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# Collaborative Eco-Industrial Networks: A Case Study

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**Abstract.** Circular Economy is the typical industry response to climate change - the ubiquitous and urgent problem of our times. Previous work has presented a multidisciplinary approach towards the optimal enactment of Circular Economy through Eco-Industrial Networking, able to deal with its many-faceted and complex aspects. This paper takes this work further by investigating the practical use of the relevant concepts within a real-world case study followed by drawing conclusions and proposing potential improvements. A concise theoretical background is followed by the explanation of the scenario and of the proposed concepts' application in practice, including challenges and benefits of the chosen approach. Finally, a reflection is carried out and conclusions are drawn, followed by proposals for future applications and development of the method.

**Keywords:** collaborative networks, eco-industrial networking, enterprise architecture, green virtual enterprise.

## 1 Introduction

The increasingly ubiquitous impact of climate change, biodiversity loss, waste, and pollution have brought forward the need for urgent and meaningful action [1]. Among the possible avenues for tackling these problems, the circular economy (CE) [2] initiative features prominently due to its potential to address the root causes of the above-mentioned challenges, by aiming to share, lease, reuse, repair, refurbish and recycle existing materials and products for as long as possible [3]. As shown in previous work [4, 5], CE can be more effectively enacted in a structured collaborative environment by adopting the Eco-Industrial Network (EIN) approach [6], which in turn builds on Environmental Management concepts applied to proven Collaborative Networking (CN) paradigms [7]. In order to deal with complexity and emergent behaviour aspects that typically manifest themselves in the EIN endeavour, some authors [8-10] have proposed adopting a multidisciplinary stance that provides a holistic approach considering all aspects relevant to the specific EIN endeavour.

This paper describes a practical EIN case study which has been tackled using this multidisciplinary paradigm while laying more emphasis on the Enterprise Architecture and Collaborative Network artefacts; the focus is on the application and benefits of the approach in practice, while observing challenges encountered and lessons learned.

## 2 Background

The industrial application of Circular Economy, namely Industrial Ecology (IE) provides the model for the formation and operation of the EIN. IE supports moving from a linear progression of the resources through the system to an integrated and circular so-called 'industrial eco-system', optimizing all relevant resource flows (including information and knowledge) to up- and down-cycle them. As they become inputs for new processes, such resources are fully utilized and thus support reducing the dependence on non-renewable natural resources [11].

The practical manifestation of Industrial Ecology, Industrial Eco-systems (IES), typically subsume a plethora of autonomous entities that in turn possess interrelated and interdependent components within their 'techno-sphere' (man-made technological systems) and their 'biosphere' (natural ecosystems) [12]; as the boundary between these components are often blurred, and in the context of the Internet of Things (IoT), IES are nowadays becoming complex cyber-physical systems (CPS).

The capability to promptly bid for and win large grants and/or projects requires an adequate set of competencies and resources; often, this is beyond the capabilities of most companies taken in isolation. Therefore, companies often form 'alliances' taking forms of Collaborative Networks (CNs) such as Breeding Environments (BE) which are set up so as to achieve the required preparedness to promptly create Virtual Enterprises (VEs) able to bid for projects as described above [13]. Typically, CNs feature one or more lead partners which orchestrate the BE and VE efforts and one or more brokers whose role is to identify and acquire new collaboration opportunities and negotiate with potential participants [14]. If successful in bidding, the VEs then build and manage projects while also possibly using resources outside the CN.

Moving on to the next knowledge area, namely Enterprise Architecture (EA), Gartner Research [15] sees it as representing a holistic change management paradigm connecting management and engineering best-practice, providing requirements, principles and models that describe future state of the enterprise. This paradigm includes humans, processes, information and technology within the enterprise, together with their internal and external relationships; according to the definition above, it can be considered that EA represents in fact the 'ontology of change'.

Typically, such viewpoints are structured in EA frameworks (EAF). Several such artefacts are currently in use worldwide, depending on various factors; in order to ensure the most relevance and coverage to the problem at hand, the author has decided to adopt a framework that represents and generalizes several mainstream EAFs, namely the Generalized Enterprise Reference Architecture and methodology (GERAM), which is described in Annex A of the ISO15704 Standard [16]. This EAF includes a reference architecture (GERA) containing a modelling framework (MF) which integrates aspects deemed of the most importance for the EIN problem at hand. An important aspect is the presence of the life cycle concept, which is absent from the majority of other approaches [17, 18] and can be used as a background to all the other viewpoints, as shown in Fig. 1, left on the vertical axis.

