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A CONCEPTUAL FRAMEWORK FOR ECO-INDUSTRIAL PARKS

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ABSTRACT

An eco-industrial park is a set of businesses that share resources in order to increase profitability and reduce environmental impact. The implementation of eco-industrial parks may significantly contribute to the creation of a sustainable economy. Despite this prospect, the actual development of eco-industrial parks is challenging, as a variety of factors must be considered. Not only technical, economic, and environmental factors are relevant but numerous stakeholder relationships as well, such as between firms, governmental bodies, and local communities. This paper presents a conceptual framework that is used to capture these diverse aspects and the relationships between them. The Unified Modeling Language (UML) is used for modeling its concepts and relationships. First, based on a literature survey, relevant concepts of eco-industrial parks are identified. One central concept is “industrial symbiosis”. A novel value-based interpretation of industrial symbiosis is presented. Second, the park’s economic, local and regional development context, as well as its internal technical components and their relationships are modeled. Finally, the framework is used for modeling a concrete eco-industrial park, in this case part of the Kalundborg eco-industrial park.

1. INTRODUCTION

Eco-industrial parks can be defined as a set of businesses within a specific geographic area which share resources and thereby increase profitability, reduce environmental impact, and improve social performance [1]. The concept of eco-industrial parks emerged during the 1990s in the context of industrial ecology [2]. Industrial ecology basically attempts to create industrial economies that are sustainable. Natural ecologies serve as a model or metaphor [3; p.1], [4]–[6].

2. BACKGROUND ECO-INDUSTRIAL PARKS

An eco-industrial park (EIP) is proposed as one approach towards a sustainable economy. Contrary to product or firm-specific sustainability approaches, EIPs have a much larger scope. Their influence stretches over three different levels: the firm, across firms, and regional and global [7]. The analysis of existing parks in China, Denmark, and Finland suggest that EIPs can substantially reduce waste and resource consumption over their life cycle [8]–[13]. Despite the promises of the EIP concept, the large number of unsuccessful EIP initiatives in the USA and Europe indicate that planned EIP development is challenging [14]. Some of these challenges are pertinent to large-scale infrastructural projects in general, such as geographic attractiveness and managing complex stakeholder relationships [14], [15; pp.25-28]. Some challenges are specific to EIPs such as the implementation of by-product exchange relationships between EIP participants, called industrial symbiosis. [16; pp.987-988], [14; p.1685]. Current research suggests that initiatives by governmental actors alone, without the support of firms, do not lead to successful EIP development [16]–[19].

Research on EIP development has just recently started. Romero & Ruiz [20] use adaptive complex systems theory for modeling and simulation of EIP operations, integrating economic, environmental, and social aspects. Romero & Ruiz [21] explore how system dynamics and agent-based modeling can be used for modeling and simulating the evolution of EIPs. Rosa & Beloborodko [22] propose a qualitative decision-support tool for evaluating existing industrial symbiosis. A scoring system is used, which takes geographic proximity, economic, and ecological performance into account. Cao et al. [23] have demonstrated the use of agent-based modeling for simulating the dynamic behavior of a hypothetical EIP. Coté et al. [24] and Chertow [25] describe existing and possible approaches to design eco-industrial parks such as guidelines, input-output matching, stakeholder processes, and material budgeting. Haskins [26], [27] and Maya Sopha et al. [28] identify disciplines that may contribute to the understanding of EIPs and ultimately how to develop them. They identify disciplines such as supply chain management, stakeholder analysis, and systems engineering. The variety of stakeholders involved in EIP development calls for a sociological analysis of EIPs. Eilering & Vermeulen [29] identify a range of social enabling factors for the successful development of EIPs. Spekink [30], [31] use event sequence graphs for mapping out the key events that lead to the foundation as well as evolution of an EIP. Ashton [32] uses social network analysis to analyse the network of actors involved in the evolution of EIPs. Zeng et al. [33] use social network analysis to analyse the vulnerability of EIPs. Furthermore, a number of optimization approaches for EIPs have been presented in recent years [34]–[38]. Schulze [37, pp.68-75] provides a comprehensive overview of existing EIP modeling and optimization approaches. The optimization objective is to find by-product exchange networks in EIPs that maximize economic and environmental performance.

To summarize, the existing literature on EIP development mainly deals with their evolution and identification of optimal configuration of exchange relationships. However, a number of aspects have not yet been addressed. For example, there is currently no approach for assessing EIP performance across different economic and regulatory contexts. Another important aspect that is not yet addressed by existing research is how different potential EIP configurations deliver value to key stakeholders.

Table 1: Overview of EIP development publications

Publications	Domain / methods used	Contribution
Haskins [26], [27], Maya Sopha [28]	Systems engineering, complexity science	Identification of systems engineering approaches for developing EIPs
Eilering & Vermeulen [29]	Sociology	Identification of social enabling factors for EIPs
Cao et al. [23], Kim et al. [34], Gu et al. [35], Maillé & Fraillet [36], Schulze, [37], Monteiro et al., [38]	Simulation / Optimization	Agent-based simulation of a hypothetical EIP; mixed-integer programming for generating EIP configurations
Coté et al. [24], Chertow [25]	Environmental sciences	Guidelines for developing EIPs
Desrochers [17]–[19]	History	Centralized planning without stakeholder involvement will probably fail.
Ashton [32]	Organizational sociology, economic geography	Exploration of relationships between EIP participants
Sun et al. [39]	Economics	Uncovering symbiosis by financial dependencies between EIP participants

This paper provides the basis for addressing these gaps by presenting an initial conceptual framework for EIPs. The framework provides a conceptual basis for later tradespace exploration and optimization of EIPs.

3. CONTEXT AND OBJECTIVES

A number of French companies are currently interested in the concept of EIP due to its potential economic and ecological benefits. One of the potential sites for such a future EIP is in the port city of Le Havre. Numerous companies are located in the city's industrial zone. However, for assessing the viability of a potential EIP, they need to answer the following questions:

- a) Which aspects need to be taken into account in order to make a decision for investing into the development of an EIP?
- b) What are the costs, benefits, opportunities, and risks of an EIP throughout its lifecycle?
- c) Who are the key stakeholders that need to be considered?
- d) How do different EIP options deliver value to key stakeholders?
- e) Which development strategies are suitable for a specific EIP?
- f) How can system properties such as flexibility and robustness built into an EIP for providing value to stakeholders in changing contexts?

