VR-EA+TCK: Visualizing Enterprise Architecture, Content, and Knowledge in Virtual Reality

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Abstract. A complex and dynamic IT landscape with evermore digital elements, relations, and content presents a challenge for Enterprise Architecture (EA). Disparate digital repositories, including Knowledge Management Systems (KMS), Enterprise Content Management Systems (ECMS), and Enterprise Architecture Tools (EAT), often remain disjointed. And even if integrated, insights remain hindered by current visualization limitations, making it increasingly difficult to analyze, manage, and gain insights into the digital enterprise reality. This paper contributes our nexus-based Virtual Reality (VR) solution concept VR-EA+TCK that enhances and amalgamates EAT with KMS and ECMS capabilities. By enabling visualization, navigation, and interaction in VR with dynamically-generated EA diagrams, knowledge/value chains, and KMS/ECMS digital entities, it sets the groundwork for stakeholder-accessible grassroots enterprise modeling/analysis and future collaboration in a metaverse. An implementation shows its feasibility, while a case study demonstrates its potential using enterprise analysis scenarios: ECMS/KMS coverage in the EA, business processes, knowledge chains, Wardley Maps, and risk analysis.

Keywords: Virtual Reality, Enterprise Architecture, Enterprise Modeling, Knowledge Management, Enterprise Content Management, Visualization.

1 Introduction

Enterprise Architecture (EA) comprises the structural and behavioral aspects needed for an enterprise to function and adapt in alignment with some vision. EA provides a comprehensive set of cohesive models to describe the enterprise structure and functions, logically arranging individual models to provide further detail about an enterprise [1]. The digital reality that EA attempts to depict has grown in complexity, spanning disparate silos (repositories) of information and content across organization and system types. As enterprises evolve, explicit knowledge of and insight into the EA becomes indispensable, be it for enterprise governance, engineering, compliance, maintenance, etc. And although architectural representations are an enterprise asset that must be governed [2], the effort expended to keep architectural views updated is known to be very high in current organizations [3]. This is mainly due to the organization's structure being the result of an asynchronous, distributed, and heterogeneous process, producing representations in different languages/notations, with different levels of detail, in different tools at different times. [4] presents an enterprise modeling vision and associated research challenges to exploit "grassroots modeling" and embed modeling in everyday work while including more stakeholder groups. Towards this vision, our contribution addresses the challenge of making enterprise models more accessible to additional stakeholders, while providing a low-effort method for supporting updated architectural views regardless of the desired timepoint via the Enterprise Architecture Tool (EAT) Atlas[1] [3], described in Section 3.

With increasing digitalization, collecting, managing, and depicting data, information, knowledge, knowledge work, knowledge workers, their associated processes (business and knowledge), and other enterprise elements and the relations between them becomes increasingly critical [5]. While there are many possible perspectives for viewing and interpreting enterprise information and knowledge, here we apply the DIKAR (Data, Information, Knowledge, Action, and Result) model [6] in an enterprise context. For digital organizations, actions taken in activities and processes are often dependent on knowledge, which presupposes information and may involve data. To support Knowledge Management (KM), Enterprise Content Management Systems (ECMS) involve the collection, management, and publishing of enterprise information in various forms or mediums via supporting technologies and processes. Since it is often a matter of a user's competency, context, perspective, or intention as to if and how digital entities are viewed, processed, or aggregated, be they DIK (*content* being a form of DIK). Thus, for this paper we view digitized enterprise *knowledge* or enterprise *content* to mean potentially any of these DIK possibilities, intentionally abstracted or generalized and serving the purpose or intention of the stakeholder involved in their enterprise context. As the digital enterprise and respectively EA Management (EAM) grows in size and complexity, integrating, modeling, visualizing, and supporting Enterprise Information Management (EIM) and KM and explicitly associating relevant DIK elements with EA elements across disparate repositories is a further challenge we seek to address.

Virtual Reality (VR) is a "real or simulated environment in which the perceiver experiences telepresence" [7], a mediated visual environment created and then experienced. By leveraging VR for the enterprise digital reality, an immersive experience in a digital context of surrounding enterprise elements can be provided to various stakeholders, while avoiding non-immersive visual distractions inherent with 2D displays (analogous to being outside an aquarium versus scuba diving). As support, [8] investigated VR vs. 2D for a software analysis task. The study found that VR did not significantly decrease comprehension and analysis time nor significantly improve correctness (although fewer errors were made). And although interaction time was less efficient, VR improved the UX (user experience), being more motivating, less demanding, more inventive/innovative, and more clearly structured. In our view, EAM could thus reap similar VR benefits without incurring significant liabilities.

