Exploring the Application of Multilayer Networks in Enterprise Architecture: A Case Study in the Smart Grid

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***Abstract*—We present an exploratory investigation on the use of multilayer network concepts and metrics to quantitatively analyse enterprise architectures. Multilayer networks can be used to visualise the overall architectural design and perform analyses across layers within elaborate architectures. Preliminary results are presented and discussed based on a case study in the Smart Grid, which is modelled using the Smart Grid Architecture Model (SGAM). The SGAM representation is later on mapped onto a multilayer network notation that allows visualising the overall structure of the architecture as well as computing quantitative metrics. We conclude with a summary of insights and open issues to be addressed.**

I. Introduction

As new ways to deliver commercial services highly rely on Information and Communications Technology (ICT), new ways to study their impact are also required. For instance, current research focuses on analysing the socio-economic impact of new services such as Uber and AirBnB [1], which exploit not only ICT and innovative business models but also bring about changes and challenges to traditional industries, e.g. informed policy-making in transportation and hospitality [1].

Similarly, the traditional energy sector is facing new challenges due to environmental concerns as well as market liberalisation [2]. The Smart Grid (SG) concept emerges in this context to optimise both power and economic flows [3]. Furthermore, it is not surprising that SG also depends on ICT and new business models to achieve such goal [4], [5]. For instance, as an alternative solution to current non-sustainable incentives in the energy sector, the so-called NRG-X-Change mechanism has been proposed to trade energy between prosumers [6]. Although NRG-X-Change has been thoroughly tested in both software and hardware [7], [8], the complexity of the underlying ICT and the socio-economic impact have not been fully analysed.

To better understand the impact of business, operational and ICT changes, we propose the use of multilayer network (MN) concepts and tools to quantitatively analyse enterprise architectures (EAs), which may provide a holistic analysis that takes into account all the relevant aspects. EAs can provide a model-driven engineering process to design new solutions capturing business, operational and ICT aspects, whereas MN can offer mathematically sound metrics to quantify resulting designs taking into account all aspects at once, i.e. providing a more holistic way to analyse elaborate EAs. In this way, EA and MN can help SG experts by supporting decision-making processes, i.e. providing information that helps them to choose among alternative designs. Moreover, one of our long-term goals is to design a business metric that combines EA and MN for assessing economic aspects like expected costs or revenues.

The contribution of this paper is the illustration of the use of MNs in EA to quantitatively analyse elaborate architectures. This illustration is achieved via two main steps. First, we show how the NRG-X-Change mechanism can be studied using EA models such as the Smart Grid Architecture Model (SGAM) —an enterprise-wide, service-oriented approach to describe an SG architecture —. Second, based on the SGAM representation, we then apply MN metrics and visualisations to analyse NRG-X-Change's overall architecture.

The remainder of the paper is structured in the following way. Section II discusses related work about quantifying EA models, whereas Section III presents our proposed approach to quantify EA models. Later on, Section IV describes our case study and Section V presents preliminary results. Finally, Section VI provides general conclusions and future research.

II. Related Work

A. Enterprise Architecture

Lankhorst et al. define an enterprise architecture (EA) as a "coherent whole of principles, methods, and models that are used in the design and realisation of an enterprise's organisational structure, business processes, information systems, and infrastructure" [9].

The former definition already highlights the importance of models as well as the different views within the enterprise engineering process, i.e. models to represent organisational structure, business processes, information systems, and infras-

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tructure are required. Such models are usually organised in layers representing different views of a whole EA [9].

Even though EAs are usually supported by standardised methodologies and tools [9], it is not trivial to perform analyses in a holistic manner that takes into account all relevant perspectives (models) at once. There are, nonetheless, important research efforts to analyse and understand the impact of business, operational and ICT changes within EAs [9], [10].

On one hand, *functional analysis* techniques provide a qualitative analysis to validate correctness and understand how a system works [9]. These techniques, nonetheless, do not provide information about quantitative aspects such as performance or costs, which are usually answered by the *quantitative analysis* techniques [9].

On the other hand, both functional and quantitative analysis can be addressed using *simulation* and *analytical* techniques [9]. The former perform statistical analyses and require the 'execution' of a model within specific situations (e.g. defined by simulation parameters) [9]. Unlike simulations, analytical techniques can provide a unique reproducible result without requiring the 'execution' of models [9].

