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Model Based Decision Support for Creation And Operation of Sustainable Infrastructure

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***Abstract*—This paper focuses on the use of system thinking, complex adaptive systems theory and modeling to help create and operate sustainable energy infrastructure. These are capital-intensive, long-lived large scale socio-technical systems that evolve over decades. To enable high-level decision support on climate policy, strategic investment decisions or transition management, we are evolving a simulation engine for Agent-Based simulation of infrastructure development. The key functionality and capability of this engine is its ability for playing out possible futures, to identify development patterns and conditions for sustainability by exploring multiple scenarios. Two of the models completed serve to illustrate the approach. These address the ecological impact of bio-electricity and the long-term effect of CO_2 policy on the electricity production technology portfolio. Limits and opportunities of the approach are discussed and an outline for future research is given.**

***Index Terms*—Agent based modeling, Complex Systems, Evolution, Infrastructure**

I. INTRODUCTION

A. *Sustainability*

With demographic developments, increasing welfare and technological capabilities, an increasing amount of economic, physical and ecological space is required for the human population which has more than doubled in the past 50 years [1]. Climate change [2], [3], habitat and biodiversity loss [4], [5], water scarcity and pollution, energy resource availability, socio-economic prosperity and equity have caused a continuously increasing demand for sustainability and have led to the possibility of a global system collapse [6]. Indeed, no sustainability related problem is isolated, but rather exists in a deeply interconnected and evolving web of interactions. Explicitly recognizing the interconnectedness of the global industrial system, one can state that these problems must be addressed at multiple levels, ranging from local, regional, national, continental or even global, and through multiple networks: social, economic, knowledge, energy, mass. These networks have evolved while society remains largely unconscious of the greater network of networks evolving. In the 21^{st}century we must learn how to manage this network of networks that forms the fabric of our society. We conjecture that to this end, we need new paradigms, new theories and new tools.

II. PARADIGM AND THEORY

A. *Large Scale Socio-Technical Systems*

The global industrial system and the infrastructure systems that increasingly form its backbone can be seen as Large Scale Socio-Technical Systems [7], or λ-systems [8]. This is a class of systems that span technical artifacts embedded in a social network. Large Scale Socio-Technical Systems include social elements such as operating companies, investors, local and national governments, regional development agencies, non-governmental organizations, customers and institutions. These develop around, sustain and depend on particular technical systems, be it a single plant, industrial complex or set of interconnected supply-chains. Examples of λ-systems are regional industrial clusters, power grids, multimodal transport networks and telecommunication networks [9].

B. *Co-evolution*

While the technical components of λ-systems *can* be engineered in relative isolation once requirements have been set, their social networks and the emergent system structures currently *cannot*. Instead, their state and structure we observe today have evolved as the result of a series of discrete decisions by a myriad of involved stakeholders, who act to pursue or safeguard their interests. Each actor is subject to influence, pressure, opportunities and constraints from within and external to the network. Global markets, national and international rules and regulations, availability of and access to capital, knowledge and skilled labor are external to λ-systemsexcept the global industrial system. Internal pressures are caused by, e.g., changes in the composition and preferences of the working populations, or by replacement of old assets with new, more advanced ones. Thus, the global industrial system, our industrial society, can be viewed as a collection of co-evolved λ-systemsṪhese are dynamic, multidimensional networks whose internal structures and functions change over time. Given this evolutionary nature of the the industrial system, we require models that allow us to adequately represent such evolution λ-systems.

