

Material cause The matter from which the thing or object is made. Dependant on the level of observation, the facility is made of concrete and steal, it has a certain shape and location.

Formal cause For designed or built things it is the plan that stated how the materials are placed. For complex systems this is difficult to determine, as there is not always one plan, objects are shaped in reaction to each other, this is revered to as the evolution of systems.

Efficient cause This is how the object came into existence or changed to its current form. This cause, most closely, resembles the meaning of the modern word ‘causality’. For the facility this is the set of workers in combination with the materials that built the facility on its current place. The laws of physics and mechanics are the efficient cause of changes in many things. In complex systems it is challenging to find the efficient cause, the efficient and formal cause are interwoven in the evolution of the system, it is often uncertain which physical changes and social interactions in a time step determine what happens in the next. Process analysis is used to unravel this, see section III.

Final cause Is the why question, the function of the object. Final cause is not absolute, people perceive different final causes for an object. The remainder of this section focusses on explaining this.

Especially the distinction between final cause (function) and material cause means that there are also different ways of classifying, that there exist ontologies that are partially overlapping. Chertow’s (2000) definition of IS contains a sentence which is an typical example of overlapping ontologies:
Industrial symbiosis engages... involving physical exchange of materials, energy, water, and/or by-products...

The sentence is a summation of concepts from two different ontologies, the concept by-product belongs to an ontology based on final cause and the other concepts belong to an ontology based on material cause, see figure 42. Water is a sub class of material, summing up water and material in one sentence is thus redundant. Mentioning by-products is strange as well, water (as mixture) can be considered as product, by-product or waste, depending on the type and amount of other materials it contains. It is illustrative for the conceptual challenges IS faces. IS exists due to the fact that one company perceives a function(final cause) for a material that another doesn’t. Expressing IS in terms of functional labels only, decreases further opportunity identification for IS. Describing IS based purely in material causes makes distinction between IS and regular supply chains linkages impossible.

In the exact sciences ontologies based on material cause are dominating, in economics and social science ontologies based on final cause are prevailing. Even in exact sciences unconsciously the final cause or functions we have in mind determines what material causes we observe in an object, it determines the focus. In CAS theory they call this observer dependence. Mikulecky (2001) uses the final cause to explain the difference between complex and simple systems.

All simple systems have their function defined in terms of their material parts and thus the suppression of function as a consideration presents no problem.

The distinction is that this is possible or acceptable for some systems. In those systems the causality (the efficient cause) is deterministic, every change is exactly and fully explainable by the change in a limited amount of other objects (a closed transformation (Ashby 1957)). Machines and computers, although sometimes fairly complicated, are such systems (Mikulecky 2001), there functions are clearly definable.

The concept energy (see figure 42) can illustrate Mikulecky’s (2001) point. Energy exists in different forms but due to the phenomenon entropy, there is a material cause that determines the quality or usability of the energy (work or heat of different qualities, exergy). Although it is thus (explicitly) possible to calculate how much work can be done by an amount of energy, the actual functionality within the larger system of society is dependent on some other circumstances. For instance, the available technology and scarcity of energy in an area determines if people consider low temperature heat as useful product. Due to the fact that fossil fuels are becoming scarcer, technologies to use low temperature differences are being developed which were previously not deemed feasible. There are different knowledge types, tacit...
and explicit, were introduced. Relative to functional ontologies, ontologies based on material cause are easier to make explicit, functions are not absolute. The energy example showed that functions are also varying based on place and time, functions evolve.

H The State description

IS cannot yet be systematically engineered. Many literature takes on the case study approach to find clues about how to bring about IS. However, among those studies there is conceptual ambiguity in describing the IS development. Therefore, this part tries to find an answer on the question: What is IS? and more concretely, what do we need to represent about IS to bring about a good description? A description that is useful in developing theories about IS, which can then bring practical implementation of IS one step closer, as explained in section ??.

- Static description
  - The main agents of IS
    - Physical description (the facility)
    - Functional description (the company)
  - The relation that we call IS
    - Physical description (material and energy exchange)
    - Functional description (the transaction)
  - IS is thus a network
- Dynamic description
  - Phases model
  - Process analysis

Figure 43: Structure of this chapter

Although IS is a dynamic development process, the given description is often a snapshot. This is not strange as detailed data for the whole development of IS in a RIS is often not available. There can be several causes for that, for instance, IS was 'uncovered' (Chertow 2007) in a late stadium or any cause grounded in the scope of the research (time scope and level of detail). This part first describes IS as a snapshot (section H), subdivided in the agents and relations. In any definition (appendix A) IS is a relation between some set of agents. How this relation and/or agents are typified is subject to debate. Both subsection, agents (H.2) and relations (H.1) are divided into a physical and functional description. The difference between the physical and functional description was introduced in section G.1 but also comes from Dijkema & Basson’s (2009) framework for analysing complex systems. The physical exchange of materials, energy and data connected to the socio-economic transaction. Dijkema & Basson (2009) argue that research should go past the analysis of the technical network. The dynamic layered aspect of IS is discussed in section I. This corresponds to a description of the Institutional and Organizational change, from a description in phases (I.1) to more detail in process analysis (I.2).

H.1 The relation we call IS

A snapshot analysis takes one moment in time and observes everything deemed important (for IS). One benefit is that in this way, it is possible to exclude causality. It is possible to create a description that is relatively objective. In complex systems the influence of element on each other is typified by multiple causation and indeterminism, which means that a static description makes classification of concepts and ontology construction easier. The static analyses thus has its limitations in explanatory power. This is discussed in this section as well.

All definitions of IS describe IS as some sort of relation between one or multiple agents, see appendix A. The differentiation between a physical and functional description of IS was given as a tool to prevent conceptual ambiguity, see section G.1. This resembles the differentiation between the technical and social network in the framework of Dijkema & Basson (2009).
H.1.1 Physical Description - Material and Energy Exchange

Energy and material exchange is the physically observable relation we call IS. The assumption is, that a good description of IS will in the end contribute to more practical implementation of IS, as explained in the intro fo part II. This means that a detailed description of the exchanged materials, chemical composition and properties, is important. Detailed knowledge of material and energy exchange makes opportunity identification easier. It is therefore that Grant et al. (2010) calls for a collaboratively established resource classification. For materials the prime classification criteria should be based on material cause (section G.1 and appendix ??), functional labels can be assigned afterwards. Listing information about required pre- or after treatment steps, as done by (van Berkel, Fujita, Hashimoto & Fujii 2009). Gives a completer understanding of the system of exchange. In the case of a heat or water cascading project, information about the temperature difference or type of contamination of the water is essential for the feasibility of the project, in section H.2 this is further discussed based on the input and output of facilities.

Another aspect of the IS-relation is the method of transport or infrastructure used. The absence or availability of infrastructure is often described as a barrier or inhibitor of IS (Mirata 2004, Tudor et al. 2007). Information about infrastructure use and/or the transportation method is also interesting regarding the spatial scale of IS. In the beginning of IS-research, geographic proximity was assumed to be a key parameter for IS (Chertow 2000). Since then research has shown that the spatial scale is only one of many parameters to consider (Jensen, Basson, Hellawel, Bailey & Leach 2011, van Beers et al. 2007). Still, listing the distance of exchanged materials, combined with other aspects of the IS-relation is informative, classifying and benchmarking special sub-types of IS could be an option.

The physical relation is always describable as a bilateral connection, even if it involves a large water or heat cascading project. The transferred substances goes from one point to another, after usage it can go to another point but this is again a bilateral connection. For the transaction (the functional description of the relation) this is different. The required investment in infrastructure or equipment is sometimes only feasible if multiple agents are involved. Considering the quantity of transferred materials brings forward the question: How much material is spared through the IS-relation? Material which would otherwise be deposited in the external environment. In literature this falls under the assessment of IS, often under the label of environmental benefits. Landfill avoided, raw resource reduction ore substitution are some terms used in regard to less material usage (Yu et al. 2014, van Berkel et al. 2009, Jacobsen 2006). Assessing pollution prevention and material savings against other alternative scenarios already complicates the physical description of IS. Pollution is a functional label so is waste (Dijkema, Reuter & Verhoef 2000). Waste only exist within a time and spatial frame, until human interpretation or legislation changes (Jensen, Basson & Leach 2011). This influences the scope of the assessment. Another problem is, that IS and cleaner production can be conflicting (Shi et al. 2010). If facilities minimise unwanted outputs, there are less opportunities for IS. Economics of scale in treatment or recycling of materials also plays a role and offers loop closing opportunities on other spatial scales (Lyons 2007). One can see the role of economics in assessing the value and functionality of the IS relation, which brings us to the next section.

H.1.2 Functional Description - the transaction

To understand the IS-relation it is necessary to understand how we value certain things. This is done by using the concept of 'value added' (Porter & Millar 1985). Not only is this concept used in macro economic evaluation by governments, it has also found its way to the IS literature. Value added is used to assesses the Circular Economy Program of China (Geng et al. 2008). It is the basis from which competitive advantage arises and it connects to transaction cost as well. It is coupled to 'the value-chain' concept, which is used in IS literature as well (Mathews & Tan 2011). The value chain within facilities is discussed in section H.2.

