Summary

Introduction Our human society exerts great pressure on Earth's carrying capacity, leading to exhaustion of natural respurces, loss of habitat and biodiversity, leading to a resource and climate crisis. To avoid a sustainability crisis, we urgently need to transform our production and consumption patterns. Given that we are part of a complex and integrated global system, interconnected by information, money, energy and transportation infrastructures, where and how should we begin this transformation? And how can we ensure that our transformation efforts will lead to a sustainable world?

We must start by viewing the industrial systems as a Large-Scale Socio-Technical Systems, or λ-systems, composed of interconnected social and technical networks situated in a geological and biological context. Second, we must recognize that global, national and regional λ-systems grow and evolve as a result of the decisions and actions undertaken by social entities (individuals and organizations) in relation to the implementation, operation, design and innovation of the technical elements of these systems.

The research theme thus became "to increase our understanding of industrial networks and help steer their evolution towards sustainability," which implies a - methodological - research question: How can we model the evolution of Large-Scale Socio-Technical Systems such as industrial networks, so as to provide support to strategic decision makers?

In this work we focus on developing a better understanding of regional industrial networks, with the aim of supporting Regional Development Authorities. We realize that this only begins to capture the complexity of the challenge implicit in the research question. The main hypothesis of this thesis, capturing the larger theme, was that the use of adequate models of λ-system evolution will improve the ability of industrial clusters to make sustainable development choices. The hypothesis has lead to the main research question: How can we create a model for exploring the evolutionary patterns of λ-systems, and how can those patterns be used to support decision makers in shaping that evolution? Three subquestions were be derived from the central research question. First, how can a generativist Complex Adaptive Systems perspective be operationalized in models that capture λ-systems evolution? Second, what are the content specifications of such models in terms of the relevant formalisms (knowledge domains)? Third, what are the specifications for a process that would create such models?

Theoretical foundations As part of answering the first two research question, we referred to the theory on Complex Adaptive Systems, which stipulates that overall λ-system behavior

can be understood as an emergent property of interactions between autonomous agents at the lowest level of the system - in our case the firms and their technologies.

In our framework for understanding λ-system evolution, a system is conceptualized as consisting of three levels: agent, network and system. At the agent level, the agent is defined as the smallest system component; its state and rules determine its conversion of inputs to outputs and its adaptivity. Agents are similar in their interaction abilities and diverse in their states and rules. At the network level, interactions between the agents create a network with a certain topology. The changes in the intensity of the connections between agents determine the network dynamics; the addition and removal of nodes and edges makes the network develop and evolve. The system level is where the entire system manifests itself as an entity with aggregate in- and outputs, this entity having an aggregate state and aggregate rules. In reality, the system's properties are emergent; they are the result of low-level interactions. The system exists within a larger environment, it self-organizes, is robust, can be unstable, and its description is observer-dependent.

The presented framework is holistic, as it looks at all aspects of a system - from the smallest individual elements to the highest level of system aggregation. It considers systems in their entirety and only reduces elements to smaller elements if they are fully interrelated with other elements. It is generativist, as it understands a system to be the result of a continuous process of emergence across multiple levels, starting with the lowest level elements. It is multiformal, as it allows different languages to be used to describe different levels and component properties.

An important insight gained from Complex Adaptive Systems theory is that predicting the exact outcome of the evolution of any λ-system is impossible, due to the intractability of the evolutionary process; there exists no faster way of predicting a system's outcome than to simply allow it to run its course. Simulation, however, can be used to generate emergent patterns of possible futures and identify system attractors.

Agent Based Modelling (ABM) was identified as the only generative modelling tool able to represent the structure and dynamics of evolving regional industrial clusters. Individual companies and their technical installations are conceptualized as the smallest system elements or agents. Suitable representations of market, environment and governance are included in the model. Process Systems Engineering is used to represented technical elements as a mass conserving black box characterized by its inputs and outputs. Corporate finance offers suitable descriptions of the bounded rational behavior of firms that own and operate the technical installations.

The number and diversity of agents in any industrial network are substantial, and need to be adequately captured. Descriptions from technical, social, financial, ecological, engineering and other fields must be incorporated. These fields represent an equal number of distinct and often incompatible languages or formalisms. Knowledge management and artificial intelligence literature demonstrate that interconnecting this 'Tower of Babel' is not a trivial exercise. Building a shared multiformalism requires an engineered social process that involves domain experts of diverse backgrounds and expertise. To facilitate the communication between different vocabularies and formalisms, ontologies were identified as a means to create an interface between experts, while retaining the domain-specific vocabularies.