In this work, we focus on a quantitative and analytical approach since our long-term goal is to design a business metric to assess *economic* aspects within EAs such as expected costs or revenues.

B. Quantifying alignment, performance and quality-related aspects

Several research efforts have been conducted to analyse EAs. For example, Sousa et al. have provided a set of heuristics to "check" the alignment between business, application and information aspects [11]. The proposed heuristics resulted from mapping authors' academic and industrial experience. Although meaningful, the set of heuristics have not been thoroughly tested in a broad domain [11].

Vasconcelos et al. [12], [13] have proposed 16 metrics to assess different properties (e.g. functionality, reliability, efficiency, maintainability, portability, and alignment) of an Information System Architecture (ISA). The metrics, nonetheless, have been only applied using the concepts related to the so-called CEO framework [12], [13].

In [9], the authors present a top-down bottom-up approach to quantify the performance of EAs. The approach propagates workloads from higher layers into lower layers. Later on, values regarding utilisation (U), processing time (T) and response time (R) are computed and propagated from lower layers into higher layers, which integrate final values for U, T and R [9].

To allow such computation the authors make two important assumptions. First, they assume a (sort of) directed graph that connects resources (nodes) in higher layers with other nodes in lower layers. Second, they assume arrival times that follow a Poisson distribution [9].

C. Quantifying economic aspects

There is also research on assessing economic aspects of EAs. Johnson et al. [14] have designed a probabilistic method to predict the profitability of business networks. The method extends the e^3*-value* ontology and applies the probabilistic architecture modelling framework (P^2AMF), which computes (using Monte-Carlo samplings) earnings per each actor within the business network [15], [14]. Due to its probabilistic nature, the method relies on probability distributions for different values such as prices and number of customers.

In a similar vein, Quartel et al. have proposed an approach for the valuation of IT portfolios [16]. The approach relies not only on information about the (perceived) importance of business processes to the organization (IBO) and business activities to business processes (IBA) but also on the effectiveness of information systems in supporting business activities (ESA). Business managers are expected to provide such information [16]. Once the information is obtained, the method can estimate the value and cost of a given architecture [16].

D. Quantifying complexity

To quantify complexity in EA, several authors have proposed the use of measures inspired by systems theory [17], [18], [19], [20]. Since EAs are usually composed of systems of systems, they are highly likely prone to exhibit inherent and epistemic complexity [21]. The former due to the high number of components and relationships, whereas the latter because of a limited understanding of their dynamic behaviour [21].

Schuetz et al. not only provide a definition of complexity in EA but also propose the use of Shannon's entropy to measure complexity [17]. The measure is designed following a goal question metric (GQM) approach, in which a measure goal is translated onto specific questions that can be used to define a suitable metric [17]. They illustrate the application of entropy to analyse the infrastructure architecture (IA) of a bank. Based on their measure, they analyse the diversity of the database management systems and the operating systems [17].

Likewise, Schmidt proposes the use of entropy to assess the complexity of IT systems by taking into account not only the number of components and relationships among them but also the heterogeneity of both elements and relationships [18], [19]. Following his approach, one could compute complexity per each layer within an EA.

Finally, Schneider et al. have conducted an empirical investigation on the application of different metrics to assess the complexity of application landscapes (ALs) [20]. They have identified three groups of complexity metrics: 1) heterogeneity-focused, 2) topology-based, and 3) industry metrics. The first group is mostly based on the use of entropy as proposed by Schuetz et al. [17], whereas the second group is based on the approach introduced by Lagerström et al., which relies on a design structure matrix (DSM) [22]. Furthermore, Lagerström et al. have also highlighted the importance of combining visualisations and measurements to analyse elaborate architectures [22]. In their work, for instance, they use visualisation based on DSMs to analyse and reveal the "hidden structure" of a telecom architecture [22]. The last group covers metrics dealing with very diverse aspects such as business application, business function, functional domain, infrastructure component and information flow [20].

Summarizing, to quantitatively analyse EAs in a holistic manner, a sound approach is yet to be developed [9], [23], [10]. In this work, we contribute some ideas to potentially develop such an approach based on MNs. Although our final goal is to quantify economic aspects, we initially focus on applying MNs concepts and metrics to quantitatively analyse EA, which can ultimately support a holistic analysis. Likewise, we believe similar metrics could be designed to quantify economic aspects within EA.