IS-Value for the facility

Any activity either brings benefits or incurs costs, traditionally costs through using labour or capital

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35Transportation cost will eventually limit the travelled distance of exchanged material (Chertow, Ashton & Espinosa 2008). Which means that a high valued material can travel further. This assumption seems to date back to deductive reasoning of Krugman (1991) and even Marshall (1890). Where the statement itself may be true, the practical usefulness is limited as argued by Jensen, Basson, Hellawel, Bailey & Leach (2011).

36Section L.1 used value in relation to properties and objects. Beware, the context is this part is very different.

37Competitive advantage is the result of successful IS (Chertow 2000)
and benefits through sales. The difference between benefits and costs is the added value of the activity as a whole. This net benefit can be distributed over the people performing labour or the owners of the capital. In regular manufacturing value-chains, the value is created during the manufacturing process and translated to monetary value through sales. In IS-value chains this is somewhat different, Jacobsen (2006) has found that for the Kalundborg district the value of IS lies in reduced cost for upstream or downstream processing of waste materials. This can be seen as reduced operation cost, IS is further subject to cost of investment and transportation cost like any other business deal. The theory of transaction cost (Williamson 1998) points to costs that were previously unaccounted for, search and information cost, bargaining cost and enforcement cost. After discussing the internal value chain of facilities (H.2), transaction cost are coupled to the development IS (H.3).

IS-Value for society
Value added is often given in a monetary unit, especially in the corporate world money is the single most dominant form of valuation. Even corporate responsibility programs lead back to monetary benefits in the form of reputation or publicity. Although every IS transaction should at least be profitable for one of the facilities involved (Mathews & Tan 2011), there is value for society in IS as well. Societal and environmental benefits, that cannot be directly measured in monetary value, are in economics known as externalities (external costs and benefits). There is no market price for these costs or benefits, unless a government body installs a tax or subsidy. It means that assessing those is a highly subjective task.

Part of the IS research is focussed on creating a framework or standard method for a holistic assessment of IS (Sidiropoulos et al. 2010, Kurup 2007). Sections ?? and ?? deal with incorporating an assessment scheme onto Enipedia.

Value as differentiation between IS and regular supply chains
Added value also plays a central role in the Porter & Millar’s (1985) theory of competitive advantage. Adding value usually results in a product with a higher value. The value of the product in relation to other products in the market determines the competitive advantage of the facility. In IS the exchanged products are not your average main product. They are often described as by-products, waste or utilities (van Berkel et al. 2009) and are thus subject to a different valuation scheme.

Product The main product, the business is initially set up to produce this product. There is a clear market demand for this product.

Utilities Are products (or services) that are required for such a large range of industries and in such quantities. That provision is organized centrally (sometimes publicly). Another reason for central organization is the required investment in infrastructure. Typical examples of utilities are water and energy.

By-products In a production process there is seldom only one output, the output that is not considered the main product is called the by-product. However there exists a reasonable assumption (based on the materials properties, for instance) that there is value in this (by-)product as well. More explanation is given in the next paragraph in regard to figure 44.

Waste Is an output that has little to no direct value any more. For the facility itself waste has a negative value as they need to get rid of it somehow, specialized treatment can transform waste into valued materials.

It raises the question if competitive advantage of IS, as mentioned by Chertow (2000), is evaluated as cost reduction for the main product or as added value in an on itself standing transaction. The differentiation on value reveals the economic difference between IS and regular supply chain linkages. It is the perceived value of the product. This perception is dependant on time, place and the people involved. There is thus no objective time invariant differentiation possible. There is no material cause

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38 Either there is less cost for pre-treatment of inputs or less cost for treatment or disposal of waste, also found by Kurup (2007)
39 Dr. Ir. R. Stikkelman said to me that companies have three reasons for engaging in business: 1. Money 2. Money and 3. Money.
40 Either through cost leadership or product differentiation, see appendix ??
41 This is already under the assumption that the competitive advantage is on the level of the facility, also leaving out the creation of dependencies between facilities. Dependencies can reduce competitive advantage.
42 EU legislation does not look at the material cause at all, even value does not play a role. There definition of waste is solely based on the word ‘discard’, were the good is going (combination of efficient and final cause) (unknown 2012).
for differentiation. This is illustrated by figure 44. Facilities that produce bulk chemicals often produce a range of (main-)products. In other industries production process are interwoven. This means that it is not possible any more to define what their original main/by-products was/is, see box D.

![Diagram](image.png)

**Box D: The product chain of PVC and NaOH**

The exchange of chlorine between the NaOH product chain and the PVC product chain is not considered IS. Why not? The exchange takes place for already some time and the industries are not considered traditional separate any more. Chlorine is a this moment a commercial product, this synergy became so successful that the PVC production is now arguably the driving force behind the chloralkali process. It shows the time dependence of what is considered IS and what not, it also shows that the industry does not consist of linear product chains. Some products are used in many processes, take for instance water and electricity used in the chloralkali-process, the industry that provides such products is called the utility industry. Are they considered traditionally separate?

The type of industries or agents involved is another reason for separating IS from other business relations.

### H.2 The main agents in IS

#### H.2.1 Functional description - Firm/Company/Organization/Individual

**Different industries**

IS involves 'traditional separate industries' (Chertow 2000), what Chertow tries to say is that the facilities involved in an IS-link should be of two different supply/value chains. In the previous section it was shown that this differentiation is only possible when the world consist of only linear value/supply chains. However, to list the industrial character of facilities gives a first impression of the available knowledge in the organization and the product network they are part of. Keeping track of industrial character is therefore the basis for any IS research. Researchers often use an industrial sector classification, the IE-wiki uses the Industry Sector overview of the European Union[43] and the north American Industry Classification System[44] and many others use their own schema for classifications of industries[45]. An industrial sector classification is orthogonal to differentiation between industries based on their respective supply chain[46], see figure 45.

**Different organizational boundaries**

In today's global economy, where multi-national play an important role, supply chains can be organized on a global, national or regional scale. They can be organized within one organization, two or multiple. Figure 45 shows that when an organization operates in multiple supply chains (horizontally), they call

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[45]for instance, Shi et al. (2010) divide TEDA into four industrial Pillars
[46]The previous section (figure 44) discussed that assuming product chains are linear is a simplified view.
this economics of scope. Vertical integration is if an organization operates in multiple steps of a supply chain. This creates challenges in the description of IS, it means that a (physical) mass flow may in one case be described as IS and the exact same mass flow may in an other case not be labelled IS, because the mass flow is within the boundaries of one organization. This differentiation only makes sense if you consider the economic/organizational reason for differentiation. The same mass flow may be more difficult to establish between different organizations than within an organization. The cost of establishing a (IS-)relation with another organization (external transaction cost) might be higher then when the same option would be available within the boundaries of one organization (internal transaction cost). This is sometimes a reason for organizations to engage in economics of scope or vertical integration. Why would the internal transaction cost be lower then the external? Because within an organization there is perceivably more trust and thus no need for (lengthy) contract negotiations, besides information flows are already established. This brings us to trust and the social aspect of IS.

**The social agent**

Like any other inter-firm relation, IS is confirmed by a contract. A contract holds formal accountability. The organization can be hold responsible and is thus a clearly defined agent. But the closing of a contract is preceded by informal and formal communication. This information exchange and possibly the building of trust, is not between organizations as a whole but between individuals within the different organizations. This makes the description or analysis of the information exchange or building of trust difficult. Is there communication or analysis of the information exchange or building of trust difficult. Is there communication between managers of facilities? How is this discussed within their own organizations? Is there next to managerial communication also inter-firm communication between other individuals (engineers or other specialists, for instance)? Trust is difficult to make explicit. It is a topic that is described by all of business literature. Some of the described components of trust are reliability, competence, goodwill(openness/benevolence), vulnerability and loyalty (Handfield & Bechtel 2004). Where concepts such as 'reliability' and 'competence' are not specifically interesting for IS, openness is a specific topic in IS. Ashton (2008) researches trust and openness (there are several interpretation of openness) by making use of the framework of social embeddedness. Ashton & Bain (2012) finds trust between managers of firms to be correlated with IS, but unable to repeat the study due to the cultural dimension of trust. The validity of studies in regard to social structures is dependant on interviewing the right person within an organization, as also acknowledge by Ashton & Bain (2012). The point to take from this paragraph, is that the individuals and their role within the organizational structure are influencing the establishment of IS.
Economic motivations prevail

The influence of social interactions of individuals is, however, of less importance than the economic feasibility. Ashton & Bain (2012) finds “cost” and “legal liability” as far more important drivers for the decision making process than “personal reference”. This corresponds to the general assumption within IS that every synergy should at least be profitable in some way. Confined by statements in literature:

- IS “as an independent business deal and established only if it was expected to be economically beneficial” (Ehrenfeld & Gertler 1997).
- IS as a business transaction for “improving the profit position of at least one firm without damaging the profit position of the others” (Mathews & Tan 2011).