Our prior work includes various VR solution concepts, including VR-EAT [9] for dynamically-generated Atlas EA diagrams, VR-EA [10] for ArchiMate® EA models,

[1] https://atlas.linkconsulting.com

and VR-BPMN [11] for Business Process Model and Notation (BPMN™) models. This paper contributes our nexus-based VR solution concept VR-EA+TCK (EA enhanced with Tools, Content, and Knowledge), extending our VR-EAT by amalgamating KM and ECMS capabilities. It enables visualizing, navigating, and interacting with dynamically-generated EA diagrams enhanced with DIK elements from Knowledge Management Systems (KMS) and ECMS, including value and knowledge chains. By visualizing enterprise models and associated knowledge and content in VR, EA-related collaboration for additional stakeholder types in a future metaverse becomes feasible and accessible. This paper is structured as follows: Section 2 discusses related work while Section 3 provides background on Atlas. Our solution concept is described in Section 4. Section 5 details our prototype implementation. The evaluation is described in Section 6, followed by a conclusion.

2 Related Work

EA visualization work includes Rehring et al. [12] that investigated possible EAM actions in Mixed Reality (MR) and VR, finding VR/MR offers affordances that can positively influence EAM decision-making quality and effectiveness. VR is not mentioned in the Roth et al. [13] survey of EA visualization tools. [14] describe PRIMate based on PRIMROSe, a visual graph-based enterprise analysis framework, and show a 2D tool PRIMate containing a graph, treemap, and 3D visualization of an the ArchiSurance ArchiMate model. Beyond our prior work, we are unaware work applying VR to the EA area with integrated EAT heterogenous metamodel, multidiagram, and EA-related standard (ArchiMate, BPMN, UML) and custom model support.

With regard to KM, Yan [15] utilizes a knowledge and an agent mesh as a representation method for complicated-knowledge, dealing with multiples sets, mapping relations, union, intersection and other operations. While graph-based and using an inference engine, it is focused on self-reconfiguration of systems and does not address EA. KOMDEVRS [16] presents an approach and methodology for open knowledge formalization and management in VR, focusing on industrial domain. It attempts to address and externalize the closed nature of the knowledge and metadata often contained in VR applications. It does not address the EA or ECMS context. Zenkert et al. [17] creates a dynamic graphical layout structure for knowledge maps based on dimensional information, using distance to arrange associated information based on word association strength. Although VR is mentioned, their solution is not applied to VR. We found no direct work applying VR visualization to enterprise KM.

As to Content Management (CM) or Enterprise Content (EC), [18] provides a comprehensive review of ECM research, while [19] evaluates ECM tools, giving insight into the various tool types and interfaces. Utilizing an asset definition language, [20] describes a means for abstractly defining content visualizations for concept-oriented CM (which can support subjective views regarding represented entities). [21] applies graph theory to enhance search results of an ECM in an innovation process to support new knowledge creation. We found no direct work applying VR visualization to enterprise CMS.

3 Background on the EA Tool Atlas

To keep architectural views up-to-date in fast-changing organizations, Atlas was developed based on an Enterprise Cartography paradigm [22][23]. Atlas consists of a repository with a fully configurable metamodel that dynamically generates fully configurable views. It contains all the information required to represent views at any timepoint and can represent each artifact in its lifecycle state [3]. Hence, the evolution of an architecture over time can be viewed. The view´s contents regarding the future are computed, processing the plans of transformation initiatives pipeline (both ongoing and planned) to produce a consolidated enterprise model state in any point in time. Therefore, one can foresee the contents of an architecture view in some desired future date by consolidating the current view´s content with the expected changes of ongoing and planned transformation initiatives whose completion date precedes the desired date [22][24]. For business processes, Atlas can generate and support time navigation in BPMN models [25]. This is a unique feature of Atlas and, in our experience, fundamental to reducing the effort of maintaining architectural views in large organizations. The configuration of the view types is based on the metamodel defined by the user. Fig. 1 shows some of the supported view types.