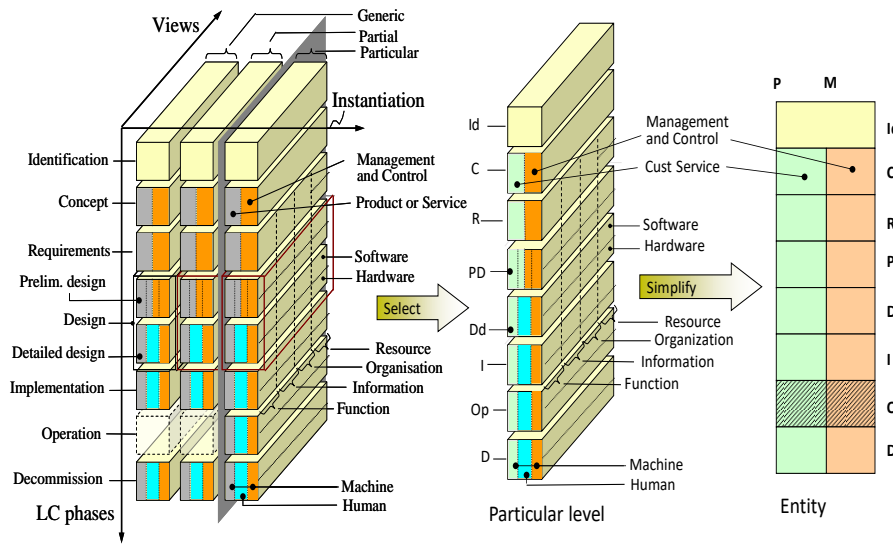


Fig. 1 Deriving the modelling constructs used to analyze specific viewpoints in the case study.

Note that the proposed MF defines requirements for the expressiveness of the candidate languages, rather than enforcing specific selections; in addition, it also integrates viewpoints present in other disciplines relevant to EIN in a multi-dimensional framework as shown in Fig. 1, left. This enables multiple analyses in a consistent manner, by allowing selected viewpoints to be examined separately at any one time, as shown in Fig. 1 right and further in Section 3.

For the reasons above, it is hereby argued that EA, as a provider of useful artefacts, is an ideal companion to the CN approach involved in this case study analysis.

### 3 A Collaborative Eco-Industrial Network

#### 3.1 Situation

A large company and developer aimed to diversify its investments by creating an industrial precinct; the decision was taken to adopt a recycling-based strategy, so as to minimize waste and pollution and realise savings on raw materials. The strategy was to attract various participants to the precinct and then get selected members to form a recycling-based environment based on their potential and willingness to connect their relevant inputs and outputs. However, there was a need a) for guidance as to how to select these partners in the initial and continuing stages and b) to define the kind of association these partners were to enter and furthermore the various ways they could connect in order to realise the circularity concept – more specifically, the various

configurations the partner association would create. In view of the above narrative, it became apparent that the theoretical background presented in Section 2 could be used to provide guidance towards the set-up and operation of the envisaged network.

### 3.2 Setting up the Breeding Environment

The above situation matched a combined CE and CN paradigm, namely the closed-loop logistics and integrating forward and reverse supply chains described by various authors [12, 19, 20]. In the particular case described, in view of the geographical co-location of the participants, the specific type of EIN envisaged was that of the symbiosis network depicted in Patala et al.'s [10] work.

From the point of view of the CN knowledge area, the situation was akin to the formation of a so-called 'Green' Breeding Environment (GBE)[12], a pool of potential participants which are pre-qualified (for instance, all the cooperation protocols and contracts are pre-established and negotiated) and thus achieve the necessary preparedness to promptly participate in various joint ventures (aptly called 'Green' Virtual Enterprises, or GVEs) as required to bid for- and win project opportunities and / or grants. The initial 'lead partner' in this case was the large company and developer; subsequently, other major participants followed: a telecommunications company ensuring the essential infrastructure (data centre and 'lake') and a tertiary education institution contributing the necessary research and innovation resources. The selection of these lead partners has been a result of investigating the relevant areas that needed to be addressed by potential partners (using the EA MF viewpoints, namely Information and Resource). Further on, several other participants have been identified and qualified as GBE members using the same multi-disciplinary approach, as shown in Fig. 2.