III. Proposed Approach to Analyse EA

To quantitatively analyse elaborate EAs, we propose the use of MN concepts and metrics. There are at least four reasons to consider MNs as suitable candidates to quantitatively analyse EAs in a holistic manner. First, MNs are supported by sound mathematical theories connecting network theory and complex systems [24], [25], [26]. Second, MNs provide mathematical tools to perform cross-layer analysis by supporting operations such as layer integration and aggregation [24], [25]. Third, MNs can handle N number of layers, i.e. they are not restricted to architectural languages with prefix number of layers [24], [25]. Finally, MNs offer a "natural" way to *visualise* multiple perspectives within an architecture, which may help to handle inherent and epistemic complexity [21]. The following paragraphs provide some MN concepts and metrics that can be used to quantitatively analyse EAs.

A. Multilayer Networks Concepts

According to Kivelä et al. [24], a multilayer network (MN) can be defined as a quadruplet $M = (V_M, E_M, V, L)$, where L defines a set of elementary layers and V is a set of nodes. Likewise, V_M defines a subset containing node-layer combinations, i.e. nodes that are present in specific layers, whereas E_M represents an edge set containing pairs of possible combinations of nodes and elementary layers, i.e. $E_M \subseteq V_M \times V_M$.

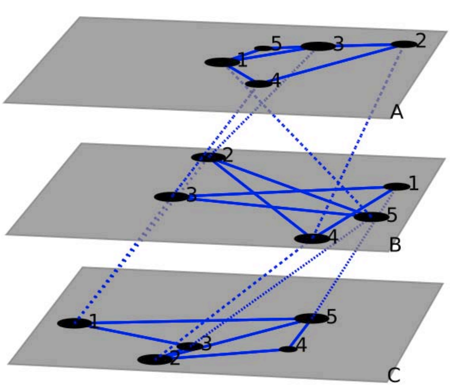

Fig. 1. Example of an MN generated using the Pymnet library [27].

Figure 1 depicts a simple MN that contains five nodes $V = \{1, 2, 3, 4, 5\}$ and a set of three layers $L = \{A, B, C\}$, which represent an *aspect* of the given MN. Although the notation provided by Kivelä et al. [24] allows representing more elaborate MNs, e.g. they also allow MNs to describe different aspects, we focus on MNs describing one single aspect.

As explained in Section II, Lagerström et al. have already explored the use of visualisations to analyse elaborate architectures [22]. They actually use 2D visuals based on DSMs to reveal the hidden structure between software applications in a telecom company [22]. Unlike, their 2D visuals that depict a single architectural layer (i.e. software applications), MNs are capable of combining more than one layer, which can potentially reveal other hidden structures between several layers. For instance, in Figure 1, layers A, B and C can be used to respectively represent business, operational and ICT layers, which depend on each other and exhibit an elaborate structure.

B. Metrics

Kivelä et al. propose five groups of metrics to diagnose MNs: 1) node degree and neighbourhood, 2) clustering coefficients, transitivity and triangles, 3) walks, paths and distances, 4) centrality measures, and 5) inter-layer diagnostics [24]. For simplicity and convenience, however, we only focus on the former two groups.

1) Node degree and neighbourhood: The degree of a node can be considered as the number of edges that are incident to the given node, whereas the neighbourhood can be considered as the set of nodes that are reachable from a given node by following its edges [24]. Both metrics help understand the overall connectivity of a given node. One way to compute the degree of a node $i \in V$ is using Equation 1 [27].

$$deg(i) = \sum_j a_{ij} \tag{1}$$

where

$$a_{ij} = \begin{cases} 1 & \text{if there is an inter-layer or intra-layer edge} \\ & \text{from node } i \text{ to node } j, \\ 0 & \text{otherwise} \end{cases} \tag{2}$$

Note that, as expressed in Equation 2, the degree of a node takes into account intra-layer and inter-layer connections to a node.

2) Clustering coefficients: The density of a network is a common clustering metric that can be defined as the fraction of existing edges versus all possible edges in a network with the same set of nodes and layers [24]. Such metric provides an idea about the overall structural transitivity of a network [24]. The density of an MN with one single aspect can computed using Equartion 3 [27].

$$D(M) = \frac{|E_M|}{(|VM| * (|VM| - 1))/2} \tag{3}$$

The next section presents a case study in the smart grid, which is later used to illustrate the application of MNs metrics to analyse EAs.

