Towards a Hypergraph-based Formalism for Enterprise Architecture Representation to Lead Digital Transformation

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Abstract. In this paper a concept will be proposed about a hypergraph-based formalism for representing enterprise architecture. The paper presents a formal model using TOGAF and hypergraph theory. Hypergraphs provide a flexible mathematical structure to describe complex relationships in an enterprise architecture, mirroring the dependencies among components, and exploring integrity and consistency issues. The proposed approach extends the analytical potential for discrepancy checking in complex enterprise architecture structures. The approach can be utilized for EAM-based analysis of information systems.

Keywords: Enterprise Architecture, TOGAF, Artifact, Formal Modeling, Hypergraph.

1 Introduction

Information strategy planning is a complex and utterly important activity in organizations, an exercise through which an organization utilizes its technological resources [17]. Information strategy is a major tool to integrate information technology (opportunities and concerns) into business planning, harmonizing the business and IT domains. The overall goal of IT planning, as part of the broader concept of IT governance is the alignment of information systems (IS) and business plans. In the era of digitalization, the growing organizational complexity, emerging disruptive technologies, and rapid technological changes make strategic planning of IS extremely challenging. Whereas classic planning approaches [16] are still in use, enterprise architecture management (EAM) based approaches became the major facilitators of the planning initiatives [10]. The planning cycle, integrated with implementation and monitoring activities requires the support of EAM. Strategic harmonization of business and IT domains is more relevant than ever before, and EAM can be a major facilitator of strategic alignment by discovering, analysing and avoiding misalignment problems and achieving competitiveness [18]. EAM provides methods to ease organizational

complexity, promotes agility, and controls uncertainties [8]. EAM helps the alignment of the organisation with strategic goals, the control of interdependencies in business and IT, and it enables organisations to agility and fast reaction.

The complexity of IT and IS infrastructures coerces the exercise of modeling of Enterprise Architecture (EA) within companies. There are several approaches of Enterprise Modeling [1, 19] that provide opportunities for semi-formal modeling through exploiting visual representations and specifications of various pre- and post-conditions. The central concept of Enterprise Architecture Modeling is the artifact that is the outcome of some modeling, designing and analysis activities. The artifacts can be considered as documents that describe architectures through complex relationships among the elements of artifacts. As the documents allow for depicting multifaceted relations among components that reflect the intricate relationships among the building blocks of architecture, the representation by a formal approach requires a flexible descripting method in which there are no restrictions on enhancing and extending the representation with new type of relationships, concepts, hierarchies, and networks. The hypergraph theory provides a very elastic mathematical structure that has the capability, on the one hand, to mirror the multifarious dependencies among constituents, and on the other hand, to exploit the graph structure for analysis utilizing the tool set of mathematics. This paper is intended to discuss the topic of EAM-based analysis of misalignment problems, introducing an existing method. The EAM-oriented analysis model is extended with our proposition for a hypergraph-based EA representation, and the foundations of the extended conceptual framework are described.

The rest of the paper is structured as follows: Section 2 summarizes the role of EA in leading digital transformation. Section 3 presents the connection between digital transformation and the modeling of enterprise. Section 4 introduces the mathematical background to hypergraphs. The hypergraph-based approach is presented in Section 5. Section 6 presents an illustrative example for the proposed formalism. At the end of the paper conclusions are drawn.