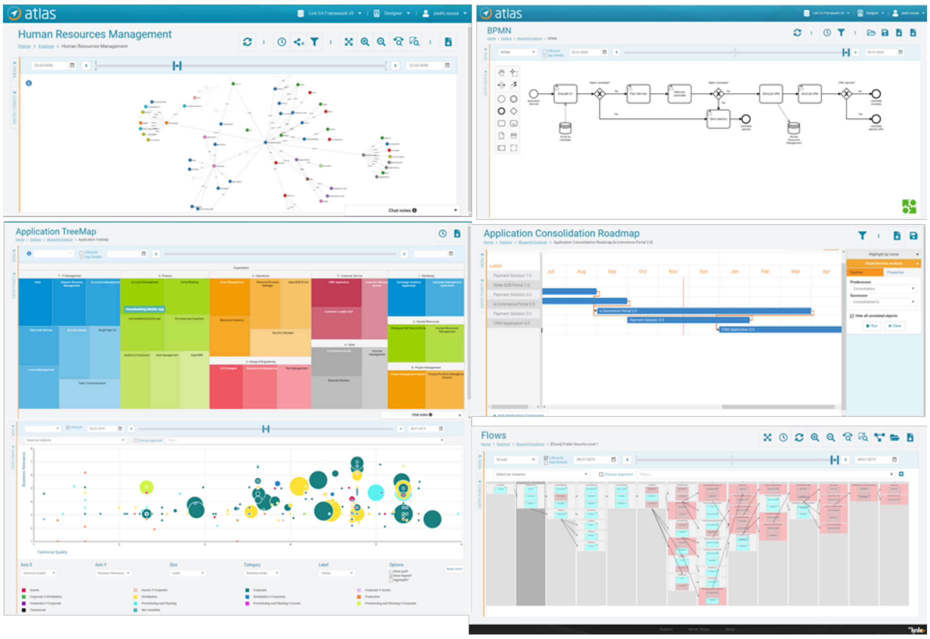

Fig. 1. Various view types supported by Atlas.

A key capability of Atlas is the generation of up-to-date architectural views with near zero effort as has been done for some cases [26][27], including the previous generation of the tool EAMS. Users can define templates of architectural views, which are instantiated on request to particular objects. Fig. 2 shows a generated view for the

Human Resources (HR) Management application, presented in the middle container. Moving leftwards, services requested by the HR Management application and the applications providing such services are shown. Moving rightwards, the service realized by the HR Management application and the applications that request it are shown. Below it, various data objects used by the services are shown.

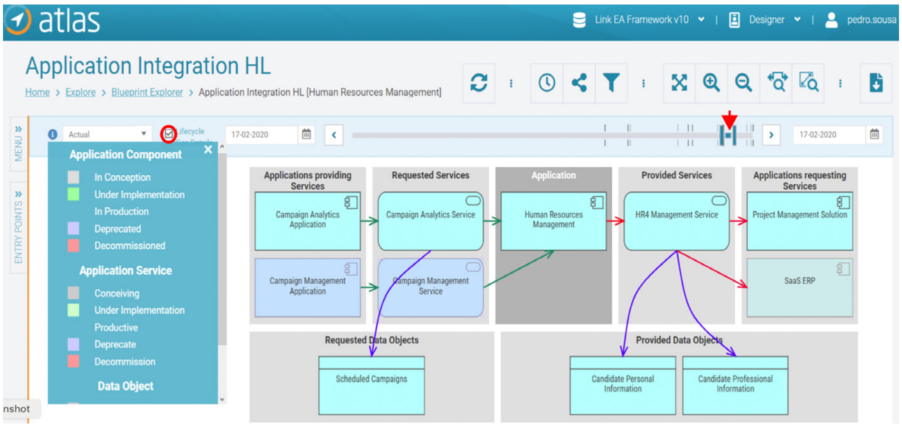

Fig. 2. High-level Application Integration Blueprint for HR Management application.

With the Lifecycle option selected (red circle), artefact symbols are shaded according to their lifetime state on the date defined by the time handler position in the time bar (top red arrow). The legend on the left presents the lifecycle states defined for Application Components and Application Services. In this case, on the selected date (17/02/2020) the Campaign Management application and service are Deprecated (light blue on the left), and the SaaS ERP application is In Conception (grey, on the right). To produce such architectural views, Atlas utilizes available information sources, such as project plans, be they simple lists of created and decommissioned artefacts or models in some notation such as ArchiMate. In this last case, since ArchiMate does not provide a way to state that some work package creates/deletes/or changes any artefact, association relationships named as "created by", "decommissioned by" or "changed by" are used. A transformation engine is provided by Atlas that allows end users to configure how each concept in an imported model (such as in ArchiMate) maps to the concepts defined in its metamodel.