Most of these questions have only be partly addressed by the existing literature. In order to answer these questions, we use a systems architecting approach, as illustrated in Fig. 1 [40], [41]. Systems architecting deals with the initial stages of systems development where stakeholder needs are translated into requirements and a first high-level design of the system, often called "system architecture" [42; p.22]. Recently, systems architecting has been introduced to developing urban areas and large-scale infrastructures [43], [44]. systems architecting methods are for example tradespace exploration, where a large number of system architectures is automatically generated and evaluated with respect to classical criteria such as cost and performance [45], [46]. Non-traditional criteria such as flexibility and robustness in changing contexts have also been considered [5]. Another method is stakeholder analysis, where actors that have a stake in the system are identified and prioritized [15], [47], [48]. Stakeholder analysis is crucial for large-scale engineering projects, as they often fail due to the negligence of key stakeholders [15]. Hence, systems architecting is the natural choice for answering questions a) – f).

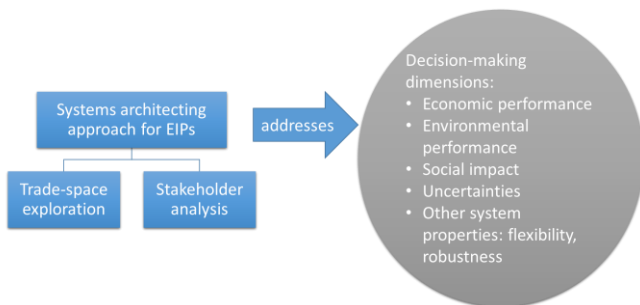


Fig. 1: Using systems architecting for addressing key EIP decision-making dimensions

The following two steps are proposed for answering questions a) – f):

1. Develop a conceptual framework for EIPs that specifies its elements and relationships between these elements. It furthermore specifies the various views on EIPs such as economic and environmental. The conceptual framework serves as a qualitative basis for quantitative models. It answers question a) and c).
2. Based on the framework, a quantitative techno-economic model is derived, which is used for exploring different EIP architectures by tradespace exploration. The resulting architectures are evaluated with respect to costs, benefits, risks, and, opportunities. The techno-economic model intends to provide an answer to question b), d), e), f).

This paper will deal with the conceptual framework from point 1 which lays the groundwork for point 2.

4. CONCEPTUAL FRAMEWORK

Developing a conceptual framework or conceptual model is a common step in modeling [49; p.9], [50; p.547]. The framework defines the entities and their relationships that need to be modeled for achieving the modeling objectives. This step precedes the development of a quantitative model. For example, a conceptual model for a pendulum may consist of a string and a weight attached to the string. The quantitative model then goes on to define parameters such as the mass of the weight and string as well as differential equations. The quantitative model is used for analyzing the motion of the pendulum. Hence, the conceptual framework serves as a basis for building later quantitative models. For constructing the framework, mainly data from available literature is used. It is validated by EIP and industrial engineering experts.

The conceptual framework is divided into a context model defining the EIP and its context and an internal model defining the EIP's internal elements. The separate modeling of a system's context and its internal structure is a standard practice in systems engineering [51], [52]. It helps to distinguish between what is part of the system and what is considered outside of the system boundary. We model the conceptual framework by using the Unified Modeling Language (UML) [53]. As UML originated in object-oriented software engineering, it distinguishes between "class" and "instance". A class can be interpreted as a template for instances. For example, the class "car" may have the attributes "maximum speed" and "fuel consumption". An instance of a car has concrete values associated with its attributes. For example, the "Ford Model T" is an instance of a car with "maximum speed: 72 km/h" and "fuel consumption: 0.17 l/km". UML class diagrams are used for defining classes and their relationships. It is used here for defining EIP model elements, taxonomies of model elements, attributes, and relationships. EIP instances are represented by the Systems Modeling Language (SysML) internal block diagram. SysML is a derivative of UML for systems engineering [54]. The internal block diagram can be interpreted as a "box-and-arrow" diagram. The "boxes" are instances and arrows are flows between instances. Flows enter and exist instances via interfaces. These interfaces are called "ports".

4.1 MODELING INDUSTRIAL SYMBIOSIS

One key concept pertaining to EIPs is "industrial symbiosis". Therefore, a conceptual framework for EIPs needs to include this concept. Industrial symbiosis describes a by-product exchange relationship in an industrial economy [55; p.2]. An extensive body of literature on industrial symbiosis has been published during the last decade and a half [56]. Two widely cited definitions of "industrial symbiosis" are from [25] and [57]. Chertow [25; p.314] elaborates that "industrial symbiosis engages traditionally separate industries in a collective approach to competitive advantage involving physical exchange of materials, energy, water, and by-products" [25; p.314]. In order to put an emphasis on more complex exchange relationships than simple one-way exchanges, Chertow [57] introduced the "3-2 heuristic". The heuristic requires that "at least three different entities must be involved in exchanging at least two different resources to be counted as a basic type of industrial symbiosis." [57]

Industrial symbiosis is usually attempted for [57; p.13]:

- Increasing economic efficiency.
- Ensuring long-term availability of critical resources such as water, raw materials, and energy.
- Reacting to regulatory pressure such as taxes on emissions and waste production.

The existing definitions of "industrial symbiosis" mostly focus on the physical aspect of the by-product exchange such as matter and energy. In this section, we will propose a wider perspective on industrial symbiosis that integrates the creation and delivery of different forms of value to stakeholders. A value-centric interpretation of industrial symbiosis is crucial for applying different systems architecting methods, as these strongly rely on the notion of "value" for evaluating systems architectures. Paquin et al. [58] mention the connection between industrial symbiosis and value. We recognize that the notion of "industrial symbiosis" has its origin in the biological notion of symbiosis. Therefore, we will demonstrate that a value-centric interpretation of symbiosis can be traced back to the literature on biological symbiosis, where it is expressed in terms of "cost" and "benefit" [59]–[64].