C. *Complex Adaptive System*

a) Evolution: While the state of an engineered, technical system can be predicted, often to high-levels of accuracy, the state of a λ-systemcannot because rather than having been

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engineered it has evolved, and the state of any evolving system is intractable [10]. A system being intractable means that no model or simulation can be predictive of the exact details of the evolutionary development of any particular λ-system in response to a given change. Any evolving system is chaotic, its future state not only may differ because of random input received from its environment but is also potentially sensitive to small parameter value changes. It is a complex adaptive system (CAS). This however does not imply that we cannot predict any characteristic of λ-systems. Evolving systems are path dependent and they have a robust, characteristic attractor structure. This means that evolving systems come *from* somewhere and that they preferentially 'want' to go *to* somewhere. Every evolving system has a stable *pattern of possible regions* (attractors) it can be in. Exactly which state the system will take is impossible to know in advance, but we might be able to estimate to which attractor (region) it will head. By carefully changing a system's parameters, namely the identity of its components, their interactions or the system's environment, we can steer or at least alter the path of the evolutionary process. If we steer correctly, we *might* prevent the system from going towards an undesirable attractor, even if we do not have control over its exact state.

b) Generative science: To learn how to manage networks of networks for sustainability we need a holistic paradigm. The central connectionist principle is that all phenomena can be described by interconnected and interconnected networks of simple units. This approach, also called Generative Science [11] describes complex behavior as a generative process. In this approach, deterministic and finite rules and parameters in the natural sphere interact to generate indeterministic and infinite system behavior. In generative science, the agent or individual component, is the theory, as it is often said. By having an explicit behavioral model of a individual, or the smallest level component, we can build/generate large-scale systems, observe and try to explain their characteristics.

In the traditional scientific paradigm since Bacon, to understand a system one would break it down into small components to be tested and experimented on in isolation. However, according to Mikulecky [12] complex systems like λ-systems can only be understood when studied from multiple perspectives requiring multiple formalisms. That is, integrating knowledge of various domain and disciplinary experts in a formalized way is essential for capturing the properties and behavior of a system. One could say that modeling λ-systems requires that knowledge from many persons' heads be transformed into a single formal model. Furthermore, studying λ-systems from the traditional reductionist paradigm *a priori* usually results in models that assume static components interaction structure, removing from view the emergent and evolutionary properties of λ-systems, while this is exactly the behavior that is of interest to researchers and planners of sustainable infrastructure. A more appropriate approach therefore is to experiment with computer models that can simulate λ-systems evolution and behavior to explore patterns of behaviour and system-attractors. Although quantitative models can never attain full predictive precision, they do enable qualitative inferences about the development and behavior applicable to the real systems.

c) Agent Based Modeling: To understand λ-systems, knowledge from multiple perspectives needs to be used in computer simulation models. The most promising simulation tool, directly stemming from CAS research, and at the core of generative sciences is Agent Based Modeling (ABM). Shalizi [13] states that: "an agent is a persistent thing which has some state we find worth representing, and which interacts with other agents, mutually modifying each others' states. The components of an agent-based model are a collection of agents and their states, the rules governing the interactions of the agents, and the environment within which they live."

Let an agent represent some individual, relatively autonomous entity such as a cell, a species, an individual, a firm, a nation. Complex Adaptive Systems can then be defined as a "dynamic network of many agents acting in parallel, constantly acting and reacting to what the other agents are doing. The control of a CAS tends to be highly dispersed and decentralized. If there is to be any coherent behavior in the system, it has to arise from competition and cooperation among the agents. The overall behavior of the system is the result of a huge number of decisions made every moment by many individual agents." [14] CAS brings the necessary theories together in a unified framework but in its current state it does not allow us to operationalize our holistic paradigm and describe or emulate real λ-systems.

ABM clearly provide a way to describe entities, their interactions and the overall system state we are interested in.

III. MODEL BASED DECISION SUPPORT

A. Problem formulated

Our hypothesis is that the use of adequate models of λ-systems evolution will improve decision-making on sustainable infrastructures. We propose that a managed evolution in both physical and social dimensions is required to shape λ-systems and ensure their sustainable future and feasibility. Furthermore, we propose that such an evolutionary process can be steered by the design of the λ-system's external world (top-down) and the adaptation and expansion of the available set of technologies or system components (bottom-up).