Where the economic profit for an agent lies is another question. Previously H.1 was discussed that, unlike 'normal' business transactions, IS does not necessarily bring profit through the sales of a (by-) product. Indirect cost and benefits play an important role. The value chain of a facility can explain this partly, see figure 46. Reduced cost in upstream or downstream processing (Jacobsen 2006) could be placed under core activities, like inbound or outbound logistics or operations. The avoidance of landfill tax through IS, could reduce the cost of the activity: ‘end of primary use’. Searching cost or cost of information can be assigned to ‘procurement’ or ‘supply chain management’. Social capital should add value in any activity but the social capital, that perceivably creates embeddedness (Ashton & Bain 2012), concerns ‘external networks’. Figure 46 is a modification on the traditional value chain. It

![Figure 46: The added-value chain extended with some activities (McPhee & Wheeler 2006), originally from Porter & Millar (1985).](image)

is chosen specifically because it includes new activities such as: 'external networks', 'end of primary use' and 'supply chain management'. Those activities illustrate that businesses are starting to think outside their firm boundaries. The Institutional and organizational change (as discussed in section ??) that is required for IS. In section H.3 the value chain is analyzed in combination to transaction cost in regard to multiple relations between agents.

**Other agents**

So far the agents that exchange goods have been discussed. But their are also agents that have a supporting task. Literature talks about coordinating entities: Government agencies, NGO (Mirata 2004), network clubs, anchor tenants (Lowe 1997) or any combination. They are the formal entities of institutions (Koppenjan & Groenewegen 2005). Those entities gain importance when the IS-network matures and becomes more complex, see section L.1. There generic function is to care for resources, enclosure of common goods and (limited) disclosure of club goods. In other words: pollution prevention and the sharing of assets and information. Facilities are successful in finding win-win synergies (Baas & Boons 2004). When the benefits lie increasingly farther in the future or are not directly expressible in monetary value, the facilities tend to be less capable in establishing a synergy link without third party intervention.

The restrictive part of a coordinating body is usually a specialized extension of the governmental structure and can thus be described as a set of rules. The stimulating part of coordination can have
many forms. Planning, facilitating, guiding or coordinating, although seemingly similar, their intensity of involvement varies. These modes of interaction influences the information exchange (Grant et al. 2010). It creates the need to describe, next to the IS-relation (between two facilities), also a facility-coordinator relation. This relation could fall under ‘the external network’ activity (figure 46), when an individual or task is assigned to this relation, it means an advanced state of IS-development.

The next section explains that the functional agent does not always correspond to the physical agent.

H.2.2 Material description - Facility

In the analysis of IS, it is challenging to define one clear (functional) agent, as described in the previous section. From a physical perspective, the agent is the entity that either (or both) supplies (and) or receives materials or energy. This always happens in a physical place. In this thesis this physical place is named ‘facility’.

Defining an agent

In the realm of business administration organizations are definable. They have an explicit subscription for the chamber of commerce, this gives them certain rights and obligations. In an economic transaction a contact is drawn up that makes this entity formally accountable. There are ownership constructions that make this more complex. Subsidiaries are often controlled by their owners but are different entities regarding taxation and liability. Where for the consumers the brand name is important, this does not tell you anything about ownership and/or liability. All these different administrative definitions of an agent, make the defining of one conceptual agent for IS challenging. Even more so, because IS has a focus on the physical exchange of materials and energy. This makes the physical agent not always the same as the legal agent. Challenges in defining an agent are not unique to IS. Similar conceptual challenges are observed in aligning land ownership and decisional power in an agent (Janssen 2005). Figure 47 shows that an organization may operate multiple facilities, those facilities can in turn have multiple physical (production) processes going on. Then there are the individuals with their (internal/external) tasks and connections, social relation (explained in previous section). The structure of the organization influences the definition of IS (and the establishment of IS, appendix ??). For example, a material exchange between

![Figure 47: Layers of an agent. The facility represents the physical infrastructure. Then there is the process the physical transformation of the product. The formal organization is bound by contracts and laws and involved in the financial transaction, whereas the informal organization consisting of individuals and groups of individuals are involved in the information exchange.](image)

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Some production and transport activities require permits or registration. So then the physical agent also follows the agent as an entity defined by law.
showed that IS does not have one clear conceptual agent. For the description of IS the question remains, if it is possible to create one agent. An agent that integrates the different views. Possibly defining an agent means asserting a focus.

**Material properties**

This paragraph focusses on the attributes the facility, physical agent, may have. IS is about the exchange of material and energy (section H.1). This sets the requirement to collect the inputs and outputs (I-O) of a facility, inputs and outputs of different facilities can then connect to form IS. This seems straight forward, but an input or an output is not just a (ambiguously) named good. It requires a whole description in itself, appendix ?? goes into the classification of substances. The I-O’s result from processes going on in the facility (see figure 47), chemical processes or some form of assembly process. This requires certain machineries, assets. Both the process and the machinery used are sources of information for the establishment of IS. However, this can also be strategic information, information that brings competitive advantage and is thus not always available for research by an outsider. Descriptive IS-literature therefore does seldom include details about the exact process or composition of the materials, or in the case of wast materials it may not be known exactly by the facility itself. Limitations to information are shortly discussed in section ??, Not only the composition but also the quantity of material is important, it influences transport and the achievement of economics of scale. A mismatch in quantity or a fluctuating supply/demand may be a deal breaker or induce the need for storage (time component?). Fluctuations in supply/demand may also be the reason behind IS, collective storage or the use of an other facilities overcapacity are possibilities. These logistic issues are also influenced by the geographic positioning of the facilities in the region, another physical property.

The boundaries of an organization may be difficult to pinpoint, but the exchange of materials and energy takes place between physical entities, facilities. This is the basis for the description of an IS-network in this thesis. The next section summarises how agents and relations together form a network, and how the physical and functional description are related.

**H.3 Thus IS is a network**

Industrial Symbiosis (IS) in a RIS is often summarized in literature by a flow diagram or network of material exchanges. The previous sections dug into the two most important components of such networks, the agents and the relations. The physical description of IS can be in the form of material or energy exchange between two facilities, however, this bilateral relation may be part of a larger network and coupled to other bilateral relations in the economic transaction. Next to the physical network and the economic transaction, there may be a network of social relation. Unlike figure 48 suggests, those social relation are not necessarily parallel to the economic transaction or the physical network. Even within the physical network there is a difference between the network (infrastructure) and the exchange taking place, the difference between the capacity of the network and the actual mass flows. Section ?? introduced IS as a two step development process, (Physical) Synergy design and Institutional and Organizational change. The synergy design is what results in infrastructure and physical flows. The organizational structure within and between companies enables the synergy design step. This is where the information exchange plays a central role. Shaped by the (macro) institutional context. The connecting layer is the economic transaction, explanation follows in the next paragraph.

The different layers presented in figure 48 are all interacting. Consider the six interactions between layers in an examples about a CHP project:

**Infrastructure-Mass flow** (1) Considering a (cooling) water (forth from A to B) and heated water (back from B to A) synergy link (figure 49). The capacity of the pipelines may be enough to supply both there needs but the supply and demand do not match within the time schedule. This would require storage (connects to 2) or logistic adaptation to each others needs (connects to 5).

**Infrastructure-Transaction** (2) The pipelines may be part of a larger network with multiple users, what is the investment distribution and who takes care of the maintenance? Same holds for the to be build storage (buffer), will the facilities reduce uncertainties in investment (3) through a long

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48 The social relation is also the layer that is already active before the establishment of a synergy link. The social relation may actually itself exist of multiple layers.

49 The example is not based on the actual real world synergy link in the figure.

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therm contract or let a market mechanism, with peak demand prices (4), provide the necessary return on investments.

**Infrastructure-Social relation** (3) Perceivably social relations can alleviate the high bargaining costs (6) associated with (asset specific) infrastructure investments. The manager of facility A has good contact with the manager of facility B and the board of directors, which makes the decision making process less heavy. Both parties also trust each other in regard to safety measures.

**Mass flow-Transaction** (4) The amount of available water or steam in time determines the value (peak load as mentioned) but the composition is another aspect which influences the value. These are all things that need to be fixed in a contract, but the information about the composition (5) is required before the contract negotiation as it may influence the feasibility of the synergy link.

**Mass flow-Social relation** (5) Certain contaminations in the water can damage the CHP plant (connects to 1 and 3). The manager of facility A tells the manager of facility B that there may be contaminations in the water now and then because a certain step in the processing of the water is not hundred percent. This is only because they trust each other, it gives the possibility to search for the solution together. This connection is also important when dealing with unexpected circumstances in, for instance, supply or demand problems. Contact can also reduce the initial searching cost, possibly the CHP plan originates from an informal talk between individuals of both facilities.

**Transaction-Social relation** (6) The first time facilities engage in a transaction, there is often uncertainty about the exact intentions of the other party. This creates higher bargaining cost. Contact can reduce distrust and thereby the bargaining cost. The reputation of a facility as trustworthy business partner may be worth more than the income from an opportunistic trade.

In principle any activity has a value. For the delivery of a product by a facility this is summarized in the value chain (section H.1). For IS this is the same, only the value of the activities may be small compared to values of the main product chain. The idea that the transaction layer summarises all added
value of activities of the other layers. However, this should only be the value that is specifically added through the IS-link. Considering the CHP example, the investment in the pipeline, maintenance and operation cost, income through spared resources (energy), tax avoidance (ground water tax), overhead and other transaction costs. Searching cost and bargaining cost are explicitly mentioned in the example, as IS is typically a transactions that is influenced by those costs. Because IS often comprises non-standardized goods (and transaction), this creates uncertainty about the market price and availability. Which is exactly the reason for the existence of transaction costs. Consider, for instance the statement of Dahlman (1979) about searching cost.