End users can also define the propagation rules between project milestone dates and the artefact lifecycles that are affected (created, decommissioned, changed) by some project. One default rule for artefact creation is that objects created by a project transition to productive upon project completion. In case a project is delayed, Atlas can update the lifecycle of dependent artefacts. Finally, end users can also define the dependency rules between projects. One default rule is that a project A is dependent on Project B if it uses some artefact affected by Project B. So, whenever a project termination date is delayed, Atlas can alert the actor responsible (e.g., via email) for an impacted ongoing or planned project.

4 Solution Concept

The unlimited space available in VR can be leveraged for visualizing the growing and complex set of EA and EC models and their interrelationships simultaneously in a spatial structure. As EA and EC models grow in complexity and reflect the deeper integration of both the business and IT reality, an immersive EA environment provides an additional visualization capability to comprehend the "big picture" for structurally and hierarchically complex and interconnected diagrams and digital elements, while providing an immersive experience for digital models in a 3D space viewable from different perspectives.

Our generalized solution concept for VR-EA+TCK is shown in (Fig. 3). VR-EA+TCK utilizes our generalized VR Modeling Framework (VR-MF) [10], which provides a VR-based domain-independent hypermodeling framework. VR-MF addresses four primary aspects that require special attention when modeling in VR: visualization, navigation, interaction, and data retrieval. VR-EAT [9] is our EAT repository integration solution, exemplified with Atlas integration, visualization of blueprints, and interaction capabilities. VR-EA EA [10] provides specialized direct support and mapping for EA models in VR, including both ArchiMate as well as BPMN via VR-BPMN [11]. VR-UML [28] provides support for UML® diagrams in VR, which may be of relevance to EA depending on the analysis and models. VR-EA+TCK builds on and extends these capabilities by integrating further enterprise knowledge, information, and content repositories such as a KMS and/or an ECMS.

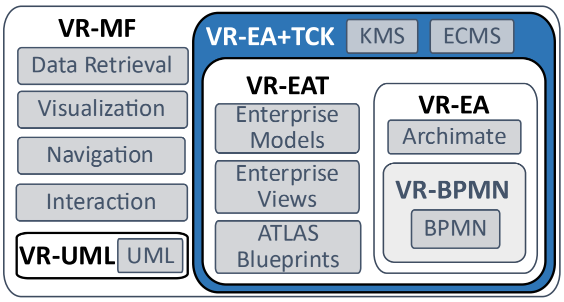

Fig. 3. The VR-EA+TCK solution concept (blue) in relation to our prior VR solution concepts.

As a representative EA tool and repository, Atlas provides access to diverse EA-related data in a coherent repository and meta-model and is not restricted to certain standards or notations. Blueprints (diagrams) are necessarily limited in scope to address some stakeholder concern, and are necessary and helpful for stakeholders to avoid information overload. Yet the larger picture of the entire digital enterprise and all of its elements and relations cannot be easily conveyed on a single 2D diagram or view. Furthermore, second degree relations and elements (beyond the diagram) or not readily seen. Thus, certain insights or missing elements, relations, or aspects may not be readily detected. Furthermore, any models retained in a repository are typically limited in scope to that repository, and inter-repository relations (such as between an

EAT such as Atlas and an ECMS) are usually not obvious or discovered. Our VR solution seeks to address such limitations. VR-EAT details the integration with Atlas.

Visualization. As there are many possible relations between digital elements, a spherical *nexus* was chosen to visualize all elements and relations in a repository (see Fig. 4). To provide some initial ordering, layering within the sphere is available as a grouping mechanism based on similar element types using the color assigned to that type, resulting in a sphere with colored layers (intra-layer element placement is random). While the color scheme is customizable, the default color scheme is loosely based on KMDL® [29]. To assist with orientation and make interaction more intuitive by providing a context for what a model represents, labeled glass boxes readable from any angle contain a nexus based on the model of a repository (ECMS, KMS). To show inter-relations between nexuses or models, we found directly drawn additional lines between nexus spheres to lead to a large crisscross of associations that was difficult to analyze. We thus utilize a dynamically-generated nexus to show the intersection between models. As 2D-based views and diagrams remain a primary form of EA documentation, they are integrated (such as from the EAT Atlas) as 3D *hyperplanes* in proximity to its nexus for contextual support. In summary, intangible digital elements are made visible and related to one another across the enterprise spectrum.