The qualification process was based on several criteria; a first qualifying condition was the initial preparedness to participate in the Circular Economy-based GBE, i.e. whether the aspiring participants had any existing or potential inputs or outputs that could connect with other GBE members. This initial analysis has involved using the IE-inspired technical and organisational domains, encompassed and complemented by the EA MF Function, Information, Resource and Organisation (FIRO) viewpoints.

A further qualifying criterion for BE membership from the point of view of SoS has been the commitment to build up adequate connectivity preparedness by developing and maintaining a 'digital twin' [21] for the potential input / output connections that could develop between the GBE members. The concept of digital twin has been used before in EIN [22]; in this case study, it was necessary in order to start quantifying the inputs and outputs of the various 'exchange streams' participants (not performed in previous cases as erroneously being deemed not necessary). Measuring the amount of matter, information and energy involved in the streams was paramount to their proper setup and operation (also involving trading) that underpinned the entire Eco-Industrial Network paradigm. From the CN point of view, the situation looked as per Table 1:

**Table 2.** CN specifics of the case study

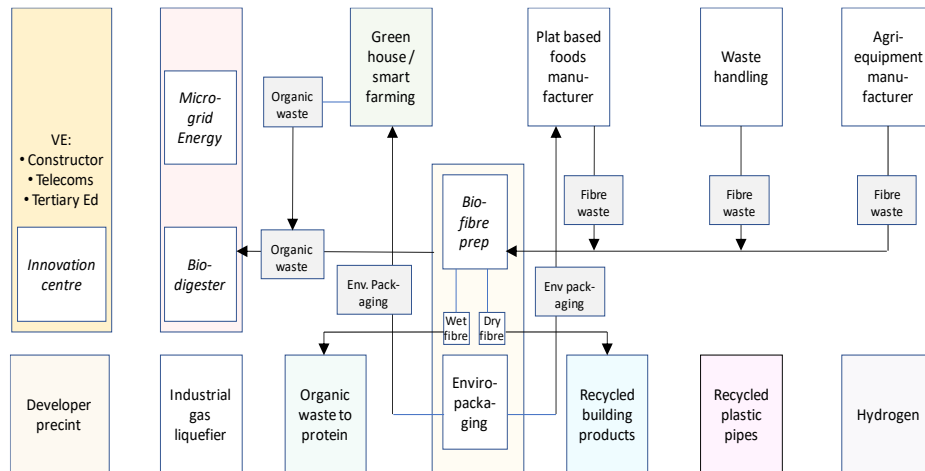
Generic CN Notion	Practical Manifestation
Breeding Environment	Qualified Network participants
Virtual Enterprise	Lead partner, Telco, Education
Broker	Green Virtual Enterprise
Streams	Exchanges via Interfaces
Reference model	Interface Templates

EA MF viewpoints have been used to detail streams; thus, e.g. functional and informational criteria have been used to elicit which exchange activities must be modelled and what data is needed to describe relevant properties of the exchanges, respectively.

### 3.3 Building the Virtual Enterprise

The lead partners within the GBE have decided to allocate resources to a workgroup whose tasks are to create input / output streams connecting GBE members and also to apply for government and private funding supporting EIN endeavours. According to the CN body of knowledge, a suitable materialisation of such a workgroup is a VE; however, in this case study, this entity is expected to have a lasting presence and take on other tasks which are not assigned to it in the typical CN realm.

The initial models had the format shown in Fig. 2, requiring a separate diagram for each exchange so as to ensure readability.



**Fig. 2** Extract from the set of initial EIN Models including the BE, VE and the Streams.

This meant that showing potential relations between streams was very difficult and required shuffling between diagrams which was very awkward for stakeholders. In addition, many essential aspects such as life cycle of the BE participants, VE and the streams and the potential relations between them could not be meaningfully represented. According to the concepts described in the theoretical background section and previous successful life cycle-based endeavours in the area of environmental management [23, 24], it has been proposed to use the modelling constructs proposed in Section 2 and analyse the results.

Fig. 3 shows the same situation in a ‘business model’ using the EA modelling construct derived as shown in Fig. 1, which allows a richer representation considering the life cycles of the participants and management / production (or service) aspects.