Both search and information costs owe their existence to imperfect information about the existence and location of trading opportunities or about the quality or other characteristics of items available for trade (Dahlman 1979).

The understanding of IS as a layered relation gives conceptual clarity for the description of IS. Although figure 48 may give the indication that the layers are parallel, this is not the case. Especially the concrete physical IS-relation needs to be separately described from the social relation. There agent boundaries are very different (figure 17) and information exchange takes place before and after concrete establishment of a synergy. Next to the establishment of the synergy link, the social relations and exchange of information may have an influence on other processes as well. How does this take place? The effect of the exchange of information and the social relations on the establishment of IS-networks requires a dynamic perspective.

I The Dynamic description

Evolution is the central paradigm in describing complex systems. In evolution there is no central plan (formal cause), only local adaptation, this means that the how question (efficient cause) can only be found in regard to a specific situation. The algorithmic character of evolution (Nikolić 2009) makes it hard to create generic rules for explaining the dynamics of evolution, however, it does leave room for finding patterns. To trace back evolution the development of IS is discretized into states. First in bigger time steps (phases I.1) and later in smaller events (process analysis I.2).

I.1 Phases of IS

In this section two phase models are discussed, each of them has three phases:

1. ‘Sprouting, Uncovering and Embeddedness-Institutionalization’ (Chertow & Ehrenfeld 2012).
2. ‘Regional efficiency, regional learning and sustainable district’ (Baas & Boons 2004).

In the sprout phase resources exchange takes place due to various reasons but cost benefit ratio should be positive, typified by low transaction cost projects that come and go identified by a middle management mostly. Once the positive externalities are identified and a more structural pursuit (together with a public body/coordinator) of similar synergy links takes place. This is described by Chertow & Ehrenfeld (2012) as the uncovering phase, usually possible benefits also become more widely known. The ‘embeddedness and institutionalization’ phase is where a collaborative environment is created that allows even more complex synergies to be considered, also the clusters as a whole tries to turn IS into a positive image. Chertow & Ehrenfeld (2012) are able to derive this model due to their personal experience in IS, next to presenting the phase model they promote the use of CAS theory in IS research. This comes back in their model as the amplifying effect of small successive events in the sprouting phase.

A gap they leave is in how the development of IS relates to overall development of the industrial regions, as IS is often only one of the developments especially in larger industrial regions. A quite similar phase model of Baas & Boons (2004) also researches how three different phases (regional efficiency, regional learning and sustainable district in this case) are possible to insert in the life stage of an industrial region. In a matured industrial region small win-win projects with environmental benefits are often difficult to find, on the other hand a industrial region that is in an early phase of its development has not yet the network to deal with collective long term environmental projects. The practical findings see also Domenech and Davies in (Ashton & Bain 2012), treat information and material flows as separate.
of Baas & Boons (2004) in the Port of Rotterdam also point to some differences with the theory of cluster developments from Porter (2000), the regional demand and image are not really of any significant influence. Does this mean that PoR is a global oriented industrial system or is this an often encountered observation in RIS.

Adaptive cycles

Although both (Baas & Boons 2004, Chertow & Ehrenfeld 2012) draw on the analogy with ecology they do not assess a possible cyclic being of industrial regions. To assess any cyclic behaviour the even broader perspective of Holling’s (2001) adaptive cycles is re-introduced. Opposed to (some) economic theories, ecology does not know never ending growth. Therefore the model of Holling also analyses the decline of socio-economic systems. Ecosystems are analysed based on three properties; potential, connectedness and resilience. Those three together determine in which functional phase the system is, see figure 50. Another concept herein is that there is a panarchy of cycles, every system can influence or can be influenced by smaller faster or larger slower adaptive cycles. The phase between exploitation and conservation is typified by increased connectedness and network formation together with more accumulation of resource within the boundaries of the system.

Figure 50: Hollings adaptive cycle, re-organization (α) followed by exploitation (r) then conservation (K) and release (Ω) (Holling 2001). The remember feedback can teach a smaller system an interesting organizational lesson, the revolt is where a smaller cycle can let a faster cycle go into the release phase for instance. From exploitation to conservation is typified by increased connectedness and network formation together with more accumulation of resource within the boundaries of the system.

and conservation is typified by increased connectedness a slight decrease in resilience due to the larger connectedness and decreased diversity but an increase in accumulation of potential in the systems. A parallel could be made with maturing of industrial regions, a larger amount of small businesses slowly develops, possibly due to synergistic linkages, into a productive industrial area with a dominance of a smaller amount of key businesses. This largely similar to the model of Baas & Boons (2004), both formulate the possibility of creating rigidities as a threat.

Ashton (2009) uses the model of Holling to analyse the development/degeneration of an industrial region in Puerto Rico also known because of their IS-activity. By drawing on surveys and previous knowledge (Ashton 2008), Ashton (2009) is able to squeeze the period from approximately 1950 to 2007.
into one cycle. The results are convincing, the difficulty lies in finding ecology attribute equivalences in the industrial system and to judge the importance of those, together with the surveys they form a factor of observer dependence. Interesting is where Ashton (2009) makes the connection to how communities are able to adapt to external events (or events from slower or faster cycles), the resilience shown by the region was most apparent in the inter-firm relations and policy initiatives, they changed to be able to remain system functioning. Holling’s (2001) adaptive cycle doesn’t work the same for all systems, he points to the ability of humans to resist or influence the cycle, mainly because of technology, communication, foresight and intentionality. This makes the influences through layers of the panarchy (figure 50) more difficult to understand, the power of multinationals to foresee revolts in a faster system and absorb them or the collective dependence on fossil fuels that thrives conservation of system structure. Especially the remember feedback should be given attention, as a common difference between socio-economic systems and ecosystems is that ecosystems do not consider sunk cost (Nikolic 2009).

The panarchy of cycles is a powerful concept but difficult to utilise, tremendous amounts of information are required and the question arises how far down or up effects of interventions will ripple through. It forms a context for IS. IS-networks as embedded systems, possibly typified by industrial regions that go from the exploitation to the conservation phase. Could rising environmental awareness and the implementation of some global protocols have been effecting IS or are small scale phenomena more important? The next section will look at IS at a more detailed scale.

I.2 Process Analysis

Several articles describe barriers or inhibitors for IS or EIP development (Mirata 2004, Heeres et al. 2004, Tudor et al. 2007), those barriers or inhibitors are mostly classified in certain categories; economical, technical, informational, institutional and organizational. Process analysis focusses on positive and negative events that together shape the process of IS, therefore barriers and inhibitors can be deduced from those analysis. The two process analysis that are discussed in this section are both based on history event analysis as described by for instance Poole et al. (2000).

- Process analysis for EIP’s and IS (Yu et al. 2014)
- Functions of Innovations Systems (FIS) method (Suurs 2009), adapted for EIP analysis by de Valk (2011).

The two approaches use different labels (see table 28) for keeping track of the type of events. It is a semi-quantitative method, the events are only assessed positive or negative (and labelled). This makes the method more objective, less dependant on valuation by an observer. However, the binary valuation means large amounts of events need to be collected before patterns (certain types of events that follow up on each other) can be found. A successful of failing IS-project is where you could start your event collection. For instance, collecting all related news items regarding the project. The event database should be as comprehensive as possible. However, there is not one specific way to achieve this. Just one

<table>
<thead>
<tr>
<th>Yu et al. (2014)</th>
<th>de Valk (2011)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Company Activity</td>
<td>Entrepeneural Activity</td>
</tr>
<tr>
<td>Technical Facilitation</td>
<td>Knowledge development</td>
</tr>
<tr>
<td>Informational Activity</td>
<td>Knowledge Diffusion</td>
</tr>
<tr>
<td>Institutional activity</td>
<td>Guidance of Search</td>
</tr>
<tr>
<td>Economic and Financial enabler</td>
<td>Facilitating IS</td>
</tr>
<tr>
<td></td>
<td>Resource Mobilization</td>
</tr>
<tr>
<td></td>
<td>Support from advocacy coalitions</td>
</tr>
</tbody>
</table>

Table 28: Two different sets of event labels for history event analyses

label of the FIS approach is changed for applying to EIP’s, Market Formation became Facilitating IS, this may give the impression that IS and innovation systems are pretty similar. However Facilitating IS shows the importance of institutional context, also the sequence of events that follow up on each other is different, so the dynamics are different in EIP’s (de Valk 2011). These dynamics form the EIP motors, entrepeneural, network and institutional EIP motors which all have slightly different dynamics.
(de Valk 2011). The different event labels from the framework of (Yu et al. 2014) will guide the remaining of this section, along with explaining those also the similarities and differences with the FIS labels will be discussed.