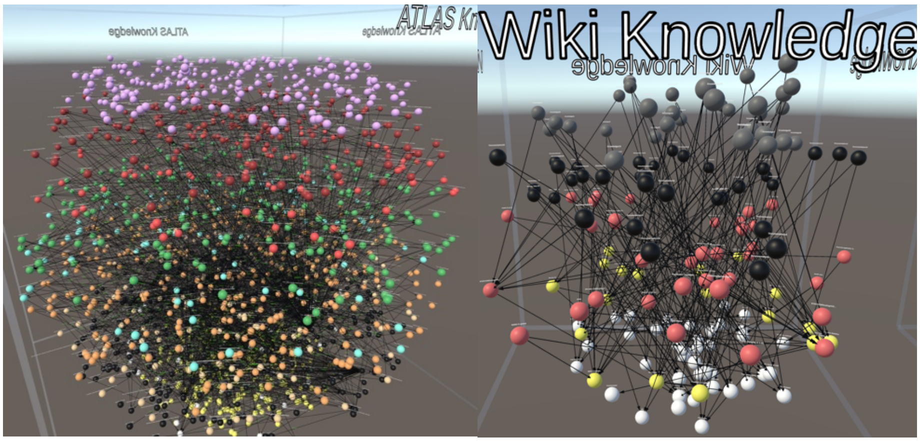

Fig. 4. VR-EA+TCK: Atlas EA nexus (left); Semantic MediaWiki nexus (right).

Navigation. VR immersion requires addressing intuitively navigating the VR space while reducing the likelihood of potential VR sickness symptoms. Two navigation modes are supported in the solution concept: the default uses gliding controls, enabling users to *fly through* the VR space and get an overview of the entire model from any angle they wish. Alternatively, *teleporting* permits a user to select a destination and be instantly placed there (i.e., by moving the camera to that position); this can be disconcerting but may reduce the likelihood of VR sickness (for those prone to it) that can occur when moving through a virtual space.

Interaction. Basic user-element interaction is done primarily via the VR controllers. Views consisting of diagrams (blueprints in Atlas terminology) are stacked hyperplanes and can be made visible or invisible by selecting the plane or equivalent icon. As VR affordances and VR element interaction are not yet standardized or intuitive, a *VR-Tablet* paradigm is used (see Fig. 5) to provide interaction support and more detailed information about a selected nexus object or depicting browser-based multimedia content. It can also be used for browsing, filtering, and searching for nodes.

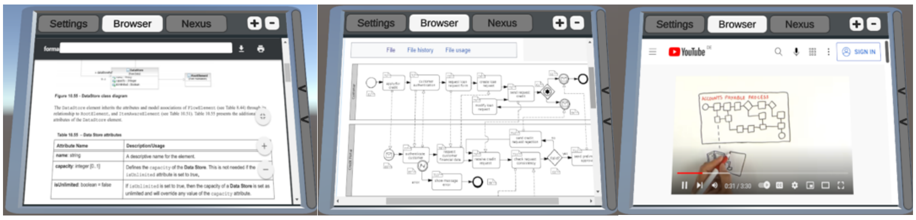

Fig. 5. VR-Tablet multimedia browser-based content: PDF (left), image (center), video (right).