2 The Role of EA in Leading Digital Transformation

Digital innovation - the use of digital technologies in the process of innovation - results in new products, services, business processes and business models. Digital transformation handles the effects of digital innovations: the emergence of new actors, new network, new structures, practices [11]. Organisations in the digital era face the changing role of digitality in their business models, organisational design, compliance, regulation and economic environment [4]. This changing role concerns business strategies as well: Digital technologies transform traditional business strategies into digital business strategies [2]. Digital transformation strategies are plans that govern organisations in transforming products, processes, organisation design due to the emerging digital technologies in the organisation. As it is becoming more and more difficult to disunite digital products and services from their underlying IT infrastructures, corporate IT plays an important role in leading digital transformation [2]. IT-

enabled processes made digital product and service architecture more complex. It is necessary to revisit the present enterprise architectures and IT governance practices to successfully manage this digital transformation. Goerzig and Bauernhansl [9] collected several aspects to compare enterprise architecture and digital transformation. According their comparison, EA and digital transformation evolve from different drivers, consist of different target groups, differ in subject, development approach, value stream and lifecycle phases. These aspects facilitate the search for new methods, models and tools of EAM in its changing role.

3 Digital Transformation and Modeling of Enterprises

The digital transformation of enterprises affects the business model and business architecture including the business process models. As the overall EA contains the process chains for value creation, the actors and roles related to processes thereby each single element of EA is impacted by digital transformation. The

> *„Digital transformation (DT) – the use of technology to radically improve performance or reach of enterprises –is becoming a hot topic for companies across the globe. Executives in all industries are using digital advances such as analytics, mobility, social media and smart embedded devices – and improving their use of traditional technologies such as ERP – to change customer relationships, internal processes, and value propositions."* [7]

As it can be seen from the quotation, the business level *meta-process* is the Digital Business Transformation [5], i.e. the profound re-structuring and engineering of enterprises or organizations. This procedure can be perceived as a total redefinition of EA. The requirements for the business can be formulated as the exploitation of the full potential of IT (Information Technology) along the entire process chain dedicated to value creation. Thus, the Digital Transformation means the application of the most recent technologies to increase the performance and enhance the scope of business services. The application of IT and other modern technologies touches several perspectives of EA, namely business processes, users and human roles, the networks of communication within and outside of the cyberspace, the operation through the business model.

As the business model is the foundation logic of enterprises, it describes the benefits for partners that can be provided and the way of access to the business services. The dimensions and elements of business models strongly correlates to EA:

- Customer/consumer dimension related to the human and user roles perspective;
- The benefits dimension for partners (services and value for money) connected to the motivation, "why" perspective;
- The value creation dimension strongly coupled to resources (data asset, business and IT networks, human actors, and roles) and business processes;
- The partner dimension linked to the (business) networks and human roles;
- The finance dimension encompasses the costs and revenues that depends on the business processes, business rules.

The goal of Digital Transformation at enterprises is to re-engineer the business model, and the business processes, the functions of the organizations, the information interchange between organizational functions. It is anticipated that enterprises will build intelligent business models that that will re-shape the customer relationship models profoundly that can be seen in phenomena as the interaction between customers and enterprises will take place through on-line, e-commerce and m-commerce channels, digitalized manner. On describing the preceding and sub-sequential states of the operating business, the Enterprise Architecture framework is an apt solution. The Zachman ontology provides the theoretical background for comprehension of the actual and future situation. However, the Digital Transformation requires lots of architectural building blocks that belong to the realm of Information Technology, and software systems.

The Open Group's TOGAF method [1] is a suitable approach for putting order in a chaotic environment, for defining a strategic, project process chain for transformation. The fundamental steps of any project dedicated to Digital Transformation is as follows scope analysis, business process modeling, gap analysis, evaluation of the architectural continuum on the specific business sector of enterprises. The TOGAF method for analysis, design and phased transition architecture yields a generic set of processes, steps, tasks, and work packages for programme and project management. The process chain at project and engineering level, which is customized and tailored to the actual situation, is good starting point to realize Digital Transformation at a single enterprise as it is an overarching approach that includes the organizational and information technology perspectives. The transition of enterprise architecture from the recent position to an enterprise architecture of a digitalized company can be perceived as Business Process Innovation involving the whole firm.