Modelling Foundations To answer the third research question an evolutionary modelling process was constructed, progressing through a series of case studies. Based on principles from collaborative modelling and insights from Complex Adaptive Systems and the evolutionary formalism, six requirements for the modelling process were formulated: open sourceness of the tools used and created, sufficient diversity in the community of modellers, the organic growth of models, recorded history, enforceable authorship, and modularity of the software stack.

Model development is a co-evolutionary process that progresses in generations, or case studies, and which takes place in a dynamic, socially constructed environment of modellers and stakeholders who determine what is useful and what is not.

Co-evolution means that an element in an evolving system never exists in isolation but is always in interaction with others. A change in the fitness (survival ability) of any component has a direct effect on all other elements with which it shares its environment. In our method for model development there are four modelling aspects that co-evolve:

1. Technical aspects of the model, namely which software and hardware systems to use, how to organize the modelling software components, how to store data, how to analyze results, etc.;
2. The social process of involving the stakeholders in identifying and collecting relevant knowledge and providing feedback on the model's outcomes - this process involves the selection of the right participants, the execution of the collaborative process, the manner feedback is organized, etc.;
3. Formalized and encoded knowledge domain representation of λ-systems - microeconomics, chemical engineering and psychology are examples of relevant knowledge domains; and
4. Factual information that describes the components of the λ-system, their interactions and the overall system behavior - for example: specific processing plants, their in- and outputs, economic performance data, etc.

The modelling process was anticipated to lead to the evolution of increasingly richer and better models and tools, while at the same time providing insights per case study. The series of 7 case studies explored in this work included three that we call 'learning case studies' because they explore the general applicability and usefulness of the modelling process, which can later be applied to practical case studies.

Learning case studies To begin with, the Flow-Based Evolution model was created to investigate whether the elected conceptualization is good enough; in other words, whether or not we can eventually meet our objectives by representing a λ-system as an input/output flow-based network in an ABM for which the industrial network consists of producers and consumers (nodes) connected by mass flows (edges). Developing the model also helped us to determine what types of facts need to be collected and led us to the conclusion that technology descriptions and economic decision-making processes must be implemented as separate but connected modules.

In the Combination Of Infrastructures case study, the focus was on designing a social process for multiformal knowledge and fact collection. The model built was intended to help elucidate the spatial combinability of infrastructures. Through this social process combinability was defined to consists of social, legal, safety and technical aspects. In the social process a proto-ontology of infrastructures and a parametrization of combinability aspects were created. The facts collected from the stakeholders allowed the construction of a fitness landscape that described the combinability of different infrastructures.

The final learning case, the Chocolate Game, involved the development and playing of a serious game and developing a model based on it. The game lead identified the information needed to create an ABM of a chocolate supply chain, that serves as a analogy of the chemical process industry. The analogy and associated information was extracted from the game using the System Decomposition Method (SDM), resulting in an ontology. This ontology serves as a formal, machine-readable representation of the language used for reasoning and communicating in the ABM. The SDM was designed as a collaboration script that consists of a group modelling exercise in which experts in relevant knowledge domains and formalisms interact. It offers a template of interfaces as well as a procedure to transform and encode their knowledge into a single multiformalism that defines the states and rules of an Agent Based Model. In the technical design aspect the conceptualization of flows was changed from discrete to continuous. The technical implementation of the ontology proved to be relatively inflexible.

Main case study In the CostaDue case study the SDM was improved and completed. A full-scale simulation engine for ABM modelling of λ-systems was developed, and knowledge and facts about chemical- and bio processes were encoded. An exploration was done of the evolutionary patterns related to the transformation of the Groningen Seaports region from a chlorine to a bio-based cluster. The agents had realistic economic properties and modular descriptions of technology, and they respected the mass balance. Basic economic reasoning was implemented through contract selection and price determination mechanisms. The possibility for the transition from a chemical to a bio-based industry was created by adding new bio-based technological options to the simulation. These options had been identified through a social process involving different stakeholders. The ensuing cluster evolution was studied under different economic scenarios representing various selection pressures. The main conclusions were that the bio-based options as identified by the stakeholders do not appear to lead to a diverse biomaterials-based cluster in the Groningen Seaports region. An enrichment of the existing cluster with bio-energy options is possible, the extent of which appears to depend on the survival of the incumbent energy-intensive industry. The importance of path dependency in cluster development is clearly demonstrated, as is the limited power that the Regional Development Agency has in controlling this evolutionary process.

Further case studies To provide a robustness and applicability test of the modelling process, model and simulation engine, three additional case studies were completed. In the Bulk Biochemicals study the performance and evolution of a bio-refinery cluster was investigated across a large economic scenario space. Latin hypercube sampling was implemented as a technique to examine this large parameter space. Multi Criteria Assessment was implemented as a rationalization of the RDAs cluster development process. This cluster is likely to emerge and be successful under the majority of economic conditions examined. Testing a variety of RDA strategies revealed that an increased rationality of the RDA does not improve the performance of the cluster, due to the limited number of technological options available.

