An Enterprise Architecture-centred Approach towards Eco-Industrial Networking: A Case Study

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Abstract: Circular Economy is one of the main avenues to tackle the ever-increasing effects of what is becoming the most urgent challenge of our times: climate change. Previous work has advocated a multidisciplinary approach towards the optimal enactment of Circular Economy through Eco-Industrial Networking, due to its many-faceted and complex aspects. This paper aims to further the research in the area by examining the practical application of the concepts proposed within a case study and drawing conclusions on applicability, potential pitfalls and improvements, while at the same time advocating a more Enterprise Architecture (EA)-centric stance due to its all-encompassing and integrating nature. Thus, a brief explanation of the theoretical background is followed by the description of the scenario and the proposed EA-focused concepts' application in practice, including challenges and benefits of the chosen approach. Finally, a reflection is performed and conclusions are drawn together with suggestions for future applications and development of the method.

1 INTRODUCTION

The increasingly ubiquitous impact of climate change, biodiversity loss, waste, and pollution have brought forward the need for urgent and meaningful action (Manisalidis et al., 2020). Among the possible avenues for tackling these problems, the circular economy (CE) (Brennan et al., 2015) 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 (European Parliament, 2015). As shown in previous work (Halog et al., 2021; Romero & Noran, 2015), CE can be more effectively enacted in a more structured collaborative environment by adopting the Eco-Industrial Networking (EIN) approach (Yedla & Park, 2017), which in turn builds on Environmental Management concepts applied to proven Collaborative Networking (CN) paradigms (Camarinha-Matos et al., 2009). In order to deal with complexity and emergent behaviour aspects that typically manifest themselves in the EIN endeavour, some authors (Haskins, 2006; Noran & Romero, 2014; Patala et al., 2014) 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 the above-described multidisciplinary paradigm, while advocating more emphasis on using the Enterprise Architecture artefacts as an encompassing concept for the other knowledge areas involved. The application and benefits of the approach are illustrated in practice, while at the same time observing challenges encountered and lessons learned towards the improvement of the proposed methodology. The rest of the paper is set out as follows: Section 2 briefly describes the theoretical background outlining the contributions of the various knowledge areas. Section 3 describes the case study itself including the setting, building the necessary artefacts, modelling them using the proposed constructs and contrasting with the legacy approach, followed by reflecting on the results, challenges and possible future development.

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Finally, the paper closes with conclusions and potential further work.

2 THEORETICAL BACKGROUND

Circular Economy and its specific industrial application, Industrial Ecology (IE), represents the paradigm guiding the formation and operation of the EIN. IE advocates the shift from a linear progression of the resources through the system towards eventually becoming waste, to an integrated circular 'industrial eco-system' optimising and redesigning all relevant resource flows (beyond just physical, e.g. also including information and knowledge) to up- and down-cycle them. By becoming inputs for new processes, such resources are fully utilised and thus contribute to reducing the reliance on non-renewable natural resources (International Society for Industrial Ecology (IS4IE), 2013).

Several viewpoints are proposed in the analysis and development of IE, as follows: 1) technical (technically feasible stream exchanges); 2) economic (economically sound exchanges); 3) political / regulatory / legal (environmental laws and regulations); 4) informational (need of data and information for decision-making management) and 5) organisational / institutional (readiness for environmental collaboration).

The practical manifestation of Industrial Ecology, namely Industrial Eco-systems (IES), typically feature a plethora of autonomous entities that in turn possess interrelated, interdependent and/or interactive components within their 'techno-sphere' (man-made technological systems) and their 'biosphere' (natural ecosystems) (Romero & Molina, 2012); therefore, IES are in fact complex cyber-physical systems (CPS).

For the reasons above, a complete EIN analysis comprising all necessary aspects needs to also resort to the Systems Engineering and Systems Theory. Adopting this knowledge area will provide EIN designers with the concepts of homeostasis, adaptation and feedback loops which may manifest themselves in a tendency towards an equilibrium state and self-evolving behaviour in response to various stimuli (as shown in Section 3 to also be applicable in this particular case study).