In biology, “symbiosis” was formerly associated with the notion of “mutualism”, where both species benefit from a prolonged interaction. For example, flowering plants that provide nutrition to butterflies and butterflies that disseminate the pollen of these plants. “Benefit” is defined as an increase in fitness. Fitness in the context of evolutionary biology is linked to a species’ ability to survive and reproduce [65; pp.1-19]. A flowering plant that provides nutrition to butterflies is more likely to reproduce, as the butterflies distribute its pollen. Influential definitions of industrial symbiosis such as Chertow [25]¹ explicitly refer to biological mutualism as a source of inspiration [25; p.314]. The benefits from a mutualistic relationship often come at a cost. “Cost” is defined as a form of investment [64]. A flowering plant that provides nutrition for butterflies invests in the production of nutrition. The relevant types of mutualism from Connor [64] are listed in Table 1.

Table 2: Mutualism types according to Connor [64]

Mutualism type	Characteristics
Byproduct exchange	Species A provides a byproduct for species B from which B benefits. A is not investing in the byproduct.
Reciprocity	The same as byproduct exchange but A expects a compensation. However, B has the possibility to withhold compensation.
Pseudo-reciprocity	Same as reciprocity without a possibility to withhold compensation.

It is worth mentioning that mutualism is only one form of symbiosis. A wide range of other persistent interactions between distinct species fall under the term symbiosis, such as parasitism [66].

The cost and benefit aspects of symbiosis are particularly relevant when it comes to industrial symbiosis. Although the biological notion of symbiosis serves as an inspiration, it is clear that it cannot be directly applied to industrial economies.

Table 2 provides an overview of the commonalities and differences between biological and industrial symbiosis with respect to key characteristics.

Table 3: Comparison of biological and industrial symbiosis

Characteristic	Biological symbiosis	Industrial symbiosis
Unit of analysis	Species and their relationships	Industries and their exchange relationships
Symbiosis development	Evolutionary	Evolutionary or deliberate planning
Exchange objects	Nutrition (larva - ants), protection (ants protect larva), locomotion (bees - pollen),	Physical objects (CO ₂ , vapor, biomass, gypsum), financial

¹ 611 citations according to Google Scholar in January 2015

	hunting support (luminescent bacteria - anglerfish), intermediate process (digestion bacteria - humans)	(money, shares), societal (infrastructure, workforce)
Symbiosis value	Fitness increase (evolutionary value)	Economic competitiveness (economic value), sustainability (environmental value), local, regional, national development (societal value)

However, a direct transfer of biological “cost” and “benefit” to industrial symbiosis would be flawed. As Ayres [6] has pointed out; biological “cost” and “benefit” need to be understood in a purely evolutionary context. “Cost” and “benefit” in industrial symbiosis is related to economics with its market mechanisms as well as other social concepts such as political influence. For using the economic and social notion of “benefit” in industrial symbiosis, we use the more common term of “value”. “Value” is a measure for the extent to which an actor receives a benefit at a cost in an exchange, such as buying a product in exchange for money. Value is not limited to economic exchanges but can be extended to other forms of social exchanges [67]–[69].

Using the notion of “value”, a value-based definition for industrial symbiosis can be formulated:

An industrial symbiosis can be defined as an exchange relationship where byproducts and utilities of industrial plants are used as resources in other, distinct industrial plants, thereby creating economic, environmental, and societal value for stakeholders.

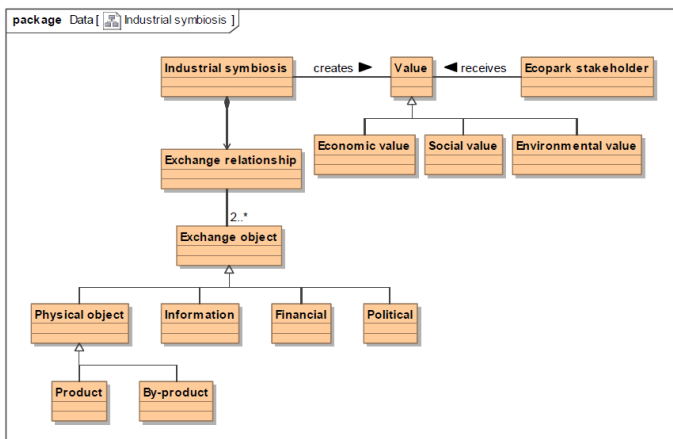


Fig. 2: Industrial symbiosis model

For an exchange relationship to be an industrial symbiosis, it needs to at least deliver economic and environmental value. Fig. 2 shows how the value industrial symbiosis generates is delivered to EIP stakeholders. Another important aspect is that an industrial symbiosis is an exchange relationship. A by-product that would otherwise be disposed provides value to the symbiosis partner. In exchange, the partner provides some form of compensation, for example informational, financial, and political. Hence, similar to the symbiosis taxonomy from Connor [64], such an exchange can be termed “reciprocal symbiosis”, as the exchange of value is or is expected to be bidirectional. Similar to biological symbiosis, creating industrial symbiosis incurs cost, mostly for the construction of the exchange infrastructure but also its operation. Contrary to biological symbiosis, the infrastructure for industrial symbiosis can be funded by sophisticated project financing methods, such as debt and equity financing or by establishing public-private partnerships [70; Chapter 8], [71], [72].

The advantage of a value-centric definition of industrial symbiosis is that it merges the spheres of material / energy exchange, relevant in industrial ecology with economic and social exchange relationships from mainstream economics and sociology.