The arrows between entities represent the role played by the originating entity in the life cycle/s of the destination entity. Note that some arrows originate from- and point to the same entity (e.g. in the case of the VE and the streams S1 and S2); this is to indicate the capacity of the entity to change itself to a certain extent (adaptation / agility), as further explained. Various line types and colours are also used as illustrated in the same figure, in order to better represent possible scenarios or behaviours.

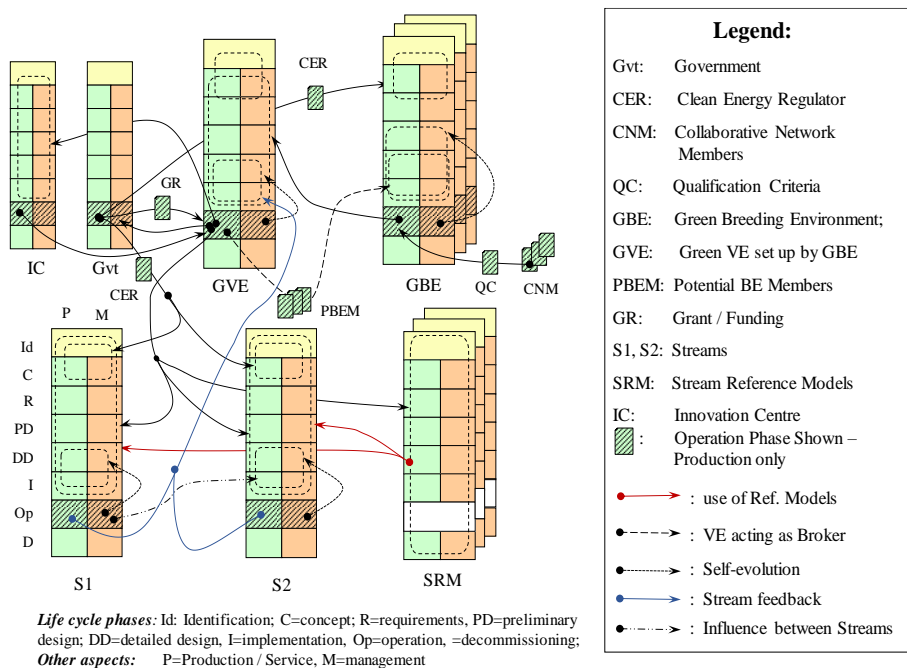


Fig. 3 A life cycle-based representation of the Eco-industrial Network in question

Should specific aspects be required to be represented, various viewpoints can be selected from the MF shown in Fig. 1 left. For example, if the contents of the streams need to be shown, the Information viewpoint may be selected and an appropriate language such as Entity Relationship- or UML Class Diagrams can be used; if the flow of data or sequence of activities within a stream need to be represented for analysis and



costing, the Function viewpoint may be selected and a view created using a language such as IDEF0 or UML Activity Diagram may be used. While one can use such languages independently of employing an (EA) MF, the advantage here is that all the viewpoints represented are linked via the framework through a common meta-model and as such, the consistency of the complete model can be intrinsically maintained.

**In Error! Reference source not found.** Fig. 3, one can see the role of governmental agencies such as the Clean Energy Regulator (CER) in the early life cycle phases (identification, concept) of the GBE and the Streams, in order to abide by the rules and qualify for potential funding (see operating ‘CER’ on arrow originating from the Government Operation phase going to GBE and Streams’ Identification and Concept life cycle phases). The Government also influences the GVE(s) created by the GBE by means of funding (‘GR’ in the figure).

A GVE is set up by the GBE for several reasons, such as: a) to bid for government grants and other types of funding for CE initiatives b) to set up the interfaces displayed to BE members for stream creation and operation and c) to act as a broker for the CN, investigating the market for new potential participants and bringing them in the GBE. In the figure, the above facts are shown as follows: a) an arrow going from the GVE to the Government management (lobbying and applying for funding), b) arrows going to the Identification through Detailed Design life cycle phases of the streams and c) arrow containing PBEM (Potential BE Members) going from the GVE to the Identification through to Detailed Design life cycle phases of the GBE, respectively.