Due to the complexity involved, an adequate analysis of EIN needs to consider each participating entity as a 'System of Systems' (SoS) (Haskins, 2007; Mennenga et al., 2019), i.e. a collection of systems that contribute their resources and capabilities to create a more complex system, featuring more functionality and performance compared to the mere sum of the constituents. Thus, SoS are considered to be 'meta-systems' composed of several other independent complex systems varying in "technology, context, operation and conceptual frame" (Keating et al., 2003). Maier's (1998) work is adding to the above two more SoS features, namely operational and managerial independence and emergent behaviour. EIN scalability, potential agenthood of network participants and stakeholder conflict mitigation is also supported by the SoS paradigm (DeLaurentis & Ayyalasomayajula, 2009)

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 (Afsarmanesh & Camarinha-Matos, 2006). 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 (Camarinha-Matos et al., 2005). If successful in bidding, the VEs then build and manage projects which can also use resources outside the CN.

Moving on to the next knowledge area, namely Enterprise Architecture (EA), Gartner Research (2012) 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, the above viewpoints are structured in EA frameworks (EAF), several of which are currently in use. In order to ensure maximum potential relevance and coverage to the problem at hand, this paper adopts a framework that represents and generalises several mainstream EAFs, namely the Generalised Enterprise Reference Architecture and methodology (GERAM), described in Annex A of the ISO15704 Standard (ISO/IEC, 2005). This EAF includes a reference architecture (GERA) which in turn features a modelling framework (MF) integrating aspects deemed of the most importance for the EIN problem at hand. Importantly, the MF includes the concept of life cycle which is absent from the majority of other approaches (see e.g. Clark et al.(2015), Nwokeji et al.(2017) ,etc.) and can be used as a background to all the other viewpoints, as shown in Figure 1(vertical axis). The proposed modelling framework provides guidance in relation to the *expressiveness* of the modelling languages to be used rather than enforcing specific choices.

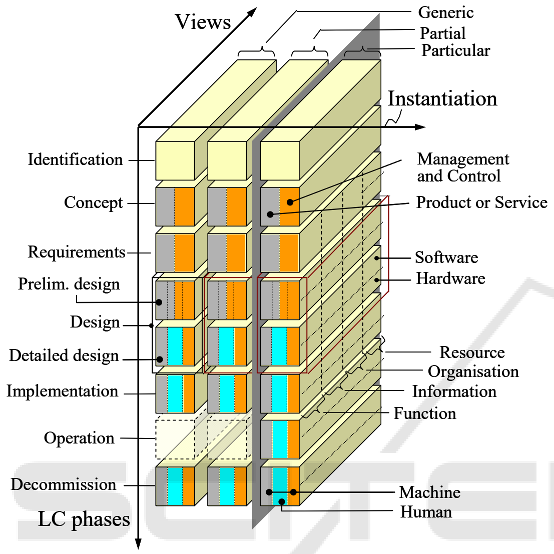


Figure 1: Enterprise Architecture Modelling Framework.

As one can see from the figure, this construct not only subsumes the viewpoints of the other disciplines relevant to EIN, but it also integrates them in a multidimensional framework. This is important as it enables multi-pronged analyses in a cohesive manner while also allowing to examine selected viewpoints separately, as shown in Figure 2 and further in Section 3. For the reasons above, it is hereby argued that EA should be the prevailing knowledge area involved in this case study analysis.

Thus, one may define the roles of the various disciplines involved in this case study as follows: CE is the defining paradigm, SoS and CN are the structural concepts while EA is the integrated overarching and multidimensional ontology of the entire endeavour.

Note that the proposed MF abstracts from time, although the concept does exist in the Reference Architecture GERA in the form of *life history*. This aspect will be used in Section 3.4.

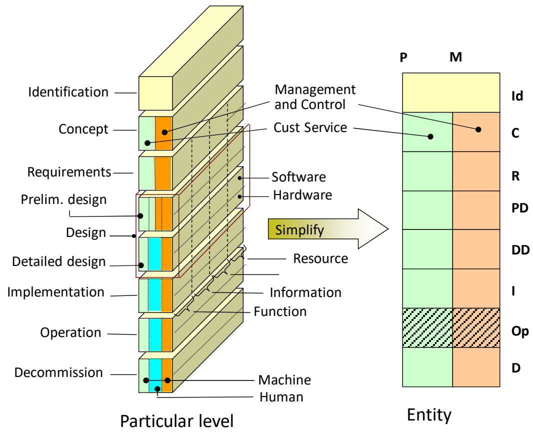


Figure 2: Deriving the modelling constructs used to analyse specific viewpoints in the case study.