I.2.1 Company Activity

Establishing a synergy link or participating in workshops or information events but also opening up information, this are all examples of company activity or similarly entrepreneurial activity. They also have there negative counterparts. Establishing the synergy link may be the end goal but they also form important stepping stones for the region, as synergy project may develop from small discontinuous projects to large continuous by-product exchanges, as is also apparent from the phase models in section 4. Shared services are often described as easy first link as they do not comprise large investments and thus do not create dependencies. If outcomes of a synergy are positive they may also be a guidance of search for others. Yu et al. (2014) as well as de Valk (2011) describe company activity as being the dependant variable based on the institutional context or positive association of IS projects. Although this seems in contradiction with cases like Kalundborg and the self-organizing model of Chertow & Ehrenfeld (2012), it is not. Because even though company activity might be the first clearly observable event, the context was already in place, an environmental law or a scarcity of a specific resource might have triggered further exploration of IS.

I.2.2 Technical Facilitation

Technical facilitation is about infrastructure, besides having the basic infrastructure in an industrial region there are specific utilities and infrastructure that can stimulate IS (depending on the type of industry present). Examples are ICT infrastructure, water treatment and supply, energy and pressure related utilities but also certain logistic services or waste treatment facilities that can deal with various wastes. In technical facilitation governments can play a central role. When it comes to ICT infrastructure development systems that can help assist finding synergies or assessing benefits of synergies (Yu et al. 2014). Enipedia could develop into such a system, specific outcomes of those systems can be put under informational activity, in the FIS models this falls under knowledge development, knowledge diffusion and guidance of search, other infrastructure development falls under resource mobilization (de Valk 2011, p.134).

I.2.3 Informational Activity

Yu et al. (2014) speaks about how information can be absent in two ways, a lack of professional information and a lack of access to information. This are respectively Knowledge development and knowledge diffusion in the FIS model. The first comprises assessment studies, research programs directed towards IS but also critical opinions of involved participants. The second is to spread information about the potential and the possibilities of IS. This is what is associated with alleviating searching cost. Workshops, conferences, training and other forms of spreading information, formation of networks or platforms is key for larger IS projects. This is where coordinator can play an important part and were systems such as Enipedia can play a side role. An example is the National Industrial Symbiosis Programme (NISP), they have knowledgeable people and a data base of all participating companies with required information, when a new company receiver or supplier comes the NISP is a consultant and facilitator in the whole process of searching for a symbiont (Jensen, Basson, Hellawel, Bailey & Leach 2011).

I.2.4 Institutional Activity

Although informal institutional context is hard to measure, there are formal or more explicit institutional activities that you can label. Regulations and policies, which despite cultural differences are important in any IS setting. Yu et al. (2014) for instance mentions the observation that restrictive policies are less effective in innovation related developments (such as IS) then performance policies which are more flexible. Clarity and equality together with some freedom for the facilities to deal with the new policy have also found to be most effective in the Dutch building sector and electricity sector. To come back to the labelling, next to policies and regulations (fall under facilitating IS and Support from advocacy coalition in the FIS model) there is the monitoring and evaluation of ongoing IS projects. If positive
outcomes of those projects becomes known to actors involved then it also falls under economics and financial enablers. This is guidance of search in the FIS model (de Valk 2011).

I.2.5 Economic and Financial Enabler

Last event label is about the acquiring of resources for IS. The label is oriented on financial enablers; tax incentives, subsidies but also positive financial performances of synergy links. The resource mobilization label of FIS includes infrastructure development also, where Yu et al. (2014) put it under technical facilitation, but probably the acquiring of funds for infrastructure under the economic and financial enabler. As described in the phase models (section [1.1]) IS tends to develop from smaller projects to larger projects in which thus the investment becomes more important which means that in a later stage the role of resource mobilization becomes a key aspect. Research from Boons et al. (2011) might confirm this. They find a positive correlation between mobilization capacity and perceived opportunity set of IS. Mobilization capacity is largely represented by resource mobilization and support from advocacy coalitions, as it comprises the ability to mobilize actors and resources. Although knowledge diffusion comes close it falls under the two other capacities of Boons et al. (2011); relational capacity and knowledge capacity. This reasoning is based on the observation that the data set of Boons et al. (2011) consist of projects that have actively expressed the intentions to become an EIP or engage in IS, thus are already in the phase of actively or deliberately pursuing IS (uncovering or regional learning). This makes the absence of a correlation between relational capacity and perceived opportunity set even more interesting. A strong point if that the data set is large and also includes failed projects.

I.3 Surveys

This brings us to the topic of surveys. The data in the study of Boons et al. (2011) is deduced from interpretations of project participants and program officials. Surveys can more explicitly give insight in the why question and thereby explain the reason about the specific sequence of events. Surveys form an interesting tool for process analysis, but they need a large set of questions including doubles and enough participants to prevent bias or observer dependence. As surveys often work an anonymous basis, a challenge lies ahead in linking this to the information on Enipedia (an open wiki).

I.4 Thus IS is a process

Process analyses needs a lot of historic data or many assumptions. In the establishment of one synergy link the situational aspect is of great influence, for the analysis of the process of IS the focus is thus broadened towards the regional industrial system (RIS). This brings also forth other activities in the region, supply chain and network formations that are not directly related to IS but may influence the shaping of the IS-process. Globalization and cluster formation, Porter (2000) explained that these are not a contradictory phenomenons. The formation of clusters and local pressure on companies could influence synergy formation. Experience by Baas & Boons (2004) has learned us that in regard to sustainability a local community cannot pressure industries enough. How does this observation influences the scope of process analysis?

A starting point is the tracking of events, they form relative objective concepts. Storing the events systematically and giving them labels based on interpretation, creates a database for future research. By storing them in an accessible manner the opportunity to find patterns arises. Finding the difference between structural mechanisms and serendipities (Lombardi, Lyons, Shi & Agarwal 2012).

J Synthesis

This part has conceptualized IS as the evolution of a network. This network exist of multiple layers, the infrastructure required, the actual mass flow taking place, the economic layer in which all cost and benefits are summarised (economic transaction) and the informational connections (Social relation). The conceptual agent is different in the description of each layer. Integrating the layers thus forms a challenge. There are possibilities for integrating the infrastructure layer, mass flow layer and economic transaction, they form the established synergy link and are clearly connected (section [H.3]). The informational connections are less tangible and are also preceding the actual establishment, they should therefore be
modelled separately. The environment in which this network evolves is represented by events, events that could have an influence on the development of IS (at large or for a specific synergy link) need to be stored for finding patterns. Figure 51 illustrates the process of network evolution in generality.

Figure 51: The process of network evolution.

The blue lines represent the 'traditional' supply relations. Figure 51 is a simple one dimensional picture, so it only shows the physical network and an event line. The connection of the events to the development of the physical network and the dynamic interaction between social entities cannot that easily be represented. For finding the reasons and or mechanisms behind IS, also quantities and values on the micro level are required. The economic transaction layer is central in this assessment (section H.3), here all possible costs and benefits should be gathered regarding individual IS-projects. The hypothesis is that IS can be assessed within the frame of regular transactions (Andrews 2001), possibly typified by larger transaction cost due to asset specificity. The facilities optimize for monetary value and the environmental benefits are a side effect (section H.1). The environmental aspect do, however, form an important aspect of IS. They need to be gathered under costs and benefits as well, and are given a monetary value when tax cuts or resource savings make them a parameter in the decision making process. The valuation of information flows (through for instance searching cost) need to be analysed further.

K Investment dilemma of IS

Required background knowledge, Competitive advantage and the determinants of an attractive industry (Porter & Millar 1985).

IS can comprise various symbiotic exchanges, but cascading is frequently coming up as the example of IS. Heat or water cascading requires specific infrastructure, conclusively investments which are only usable for a specific purpose, in financial terms they call this asset specificity. Cascading means dependence on infrastructure and the other participants in the cascading network, while it does not usually generate a lot of profit and thus a low return on investments. Not all IS links have this combination of dependence and relative small return on investments. But if you look at other business exchanges, generally speaking, cascading is not commercially most attractive (this is dependant on raw material cost in comparison with investment cost), see figure 52. Consumer products are less dependant on infrastructure and less dependant on suppliers or buyers compared to cascading, figure 29. Pharmaceutical companies have large investments in R&D and thus asset specificity, but they often make a lot of profit when successfully introducing a medicine (due to the fact that buyers only have no other option). Some consultancy companies make their clients dependent on them and on the other hand their only dependence is a high quality pool of employees, which are adaptive so can adapt to changing circumstances (flexible investment). Cascaded heat probably needs to draw on long-term contracts, but which participant will carry the risk for price fluctuations or other changing circumstances. These statements are only true in relation to the current competitiveness in the markets mentioned. Conclusion The whole notion of IS being good for competitive advantage (Chertow 2000) is not as straight forward as thought. Where consumer products are often focussed on cost leadership and pharmaceutical companies on differentiation and focus. Cascading is differentiation but instead of less, more dependence on buyers or suppliers is
created. In the case of a successful cascading project the participants as a whole acquire competitive advantage over other industrial areas.