By playing-out scenarios in a simulation, we may reduce uncertainty by answering "what if" questions and communicate the insights back to the systems stakeholders. Our objective is to increase our knowledge of λ-systems evolution patterns by simulation of physical and social network evolution, where technologies and stakeholder identities as well as external regimes vary. The ultimate goal is to provide decision support for those involved in shaping the development of λ-systems. The problem can be formulated as "how to develop modular, adaptive models, using knowledge from wide array of disciplines that are useful for aiding the stakeholders in creating and operating sustainable infrastructures".

B. Criteria for Model Development

We postulate that a model development process must follow requirements outlined in table I.

TABLE I
OVERVIEW OF PROCESS AND OUTCOME REQUIREMENTS

Process	Outcomes
Open source	Useful
Sufficient community diversity	Testable
Organically growing	
Recorded history	
Enforceable authorship	
Modular	

The requirement of open source calls for the availability of all knowledge and data needed to perform the modelling exercise.

The community diversity requirement ensures that a sufficient number of formalisms, in the form of different domain experts and modelers, is present in order to deal with the multiformal nature of the λ-systems we are attempting to understand.

The requirement of organic growth is based on the concept of local optimization, that is, every change to the design should be directly useful and should improve a direct problem. Furthermore, organic growth is bottom-up, ensuring the involvement of all stakeholders.

The requirement of recorded history ensures that all changes to the software, formalized knowledge and collected facts are recorded and can be undone if necessary.

Based on the previous requirement of recorded history, we also need to know *who did what and when*, both for credit and blame.

The requirement of modularity ensures maximum flexibility in the design, as it jointly enforces a standard interface between components and allows for the piecemeal replacement of components that become inadequate.

The usefulness requirement has been defined at two levels: that of the process and that of the model's outcomes. A step in the process must either be useful in further improving the process itself or by providing an improved model.

The requirement of testability ensures the scientific nature of the entire exercise. If a developed model or process cannot be tested, it cannot be verified.

C. Approach

To create modular and adaptive models, we have developed and applied a modeling process that itself is an evolutionary process. Therein, four aspects of the modelling process interact: the technical design of the model, the social process for knowledge formalization and modelling, the knowledge formalized and facts collected. These can be considered the four dimensions of fitness landscape. In this landscape, whenever an aspect in one dimension changes, the fitness of the other aspects is affected. For example, when the technical design is extended to incorporate a new formalism, the social process design aspect becomes less fit, as the model developers initially will be unable to encode this new type of knowledge until their understanding of it has improved. The modeling process progresses in generations, each of which consist of a case study completed, improving different aspects with every generation. The process is co-evolutionary: changes in one dimension create new possibilities and challenges for other dimensions and the results of the interaction drive the overall process forward.

The guidelines and requirements defined above have lead to the evolution of the System Decomposition Method, a social process used to create a shared insight into the problem structure. The SDM has been reported in more detail in [15]. It is essentially a collaboration script that, following the criteria and guidelines, allows for reliable and repeatable knowledge identification, structuring, collection and formalization. The SDM results on a formal shared ontology defining the relevant concepts, a collection of facts contained in the ontology and a conceptual design of the simulation of the problem at hand.

The formalized conceptual design is implemented in the simulation engine, a modular hardware-software stack that consists of a wiki-based knowledge acquisition and management system, a source-code versioning system, generic simulation components and a specific model. Several case studies have been developed using the evolving system designed in the guiding principles and requirements. As will be shown, the use of a common platform creates an environment where people focusing on different problems can leverage others diverse approaches and insights into further improvements in the modeling platform. As showed below, the setup allows for a broad variety of models. This strategy means that others efforts are not lost but contribute to a design process involving the iterative refinement of collective knowledge.

The foundation of the model is based on a physical and socio-economic model where agents must buy resources and then sell what they produce. From this simple concept, supply chains self-assemble. The case studies performed investigate different technological systems and different behavioral aspects. Several layers of behavior can be explored ranging from more immediate daily operational concerns, to longer term strategic decisions.