3 THE CASE STUDY

3.1 Setting

A large company and developer aimed to diversify its investments by creating an industrial precinct; in the context of the current climate change challenges and global competition, the decision was taken to adopt a recycling-based strategy, so as to minimize waste and pollution and realise savings on raw materials. The overall 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 for guidance as to how to select these partners in the initial and continuing stages. Furthermore, there was a need 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 Building the Breeding Environment

The above situation matches a combined CE and CN paradigm, namely the closed-loop logistics and integrating forward and reverse supply chains described by various authors (Meade et al., 2007; Romero & Molina, 2012; Srivastava, 2007). In the particular case described, in view of the geographical co-location of the participants, the specific type of EIN envisaged was the symbiosis network depicted by Patala et al.'s (2014) work.

From the point of view of the CN knowledge area, the situation is relevant to the formation of a 'Green' Breeding Environment (GBE)(Romero & Molina, 2012), a pool of potential participants which are *pre-qualified* (i.e. all the cooperation protocols and contracts are pre-established and negotiated) and thus achieve the necessary preparedness to promptly participate in various joint ventures ('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 applying the other knowledge areas towards achieving suitable emergent properties for the partner associations (SoS area) and of investigating the relevant areas that needed to be addressed by potential partners (using the EA Modelling Framework viewpoints, namely Information and Resource).

Further on, several other participants have been identified and qualified as GBE members using the same multi-disciplinary approach:

- Green energy producer
- Plant-based food manufacturer
- Waste handling facility
- Research facility
- Telecommunications company
- Agricultural equipment dealer
- Plastic pipe manufacturer
- Building products manufacturer
- Enviro-fibre packaging manufacturer
- Plastic decontamination/Protein Manufacturer
- Industrial / food grade gases manufacturer and liquefier
- Hydrogen industrial gas manufacturer

The qualification process was based on several criteria, such as shown below.

A first qualifying condition was the suitability (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 (see Section 2) encompassed and complemented by the EA Function, Information, Resource and Organisation (FIRO) MF 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' (Negri, 2017) for the potential input / output connections that could develop between the GBE members. The concept of digital twin has been used before in EIN (Rojek et al., 2021); in this case study, it was necessary in order to start quantifying the inputs and outputs of the various exchange streams participants (previously not performed as not being deemed 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.

Table 1: Specific CN situation of the case study.

CN Concept	Case Study Materialisation
Breeding Environment	Qualified Network participants
Virtual Enterprise	Lead partner, telco, education
Broker	Green Virtual Enterprise
Streams	Exchange connections
Reference model	Interface templates

To summarize, from the point of view of the CN discipline, the situation looks as shown in Table 1:

EA MF viewpoints have been used to scope out streams, e.g. using functional and informational criteria to determine what exchange activities must be modelled and what data is needed to describe relevant properties of the exchanges, respectively.

3.3 Building the Virtual Enterprise/s

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.

Initially, a representation such as the one shown in Fig. 3 has been used. To start with, a diagram is required for each stream to preserve readability. This means that showing potential relations between streams is very difficult and requires shuffling between diagrams which is very awkward for