5 Realization

shows our solution concept realization for VR-EA+TCK. To implement visualization, navigation, and interaction for VR-MF, Unity 2020.3 with OpenVR XR Plugin 1.1.4 is used, shown in the Unity block (top right, blue). It includes support for Nexus and Atlas Blueprint view depiction. The Data Hub (center, orange) is based on .NET and provides data integration, storage (bottom, via MongoDB 5 as BSON), and retrieval (as JSON). Atlas integration (top left, green) is cloud-based, including repository data and service access via REST queries, which retrieves JSON blueprint (diagram) data. This data is loaded into the Data Hub and saved to MongoDB in our internal BSON schema format, to permit us to transform and annotate the data as needed for VR. A command line extension (left) provides helper functions for configuration, mapping, and data loading for the Data Hub. To illustrate the ECMS/KMS VR capability, we integrated the Semantic MediaWiki (SMW). SMW (bottom right, purple) consists of MediaWiki 1.35.4 with PHP 7.4.26 and SMW 4.0.0 (run in a Docker 20.10.12 container) with MariaDB Version 10.6.5 running in a separate container. The MediaWiki Ontology is exported via the SWW script dumpRDF, which is parsed with dotNetRDF 2.7.2. Further multi-model integration - independent of the Data Hub and direct with Unity - is shown (upper right, green,), and includes ArchiMate (VR-EA), BPMN (VR-BPMN), and UML (VR-UML) (not shown).

To support type and relational analysis in VR, all node types are represented as spheres in a glass meta-layer above a nexus (see Fig. 7a), differentiated by color and size indicating the relative number of instances (largest has the most). Type selection at the meta-layer selects all instances in a nexus via a glow (Fig. 7b), ghosting non-related nodes. Likewise, selecting a node highlights its type at the meta-layer, while its first-degree neighbors and relations remain shown and the rest are ghosted (Fig. 8).

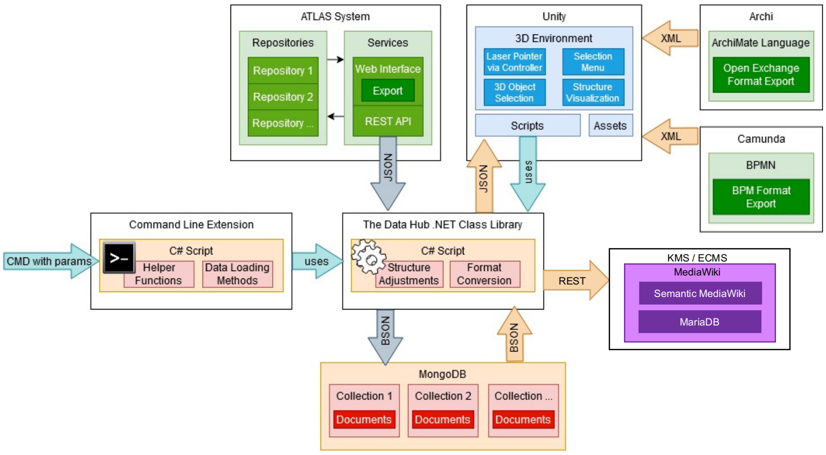

Fig. 6. VR-EA+TCK logical architecture.

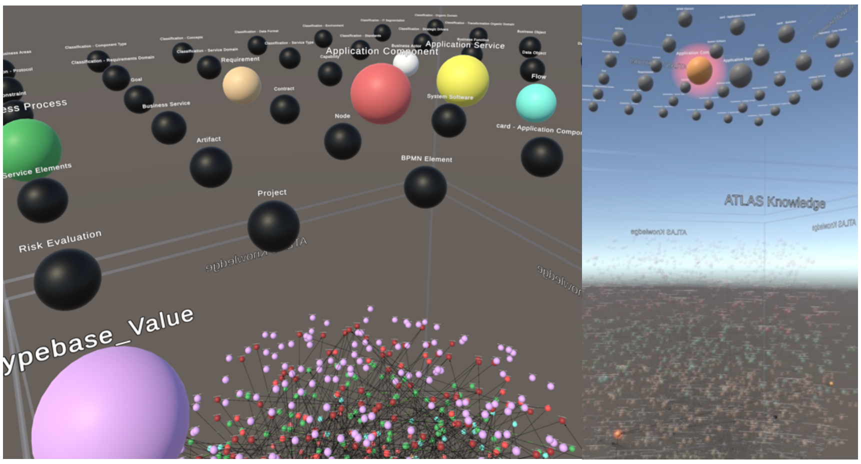

Fig. 7. a) Atlas meta-layer (left); b) type vs. node instance(s) selection highlighting (right).