4.2 EIP CONTEXT

Fig. 3 shows the EIP and its context. An EIP is characterized by its economic, environmental, and social effects. These effects may lead to the creation of value for EIP stakeholders. EIP stakeholders have an interest in the EIP and can also affect the EIP. A specific type of EIP stakeholder is an EIP company. An EIP company is an owner of an EIP element such as a power plant. The EIP can have a governing body that oversees the EIP’s development and operation. The governing body usually consists of EIP stakeholders. In general, EIP stakeholders can take part in relationships with other EIP stakeholders. Stakeholders can be competing, cooperating, or indifferent. For example, collaboration between companies is a prerequisite for forming an EIP [25]. Relationships can also be defined by value exchanges between stakeholders. Types of value exchanges are financial, political, goods and services [15]. Geography also plays a crucial role in EIP development [14]. The topology of the land influences the cost of constructing plants and exchange infrastructure. For example, terrain features such as rivers and hills increase the cost of constructing a pipeline [73], [74; p.72]. Preexisting industry may provide a supply of highly qualified personnel as well as an established transportation infrastructure. Furthermore, ownership of land influences its availability and the cost of buying or leasing it. Finally, an EIP must be financed. Project financing deals with funding large engineering projects [70; Chapter 8], [71], [72]. The financial mechanisms for financing an EIP can consist of various debt and equity financing schemes [70; Chapter 8]. Allocating risks to investors is a key criteria for choosing a financing scheme [75].

After the EIP context has been modeled, the internal elements of an EIP are defined.

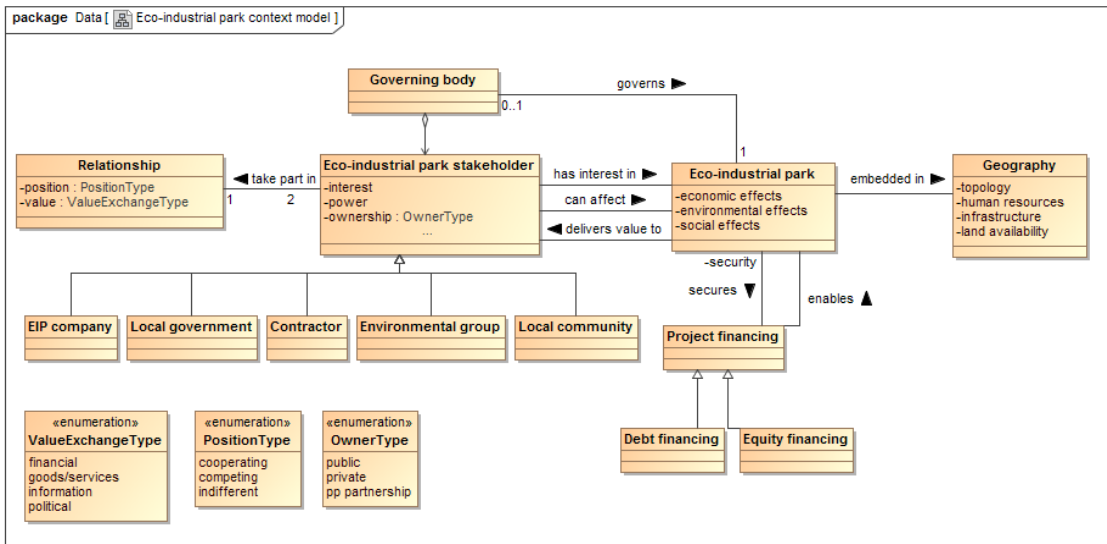


Fig. 3: EIP context model

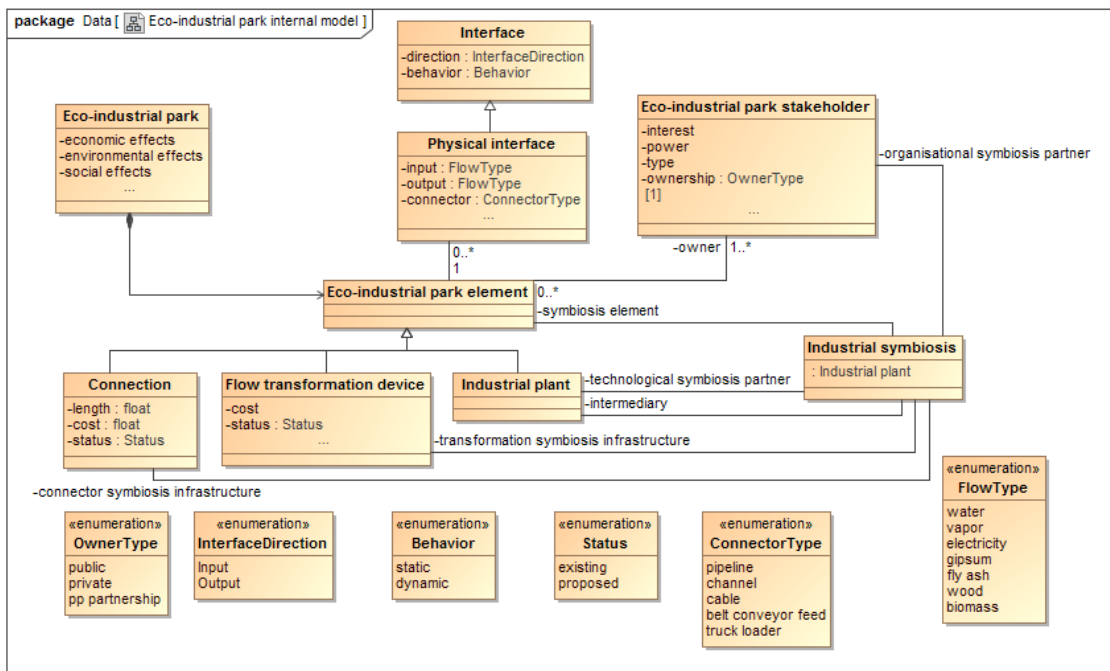


Fig. 4: EIP internal model

4.3 EIP INTERNAL ELEMENTS

Fig. 4 shows the internal elements of an EIP. An EIP is composed of EIP elements. The arrow with the diamond represents a “whole-part” relationship. The whole is the EIP and the EIP elements are parts of the EIP. An EIP element can be either an industrial plant (factory, power plant, etc.), a flow transformation device (heat exchanger, condenser, etc.) or a connection (pipeline, electrical circuit etc.). What is the difference between a flow transformation device and a connection? A flow transformation device is deliberately designed for transforming the state of a flow. For example, a condenser transforms vapor into water. A connection’s primary purpose is to transport a flow. A connection usually changes the state of the flow. For example, a pipeline induces a pressure drop into the transported liquid or gas. The main difference is that the change in state is undesired.