L The Resource Description Framework and Semantic wiki’s

The Resource Description Framework (RDF) is a way to store data on the web, developed by the World Wide Web Consortium (W3C). How this is exactly built up is not the concern of this thesis. So here the only part of RDF described, is the part needed for understanding and constructing an ontology. The backbone of RDF is the RDF triplet, all data is stored in the form of triplets, subject - predicate - object, see also figure 53. For people that are familiar with graphs, a triplet can also be seen as a (named)graph, node 1 - edge - node 2. On the web each part of a triplet has a Uniform Resource Identifier (URI), see figure 53. On a Semantic wiki this means that the three parts of the triplet are all represented by a different page on the wiki. Those pages have unique names that identify the page, the name space of a page. Thus it is important to think about a proper name. The base of the URI’s is the same for the pages on the wiki, for Enipedia this is; http://enipedia.tudelft.nl/wiki/, see also figure 53. Therefore it is possible to direct to the URI without mentioning the base. For the property IndustrySector the full URI is given. For the page UnicoTEDA the base is left out. Enipedia uses the RDFS as basis for specifying categories and properties. So for the ‘is’ or ‘is of type’ relation it directs to the W3C website. A subject can be an object in a different triplet, this is determined by the direction of the property. So in the remaining of this thesis mostly the word ‘object’ is used.

51see the W3C documentation, http://www.w3.org/TR/2004/REC-rdf-primer-20040210/
Figure 53: RDF triplets. Above the concept triplet, below a practical example of Enipedia. Understandable by humans through naming and understandable for computers through the URI's. The base of all URI's on Enipedia is http://enipedia.tudelft.nl/wiki/.

Box C: Different vocabularies on Enipedia

URI's are used so that the computers are able to understand RDF graphs. However, this identification by URI's is made more human readable on the wiki. For instance, abbreviations are used. To prevent mixing up the different vocabularies, an example is presented here.

**URI** As presented in figure 53, an URI corresponds to the web address. Spaces in the name-space need to be presented by an underscore (_).

**Wiki-text** With wiki-text, the base can be left out. Wiki text is used on pages to direct to other pages on the wiki.

**SPARQL** For querying the URI's are needed again. But instead of listing the full URI, abbreviation are available when setting up a query pattern.

http://enipedia.tudelft.nl/wiki/Special:SparqlExtension

This is the location where the abbreviations for SPARQL on Enipedia are, here you can also run test queries. Spaces in the name-space need to be denoted by an underscore (_), sensitivity to capitals is also an issue. Figure 54 uses the SPARQL abbreviations.

The three vocabularies for: 1) a page in a category (article) and 2) a property.

<table>
<thead>
<tr>
<th>URI</th>
<th>Wiki text</th>
<th>SPARQL</th>
</tr>
</thead>
<tbody>
<tr>
<td>enipedia.tudelft.nl/wiki/UnicoTEDA</td>
<td>UnicoTEDA</td>
<td>a:UnicoTEDA</td>
</tr>
<tr>
<td>enipedia.tudelft.nl/wiki/Property:Distance_between_facilities</td>
<td>Property:Distance_between_facilities</td>
<td>prop:Distance_between_facilities</td>
</tr>
</tbody>
</table>

L.1 Category - Property structure

The category - property structure can be found on any Semantic Wiki, if it uses the Semantic MediaWiki (SMW) package. The category - property structure is useful for constructing relatively flat ontologies. In
section 8, ontologies were discussed from there philosophical background, properties can be seen as the equivalent of attributes and relations. Categories are the abstraction layer, every object in a category has the same properties, only the value of the property differs. For instance UnicoTEDA belongs to the category FacilityIS, this means that it inherently has the properties; Location, IndustrialSector and all other properties specified for the category FacilityIS. The particular value of these properties can differ for every object, UnicoTEDA has location TEDA, but Asneas has Location Kalundborg. Properties are part of an abstraction hierarchy as well, there exist different property types. Properties differ based on the kind of object they connect to.

L.1.1 Property type

A property is embedded on a page, the property can connect the page to a couple of different objects:

- Another page, this means the object has a page were information about the object is specified. In figure 54 those objects are represented by the yellowish ovals.
- Web-page, the property connects the object to a web-page (generally outside of the wiki).

In section 9 the concepts within ontologies were presented, such as classes, attributes and relations. It is possible to see the above properties as relations, as the object they connect to is an object that can itself have other properties. The below property types connect to an object that cannot itself have properties, these property types are attributes.

- Number, the property connects an object to a number.
- String, the property connects the object to a word or sentence, see for instance the property name.
- Boolean, yes or no.
- Coordinates, consist of a longitude and a latitude, to pinpoint the geographic location, see the property point.
- Quantity, this property is discussed in the next paragraph, basically this property refers to something with a numerical value with a unit. Furthermore it provides automatic unit conversions.
- Temperature, similar to quantity but then with a non-linear conversions between different units.

Figure 54 gives some of the properties of UnicoTEDA and how Unico is connected to other pages. Those pages itself can belong to the same or another category also. VestasTEDA, for instance, has the same category, FacilityIS, thus it has the same properties (with different values) as Unico. For the sake of keeping the figure clear, the properties of Vestas are not given in figure 54.

This paragraph explains the special property type quantity. Properties with this type refer to objects that have a numerical value with a unit. Unit conversions can be specified, from kilo to tons, for instance, or foreign ways of measuring such as from kilometres to miles. Figure 55 shows how this is set up for the property distance between facilities. The code given, can also be found by editing the page on Enipedia. Only linear unit conversions can be put in place. For conversions such as from Celsius to Fahrenheit there is a separate property type temperature.

Grouping by means of categories is sometimes not enough when structuring data. There might be the need to make sub groups or groupings based on only one property. For instance, someone is interested in all facilities that have the property IndustrySector with value Waste recycling. From an ontological perspective it doesn’t make sense to make a separate category just for this one property. Enipedia therefore provides SPARQL (SPARQL Protocol and RDF Query Language). SPARQL makes it possible to search the ontology for specific pieces of information, as well as making aggregate listings and comparisons based on certain properties or values. Back to the example, in this case SPARQL enables us to retrieve a list with facilities that have the value Waste recycling for the property IndustrySector.

\[^{52}\text{Value does not necessarily refer to something numerical, a page or a string can also be a value.}\]

\[^{53}\text{http://enipedia.tudelft.nl/wiki/Property:Distance\_between\_facilities}\]
Figure 54: Part of the ontology of IS. The abbreviations as used in the figure, are as used in SPARQL as well. SPARQL and the path of the red character are explained in section 1.2.

Property: Distance between facilities

This is a property of type Quantity.
Display units are in km.

<table>
<thead>
<tr>
<th>Unit</th>
<th>Description</th>
<th>Value and possible names</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>km</td>
<td>kilometer</td>
<td>1 km</td>
<td>standard unit, as in SI</td>
</tr>
<tr>
<td>miles</td>
<td>mile</td>
<td>1 km corresponds to 0.6213712 miles</td>
<td>English measurements</td>
</tr>
</tbody>
</table>

Figure 55: The property distance between facilities has the type quantity. This lets the property point to a number with a unit. The property can hold unit conversion on its page. The page holds a template that makes it easy to fill in the unit conversions.
L.2 SPARQL

SPARQL (SPARQL Protocol and RDF Query Language) is a way of retrieving specific parts of information out of the stored RDF graphs. With SPARQL RDF triplets can be traversed one by one until the target is reached. Besides this section, there are two useful places to learn about queries and SPARQL in particular:

- The SPARQL Tutorial by Cambridge Semantics, this tutorial explains all features of SPARQL with examples. SPARQL By Example http://www.cambridgesemantics.com/semantic-university/sparql-by-example#%281/

An example, figure 56, tries to explain how a query or search pattern can be established. However, the only way to really grasp querying, is by trying to make a query yourself. In the example (figure 56), geographic coordinates from a facility are queried onto another page. The query comes from the template SynergyLinkQueries. By using the template to define the category SynergyLink, every instance of SynergyLink automatically contains the distance between the symbiont and receiver facility. Figure 54 from the previous section, gives the possibility to visually follow the search pattern, as the red character follows the same path as the query. The query, when run from the page SynergyLinkVestasUnico, basically says:

Go from this page via the property ToFacility to another page (?facility - UnicoTEDA), this page needs to have the property Point, return the object (?to) to which that property refers.

The code for this query has a different sequence than human language. Figure 56 gives the full query as it also needs to be given on a page on Enipedia. So every query has those four components:

1. Prefix declarations and dataset definitions. For Enipedia this is already done under SPARQL Endpoints, see also box C. Therefore it is not visible in figure 56. The prefix declarations contain the abbreviations used for the data set.

2. The result clause. After SELECT, the variable that needs to be retrieved is stated. A variable is denoted by a question mark in front of the word, which can represent anything. The query pattern is then specified how to get to the variable or what properties it should have. It is possible to let a query return multiple variables. When a star(*) is given in the result clause, the query returns all variables in the query pattern. If one variable can result in multiple returns, the result is a list. Duplicates can be removed by putting DISTINCT in front of the variable. Within the result clause, calculations (+, -, =, SUM, AVG) and renaming (AS) etc. can also be done.
3. The query pattern. This is given between brackets after the WHERE command. This is where you walk through the RDF triplets. When the query does not find any matches for one triplet, the whole query fails. The OPTIONAL command can be used to prevent this. For instance, if you search for multiple variables and one cannot be retrieved, but you want to give the others anyway. An application is shown in the next section L.3.