The alignment requirements between business model and technology to be applied can be examined in a systematic approach. A simplistic version of IT strategy formulation and alignment can be utilized (illustrated in *Figure 1*):

Analysis of the impact of the Information and Digital Technology on the Business Sector. Several scenarios are elaborated for investigation of possible amendment of value creation whereby the technologies to be applied and the market niche scrutinized. The deliverable is a proposal for changes.

Gap analysis of actual EA, and technology position of the enterprise, and opportunities. The second stage comprises the analysis of products, services, customers/consumers, and geographical distribution including cyberspace, thus, an IT and digital strategy for business will be developed. The deliverable will enclose the description of gaps on the competencies and enterprise engineering.



Fig. 1. The method elements for aligning EA and opportunities for Digital Transformation

Develop the roadmap for alignment between future business model and actual EA. The alternatives of future scenarios will be developed. The various aspects of Digital Transformation are conceptualized in detail. Several perspectives of EA will be affected as e.g. Business Process for Value Creation, Collaboration and Workflow Model, the Functioning Enterprise. In this way, the future EA is articulated, then the layer for technology, physical and operational architecture is worked out. The alignment between the operation model and business and IT services will be carried out.

4 Mathematical Background for Hypergraph Formalism

The hypergraphs, especially the generalized hypergraphs provide a flexible structure to describe complex relationships that can be explored among models during analysis and design of IS [6].

Definition 1. The concept of the directed hypergraphs is an ordered pair of vertices and hyperarcs that are directed hyperedges, i.e. each hyperarc is an ordered pair that contains a tail and a head.

Definition 2. The generalized or extended hypergraph. The notion of hypergraph may be extended so that the hyperedges can be represented – in certain cases – as vertices, i.e. a hyperedge e may consist of both vertices and hyperedges as well. The hyperedges that are contained within the hyperedge e should be different from e [12].

The hypergraphs as a tool for describing Information Systems from various viewpoints yields a formal method to analyze the system, and to check the conformance, compliance, and consistency of the set of models [13]. A hypergraph is a generalization of an ordinary graph where edges, called hyperedges, can connect any number of nodes. Formally, let $G\ (V, E)$ denote a hypergraph, where V denotes a finite set of nodes v, E denotes the set of hyperedges e. Each hyperedge $e \in E$ is a subset of V.

Definition 3. A directed hyperedge or hyperarc is an ordered pair, $E = (X, Y)$, of (possibly empty) disjoint subsets of vertices; X is the tail of E while Y is its head. The tail and the head of hyperarc E can be denoted by $T(E)$ and $H(E)$, respectively, or alternatively a hyperarc $\vec{e}_i \in \vec{H} = (V; \vec{E} = \{\vec{e}_i | i \in I\})$ can be perceived as an ordered pair $\vec{e}_i = \left(\overrightarrow{e_\iota^+} = (e_i^+; i); \overrightarrow{e_\iota^-} = (e_i^-; i)\right)$, where $e_i^+ \subseteq V$ is the set of vertices of $\overrightarrow{e_\iota^+}$ and $e_i^- \subseteq V$ is the set of vertices $\overrightarrow{e_\iota^-}$. The elements of $\overrightarrow{e_\iota^+}$ (hyperedges and/or vertices) are called *tail* of $\vec{e}_i$, while elements of $\overrightarrow{e_\iota^-}$ are called *head* [6].

Definition 4. Limb is either the head or the tail of a hyperarc and designated by $\vec{e}_i^{\mp}$.

Definition 5. *Architecture Describing Hypergraph* is a generalized hypergraph that can be extended by some functions and operations [12]. It can be designated as a tuple $\langle V, A, E, E_U, E_D, Attr \rangle$:

V is the set of *vertices*;

A is the set of arcs, i.e. directed edges, an arc is an ordered pair $\langle i, j \rangle$, where $i, j \in V$ (in the sense of traditional graph theory);

E is the set of hyperedges;

$\boldsymbol{E}_U$ is the set of the *undirected* hyperedges, because of the properties of generalized hypergraphs, a hyperedge e is