A pipeline with less pressure drop is considered better than a pipeline with a larger pressure drop. An EIP element can be owned by an EIP stakeholder. A stakeholder that owns an EIP element is assigned the role “owner”. An EIP element can have one or more owners. A stakeholder may own an arbitrary number of EIP elements.

The internal EIP model further introduces the concept of “interface”. Interface compatibility is defined at the level of the connector and the flow entering or leaving the interface [54], [76; p.176]. A connector is for example a power plug and socket. A power plug is compatible with a power socket on a connector level if the two can be connected. In this case the connection is mechanical. For software interfaces the connection might be logical. However, compatibility on a connector level is not a sufficient condition for allowing interactions between two components. For example, the required voltage of the “female” socket might be 100V and the provided voltage of the “male” socket 50V. In such a case, there is a mismatch between the required and provided flow. Hence, the interfaces are incompatible. An example from an EIP would be a mismatch of required and provided vapor pressure and temperature between two plants.

How does the initially defined industrial symbiosis fit into the internal EIP model? An industrial symbiosis assigns certain roles to EIP elements. An EIP element taking part in a symbiosis is called “symbiosis element”. An industrial plant taking part in a symbiosis is called “technological symbiosis partner”. In some cases an industrial plant only serves as an intermediary between two symbiosis partners. Such a plant is called “intermediary”. A connector taking part in a symbiosis is assigned the role “connector symbiosis infrastructure”. A flow transformation device taking part in a symbiosis is assigned the role “transformation symbiosis infrastructure”. According to our definition, industrial symbiosis is not only an exchange relationship on a technological or physical level but also involves stakeholders that receive value from the exchange. Such stakeholders are called “organizational symbiosis partners”.

4.4 EIP INSTANCE

The conceptual framework is used for modeling an EIP instance. A part of the Kalundborg EIP is modeled, as it is the most widely known instance of an EIP [77]. The instance is created by using the Systems Modeling Language (SysML) internal block diagram. The internal block diagram is used for modeling the exchange of flows between instances. Fig. 5 shows the exchange of deionized water between the Dong Energy Annaes Power Station and the Statoil plant via pipeline. Drain water is exchanged via channels and an intermediate re-use basin. Fly ash from the power plant is transferred to the cement industry. The framework model elements are represented as UML / SysML stereotypes, which appear in “<< >>” brackets at the top of the instances. The roles assigned by the industrial symbiosis is represented by the names in front of the “:” of the instances. For example, the Statoil plant has the role “symbiosis partner 2” assigned to it. What is not depicted in Fig. 5 are the exchange relationships taking place at an organizational level. These exchanges would be modeled in a separate internal block diagram, showing the flows between the organizations.

5. DISCUSSION

One of the challenges of creating a conceptual framework in the field of industrial ecology is the immaturity of the domain. Immature means that there is no consensus on the definition of key concepts within the domain. Without a consensus on what industrial symbiosis is, any conceptual framework can only represent a certain perspective on industrial symbiosis. This means that our interpretation of industrial symbiosis may be inconsistent with other definitions. Nevertheless, we think that our definition may open up fruitful new avenues of research by bringing different forms of exchanges together, such as material / energy exchanges between plants and exchanges on an organizational level. These are all interpreted as exchanges of value. “Value” is essentially an economic term. Using an economic term in the context of sustainability has its challenges. For example, there is ongoing debate on how “environmental value” can be defined and measured [78]. Ecological economics and environmental economics try to develop approaches for bridging the gap between mainstream economics and ecology [6], [79]. Therefore, progress in these domains may also help to advance research on industrial symbiosis.

6. CONCLUSIONS

This paper presents an initial conceptual framework for architecting EIPs. The conceptual framework includes industrial symbiosis, which is pertinent to EIPs. A novel value-centric definition of industrial symbiosis extends the existing industrial symbiosis perspective on industrial symbiosis. This perspective may open up the possibility to use approaches from mainstream economics and sociology to analyze industrial symbiosis. Furthermore, an EIP's internal and contextual elements are defined.

The conceptual framework is a first step towards the application of system architecting methods such as tradespace exploration and stakeholder analysis to EIP development. For the application of tradespace exploration, the current qualitative model needs to be quantified by adding values for key attributes for plant inputs and outputs as well as basic relationships that describe infrastructure cost and changes in flow parameters.

A further interesting avenue of research is the use of system architecting methods to conduct an integrated technological, organizational, as well as project finance analysis to EIP development.