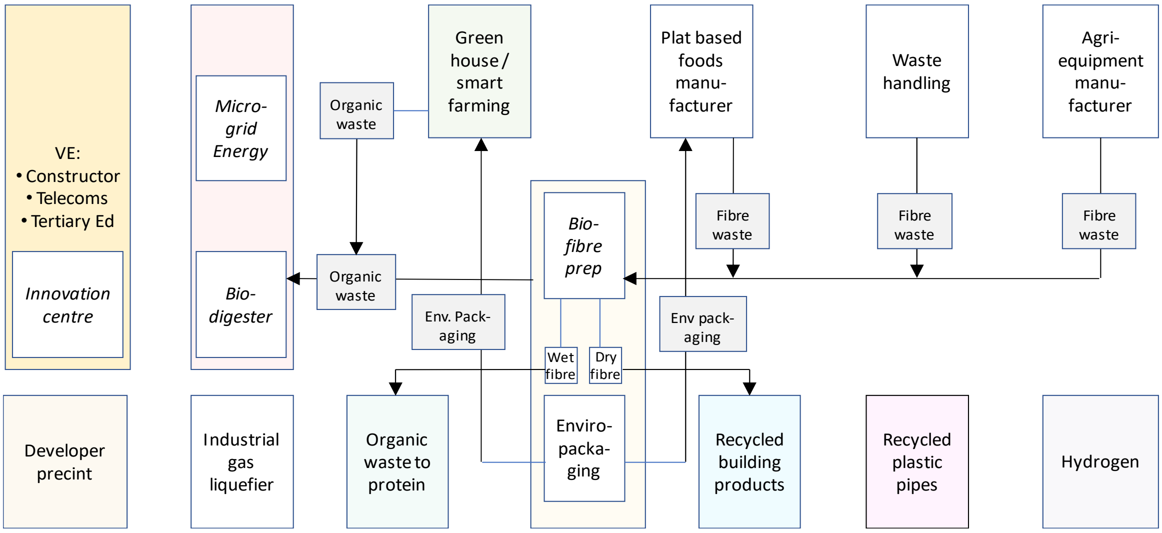


Figure 3: Initial EIN Models including the BE, VE and the Streams.

stakeholders. In addition, as one can see from the figure, many essential aspects, such as life cycle of the BE participants, VE and the streams and the potential relations between them cannot be meaningfully represented.

According to the concepts described in the theoretical background section and satisfactory previous life cycle-based endeavours in the area of environmental management (Lewis & Demmers, 1996; Noran, 2010), it is proposed in this paper to represent the situation using modelling constructs proposed in Section 2 and analyse the results.

Figure 4 shows the same situation using the EA modelling construct derived as shown in Figure 2; as can be seen, this construct allows a richer representation taking into account the life cycles of the participants and management/ production (or service) aspects. Note that not all aspects need to be represented for all participating entities; for example, in Fig. 4 some entities are only represented through their Production side of the Operation life cycle phase (see for example potential BE members or CN members) since only that area is relevant to the model in question.

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 in fig. 4Figure 4); this is to indicate the capacity of the entity to change itself to a certain extent (adaptation) as further explained. Various line types may also be used as illustrated in the same figure, in order to better represent possible scenarios or behaviours.

Should specific aspects be required to be represented, various viewpoints can be selected from the MF shown in Figure 1. 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 essential advantage when using such an artefact 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.

The following gives a brief explanation of certain aspects of the dynamic business model of the case study represented in Fig. 4.

Thus, one can see the role of governmental agencies such as the Clean Energy Regulator (CER)(Australian Government, 2021) 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. This is represented in the figure by arrows containing the 'CER' designation originating from the Government Operation phase going to GBE and Streams' Identification and Concept life cycle phases. Note how CER is represented in the figure by the Production side of its Operation phase, since only that aspect is relevant to the situation. The Government also influences the GVE(s) created by the GBE by means of funding