- either $e_i \neq \emptyset, e \subseteq V$, (*basic hyperedge*),
- or a *bag* of hyperedges;

$\boldsymbol{E}_U$ is divided up at a meta-level into partitions:

- $\boldsymbol{E}_C$ consists of the *configuration hyperedges*. Each $h_i \in \boldsymbol{E}_C$ is a simple hyperedge, i.e. containing only vertices, not complex structures and other hyperedges. All $h_i \in \boldsymbol{E}_C$ can be labeled unambiguously. The configuration hyperedges manifests the structure of "things", the vertices within a hyperedge are the properties of the specific "thing". The properties can be perceived as variables or attributes (depending on the context) that can be valuated thereby they linked to an individual value (vertex in D (see **Definition 5**.)) or a set of values, e.g. to a grouping hyperedge.
- $\boldsymbol{E}_E$ is composed of the e*xtensional hyperedges*. The extensional hyperedges can represent collections of data, the instances of *generic artifacts*. For example, the collections of data can be built up by tuples of data items, the instances of artifacts can be composed of certain bags of free variables that are contained in the particular artifacts' object/element structure. In these examples, the distinct elements, the vertices of these hyperedges can be considered as constituents of extensional hyperedges.
- $\boldsymbol{E}_I$ comprises the *intensional hyperedges*. The intensional hyperedges show the logical and rule-based interrelationships among the vertices (models within the architecture), moreover configuration hyperedges.
- $\boldsymbol{E}_G$ is made up of *grouping hyperedges* that embody various structuring principles on components, as e.g. view, viewpoint and perspectives etc. in architecture describing approaches; they symbolize interrelationships between certain models and pieces or parts of documents as e.g. business activity models, business process models, catalogues of architecture building blocks and responsibilities of roles within an organization unit. The hyperedge $h \in \boldsymbol{E}_G$ can be utilized for sorting out the vertices (representing either artifacts, viewpoints, or models) into organizational-related, artifact-related and activity related relationships.

$\boldsymbol{E}_D$ is a set of *hyperarcs*, i.e. *directed hyperedges;* the hyperarc $\vec{e}_i \in \boldsymbol{E}_D$ can be as it follows (see **Definition 2**.):

$$\vec{e}_i = \langle v_j , \vec{h} \rangle = \left(\vec{e}_i^{+} = \left(e_i^{+} = \langle v_j, i \rangle \right); \vec{e}_i^{-} = (\langle i, e_i^{-} = h \rangle) \right)$$

where $v_j \in V$, and $\vec{h} \in \boldsymbol{E}_G$;

$\vec{e}_i = \langle v_j , \vec{h} \rangle = \left(\vec{e}_i^{+} = \left(e_i^{+} = \langle v_j, i \rangle \right); \vec{e}_i^{-} = (\langle i, e_i^{-} = h \rangle) \right)$, $v_j \in V$, and $\vec{h} \in \boldsymbol{E}_C$;

$\vec{e}_i = \langle v_j , \vec{h} \rangle = \left(\vec{e}_i^{+} = \left(e_i^{+} = \langle v_j, i \rangle \right); \vec{e}_i^{-} = (\langle i, e_i^{-} = h \rangle) \right)$ where $v_j \in V$, and $\vec{h} \in \boldsymbol{E}_E$; there does not exist two hyperarcs $\vec{e}_i = \langle v_j , \vec{h} \rangle$ and $\vec{e}_k = \langle v_l , \overrightarrow{h'} \rangle$ that either $\vec{h}, \overrightarrow{h'} \in E_C$ *or* $\vec{h}, \overrightarrow{h'} \in E_E$, i.e. every vertex $v_j \in V$ is linked, at most, to one configuration hyperedge ($\boldsymbol{E}_C$) and at most to one extensional hyperedge ($\boldsymbol{E}_E$). These conditions can be interpreted the following way: a vertex may belong to a configuration structure (either artifact or model), or it may belong to an extension that represents the instantiation of either an artifact or a model.