4. The query modifier. Here the query results can be rearranged; in this case the FORMAT is not table but inline. Other modifiers are ORDER BY, LIMIT etc.

In queries it is important to keep track of what the subject and what the object is in a triplet. The predicate (property) has a direction, so the triplet does not work both ways. The query needs the exact naming, for a page this is the name-space for properties as well, but the properties are not always given in their exact name on a page. Browsing all properties is a lengthy option for acquiring the exact naming of a property. A quick good solution is, editing the page and including the _SHOWFACTBOX_ command, then on the bottom of the page the properties embedded on the page are given. In the next section another example of a more advanced query is given and section ... gives also an example of a interesting query.

L.3 Semantic Internal Objects (SIO)

Although language has many possibilities for expressing the meaning of a property, sometimes one stumbles upon one or a couple of properties that could be specified more efficiently. The Semantic Wiki community probably has the solution ready somewhere, such as the special property type quantity L.1.1 Another example is Semantic Internal Objects (SIO), developed by Yaron Koren[54]. To illustrate when SIO can be beneficial he gives the example of the recipe. A recipe contains:

- The products or ingredients you need.
- The amount or quantity of the products.
- The unit of the amount or quantity, as sometimes the quantity is given in liter but sometimes in spoons or maybe in gram.
- Possibly some specific instructions are coupled to this ingredient.

When there are for instance four ingredients, there would be the need to specify twelve properties. Not only would this result in a lot of work and a strange naming (Quantity of ingredient four), it would also result in a long list on the respective object’s page. More visually attractive would be a table with multiple columns. What SIO provides is the ability to establish a blank node(an object without a page on the wiki) which groups the properties linked to an ingredient. Figure 57 gives an example of the inputs of facility UnicoTEDA. So an additional property, in this case InputOfFacility, connects to the blank node and the node connects to the other properties. Figure 58 shows how this is done by means of two templates. Templates are explained in the next section(L.4.1). In the first template the connecting property, InputOfFacility, is set by the #set_internal command. The properties that are then connected to the blank node are also specified in that template, Product, Amount, Unit, Temperature, Hazardous, OtherInfo, Contains1 and Contains2. Now the properties are stored on a blank node connecting to the objects page. To get everything on the right page, in this case UnicoTEDA, a query is needed. This query can be put on the page or in a template embedded on the page, see the second template in figure 58. So for SIO to work at least two templates are needed. In any query first the variables are named in the select clause. Then the query starts with the triplet that connects the blank node (?productSIO) to the objects page (UnicoTEDA). From the blank node the first property, Product in this case, needs to have a value. All other properties are optional. The result of the query on the page is also given in figure 58. SIO can be used in combination with a form (the form is explained in section L.4.1). When editing the page with a form, a button with ‘add” or ’remove’ appears. This way it is possible to add a new row of property values. It actually means you connect a new blank node to the page.

Figure 57: Graph of a Semantic Internal Object (SIO). Without SIO there would be the need to specify at least 3 additional properties per extra type of input. The other option, specifying each input on a different page, comes at the cost of clarity, as in this case not all information would be on the same page. The principle of the blank node and SIO together with the option to query the information onto another page, satisfies the need of the computer and the human-user.

Figure 58: The SIO templates, the template with query and the result on the page of Unico.
L.4 Using a Semantic wiki

Creating an ontology does not only require the understanding of RDF and the category-property structure. Another side is the construction of the ontology on a Semantic wiki and the interaction of users with the ontology. On Enipedia any page can be edited. Plain text can be inserted and the Wiki mark-up language\(^{55}\) can also be used for creating (hyper) links or structuring and visualizing the information on a page, which is similar to a normal wiki. Creating links with semantic annotations is the next step. Most structured option is with the means of templates and forms, this is explained in the next section (L.4.1). Another enabler for ease of use and quality control is the edit history. Each page has an edit history. It provides the possibility to keep track of whom has made changes to the page and the possibility to undo this in case of errors or vandalism.

L.4.1 Templates and forms

Pages on the wiki can be created by typing in a new name-space, putting text, adding properties and running queries, which is all possible on a page. However, when making a large data structure or ontology, this is a lot of work. To make it easier and more structured, the SMW package provides the possibility to use templates and forms.

Template Templates make it possible to build in a modular fashion. A template is basically a set of properties including the make-up, but it can also contain queries or other specific features. A template is added to a page (or a form), in this way the lines of code needed are typed only once. Changes made in the template then also automatically occur on the page, only the property values need to be put in by hand. An example is the templates that create the possibility to make a reference to an website or a saved document on the wiki. This is an options that is useful for almost any page, thus the effort of making a standard template for referencing really pays off. Templates enable modularity as required for the co-evolutionary modeling of CAS (Nikolć 2009), see also appendix F. Templates are especially efficient when used in combination with the category structure, as every page in that category then makes use of the same template.

Form Forms make the wiki more user-friendly. Forms provide an interface, which makes it easy for people with no understanding of Semantic wiki’s, to fill in data. Instead of ‘edit’ the user can press ‘edit with form’, then data can be filled into nice boxes and there is the option to draw on functions such as auto-completion, it is also the layer where the knowledge engineer can put information to assist the user/contributor. A page can only have one form, the form can have multiple templates embedded. The form is what enables the shared effort (Nikolic 2009), see also appendix F.

The first step of making an ontology on a Semantic wiki is specifying everything in a category-property structure. Templates and forms come in action when putting this structure on the wiki. The steps in creating a category are shown in figure 59. Before creating one or multiple templates for a category, the properties already need to be created. It is possible to check the list with properties (Special:Properties) to see if similar properties are already present on the wiki. The creation of a template does not need much information other then given on the Special:CreateTemplate page. The naming and selecting of properties is done in the first box. The second box is for embedding a query on the page. This query asks for the selected property; ‘which pages are linked to this page with that property’. Normally a triplet is created by a property, instead the second box asks if there exist a triplet already. For instance, the property *ParticipantIn* is used to connect Unico to the synergy links it is involved in. The property is given on the page of Unico, still it is useful if Unico also shows up on the page of the synergy link. Therefore you can use this second box. So it doesn’t add semantic annotations, it is for purpose of user navigation.

The next step is adding the template or multiple templates to a page or a form. When creating a category, thus multiple instances, the form is the best option. Figure 59 also shows that a page has a visual representation and a layer where editing is possible. The pages in categories on the wiki are sometimes referred to as articles, a page that makes use of a form has a third layer. This layer is a user friendly interface for filling in data. Templates and forms also have a page on the wiki. When editing the page of a template or form, the part under ⟨includeonly⟩ is embedded on all pages that make use

Create a Category

Step 1
• Create properties
  (Special:CreateProperty)
• Select type

Step 2
• Create template(s)
  (Special:CreateTemplate)
• Add properties
  • Optional, template defines category.

Step 3
• Create a form
  (Special:CreateForm)
• Add templates

Category created

Step 4
Create instances of the category by
typing the name on the form page
(Form::'name category').
And fill in the values of the properties.

Figure 59: Creating a category (left) and layers of a page (right). The best way of getting a feeling with using a Semantic wiki is just creating a small ontology with at least one category.
of the template or form. The part under \textit{noinclude} is given on the page of the template or the form itself.

L.4.2 Extending an existing page

There is no definite end state for research or modelling (Nikolč 2009). This means that the ontology should be able to change, not only the concrete side of the ontology\textsuperscript{56}, also to the abstract structure. Adding a property (with value) to an existing page or template is an example. Figure 60 shows the code needed for three different options. The first option is manually adding the property. The second option is adding the property to the respective template and then adding the value to the page. If a form is specified for the page, the property should be added to the template and the form, after which the value can be filled in through editing the page with a form. The first option is useful if the property is specifically for that page only, so if the property \textit{Location} with value \textit{TEDA} was only needed on the page \textit{UnicoTEDA}. Option two and three provide the property to all pages that use the template. This is useful if the property is contributing to defining a category or a good addition to the template in general. For \textit{location}, it is the category \textit{FacilityIS} with its respective templates and form.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig60.png}
\caption{Adding a property to a page. The property \textit{Location} with value \textit{TEDA} is added to a page in three different ways. Only where two colons (\texttt{::}) are preceded by \textit{Location}, the real property name is needed. In the other cases a different (but consistent) name can be used for presentation purposes.}
\end{figure}

M Evaluating capabilities of a Semantic wiki

Enipedia as a semantic wiki provides capabilities for representing information. The core is RDF, directed graphs for knowledge representation (section L). This section is not about evaluating RDF, it is about some of the functionalities brought by the many packages and extensions made for a Semantic Wiki. Basically the wiki is a great knowledge representation tool (personal opinion). This section just points to a couple of features that are not working as well as I would like. It is possible that a remark is made unjustly because of the lack of knowledge about SMW/SPARQL of the researcher (me). If that is the case, it shows that working with a Semantic wiki is almost a domain in itself.