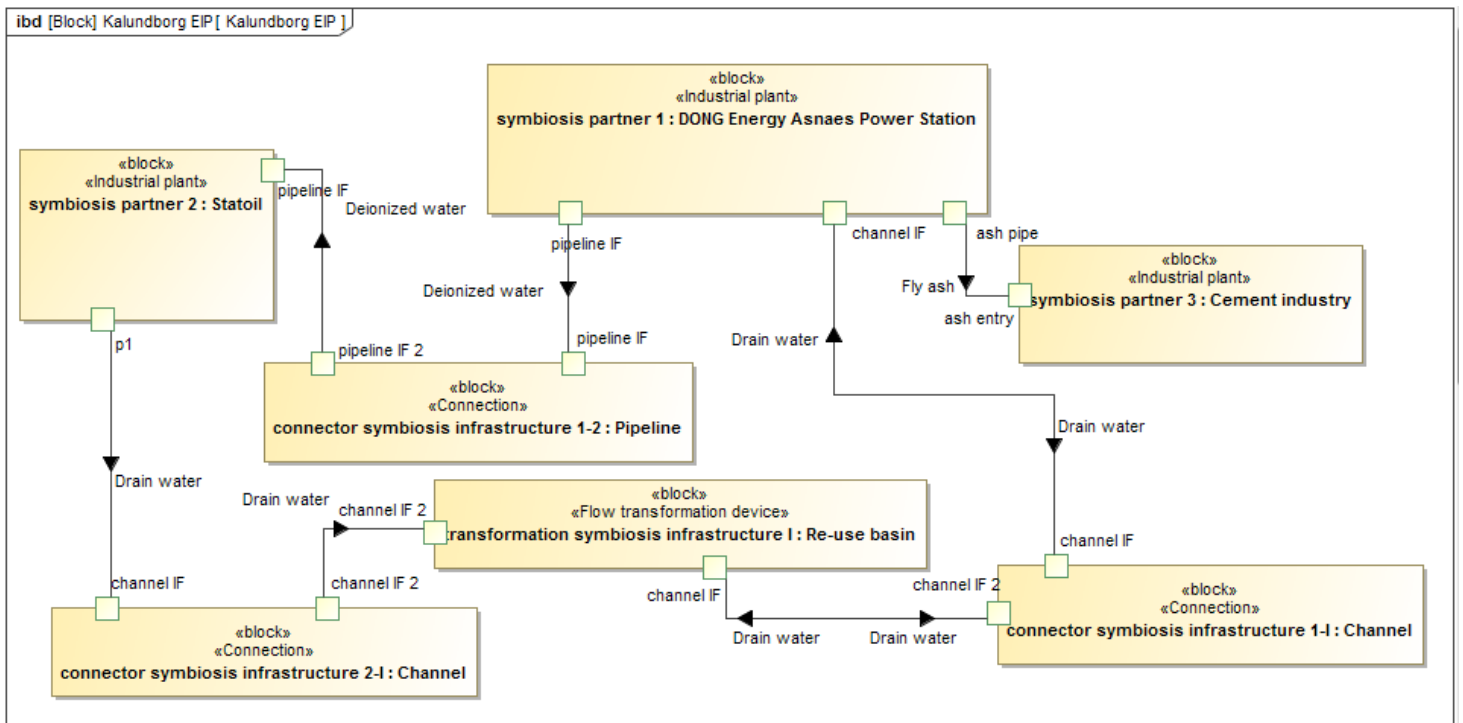


Fig. 5: Part of the Kalundborg EIP as an instance of the conceptual framework

REFERENCES

- [1] E. A. Lowe, "Eco-industrial park handbook for Asian developing countries," 2001.
- [2] N. E. Frosch, R. A., Gallopoulos, "Strategies for manufacturing," *Sci. Am.*, vol. 261, no. 3, pp. 144–152, 1989.
- [3] S. Erkman, "Industrial ecology: an historical view," *J. Clean. Prod.*, vol. 5, no. 1, pp. 1–10, 1997.
- [4] G. Hess, "The Ecosystem: Model or Metaphor?," *J. Ind. Ecol.*, vol. 14, no. 2, pp. 270–285, 2010.
- [5] H. McManus, M. G. Richards, A. Ross, and D. Hastings, "A Framework for Incorporating 'ilities' in Tradespace Studies," *Am. Inst. Aeronaut. Astronaut.*, no. Conference and Exposition, pp. 1–14, 2007.
- [6] R. U. Ayres, "On the life cycle metaphor: where ecology and economics diverge," *Ecol. Econ.*, vol. 48, no. 4, pp. 425–438, 2004.
- [7] M. R. Chertow, "Industrial symbiosis," *Encycl. energy*, vol. 3, pp. 407–415, 2004.
- [8] H. Shi, M. Chertow, and Y. Song, "Developing country experience with eco-industrial parks: a case study of the Tianjin Economic-Technological Development Area in China," *J. Clean. Prod.*, vol. 18, no. 3, pp. 191–199, Feb. 2010.
- [9] N. B. Jacobsen, "Industrial Symbiosis in Kalundborg, Denmark: A Quantitative Assessment of Economic and Environmental Aspects," *J. Ind. Ecol.*, vol. 10, no. 1–2, pp. 239–255, 2006.
- [10] J. Korhonen and J. P. Snäkin, "Analysing the evolution of industrial ecosystems: Concepts and application," *Ecol. Econ.*, vol. 52, no. 2, pp. 169–186, 2005.
- [11] L. Sokak, "Local systems, global impacts : Using life cycle assessment to analyse the potential and constraints of industrial symbioses," *VTT Publ.*, no. 768, pp. 1–158, 2011.
- [12] D. R. Chertow, M. R., Lombardi, "Quantifying economic and environmental benefits of co-located firms," *Environ. Sci. Technol.*, vol. 39, no. 17, pp. 6535–6541, 2005.
- [13] M. Hodge, J. Ochsendorf, and J. Fernández, "Quantifying potential profit from material recycling: A case study in brick manufacturing," *J. Clean. Prod.*, vol. 18, no. 12, pp. 1190–1199, 2010.
- [14] D. Gibbs and P. Deutz, "Reflections on implementing industrial ecology through eco-industrial park development," *J. Clean. Prod.*, vol. 15, no. 17, pp. 1683–1695, Nov. 2007.
- [15] W. Feng, "Strategic Management for Large Engineering Projects: The Stakeholder Value Network Approach," Massachusetts Institute of Technology, 2013.
- [16] R. R. Heeres, W. J. V Vermeulen, and F. B. De Walle, "Eco-industrial park initiatives in the USA and the Netherlands: First lessons," *J. Clean. Prod.*, vol. 12, no. 8–10, pp. 985–995, 2004.
- [17] P. Desrochers, "Industrial ecology and the rediscovery of inter-firm recycling linkages: historical evidence and policy implications," *Ind. Corp. Chang.*, vol. 11, pp. 1031–1057, 2002.
- [18] P. Desrochers, "Cities and industrial symbiosis: Some historical perspectives and policy implications," *J. Ind. Ecol.*, vol. 5, no. 4, pp. 29–44, 2001.
- [19] P. Desrochers, "Industrial symbiosis: The case for market coordination," *Journal of Cleaner Production*, vol. 12, no. 8–10, pp. 1099–1110, 2004.
- [20] E. Romero and M. C. Ruiz, "Framework for applying a complex adaptive system approach to model the operation of eco-industrial parks," *J. Ind. Ecol.*, vol. 17, no. 5, pp. 731–741, 2013.
- [21] M. C. Romero, E., Ruiz, "Proposal of an agent-based analytical model to convert industrial areas in industrial eco-systems," *Sci. Total Environ.*, vol. 468, pp. 394–405, 2014.
- [22] A. Rosa, M., Beloborodko, "A decision support method for development of industrial synergies: case studies of Latvian brewery and wood-processing industries," *J. Clean. Prod.*, vol. In press, 2014.