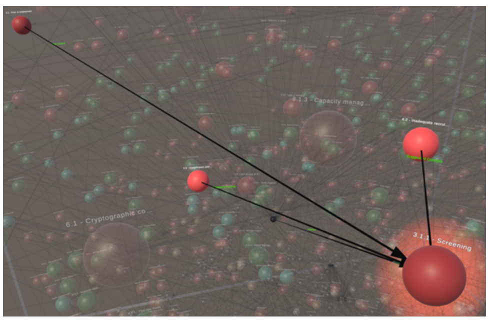

Fig. 8. Nexus node selection (glow) and first-degree neighbors and relations shown.

Atlas-specific VR integration and navigation was realized via blueprint diagram stack placement in proximity to the nexus as shown in Fig. 9. If an element on a blueprint is selected, that corresponding node in the nexus is highlighted and the rest are ghosted, while the dynamic blueprint stack on the right is updated to show all blueprints that include that element. If all elements in a blueprint are selected (Fig. 10a for the Application Management blueprint), then all nodes in the nexus are highlighted with a different colored glow and the rest are ghosted (Fig. 10b).

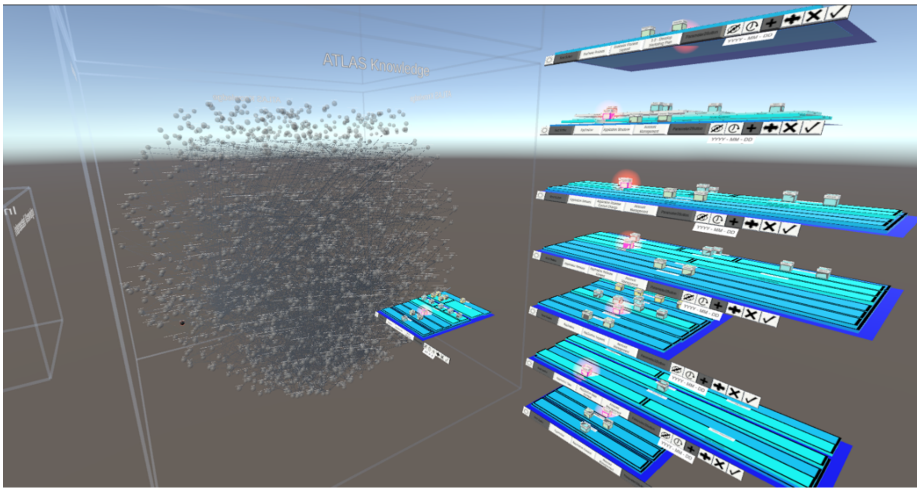

Fig. 9. Selecting Atlas element highlights nexus node and displays diagrams with that element.

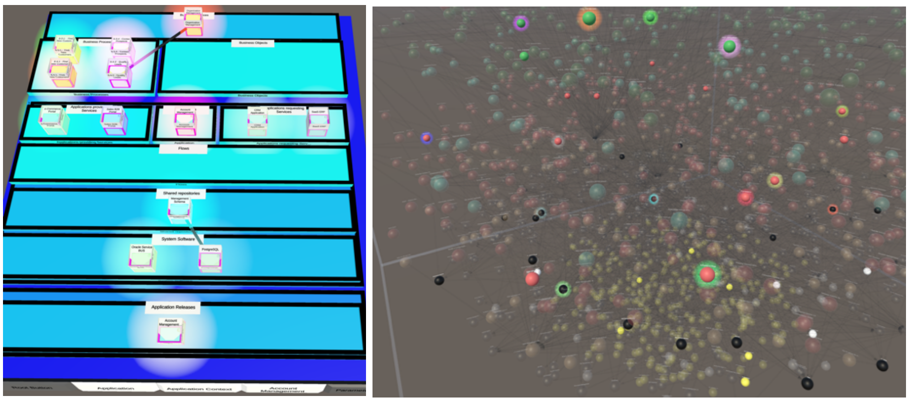

Fig. 10. Selecting all Atlas diagram elements highlights corresponding Atlas Nexus nodes.

VR-based navigation of the nexus will show details for a selected object. For VR support for ECMS/KMS, if the object is associated with a web address (wiki page), in browser mode the VR-tablet is dynamically updated with content (Fig. 11a). Fig. 11b shows the wiki ontology in the meta-layer, including an actor subclass external actor.