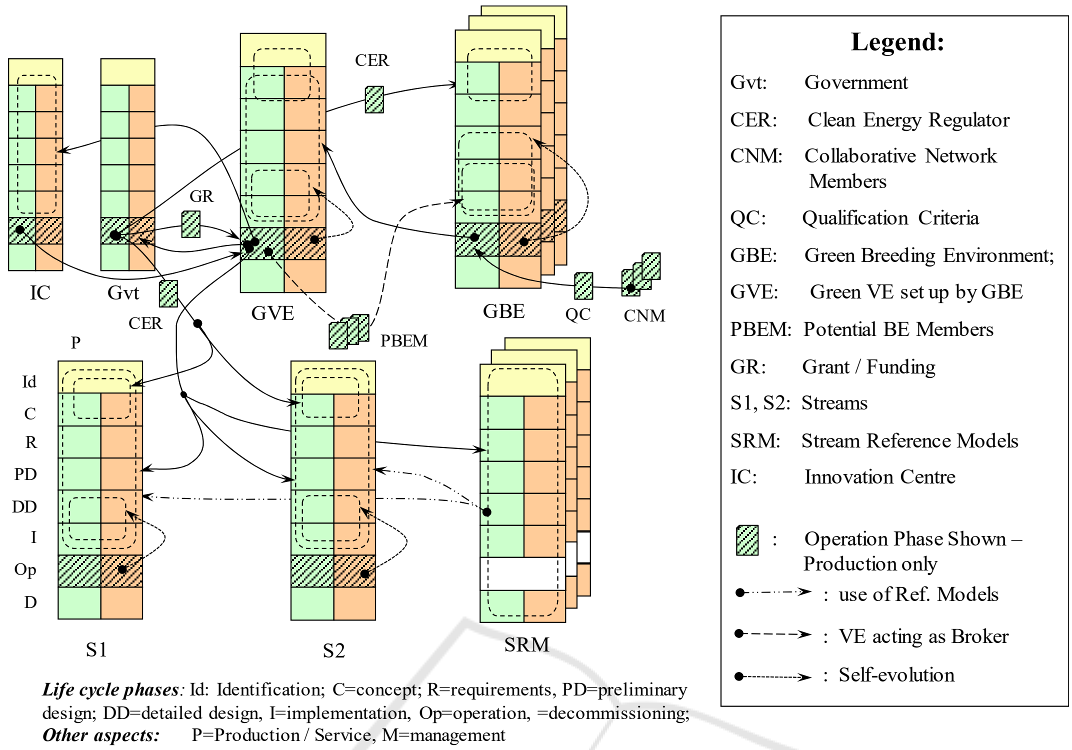


Figure 4: Possible business model of the EIN in an EA MF life cycle-based representation.

('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.

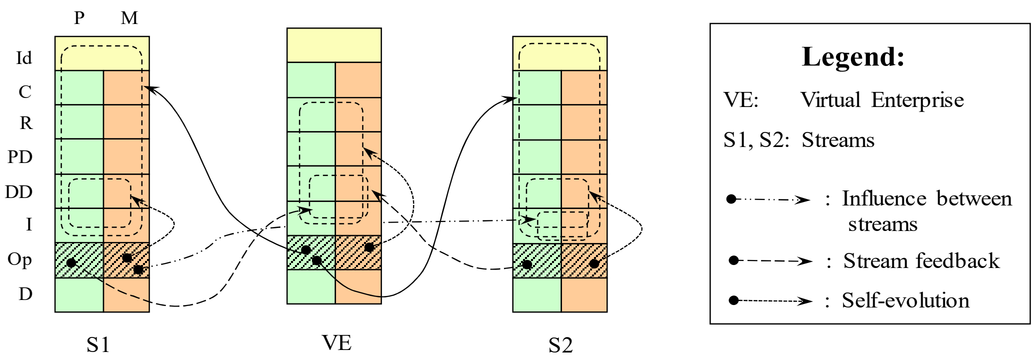
In the figure, these avenues of action are shown as follows: a) an arrow going from the GVE to the Government management (lobbying and applying for funding), b) arrows going to the Identification through Detailed Design life cycle phases of the streams and c) arrow containing PBEM (Potential BE Members) 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. 4), 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 take the form of e.g. partially instantiated interfaces presented to GBE members; they can also be used to prepare new entrants for GBE membership. To be able to investigate and handle new stream scenarios that do not fit any existing knowledge that can be reused, and to enable the continuous improvement of the existing streams and the EIN in general, the GVE (mainly via the resources of its tertiary education lead partner) created an Innovation Centre (IC). In its operation, the IC assists the GVE in finding solutions to new problems and evolving the EIN to ensure its agility and preparedness in the face of changing environment conditions.

The same figure also shows how Collaborative Network members (CNM) may contribute to the GBE if they satisfy the Qualification Criteria (QC in the figure) which, as described in Section 3.2, include suitable preparedness to participate in Streams and agreement to develop Digital Twins.

3.4 Setting up the Streams

The streams' interfaces are designed by the GVE according to various criteria, such as the Function, Information, Resource and Organisation set of viewpoints present in the EA MF (see fig. 1). As mentioned, on entering the GBE, the CN participants agree on creating Digital Twins which can be subsequently used to quantify their participation in streams. For example, if within a stream a participant requires CO_2 of a certain concentration, composition etc. delivered in a certain way one can use the Information, Function and Resource viewpoints



Life cycle phases: Id: Identification; C=concept; R=requirements, PD=preliminary design; DD=detailed design, I=implementation, Op=operation, D=decommissioning;
Other aspects: P=Production / Service, M=management

Figure 5: Relations between the streams and the VE.

respectively to model this aspect, while the Organisation view may depict (if necessary) the organisational changes required for this stream to exist and operate. The automation viewpoint (shown as 'machine' and 'human' in Fig. 1 and 2) may be used to define any necessary human / machine / agent aspect of the processes involved (Bichraoui et al., 2013). Furthermore, the Management vs. Production distinction present in the EA MF can also be used to scope the Stream to the level of detail desired. As an example, in Fig. 4 this distinction is used to represent how the management of the stream enables its own evolution (within limits shown as the circled life cycle phases) as a complex system.