In the Metals Network case the evolution of a global aluminum and copper production network was studied under different economic conditions and different agent investment strategies. The case study extended the agents reasoning with Net Present Value and Internal Rate of Return calculations, as well as added a dynamic world market with global interest rate developments, next to encoding a wealth of metallurgical processes. Global economic conditions and agent investment policies appear to have little effect on the development of this cluster.

The Bioelectricity study was completed to examine the evolution of the Dutch bioelectricity production network under different CO_2 tax levels and under different agent reasoning strategies. The incorporation of Life Cycle Assessment (LCA) enabled agents to reason about their environmental impact across their supply chain. Incorporation of the EcoInvent LCA database enabled the World Market to provide goods with associated environmental impacts from 3000 different production processes. The case solved a number of complex algorithmic and computational challenges in combining a static analysis tool (LCA) with a dynamic pattern generation tool (ABM). The main methodological outcome was a practical way to combine LCA with ABM. The study showed that high levels of CO_2 taxation allow for structural change in the way bioelectricity production is organized.

Results Returning to the idea of the four modelling aspects, the main accomplishment in the technical dimension is the design and implementation of the modular, open source simulation engine. Recognition of the necessity of recording its development history is important to the science and engineering of modelling. In the social dimension, the results are the formal System Decomposition Method (SDM), the community that has emerged around the tacit knowledge of co-evolutionary modelling processes and the models that have been developed and recorded in a wiki system. The results of the knowledge formalization process are the formalizations of the PSE, microeconomics, corporate finance, industrial clusters, evolution and Complex Adaptive Systems domains. This knowledge is formalized in an ontology. The practical outcome of the fact collection process is the encoding of large numbers of industrial processes, their flows and economic properties.

Domain insights On the basis of the modelling, case study results, insights from Complex Adaptive Systems and evolution theory, seven general guidelines for shaping and steering the evolution of industrial clusters can be given.

First, cluster development is strongly path dependent, and RDAs must strive to develop an understanding of clusters' future development patterns. Order of firm appearance matters. Second, once established, the network structure is relatively robust. Third, the social, legal, institutional and regulatory contexts can make or break a industrial network, even if the right firm and technology mix is present. Fourth, given the importance of past decisions and the chaotic nature of the evolutionary process, it is inevitable that mistakes will be made. Consequently, RDAs must at all times retain control of the land use for the lots under their control. Fifth, RDAs must be aware of the importance of diversity - in types of firms and in their physical installations, as well as in the options available for the same types of processes within their cluster. Without diversity, evolution is impossible. Sixth, the importance of the long-term view must be emphasized. In order to be able to plan the evolution of clusters, RDAs must be able to look ahead several generations of firms or technical installations. Given the average installation lifetime of 15 years or more, RDAs need to use a multi-decade perspective. Finally, RDAs must strive for balance. Too much top-down control will stifle change, and too much of bottom-up initiative will destroy the clusters coherence.

Conclusions Concluding, the execution of seven case studies in an evolutionary modelling process has allowed us to answer the three research questions and to conclude that the posed hypothesis that "the use of adequate models of λ-system evolution will improve decision-making abilities in industrial cluster development" was not falsified.

Central to this thesis has been the development of a method for creating models. Operationalizing insights from complex adaptive systems theory and evolutionary thinking, a modelling process - SDM - was developed using requirements for modelling process, content and outcome. It has been used to create consecutively "good enough" models of λ-systems evolution. These models are "good enough" in the sense that they provide useful insights that can support strategic decision makers involved in industrial cluster development. The main practical result presented is the description of the modelling process, a modular, expandable simulation engine, a collection of domain knowledge formalized in an ontology and the encoding of a large number of facts on industrial network elements. The main strength of the models presented in this work is that their system representation of λ-systems is intuitively understood by users and modelers. Their main weaknesses are large data requirement for realistic models and relatively complicated implementation. The main opportunities lie in the fact that ABMs represent an exciting new paradigm, through which collective understanding can be expressed. Main strengths of the modelling process are that it is a socially inclusive, adaptive process for long term capacity building with a high scientific output. Its weaknesses are that it is relatively expensive in terms of people and time, it has a slow takeoff phase, it is very dependent on the quality of the social network and is relatively "far out" of the ordinary modelling paradigm.

The co-evolution of the technical design of the models, the social process involved, the knowledge and facts encoded, and the process and outcome requirements of systems modelling have been set in motion. As this body of knowledge gathers speed and momentum it will continue to increase our understanding of λ-system evolution. We hope that it will ultimately contribute to a more sustainable human existence on planet Earth.