IV. Case Study

The smart grid (SG) is a system of systems that aims to 'smartly' manage electricity consumption and production by promoting synergetic interactions among people, technology and natural resources [3]. For example, citizens can currently use photovoltaic panels to exploit solar energy producing electricity that can be directly used to satisfy their needs or traded with electricity operators [3].

Engineering SGs, however, faces inherent as well as epistemic complexity [21]. The former is related to all dynamic relationships among customers, prosumers (those who consume but also produce electricity), network operators and markets; whereas the latter refers to our limited understanding about SG's issues, e.g. assessing whether some architectural designs might be more sustainable than others [3], [21].

A. SGAM Framework

To alleviate these complexity issues, researchers and SG professionals have proposed the Smart Grid Architecture Model (SGAM) framework, which suggests an enterprise-wide, service-oriented approach to describe an SG architecture [28]. SGAM relies on *domains*, *zones* and *interoperability* layers. SGAM *domains* capture aspects related to the electrical conversion chain (from generation to customer premises), whereas *zones* represent different level of power system management. SGAM *interoperability* layers integrate all aspects related to business objectives, functionality, information exchange, communication protocols and ultimately the technical infrastructure of SGs [28]. Since a detailed description about SGAM is outside the scope of the paper, we recommend interested readers to consult the work published in [28].

B. NRG-X-Change

NRG-X-Change is a mechanism to trade energy among consumers and prosumers [6]. It proposes an innovative idea that relies on two business services. The first service (NRGcoin billing service) allows both prosumers and consumers to buy and sell energy from and to an energy retailer (e.g. a substation) using NRGcoin, which is crypto-currency inspired by Bitcoin [6]. The second service offers a cloud market in which prosumers and consumers trade NRGcoins (NRGcoin exchange service) [6].

Although NRG-X-Change has been thoroughly tested in software and hardware [7], [8], the underlying architecture that support its operation has not been analysed. The next paragraphs elaborate on how we use SGAM to model the NRG-X-Change mechanism so that we can analyse its architecture using MNs.

Since NRG-X-Change is focused on trading energy at the level of dwellings, we only cover three SGAM domains of the electrical conversion chain, namely: Customer Premises, Distribute Energy Resources (DER) and Distribution. The former two respectively deal with customers and prosumers aspects, whereas the latter one covers retailer's aspects.

The description of each interoperability layer is based on guidelines provided by [28]. Briefly, 1) the business layer covers business portfolios (e.g. *products and services*), 2) the function layer describes actor-independent *functions and operations*, 3) the information layer specifies the *information* that is used and exchanged between functions, services and components, 4) the communication layer defines *protocols and mechanisms* for the exchange of information between components, and 5) the component layer focuses on the *basic connectivity* and the *physical distribution of all participating components* [28].

1) Business Layer: Figure 2 depicts the two business services offered by NRG-X-Change. The NRGcoin billing service deals with energy management as it carries on payments based on energy consumption and production [6]. The NRGcoin exchange service offers the possibility to trade NRGcoins in a cloud-based market. Note that since both services are independent from each other, different actors could be expected to participate. In this way, there might be actors that participate only in the NRGcoin exchange service as it may be profitable for them.

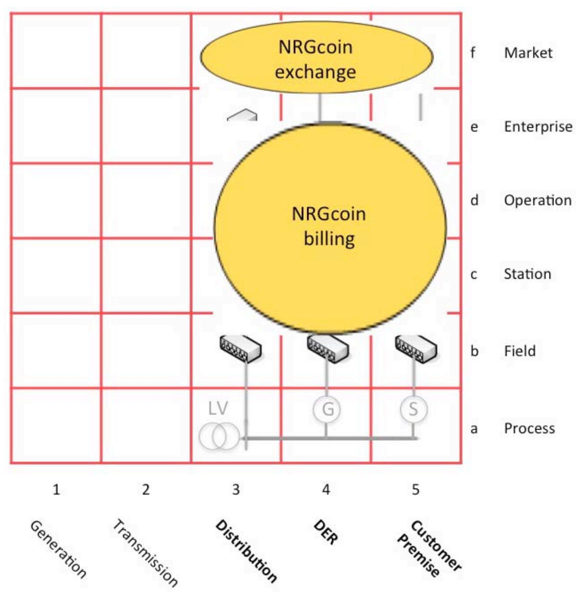

Fig. 2. Business Layer.