- [23] H. Cao, Kai, Feng Xiao, & Wan, "Applying agent-based modeling to the evolution of eco-industrial systems," *Ecol. Econ.*, vol. 68, no. 11, pp. 2868–2876, 2009.
- [24] E. Côté, Raymond P. et Cohen-Rosenthal, "Designing eco-industrial parks: a synthesis of some experiences," *J. Clean. Prod.*, vol. 6, no. 3, pp. 181–188, 1998.
- [25] M. R. Chertow, "Industrial symbiosis: Literature and taxonomy," *Annu. Rev. Energy Environ.*, vol. 25, no. 1, pp. 313–337, 2000.
- [26] C. Haskins, "Multidisciplinary investigation of eco-industrial parks," *Syst. Eng.*, vol. 9, no. 4, pp. 313–330, 2006.
- [27] C. Haskins, "A systems engineering framework for eco-industrial park formation," *Syst. Eng.*, vol. 10, no. 1, pp. 83–97, 2007.
- [28] B. M. Sopha, A. M. Fet, M. M. Keitsch, and C. Haskins, "Using systems engineering to create a framework for evaluating industrial symbiosis options," *Syst. Eng.*, vol. 13, no. 2, pp. 149–160, 2010.
- [29] J. A. M. Eilering and W. J. V. Vermeulen, "Eco-industrial parks: toward industrial symbiosis and utility sharing in practice," *Progress in Industrial Ecology, An International Journal*, vol. 1, no. 1/2/3. p. 245, 2004.
- [30] W. Spekink, "Institutional capacity building for industrial symbiosis in the Canal Zone of Zeeland in the Netherlands: A process analysis," *J. Clean. Prod.*, vol. 52, pp. 342–355, 2013.
- [31] W. Spekink, "Building capacity for sustainable regional industrial systems: an event sequence analysis of developments in the Sloe Area and Canal Zone," *J. Clean. Prod.*, vol. In press, 2014.
- [32] W. Ashton, "Understanding the organization of industrial ecosystems," *J. Ind. Ecol.*, vol. 132, no. 9, pp. 34–51, 2008.
- [33] Y. Zeng, R. Xiao, and X. Li, "Vulnerability analysis of symbiosis networks of industrial ecology parks," in *Procedia Computer Science*, 2013, vol. 17, pp. 965–972.
- [34] S. H. Kim, S. G. Yoon, S. H. Chae, and S. Park, "Economic and environmental optimization of a multi-site utility network for an industrial complex," *J. Environ. Manage.*, vol. 91, no. 3, pp. 690–705, 2010.
- [35] C. Gu, S. Leveneur, L. Estel, and A. Yassine, "Modeling and Optimization of Material/Energy Flow Exchanges in an Eco-Industrial Park," *Energy Procedia*, vol. 36, pp. 243–252, Jan. 2013.
- [36] J. M. Maillé, M., & Frayret, "Industrial By-Product Reuse and Synergy Optimization," 2013.
- [37] F. Schulze, "Classification and development of mathematical models and simulation for industrial ecology," University of Rhode Island.
- [38] J. G. M. S. Monteiro, P. A. C. Silva, O. Q. F. Araújo, and J. L. Medeiros, "Pareto optimization of an industrial ecosystem: Sustainability maximization," *Brazilian J. Chem. Eng.*, vol. 27, no. 3, pp. 429–440, 2010.
- [39] J. C. Sun, N. M. Wang, and S. C. Cheng, "Measuring interdependency in industrial symbiosis network with financial data," in *Energy Procedia*, 2011, vol. 5, pp. 1957–1967.
- [40] E. Maier, M. W., & Rechtin, *The art of systems architecting*, 2nd ed. CRC Press, 2006.
- [41] E. Crawley, O. Weck de, S. Eppinger, C. Magee, J. Moses, W. Seering, J. Schindall, D. Wallace, D. Whitney, and O. De Weck, "The Influence of Architecture in Engineering Systems," *Eng. Syst. Monogr.*, p. 30, 2004.
- [42] D. Selva Valero, "Rule-based system architecting of Earth observation satellite systems," Massachusetts Institute of Technology, 2012.
- [43] A. Alfaris, A. Siddiqi, C. Rizk, O. de Weck, and D. Svetinovic, "Hierarchical Decomposition and Multidomain Formulation for the Design of Complex Sustainable Systems," *J. Mech. Des.*, vol. 132, no. 9, p. 091003, Sep. 2010.