Figure 5 illustrates in more detail the manner in which the chosen EA-based representation allows depicting the relations between the streams and with the managing GVE in the context of their life cycles. This representation enables reasoning about the alternative forms of such relations, possibly uncovering *emergent* features that did not exist in the participants, and about their effects which may be positive (EIN enhancement) or needing to be avoided (if hindering the EIN operation as a whole).

Fig. 5 shows how feedback from stream operation analyses can flow back to and influence the GVE (dashed arrows in the figure from stream operation to GVE detailed design life cycle phase), which may result e.g. in redesign or reconfiguration to optimise the streams in question.

An example in regards to the previously-mentioned self-evolution of the streams can be as follows: in the process of stream operation there may be discoveries made by the participants by way of unforeseen optimisations and innovation which illustrates emergent (not previously planned) behaviour. This may result in autonomous changes up to a certain level (in the figure, 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, if there are limited adjustments in how the food-grade gases are produced and delivered (e.g. in the concentration / composition requested by the customer) this can be handled by the stream. Else, e.g. if there is a major change (e.g. hydrogen is produced for example in a 'blue' rather than 'green' manner (Howarth & Jacobson, 2021) due to e.g. economic reasons), that may imply more significant changes, which need to be handled by the GVE.

Last but not least, the streams can influence each other; 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 (see e.g. the dash-dot arrow from Stream 1 to Stream 2 in Fig. 5). 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 magnitude of the issue.

3.5 A Time-based Representation

As mentioned in Section 2 and shown in Fig. 1 and 2, the EA-based modelling constructs proposed intentionally abstract from time so as to better focus on the other aspects. However, in practice, at some point it becomes necessary to determine the timing of all the interactions (be it activities, information, etc.) within the life cycle phases so as to enable adequate management. For example, it is important to know which- but also *when* the life cycle phases of the GVE and streams are being influenced by other entities. In addition, one may need to repeatedly go through some