2) Function Layer: By the same token, Figure 3 describes the functions that are required to operationalise the NRG-X-Change services. On one hand, it shows energy related aspects such as data acquisition, energy payment and billing. On the other hand, it shows market-oriented aspects such as bidding and market clearing, which are needed for the NRGcoin exchange service.

3) Information Layer: Different data models rule the information being exchanged between all components. Figure 4 depicts such models. Station and field components must use

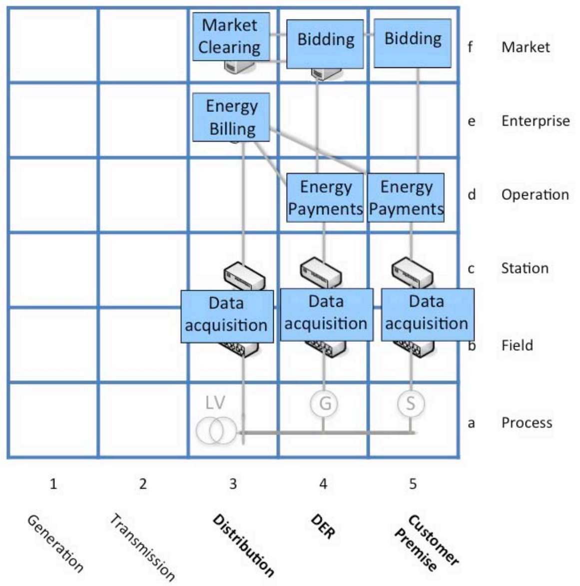

Fig. 3. Function Layer.

IEC-based models described in the IEC 61850 standard [28]. Operation and enterprise components must use data models required to operate the NRGcoin protocol [6]. For instance, data models describing NRGcoin-based billing. At the upper level, market components must implement market specific models (MSM) to describe bids, transactions among other orderbook-related aspects [6].

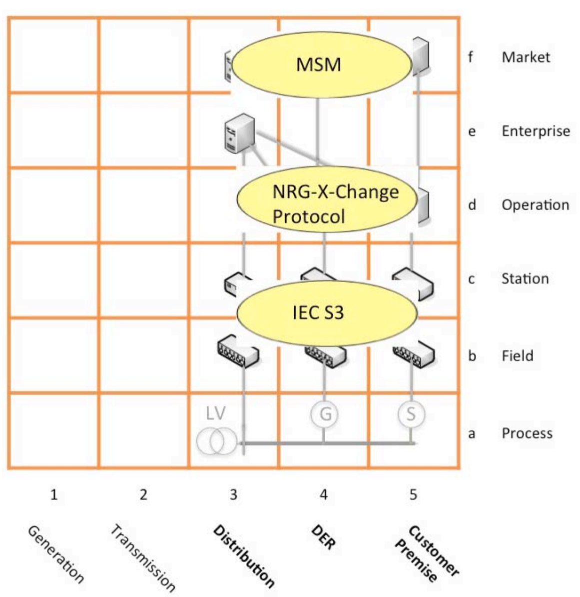

Fig. 4. Information Layer.

4) Communication Layer: The elements described in the component layer communicate with each other using different protocols. These protocols are depicted in Figure 5. We assume that communication between Field and Station elements as well as between Station and Operation elements can rely on International Electrotechnical Commission's (IEC) standards described by IEC 61850 [28]. Communication between Operation and Enterprise elements can be based on either LAN or MAN protocols as it mostly depends on the coverage being planned. Finally, communication between Market elements requires HTTP-based protocols as the NRGcoin market runs on the cloud, i.e. HTTP-based platform.