D. Description

1) Social process:

a) SDM: The SDM is a practical and structured collaboration script that extracts unformalized knowledge residing in the heads of domain experts and stakeholders and converts it into an agent-based model. The collaboration script has been reported in [15], and we will not elaborate on in for the sake of brevity. The SDM process consists of a number of knowledge states and knowledge interfaces. Starting with a stakeholder's question, knowledge about a λ-system's state and behavior moves from the unshared and unstructured knowledge held in different minds, across the soft-soft interface to a shared unstructured state. From there, the knowledge moves across the soft-hard interface, where it is structured into an ontology, becoming shared and structured. This knowledge then crosses the hard-hard interface, becoming a model specification. The final transition is across the hard-soft interface, where the model is used by the stakeholder to answer the initial question.

2) Simulation engine: The simulation engine design consists of several modular components. These are the hardware and operating system, knowledge management, simulation software, and data and knowledge processing & analysis. We view the simulation engine as an integrated physical-logical experimental device, allowing us to explore the synthetic universe contained within it. The engine design is guided by the guiding principles and requirements presented above.

a) Hardware and Operating System: The relevant requirements at this level are open source, organic growth and modularity. Currently, the main way to increase the performance of a computer is to increase the number of processing units (CPUs), allowing many model runs and analyses to be executed in parallel. The natural choice for scalable, flexible clusters is the GNU/Linux operating system.

b) Knowledge Management: Large amounts of data and knowledge are necessary for model based decision support that needs to be stored and managed. The knowledge management component of the simulation engine consists of several modular components. The knowledge management system needs to satisfy the following requirements: provide enforceable authorship; provide an unchangeable historic record; be modular; and be open source.

Next to authorization and authentication, a system is needed to create, organize and manage the content. Wiki allows users to freely create and edit Web page content using any Web browser. Wiki is mainly used to store unformalized knowledge.

In addition to the unformalized knowledge managed by the wiki, there is a need to manage formalized knowledge. There are two types of formalized knowledge that need managing: the "What Is" knowledge and the "How To" knowledge. The "What is" knowledge is maintained in a formal ontology. This is stored and managed through the Protégé , a free, open source ontology editor and knowledge-based framework. The formal "How to" knowledge consists of computer algorithms that describe how things are to be done. This knowledge is stored in a file version control system, Subversion. Subversion allows for the free experimentation with files and computer code and removes the fear of breaking things, as there is always the previous version.

c) Simulation Software: The simulation software is developed in the Java language using Eclipse Integrated Development Environment. The Recursive Porous Agent Simulation Toolkit (Repast) [16] is used as the basic Agent Based Model platform. It schedules agents interaction, does all the data collection and facilitates parameter sweeps.

d) Simulation Generics: Modularity is an important modeling requirement that reduces the time needed to develop a model, reduces the number of potential errors in models and allows for easier and faster collaboration, since it reuses existing and tested code. This notion led to the development of Simulation Generics, a collection of model components that can be reused in any model developed using the ontology.

IV. CASE STUDIES

A. Bio-electricity and LCA

1) Case description: The case on bio-electricity [17], [18] focused on the integration of Life Cycle Analysis (LCA) within the Agent Based Modeling (ABM) framework. Agents were created to represent actors within a supply chain network, stretching from the producers of biomass all the way to electricity generating power plants. Power plants were given the choice of using a range of biomass or fossil-based fuels, which in turn would determine which types of supply chains were viable. Agents were given the choice to either buy feedstocks with either the lowest cost or the least environmental emissions, based on the results of an LCA conducted by each agent in the simulation.