$label_{node}: V \longrightarrow L_{node}$; where L is a set of labels, it is a vertex labeling function;

$label_{edge}: V \longrightarrow L_{edge}$; where L is a set of labels, it is an edge labeling function;

$source_E: E \longrightarrow V$, $target_E: E \longrightarrow V$ these functions return the source and target vertices of an edge *E;*

$attr: Attr \longrightarrow V$ attribute assignment function;

$source_{Attr}: Attr \longrightarrow V$; he vertex that owns the attribute is returned;

$target_{Attr}: Attr \longrightarrow D$. The *data values* of attributes are yielded; *D* represents the set of data;

D can be grasped again as vertices within the hypergraph and it can be interpreted as *variables*. Over *D* as a set of variables, set of operations (*OP*) can be defined that can be used to describe constraints and rules within formulas.

5 Enterprise Architecture Representation with Hypergraph Formalism

In this section our high-level description will be presented about the hypergraph-based structure of an enterprise architecture. The Enterprise Architecture at a given organization can be perceived as an overarching artifact that contains all potential artifacts and represents the architecture in a comprehensive way. This overarching conceptual artifact consist of generic artifact types that comprise artifact types. The hierarchical relationships can be described by *configuration hyperedges* ($\boldsymbol{E}_C$); the instances of a member of a hierarchy that is made of either generic artifact types or artifact types can be perceived as extensions and can be represented by extensional hyperedges. Thereby, this way of representation makes possible for a recursive definition of artifact types and grouping them into a generic artifact type. A *generic artifact type* ***GAT*** is a *hierarchy of artifact types* ***ATH***. The elements of ***ATH*** can belong to a configuration hyperedge $e_{C_i} \in \boldsymbol{E}_C$ as vertices. The generalized hypergraphs allow that the vertices may appear as complex structures, as hyperedges. Therefore, a node can be a hyperedge that itself a configuration hyperedge that contains a hierarchy of document types. Thereby, the representation makes possible for a recursive definition of document types and gathering them into a generic document type [12].

Definition 6. The elements of a Metamodel Entity in an Enterprise Architecture are represented in hypergraph by hyperedge m_i where $m_i \in \boldsymbol{E}_{\boldsymbol{mm_ent}} \subseteq \boldsymbol{E}$ the set of hyperedges. The elements of m_i are the vertices that represent metamodel entities that will describe an artifact. In the Metamodel Entity hyperedge metamodel relationships enmesh the set of metamodel entities by using directed hyperedges.

According to our model, an artifact is composed of a set of metamodel entities and the related overarching metamodel relationships.

Definition 7. The elements of an Artifact in an Enterprise Architecture are represented in hypergraph by hyperedge a_i where $a_i \in \boldsymbol{E}_{\boldsymbol{art}} \subseteq \boldsymbol{E}$ the set of hyperedges. The elements of a_i are the vertices that represent a set of metamodel entities that describe the artifact in the TOGAF Metamodel. Overarching metamodel relationships that enmesh the set of metamodel entities are also connected to an artifact hyperedge by using directed hyperedges.

After defining the concept of artifacts, we now turn to build the different grouping options for dimensioning, structuring and categorizing the artifacts, using viewpoints, architecture layers and artifact types. We start the description of grouping options with defining Viewpoints, which serve as a container of artifacts to create a specific perspective of the architecture for a specific stakeholder group.

Definition 8. The elements of a Viewpoint in an Enterprise Architecture are represented in hypergraph by hyperedge h_i where $h_i \in \boldsymbol{E_{viewp}} \subseteq \boldsymbol{E}$ the set of hyperedges. The elements of h_i are the vertices that represent artifacts that each of them describes a single model.

Artifacts can be parts of several Viewpoints at the same time. After defining Viewpoints, we now turn to the dimensioning option of EA by describing the concept of Architecture Layer in hypergraph-based manner.