Templates, forms and editing - Section L.4.1 discussed how a property can be added to a category and thus to all pages in that category. Logically the property needs to be added to the template, but the property also needs to be added separately to the form if the category makes use of a form. Otherwise

\textsuperscript{56}\text{The concrete side means the actual data on the wiki, so a more complete data set for certain IS linkages or putting additional case study results on the wiki}
the page will have the property but it will not show, when using 'edit with form'. So adding a property
require two editing steps, copy-past is your friend here, as the text sequence needs to be exact. Also
you need to keep track of the real property name and the text sequence that appears on the page. It is
possible to give the property another name for appearance on the page. Basically means that you can
make a lot of errors in the process of adding a property. When making use of SIO and then adding a
property it is even easier to make a mistake. For SIO you need next to a template also a query, so you
have the real property name, the name for appearances and the variable name in the query. Sometimes
until you actually saved data on an actual page (through the from) that you discover an error. The 'show
preview' function does not work with SIO and sometimes you actually need to refresh the page before
everything becomes visible. Also sometimes old data put in by SIO will remain on the page somehow.
All of this is only a problem when multiple people work on the data structure around the same time.

A last small remark is that sometime after an update of Enipedia not all data will show up on the
pages. This holds for data put there by SIO and by the geographic proximity query ([56]). Manually
refreshing all pages takes a while. In the mean time people might visit the pages and think there is no
information there.

Something word considering is to cancel the possibility to give the property another name for ap-
pearances. The need for this function means that some properties are apparently not correctly named.
It also helps the user to understand the underlying structure of the wiki. Personally I like the'SHOW
FACTBOX' command anyway; basically this command shows the real property names.

**Semantic Internal Objects -** Small problems with editing do not outweigh the great functionality
SIO brings (section [L3]). Maybe this functionality could even be improved on two points.

1. Make SIO work better with the special property type: quantity.

2. Make SIO work with ASK queries.

The special property type quantity (section [L1.1]) makes it possible to make properties that have a
numerical value and an unit. Also you can specify how one unit can be conversed into another. One
of the applications of SIO is also to list two properties next to each other in a table, a numerical value
(property type number) and a unit (property type page). So are SIO and the special property type
redundant? No, sometimes you want to give multiple different numerical values with unit in a table, an
example is table [21]. SIO and the property type quantity can be used together. Only the unit does not
appear in the table, it is just the numerical value. The hidden unit of this numerical value is the first
unit specified on the special property type page. Even if you put the data in another unit onto the wiki
it automatically converses it into the basic unit.

The timeline is a special representation format of the ASK query (section [L4.1]). You ask for all pages
who have a certain property and a property with type date. The timeline format orders them on date
in a timeline visualization. If one of the properties is stored through SIO, the page does not show in the
timeline visualization. This is quite logical because SIO stores the properties on a blank node connected
to the actual page. A solution would be to make it possible to follow triplets with the ASK query as
well. Or the development of a timeline format for SPARQL.

**SPARQL -** The amount of possibilities of SPARQL could be referred to as large or enormous. Account-
ing with dates, interval (research xsd, fn) possible that it is fixed already, a prefix that refers to a part
of the RDF’s Bar chart visualization, commonly used representation of data should be possible to make!

Statistics and SPARQL SPARQL and R

A big data tool should be able to give statistics, one of the
applications in the previous sections, combination of oversight and statistics

**N  Adding data to the wiki**

Enipedia has a page for *Industrial Symbiosis*, on this page is explained how you can contribute to the
wiki in regard to industrial symbiosis. It also provides some links to the relevant pages , see [51]. If you
have read the previous section [4] this will be relatively straightforward.

O Level of detail

In ontology engineering there is always a moment when you need to decide on the level of detail. What level of detail needs to be represented by the ontology? The difference in amount of categories between figure 61 a and b is already quite large. It is expected that the amount of instances will not expand linear, especially because representing multiple events and or values for a single IS-project would be required.\(^{58}\)

**Individuals** Individuals and their connections play a role in coming towards an IS project, see Ashton & Bain (2012) and Gertler (1995). Do they need to be represented and how?

**Physical assets** A boiler that needs to be replaced, a small storage capacity or a reactor that does not use full capacity. These are triggers for engaging in IS. But representing them requires the addition of categories to the ontology. Companies are also not always willing to give detailed information about their physical assets.

**Composition of mass flows and inputs/outputs** Companies are not eager in giving this information. Purity and trace components in an input/output can influence the decision whether or not to engage in IS. The IS-community will need to make a decision on the level of detail in regard to representing resources. And the degree of standardized namings.

**Contracts and financial performance** Economic performance is still the most important reason to engage in IS. Insight in the exact way a synergy contributes to financial being of a facility can give insight in drivers and barriers for IS.

**Ownership structures** IS-literature sometimes mentions a shared owner or a partnership, does this need to be represented by the ontology?

**Small businesses and households** Not all IS takes place between large manufacturing companies. Households and small business are sometimes involved. How should those be represented? It is a lot of work to represent them all individually, especially with households.

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\(^{58}\) Archiving objects based on their *EndDate* could be considered.
Axiomatic Design

This section introduces the Axiomatic Design (AD) framework and the difficulties of applying it on CAS. The conclusion is that although despite opposing ideologies the differences between CAS and AD are workable, however to incorporate the whole AD framework into this research seems not worth the effort. Only the notion of designing based on function instead of physical being is taken as a learning point.

P.1 How axiomatic design (AD) works

To secure that a design is good, axiomatic design (AD) (Suh 2001) can be used. Axiomatic Design is a systematically design method, about the mapping from customer attribute (CA’s) to functional requirements (FR’s) to design parameters (DP’s) to process variables (PV’s). Furthermore the design method is based on two axioms:

1. The Independence Axiom. Maintain the independence of the functional requirements (FR’s).
2. The Information Axiom. Minimize the information content of the design.

So the key to a good design is that either each FR is fulfilled by only one DP (ideal design) or that there exist a matrix such as (1) in figure 62 so the design can be built up by first adapting to one FR then to the next without needing to iterate between DP’s as shown by equation two, this is called a decoupled design. A coupled design is presented by any matrix that has not an upper or lower triangular with zeros, which means that it violates the first axiom. Remember it is a design method not mathematics, so matrix operations can not be applied because often the design matrix represent physical things that can not be transformed. Equation three gives the mapping to the process domain, this means next to

\[
\begin{bmatrix}
FR_1 \\
FR_2
\end{bmatrix} =
\begin{bmatrix}
A_{11} & 0 \\
A_{21} & A_{22}
\end{bmatrix}
\begin{bmatrix}
DP_1 \\
DP_2
\end{bmatrix}
\]

(1)

\[
FR_1 = A_{11} \cdot DP_1 \\
FR_2 = A_{21} \cdot DP_1 + A_{22} \cdot DP_2
\]

(2)

\[
[FR] = [A][DP] = [A][B][PV] = [C][PV]
\]

(3)

Figure 62: A decoupled design (1) means that one of the functional requirements is dependent on two design parameters (2), when mapping to the process domain equation (3) needs to be considered. (Suh 2001)

the requirement that matrix B should not be coupled, matrix C should also not be coupled, this means that if one of the matrices A/B is a triangular the other should be a triangular of the same shape or a diagonal. Axiomatic design was developed for product manufacturing but is also applicable to systems and software according to Suh (2001).

P.2 AD for CAS

At first sight there are some incompatibility issues regarding AD on the one hand and CAS, thus also incompatibilities between axiomatic design and the guidelines for co-evolutionary modelling from Nikolić (2009) on the other. Were Suh (2001) uses a top down approach to decompose a system into parts based on functionality and explicitly states that:

A system must be designed; it cannot evolve by adding on subsystems and components without designing the entire system (Suh 2001, p. 195).

Within CAS, evolution is a central paradigm also for the design of models, furthermore another thing in CAS is that one function is hardly ever fulfilled by only one physical part, as Mikulecky (2001) says:
The functional component has no 1:1 mapping to the material parts even though it arises from them.

The whole ideology of IS that someone’s waste can be very functional to someone else illustrates that multiple functions can exist for one component. The synthesis of AD with the CAS framework looks therefore challenging. The differences are smaller then one would expect from the above statements. Large flexible systems are systems which need to satisfy different sets of FR’s during their lifetime, they draw on a rich data- or knowledge-base of DP’s to satisfy these FR’s (Suh 2001, p.202). This comes closer to the description of CAS, were for modelling CAS Nikolíc (2009) reveres to Gall (2002)

Gall (2002) provides us with a somewhat tongue-in-cheek but nonetheless important observation on complex systems:

A complex system that works is invariably found to have evolved from a simple system that worked. The inverse proposition also appears to be true: A complex system designed from scratch never works and cannot be made to work. You have to start over, beginning with a working simple system.

Which implies that at the start of the modelling process the system should be simple. Separating functional requirements and trying to let one function be fulfilled by as little design parameter’s as possible is a good option for simplification. After the first design the further development will be an evolutionary process coupling of FR’s can take place, but it prevents the system to be entangled immediately from the start. Some anticipation on future needs would benefit the system to stay decoupled for longer.

**P.3 Conclusion about AD and CAS**

AD is not incorporated in this study, only ideology of separating between functions and physical parts is taken as a learning point. How AD is applicable to the building of Semantic Wiki’s, the way you construct categories and properties with templates and forms, still needs to be investigated further. How the building of the a wiki fits with the AD process domain.