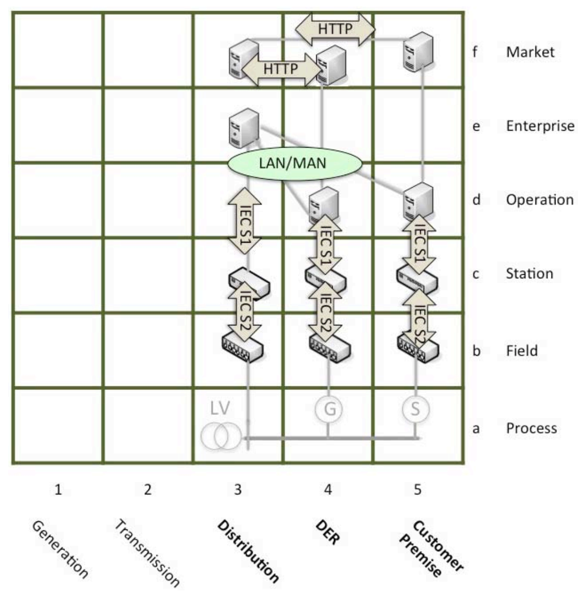

Fig. 5. Communication Layer.

5) Component Layer: The bottom layer of the NRG-X-Change is depicted in Figure 6. It shows how power and information flows link all components. At the process level, where power flows occur, we have low voltage (LV) distribution components (substation), DER components (G) such as solar panels, and energy consumption components (S). At the field level we have sensors that perform measurements and send those measurements to components (e.g. SCADA) located at the station level. At the operation level prosumers' and consumers' smart meters communicate with substation's devices to perform energy payments and billing. At the market level, the energy retailer supports the NRGcoin market in which prosumers and consumers trade NRGcoins.

Figures 2 to 6 cover all the interoperability layers defined by SGAM. They also help to understand the zones and domains that are relevant for the operation of the NRG-X-Change mechanism. As one can see, each layer aims to describe different perspectives as well as support the analysis and communication among different stakeholders. For instance, business and operational aspects can be discussed using the business and function layers, whereas purely technical aspects can be analysed using the information, communication and component layers. Furthermore, as explained in the following section, MNs can be used to support advanced discussions and

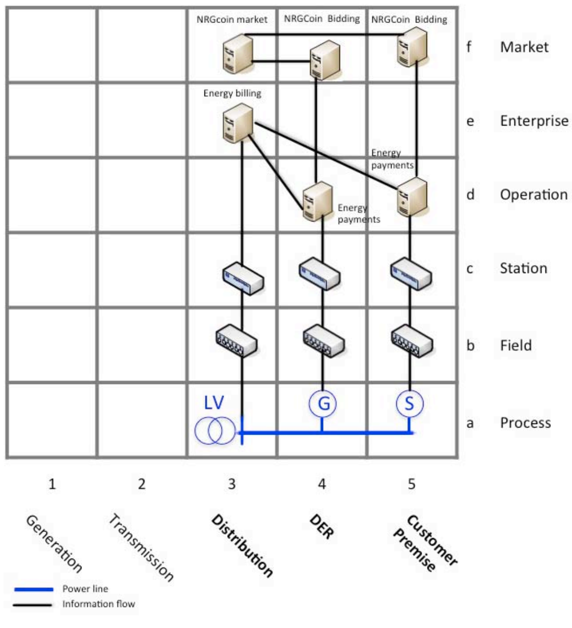

Fig. 6. Component Layer.

analyses.

V. Preliminary Tests

This section illustrates the use of MN metrics to quantitatively analyse an ICT-based system that can be described using EA. Unlike Lagerström et al. who use a design structure matrix (DSM) for visualising and measuring EAs [22], we use MNs to visualise and quantitatively analyse EAs. MNs not only provide a more "natural" way to visualise and organise different EA layers but also support a quantitative and analytical approach [24].

A. Visualising EA

Figure 7 shows an MN that depicts the topology of the NRG-X-Change mechanism based on SGAM interoperability layers. Briefly, V contains 38 nodes across five layers, i.e. $L = \{$01-BL, 02-FL, 03-IL, 04-CL, 05-CompL $\}$. Furthermore, the visualisation was generated using concepts and tools provided by Kivelä et al. [24], [27].

As one of the motivations to visualise the topology of EAs is to discover hidden patterns [22], [20], in Figure 7 the size of a node represents its degree. In this way, it is possible to visualise nodes that are highly connected across layers. For instance, nodes in the information layer (03-IL) show high connectivity, which highlights the importance of the information layer.