Definition 9. The elements of an Architecture Layer in an Enterprise Architecture are represented in hypergraph by hyperedge l_i where $l_i \in \boldsymbol{E_{layer}} \subseteq \boldsymbol{E}$ the set of hyperedges. The elements of l_i are the vertices that represent artifacts that each of them describes a single model.

Like viewpoints, architecture layers provide similar multi-containing possibilities. To complete the definition of grouping options, we now specify Artifact Type, which provides categorization for the different kind of artifacts.

Definition 10. The elements of an Artifact Type in an Enterprise Architecture are represented in hypergraph by hyperedge at_i where $at_i \in \boldsymbol{E_{art_type}} \subseteq \boldsymbol{E}$ the set of hyperedges. The elements of at_i are the vertices that represent artifacts. An artifact has a single artifact type: at_c stands for *catalog* artifact type, at_m stands for *matrix* artifact type, while at_d stands for *diagram* artifact type.

Unlike viewpoints and architecture layers, the sets artifact types are disjoint, i.e. every artifact has only one artifact type: catalog or matrix or diagram. *Figure 2* presents our concept for describing enterprise architecture in a hypergraph-based structure, using the above introduced definitions.

Constraints for defining an enterprise architecture by using this hypergraph-based approach include: 1) An artifact covers a set of metamodel entities. This set is enmeshed by metamodel relationships. 2) An artifact can be part of several viewpoints. 3) An artifact can be part of more architecture layers. 4) An artifact can be part of both viewpoints and architecture layers. 5) Hyperedges of artifact types are disjoint. Finally, we define relationships between the components of an EA. In the proposed concept has-a and is-a relationships cover the whole architecture.

Definition 11. We refer to relationships as a hyperedge $r_i \in \boldsymbol{E_{rel}} \subseteq \boldsymbol{E}$ that contains directed hyperedges r_{is-a} and r_{has-a}. These hyperedges contain hyperedges (the components that we will connect to each other) on both the head and the tail parts. The relationship is composed by defining edges between the head and the tail. *Figure 3* presents our view for defining is-a and has-a relationships.

6 Motivating Example and Preliminary Results

This part of the paper presents a motivating example for utilizing the hypergraph-based approach to describe an enterprise architecture and analyse strategic misalignment. The problem of revealing the typical symptoms of misalignment will be addressed in order to assess the state of alignment in an organization [17]. The illustrative example focuses on a public sector organisation. The analysis was performed in a fragment of the organisations's EA model structure. The initiative is a pilot project for setting up the EA practice in the organisation. It was set off to outline the process of road control with EA methods over 2 set of changes. To-be phases deal with the changes in process execution, supportive applications and underlying technological infrastructure. We use the organization to utilize the proposed hypergraph-based approach for analysing strategic and structural misalignment problems in an enterprise architecture structure.

In a former approach [14, 15] an XML-based analysis tool was created, which detected the symptoms of misalignment with rule assessment techniques. The applied research methodology used an alignment perspective-driven approach. In the first step, traditional alignment perspectives were connected with typical misalignment symptoms. In the second step, relevant artifacts were provided with the misalignment symptoms, i.e. the models which may contain the symptom in question. In the third step, suitable EA analysis types were suggested to the misalignment symptoms. These EA analysis types were able to detect the symptoms in the recommended containing artifacts [17]. To translate the above introduced methodology into the hypergraph-based approach, we need the following concepts: 1) Alignment perspectives: This list contains the corresponding alignment perspective for symptom detection. 2) Misalignment symptom catalog: This list comprises the perceived misalignment symptoms. 3) Artifact catalog: This list encompasses the possible containing EA models. 4) EA analysis catalog: This list includes the possible EA analysis types to recommend. 5) Presence in the artifact: This concept describes the sign of the symptom in the EA models. 6) Occurrence on model entity level: This concept defines how the symptom is manifested on model entity level. 7) Occurrence in XML model export: This item describes how the symptom is manifested in the XML export of the EA model. 8) XML-based query. We provide some examples of artifact representation in the proposed hypergraph structure. *Figure 4* presents an incidence directed hypergraph (dir-hypergraph). This illustration shows how Artifact hyperedges exist in the Metamodel Entity hyperedge. The figure consists of two further representations for the incidence dirhypergraph: an incidence digraph of the dirhypergraph, and a line directed graph for the dirhypergraph. *Figure 5* illustrates an Architecture Layer hyperedges and the related incidence graph. The hypergraph-based description and representation of EA models provides extended analysis potential based on a formalized conceptual framework. While the original rule-based framework was appropriate to discover the misalignment problems represented in the EA models, the results were highly constrained by the quality of the EA models. By extending the approach using the hypergraph concept a more detailed and formalized description and representation of EA can be achieved.