The GVE may also create and maintain a set of Stream Reference Models (SRM in Fig. 3), which will be used to store and reuse accumulated knowledge from the creation and operation of previous streams in view of accelerating the creation of new streams. The reference models can be e.g. partially instantiated interfaces presented to GBE members; they can also be used to prepare new entrants for GBE membership.

Notably (and in a deviation from the canonical CN concepts), a so-called ‘Innovation Centre’ (IC) was also created by the GVE using the capabilities of its tertiary education lead partner, so as to be able to discover and manage new stream possibilities that did not fit any existing / reusable knowledge, while at the same time enabling the continuous improvement of the existing streams and the EIN in general.

Fig. 3 also shows how Collaborative Network members (represented as ‘CNM’) may contribute to the GBE if they satisfy the Qualification Criteria (shown as ‘QC’), importantly including adequate preparedness to participate in Streams and agreement to develop Digital Twins.

### 3.4 Setting up and Operating the Streams

The streams’ interfaces are designed by the GVE according to criteria that are mostly specialisations of fundamental viewpoint types present in the above-mentioned MF. When joining the GBE, the assenting CN participants create Digital Twins, which are then employed to quantitatively assess their participation in Streams. For example, if within a stream a participant needs CO<sub>2</sub> of certain parameters delivered in a certain manner one can use the Information, Function and Resource viewpoints respectively to model this aspect as required, while the Organisation view may depict the managerial

changes required for this stream to occur. The automation viewpoint (see ‘machine’ and ‘human’ depictions in Fig. 1) may be used to define any necessary human, machine, or combination thereof trait of the processes involved [25]. Furthermore, the Management vs. Production distinction present in the EA MF can also be used such as for example in Fig. 3 in order to represent how the management of the stream supports its own evolution (within limits shown as the circled life cycle phases).

Fig. 3 also depicts the relations between the streams and with the managing GVE in the context of their life cycles. This enables the analysis of alternative forms of such relations, possibly uncovering emergent features that did not exist in the participants, and their positive or negative effects. Thus, Fig. 3 shows how feedback from stream operation analyses can flow back to- and influence the GVE (arrows in the figure from stream operation to GVE detailed design life cycle phase), which may result in restructuring so as to optimise the streams in question.

Note that in the process of stream operation there may be emergent unpredicted optimisations, which may result in autonomous changes (self-evolution) up to a certain level (shown in Fig. 3, as arrows from Management side of Operation up to Detailed Design and Implementation life cycle phases), beyond which the GVE has to be involved in the redesign effort. For example, in the particular case study, there may adjustments in concentration and composition of the gases’ production and delivery which can be handled by the stream; however, any major change (e.g. ‘blue’ rather than ‘green’-produced hydrogen for economic reasons) will need to be handled by the GVE.

The streams can also influence each other (see e.g. the dash-dot arrow from Stream 1 to Stream 2 in Fig. 3); for example, in the specific case study if fibre waste is collected from several outputs using shared infrastructure, optimisations may be possible but also bottlenecks may occur. These situations may be modelled showing the extent of the affected life cycle phases (with other viewpoints added as required) and suitable action can be designed and assigned to streams’- or to GVE management, depending on the importance of the issue as previously described.

## 4 Conclusions and Further Work

This paper has aimed to apply previous research investigating the use of several knowledge areas in EIN to a real-world case study, while laying emphasis on the CN and EA-specific artefacts. Thus, various cohesive models of the EIN have been created and assessed in contrast with the previous approach featuring limited clarity and usability; unfortunately, the available space has limited the number of perspectives that could be exemplified in this paper.

The conclusion has been that EA-based artefacts have enabled a rich and integrated representation of all the required aspects of the relevant entities within the project, especially life cycle, which has facilitated stakeholder synergy underpinned by a common understanding of the present and future situations. Thus, a major contribution of this paper is in the assistance it provides to stakeholders by providing a more coherent, life cycle-based and overarching view of complex projects, enhancing agility and future-proofing by its ability to seamlessly integrate present and emerging modelling concepts.

Beyond reinforcing and refining the application of CN and EA concepts in more case studies, further work may also include incorporating a supporting artefact enabling the creation of directly applicable stream setup, operation and overhaul methods for specific EIN scenarios, such as a meta-methodology [26]. This would provide additional guidance and user friendliness to practitioners seeking to apply the proposed EA artefacts in their projects.

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