In Section IV-B we assume that an energy retailer is in charge of both business services (NRGcoin billing and NRGcoin exchange). It is possible, nonetheless, that different companies could operate those services. For instance, the retailer may be willing to outsource the operation of the NRGcoin exchange service. In this case, to determine risks

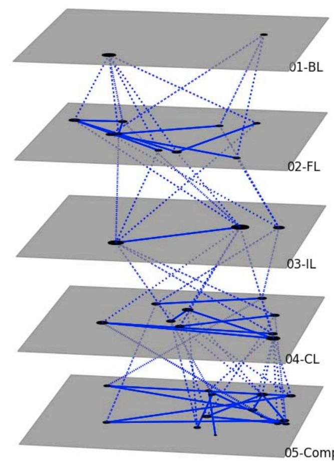

Fig. 7. SGAM-based NRG-X-Change architecture mapped onto an MN. $01-BL, 02-FL, 03-IL, 04-CL$ and $05-CompL$ correspond to business, function, information, communication and component layers respectively.

and/or opportunities for outsourcing, it could be useful to analyse the overall topology supporting each service. Figures 8 and 9 show the topologies of the NRGcoin exchange service and the NRGcoin billing service respectively. As can be observed, the NRGcoin exchange service is composed of fewer elements since it only covers the trade of NRGcoins between prosumers within the NRGcoin market.

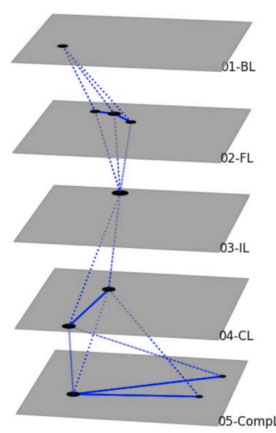

Fig. 8. SGAM-based NRGcoin exchange service mapped onto an MN. $01-BL, 02-FL, 03-IL, 04-CL$ and $05-CompL$ correspond to business, function, information, communication and component layers respectively.

In contrast, as seen in Figure 9, the NRGcoin billing service shows a more elaborate topology since it must perform several functions such as data acquisition and energy payments as well as connect different components like photovoltaic panels, smart meters and substation's devices.

B. Quantifying EA

We have computed metrics to analyse degree distribution and density, which are described in Section III-B and are based on [24], [27]. Figure 10 shows the degree distribution of the

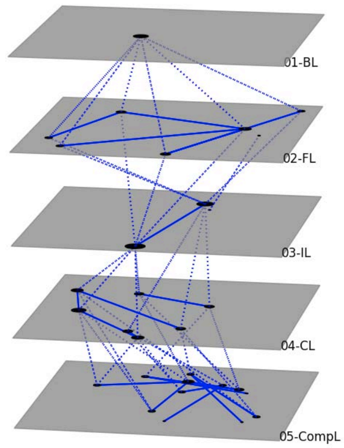

Fig. 9. SGAM-based NRGcoin billing service mapped onto an MN. $01-BL, 02-FL, 03-IL, 04-CL$ and $05-CompL$ correspond to business, function, information, communication and component layers respectively.

NRG-X-Change mechanism as well as the degree distribution of the NRGcoin exchange and NRGcoin billing services. As can be observed, NRG-X-Change shows a high number of nodes (26) whose degrees are three and four, which means than more than 50% of the nodes have a neighbourhood composed of three or four nodes. In contrast, the NRGcoin exchange service shows a more "flat" degree distribution but with 70% of the nodes having a neighbourhood composed of three or four nodes. Note, however, that the degree of a node is computed across layers, i.e. as explained in Section III-B, it is the number of inter-layer and intra-layer edges that are incident to a given node.

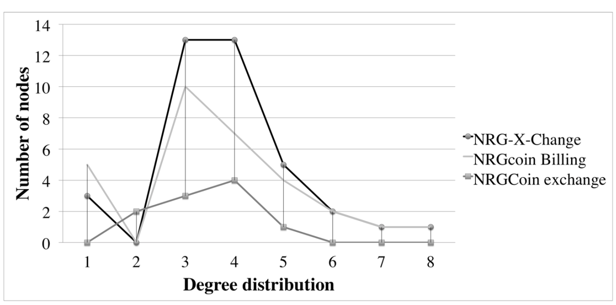

Fig. 10. Degree distribution for NRG-X-Change, NRGcoin billing service and NRGcoin exchange service.