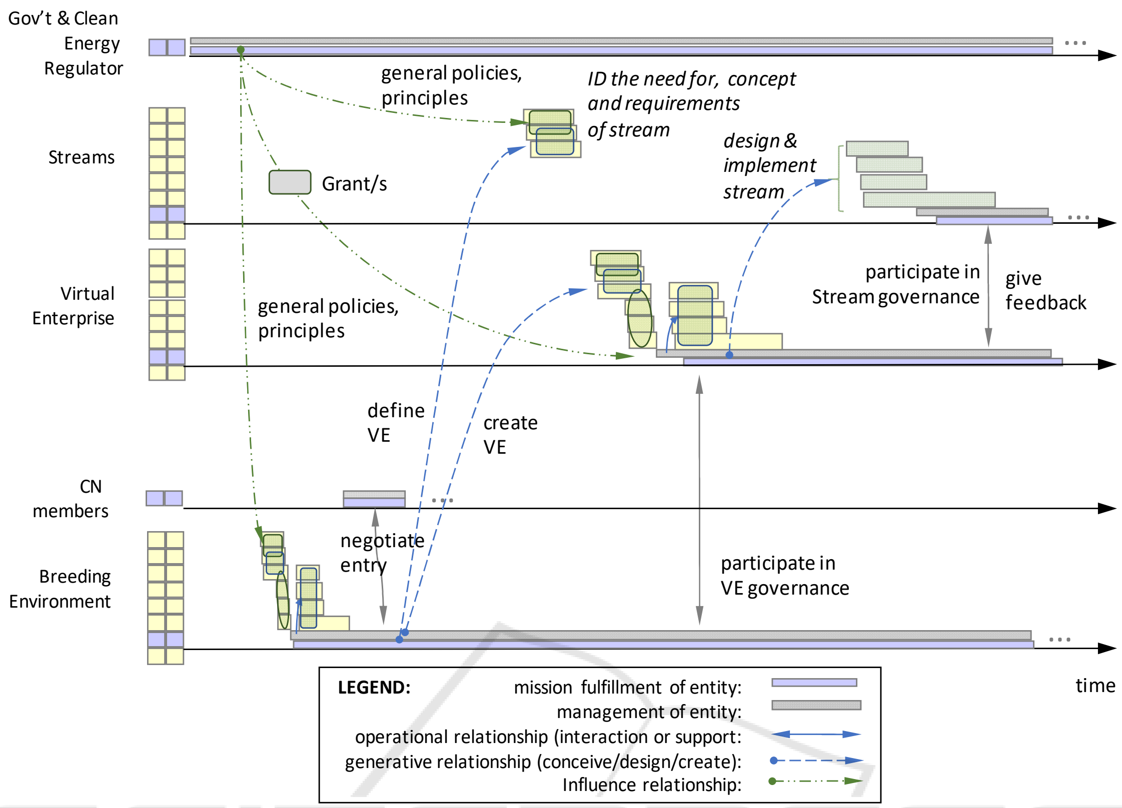


Figure 6: Parallel life histories of entities of interest.

life cycle phases of the participating entities – e.g. in this case, during the re-design of the GBE, GVE, or the streams. In order to cater for the management of the project, one needs to also add the time dimension to the previous representations.

As previously mentioned, GERA (see Section 2) also contains a time-relevant construct called *life history*. Its use is illustrated in Figure 6. for the entities 'of interest' (involved in the EIN), where the life cycle-based constructs defined in Section 2 and used in Figure 4 and Figure 5 are now represented orthogonal on a horizontal time dimension.

Using this type of figure, the stakeholders can agree on the procedure and timing to set up the GBE, GVE and streams and other important entities that may be involved; for example, the Clean Energy Regulator setting up a general framework for policies and principles of GBE and GVE, or the Government awarding various grants to the GVE in order to set up the streams enabling the EIN operation.

Due to the time dimension presence, this representation can uncover new precedence and succession insights, such as for example the need for- and the concept for specific Streams being possibly defined *before* the creation of the VE that will design and implement them (see arrow from Government / CER to the upper life cycle phases of the Streams in Figure 6). Note that the involvement of the CER in the life cycle phases of the GBE and the potential government support in the form of grants, initially shown in Figure 4, is also represented here to ensure consistency of the models.

4 REFLECTIONS ON THE RESULTS

A significant problem in large and distributed projects is the lack of a common understanding by the stakeholders of the present and desired future states, leading to conflicts and delays and eventual failure (Davis, 2018); another is the real possibility of failing to address every required aspect of the project, due to complexity (Cristóbal et al., 2018). In this case, the use of the EA artefacts in the representations has enabled reasoning about the creation of the GBE, GVE and streams in terms of the relevant aspects, such as for example who designs, manages and operates these structures, how do these entities interact, what are other interfacing possibilities and so on. Hence, the use of EA artefacts has allowed stakeholders to better visualise, internalise and agree on a common perspective on the present (AS-IS) and selected future (TO-BE) states.

The initial models used were limited in their expressivity and cumbersome as they required the simultaneous use of several diagrams. The use of EA artefacts, shown to be able to subsume concepts brought by other disciplines (CN, SoS, IE), has allowed to model the streams in a more expressive way and importantly, in the context of their lifecycles.

Thus, the proposed modelling approach was able to represent important interactions and influences between the participant entities occurring during their entire life rather than just during operation.

The Management vs. Mission fulfillment viewpoint has allowed to reveal other relevant aspects in the models such as for example the ability of the entities to adapt, in the case of the streams and the VE.

The use of the FIRO viewpoints has allowed to model separately the flows of information and material, while at the same time allowing to check consistency between these flows and thus ensuring model integration. This has supported the creation and maintenance of meaningful and representative digital twins, essential in life cycle management (Macchi et al., 2018).

A potential challenge in the proposed approach can be achieving the necessary competency in using the modelling constructs and the fact that background domain knowledge is still required. Along these lines, one step further could be the use of a supporting artefact that creates customised, directly applicable stream setup operation and maintenance methods for specific scenarios, i.e. a *meta-methodology* (Noran, 2004; Thomann, 1973). This would allow for the needed guidance in applying the proposed EA artefacts to the projects at hand.

5 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 at the same time analysing the possibility and benefits of a more EA-focused approach in EIN. Thus, various models of the EIN have been created and assessed in contrast with previous approaches. 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 a common stakeholder 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.

Further work will seek more case studies focused on various CE areas in order to evolve and detail the approach presented and potentially testing the proposed assisting meta-methodology artefact.

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