2) Objective: The objective of this case study was to show that this combination of tools could be achieved, allowing for global-level analysis of dynamic, growing infrastructure subject to different policy and economic scenarios. Since one of the motivators for bio-electricity is the potential for CO_2 reductions, LCA is an important tool due to its ability to account for emissions occurring throughout the global supply chains and to help assess whether this represents (more) sustainable infrastructure. The recent controversy on the conversion of rain forest into palm oil plantations [19] has demonstrated the importance of such a global and dynamic perspective. For policy makers, this type of analysis is important since they are interested in creating legislation that effectively lowers CO_2 emissions, while avoiding unanticipated negative side effects. These side effects can occur throughout space (who is connected in the supply chain) and time (how the system evolves).

3) Results: It was found that many of the defined large-scale technologies currently in-use in the electricity infrastructure were limited in their range of options to achieve possible emissions reductions. This was due to the assumption that many large-scale power plants could only use a limited amount of biomass as fuel. So even though the agents operating these technologies may have tried to choose the "greenest" feedstock, this did not make as much difference as changing the portfolio of technologies used to generate electricity.

4) Insights: Combining LCA within ABM enables an LCA to be performed dynamically where the ABM is used to generate complexity due to the interactions of the agents, and the LCA is used as a type of network metric to analyze the characteristics of the system that has emerged [17]. In using this model, we were able to explore several different configurations of bio-electricity supply chains that could emerge based on different policies. Creating this model has shown us how the ABM simulation engine can be expanded to use environmental analysis tools to better analyze the sustainability of dynamic systems.

B. Carbon policies' impact on Power Generation

1) Case description: A series of models were developed [20]–[22] to evaluate the merits of policies aimed at CO_2 reduction. Nowadays in the electricity infrastructure, central planning is largely absent. Change in the power generation portfolio and its characteristics is through investment of individual, autonomous companies in response to demand variation and market signals. Therefore, also the effect that policies have is ambiguous: it is dependent on the actions of the companies in the power sector and many external factors.

2) Objective: The main objective of these models is to gain insight in the co-evolution of technological capability and characteristics, the development and implementation of policy and the behavior of actors in the power generation sector. The first development was to outplay the effect of the European Emission Trading Scheme (ETS) on power generation [20], [21]. A second development included a different set of assumptions and the comparison with the much debated alternative: carbon taxation [22].

3) Results: All models of this series combined modeling creation and operation of infrastructure. Not only investment in electricity generation technology by power producing agents is central, but also power and fuel trade is modeled to sustain daily operation. The different carbon policies, emission-trading and carbon taxation have been implemented to assess their potential impact on this λ-systemwhile it evolves over decades. Power producing agents strategically manage by investing in new power plants or dismantling existing ones with unique sets of criteria to do so and are aware of the policy in place, optimizing their behavior. In addition, electricity producing agents exhibit operational behavior by negotiation and engaging in contracts. The modeled system contains also other agents, i.e. government, markets for CO_2 rights, power and fuels, power consumers and the underlying technology (power plants, consumer technology, physical networks and flows). Scenario analysis was used operationalize the parameter space and outplay system developments under different exogenous conditions and trends.

4) Insights: The main insights from these model development trajectories include are on the content and on the development process. On the content: When one assumes emission rights can be imported from other sectors and countries, it is unlikely that emission trading will contain the CO_2 emissions from power generation [21]. When one assumes the contrary - there is a fixed amount of rights available for the sector only - it is likely to be outperformed by carbon taxation in terms of effectiveness and efficiency [22]. This exercise showed that agent-based modeling can be used to allow decision makers for better informed decisions on their sustainability policies: they can play with possible scenarios, pull and push the virtual levers of the system and observing the models' sustainability indicators. It showed that we need models to understand even parts of these complex systems and that we need a solid approach to successfully develop such models. Finally it brought up many new questions for modeling and analysis of the results.

V. LIMITS AND OPPORTUNITIES OF THE APPROACH

A. Models

a) What the models can *do:* The main thing that Agent Based Models of λ-system evolution can do is to help us explore and provide a sense of the range of possible system futures given an explicit set of assumptions. By examining the models across a wide range of parameter values, a map or pattern of possible future development can be seen, depending on, for example, market changes, the introduction of new technologies, policy changes or changes in management styles of individual actors in the modeled system.