In a similar vein, Figure 11 shows the density of NRG-X-Change, the NRGcoin billing service and the NRGcoin exchange service respectively (see also Section III-B). For instance, the density of NRG-X-Change is computed based on Equation 3 as follows:

$$D = \frac{|E_M|}{(|V_M| * (|V_M| - 1))/2} = \frac{55}{(150 * (150 - 1))/2} = 0.004$$

Since density aims to measure transitivity across the overall MN, the NRGcoin exchange service (composed of fewer nodes and edges) shows higher density compared to NRG-X-Change and the NRGcoin billing service, which suggests that elements in the NRGcoin exchange service are highly interconnected across layers (i.e. small architectural changes could impact several elements at once).

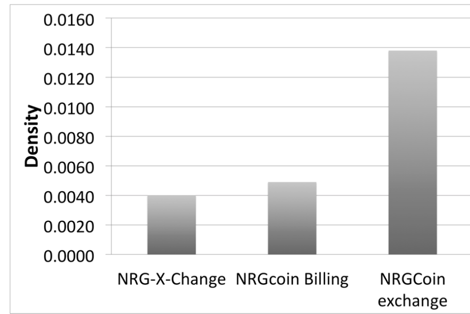

Fig. 11. Densitiy for NRG-X-Change, NRGcoin billing service and NRGcoin exchange service.

Based on Figures 10 to 11, one can see that MN metrics provide different ways to diagnose an EA. Moreover, combining visual representations together with quantitative measures can provide better insights to support SG and EA practitioners when evaluating different design choices.

C. Lessons Learned

During this exploratory investigation we have learned several things. First, the modelling of elaborate architectures, as the one presented in our case study, requires substantial knowledge from experts. For instance, to define the communication and information layers in SGAM, one needs to understand not only the overall architecture being designed but also the current protocols and standards in the energy sector [28].

Second, although the smart grid field is of relevant importance nowadays [3], the SGAM framework does not have the same level of maturity as well-known architectural frameworks in other fields, e.g. ArchiMate [28], [9]. This lack of maturity, nonetheless, provides new opportunities to conduct research while improving SGAM's acceptance and standardisation.

Finally, unlike most of the current EA metrics that focus on few architectural layers [11], [13], [22], [17], [19], [20], MNs may actually provide a holistic analysis by supporting visualisation of elaborate architectures as well as the application of quantitative metrics across layers [10]. It is important to mention that top-down bottom-up approaches proposed in [9], [16], provide already some work towards a holistic analysis of EAs.

VI. Conclusions and Future Work

Multilayer networks (MNs) are very attractive tools to quantitatively analyse Enterprise Architectures (EAs). Sound mathematical theories provide different metrics to measure structural, statistical and behavioural aspects within MNs [24], [25], [26]. Likewise, MNs can handle N number of layers while offering a "natural" way of visualising elaborate architectures, which may help to handle inherent and epistemic complexity in EAs [24], [25], [26]. Furthermore, we have shown how SGAM and MNs can be combined to provide meaningful insights to analyse new Smart Grid services that will undoubtedly rely on ICT even more [2]. In this paper, therefore, we illustrated the use of MNs to visualise and quantitatively analyse elaborated EAs.

Although we have focused on quantifying SGAM-based models, we plan to use MN concepts and tools to quantify economic aspects in generic EA models (e.g. ArchiMate [9]). Actually, our ultimate goal is to design a business metric to assess the economic feasibility of services that rely on complex architectures (i.e. business, operational and ICT aspects), which may help us to monitor and adapt to market changes, [21], [23]. For example, based on the node-layer set V_M and the edge set E_M (i.e. "flows" between nodes), we could design a metric that computes the net present value, so that we can identify opportunities to adapt the overall architecture [9], [23].

As any research in progress, our proposal faces several challenges and limitations. For example, it is probably not trivial to apply MN concepts, metrics and visuals on top of well-know architectural languages such as ArchiMate [9]. In a similar vein, at their current state, MNs lack any (semantic) support to perform high level reasoning that allows to automatically check consistency between different layers [24], [26].

To conclude, we consider that using MNs together with EA provides a new insightful approach that opens the door to new ways of performing business analytics within elaborate ICT-based systems.

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