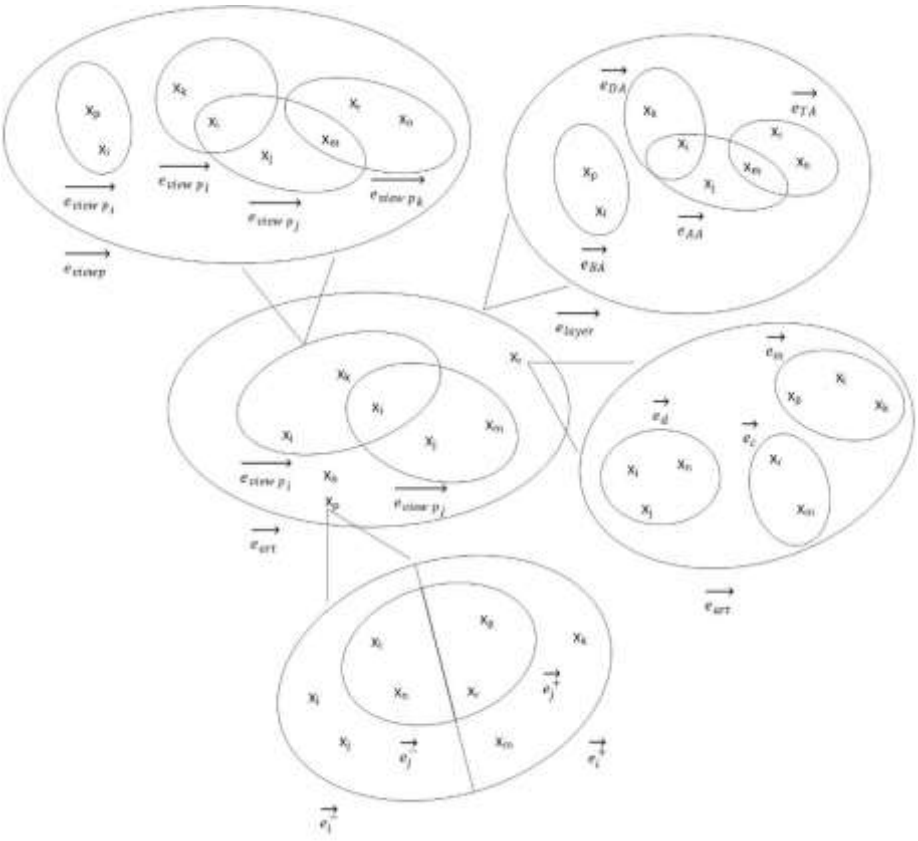


Fig. 2. Schematic View of Hypergraph-Based EA Representation.