Humans are relatively weak at systematic reasoning across a myriad of interactions between system elements, but are excellent at pattern recognition. Computers, and computer models are, as Steve Jobs has observed, "bicycles of the mind" [1], systematically exercising the relations between system elements, creating complex behavioral patterns. It is up to us to interpret those patterns.

The created models are built on objective physical characteristics and mechanisms of technical networks and on the beliefs and assumptions of stakeholders about the properties and mechanisms of the social network. Using the created ABMs of λ-system evolution provides us with a formal mechanism for testing the understanding and the intuition of the stakeholders. The ABMs often surprise us by showing emergent properties - logical but nonetheless surprising - caused by unpredicted interactions of agents.

b) What the models cannot *do:* The models produced each have a different focus: some focus on the strategic level and others on the tactical or operational level. The models are meant to support the thinking process of decision makers and therefore are inherently limited in scope. Dijkema and Lukszo have explored the implications of linking operation and evolution in a single model [23].

On a more fundamental level, there is a theoretical limit to what any generative model of an evolving system can do. Evolution is intractable, so there can never be a model that can exactly predict the future state of an evolving system. We may however find models that provide *good enough* predictions, for varying levels of that qualification, given certain resources.

B. Process

c) What the process can and cannot *do:* The co-evolutionary modelling process as presented in this paper can integrate many different formalisms into a single coherent vision on λ-system evolution. It can involve many different participants in collaborating on a greater whole, greatly increasing the overall output of the process. The process, being a Complex Adaptive Systems itself, can display emergent, surprising outcomes. If the process requirements are followed carefully, these emergent outcomes will be useful and insightful.

On the other side, the process cannot be used as a top-down steering mechanism, as it is by design bottom-up and

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[1] http://www.youtube.com/watch?v=PUagMQZ_WFQ

distributed. Also, the co-evolutionary process can not guarantee any particular outcome, due to its chaotic nature, and finally, the co-evolutionary modelling process is not something one can perform alone.

d) When should the process be or not be *used?:* The process is suitable in supporting long-term multidisciplinary research with a coherent theme. It is useful when the modelers wish to build strong relationships with stakeholders, and the problem addressed is complex, multi-actor, multi-perspective and multi-scale.

The presented model should not be used to create 'quick and dirty', one off models, nor should it be used when it is important to urgently answer a new, burning question. The process is a long-term, multi-person effort that does not downscale well. It is also not suitable for rapid model prototyping and testing of ideas, unless they are evolutionary off-shoots of a larger modeling process.

VI. CONCLUSION

Model based decision support for the creation and operation of sustainable infrastructure is a daunting challenge that we have only begun to explore. In this paper we have given an overview of the system conceptualization we deem useful, large-scale socio-technical systems, and we have given an overview of the modeling approach developed. Therein, we create models as a means to conceptualize complex systems and to test how the relationship between entities can affect the overall system behaviour. This requires an extensive simulation engine or software stack, that we have only touched upon. Two models, LCA of an evolving bio-electricity infrastructure and a model to assess the effect of carbon policy serve to illustrate the applicability and power of the approach. The core issue we have addressed is the modeling process. Creating models of infrastructure, λ-systems, ultimately means dealing with systems of such a scale and complexity that it requires a collective effort to conceptualize these systems. Therein, different domain experts must contribute and interlink their knowledge of these systems. In the development of a suitable, collective modeling process, we have observed that it is a non-trivial exercise to take tacit knowledge from experts and convert it into a form usable within a model. A detailed collaboration script has been developed. The use of social software allows us not to only formalize and represent knowledge, but also to capture it and make it available for review and improvement. Thus, a set of theories and tools has been created that truly supports an ongoing evolutionary modeling and simulation engine development process. The illustrations led us to believe that we are on an attractor - we are on a route that will enable us to provide model-based decision support.

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[2] http://www.nginfra.nl/

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