- [44] A. Adepetu, E. Arnautovic, D. Svetinovic, and O. L. de Weck, "Complex Urban Systems ICT Infrastructure Modeling: A Sustainable City Case Study," *IEEE Trans. Syst. Man, Cybern. Syst.*, vol. 44, no. 3, pp. 363–374, Mar. 2014.
- [45] A. M. Ross, D. E. Hastings, J. M. Warmkessel, and N. P. Diller, "Multi-Attribute Tradespace Exploration as Front End for Effective Space System Design," *Journal of Spacecraft and Rockets*, vol. 41, no. 1. pp. 20–28, 2004.
- [46] A. M. Ross and D. E. Hastings, "The tradespace exploration paradigm," in *INCOSE International Symposium 2005*, 2005, p. 13.
- [47] R. E. E. Freeman and J. McVea, "A Stakeholder Approach to Strategic Management," Pitman, 2001.
- [48] R. Hein, A. M., Tziolas, A. C., Osborne, "Project Icarus: Stakeholder Scenarios for an Interstellar Exploration Program," *J. Br. Interplanet. Soc.*, vol. 64, no. 6/7, pp. 224–233, 2011.
- [49] J. A. Sokolowski and C. M. Banks, *Modeling and Simulation Fundamentals: Theoretical Underpinnings and Practical Domains*. John Wiley and Sons, 2010.
- [50] K. G. Costanza, R., Wainger, L., Folke, C., Mäler, "Modeling complex ecological economic systems," *Bioscience*, vol. 43, no. 8, pp. 545–555, 1993.
- [51] A. Karban, R., Weilkiens, T., Hauber, R., Zamparelli, M., Diekmann, R., & Hein, "Cookbook for MBSE with SysML," 2011.
- [52] S. Habermellner, R., de Zeck, O. L., Fricke, E., Vössner, *Systems Engineering: Grundlagen und Anwendung*. Orell Füssli, 2012.
- [53] O. M. Group, "UML 2.0 Superstructure Specification," Needham, 2004.
- [54] S. Friedenthal, A. Moore, and R. Steiner, *A practical guide to SysML: The systems modeling language*. Morgan Kaufmann, 2008.
- [55] P. Desrochers and S. Leppala, "Industrial Symbiosis: Old Wine in Recycled Bottles? Some Perspective from the History of Economic and Geographical Thought," *International Regional Science Review*, vol. 33, no. 3. pp. 338–361, 2010.
- [56] C. Yu, C. Davis, and G. P. J. Dijkema, "Understanding the Evolution of Industrial Symbiosis Research," *J. Ind. Ecol.*, vol. 18, no. 2, pp. 280–293, Apr. 2014.
- [57] M. R. Chertow, "'Uncovering' Industrial Symbiosis," *J. Ind. Ecol.*, vol. 11, no. 1, pp. 11–30, 2007.
- [58] J. Paquin, R., Howard-Grenville, "Facilitating regional industrial symbiosis: Network growth in the UK's National Industrial Symbiosis Programme," in *The Social Embeddedness of Industrial Ecology*, J. A. H.-G. Frank Boons, Ed. Edward Elgar Publishing Limited, 2009, pp. 103–127.
- [59] M. Matsuda, H., Shimada, "Cost-benefit model for the evolution of symbiosis," in *Mutualism and community organization: behavioral, theoretical and food-web approaches*, Oxford Science Publications, 1993, pp. 228–237.
- [60] G. Koide, R., & Elliott, "Cost, benefit and efficiency of the vesicular-arbuscular mycorrhizal symbiosis," *Funct. Ecol.*, vol. 3, no. 2, pp. 252–255, 1989.
- [61] D. H. Boucher, *The biology of mutualism: ecology and evolution*. Oxford University Press, 1988.
- [62] A. H. Fitter, "Costs and benefits of mycorrhizas: implications for functioning under natural conditions," *Experientia*, vol. 47, no. 4, pp. 350–355, 1991.
- [63] N. C. Johnson, J. H. Graham, and F. A. Smith, "Functioning of mycorrhizal associations along the mutualism-parasitism continuum," *New Phytol.*, vol. 135, no. 4, pp. 575–586, 1997.
- [64] R. C. Connor, "The benefits of mutualism: a conceptual framework," *Biol. Rev.*, vol. 70, no. 3, pp. 427–457, 1995.
- [65] A. Etxeberria and J. Umerez, "Conceptual Issues in Evolutionary Biology (3rd ed.)." *Artif. Life*, vol. 14, no. 2, pp. 235–238, 2008.

- [66] M. D. Bradford and E. Schwab, "Current Usage of Symbiosis and Associated Terminology," *Int. J. Biol.*, vol. 5, no. 1, pp. 32–45, 2012.
- [67] R. Cropanzano, "Social Exchange Theory: An Interdisciplinary Review," *Journal of Management*, vol. 31, no. 6. pp. 874–900, 2005.
- [68] M. Zafirovski, "Social exchange theory under scrutiny: A positive critique of its economic-behaviorist formulations," *Electron. J. Sociol.*, vol. 2, pp. 1–40, 2005.
- [69] R. M. Emerson, "Social exchange theory," *Annu. Rev. Sociol.*, vol. 2, no. 1, pp. 335–362, 1976.
- [70] D. R. Miller, R., Lessard, *The strategic management of large engineering projects: Shaping institutions, risks, and governance*. MIT press, 2000.
- [71] D. R. Lessard, V. Sakhrani, and R. Miller, "House of Project Complexity - Understanding Complexity in Large Infrastructure Projects (in press)," *Eng. Proj. Organ. J.*, 2014.
- [72] B. C. Esty, "Why Study Large Projects? An Introduction to Research on Project Finance," *Eur. Financ. Manag.*, vol. 10, no. 2, pp. 213–224, 2004.
- [73] P. K. Dey, "An integrated assessment model for cross-country pipelines," *Environmental Impact Assessment Review*, vol. 22, no. 6. pp. 703–721, 2002.
- [74] OGJ, *Oil Gas Journal Data Book 2008*. Penn Well Books, 2008.
- [75] M. A. Brealey, R. A., Cooper, I. A., Habib, "Using project finance to fund infrastructure investments," *J. Appl. Corp. Financ.*, vol. 9, no. 3, pp. 25–39, 1996.
- [76] M. F. Brandstätter, "Kompatibilitätsmodellierung im Systems-Engineering Umfeld," Technische Universität München, 2009.
- [77] J. Ehrenfeld and N. Gertler, "Industrial Ecology in Practice: The Evolution of Interdependence at Kalundborg," *J. Ind. Ecol.*, vol. 1, no. 1, pp. 67–79, Dec. 1997.
- [78] R. Brouwer, "Environmental value transfer: state of the art and future prospects," *Ecol. Econ.*, vol. 32, no. 1, pp. 137–152, 2000.
- [79] E. Gómez-Baggethun, R. de Groot, P. L. Lomas, and C. Montes, "The history of ecosystem services in economic theory and practice: From early notions to markets and payment schemes," *Ecol. Econ.*, vol. 69, no. 6, pp. 1209–1218, 2010.