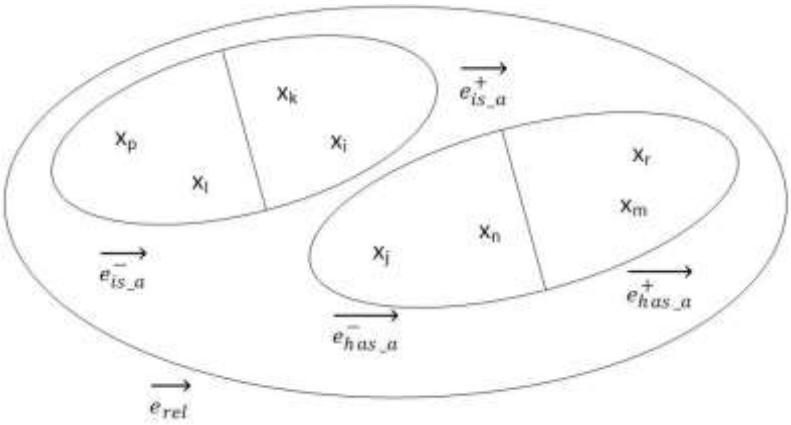


Fig. 3. Schematic View of Relationship Types.

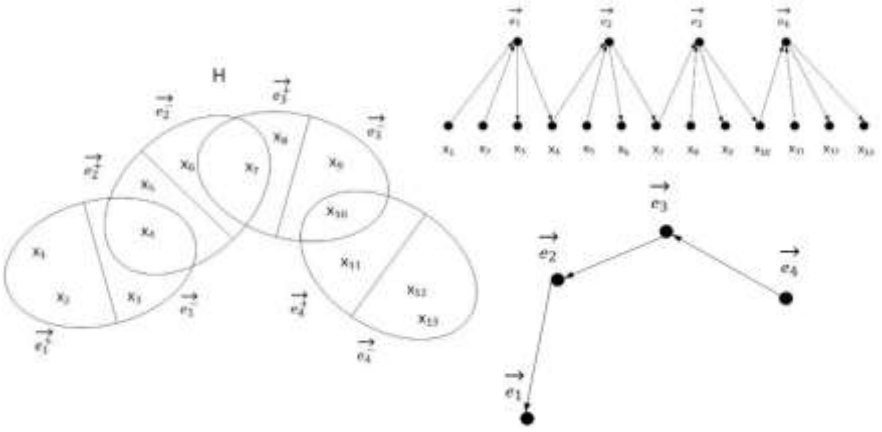


Fig. 4. (a) Example of an Incidence Directed Hypergraph: Artifact Hyperarchs in the Meta-model Entity Directed Hypergraph, (b) Incidence Digraph of the Directed Hypergraph and (c) Line Directed Graph of the Directed Hypergraph.

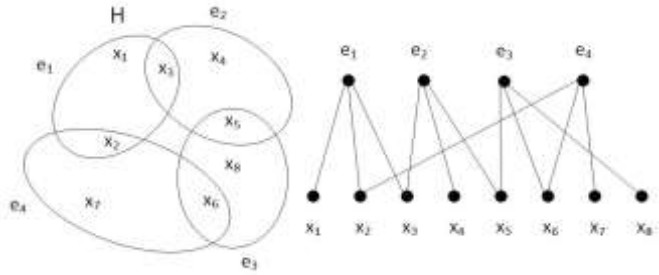


Fig. 5. (a) Example of Viewpoint Hyperedges within Artifact Hyperedge, (b) Example of Architecture Layer Hyperedges with Incidence Graph.

7 Conclusion

The proposed approach provides the opportunity to make use of formal and mathematical analytic methods for discovering misalignment among IT strategies, information systems and information architecture. The hypergraph modeling and representation offers the chance to check and control the discrepancies in complex enterprise architecture structures. Our proposed model gives way to automatized and algorithmic analysis as well. The approach enables organizations to explore and analyse misalignment symptoms, but workflow patterns, implementation phases-related issues, dynamic changes, broader business and management concepts can also be involved (e.g. "case management" [3]). Based on our conceptual model for EA description, future work needs to be done to formulate restrictions when building an enterprise architecture. These constrains will later be built into the hypergraph-based representation of EA.

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