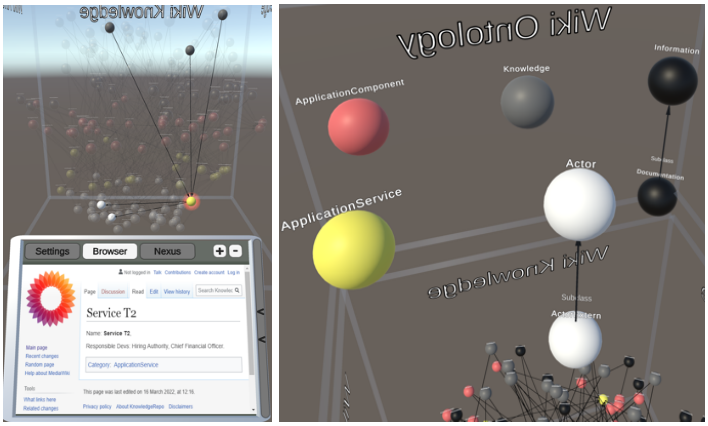

Fig. 11. Wiki Knowledge Nexus: a) node content in tablet (left); b) ontology meta-layer (right).

Immersive heterogeneous multi-model analysis is supported by loading multiple models in VR as shown in Fig. 12, with the ECMS/KMS Wiki Knowledge Nexus (left), EA Atlas Nexus (middle), Atlas Blueprint (right bottom, blue), and ArchiSurance Archimate model (far right).

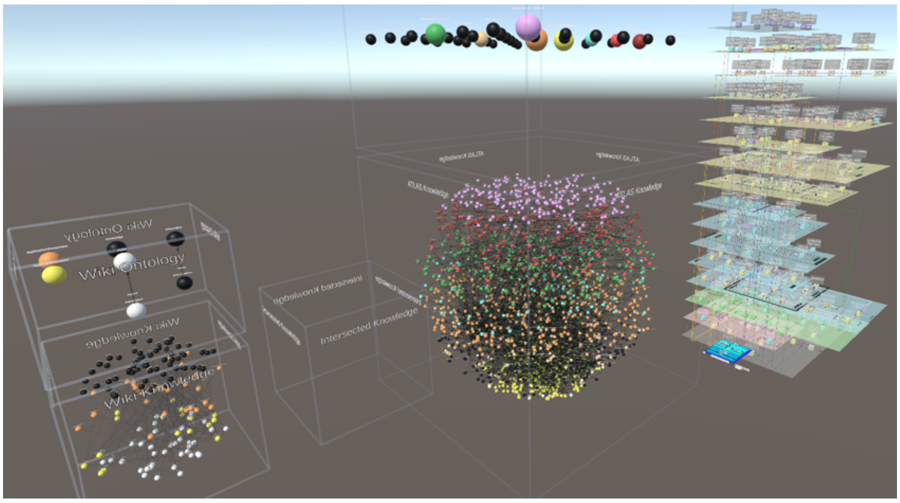

Fig. 12. Heterogeneous multi-model visualization and analysis capability.

6 Evaluation

To evaluate the practicality of the VR-EA+TCK solution concept and realization, a case study is used focusing on five illustrative enterprise analysis and decision-making scenarios: 1) ECMS/KMS Coverage, 2) Business Processes, 3) Knowledge Chains, 4) Wardley Map Value Chains, and 5) Risk and Governance Analysis.

The Atlas repository contained 66 sample core blueprints and via parameter choices results in 7843 different blueprints considering all selection combinations. This results in a total of 2034 nodes (unique entity instances) from 43 types and 2357 intra-nexus relations. As an ECMS/KMS, the Semantic MediaWiki contained semi-random Internet content, resulting in 165 nodes of 7 types with 246 intra-nexus relations.

6.1 ECMS/KMS Coverage Scenario

To support analysis and decision-making, an EA should be documented and maintained. To analyze content/knowledge coverage of an EA, VR-EA+TCK can generate an Intersected Knowledge Nexus via the VR-Tablet. It shows Atlas Nexus nodes that have (or do not have) associated content, as shown in Fig. 13. With our sample data, it consists of 92 nodes, 117 intra-nexus relations, and 142 inter-Wiki and 260 inter-Atlas relations. The right sphere half type color is from Atlas, the left sphere half type from the Wiki Knowledge Nexus; unrelated nodes in source nexuses are ghosted. The intersection set is determined by type-based string matching and can be extended for ID matching via an Atlas content ID property. Thus, the intersection of the nexus sets and their differences (missing information) via ghosting can be readily ascertained.

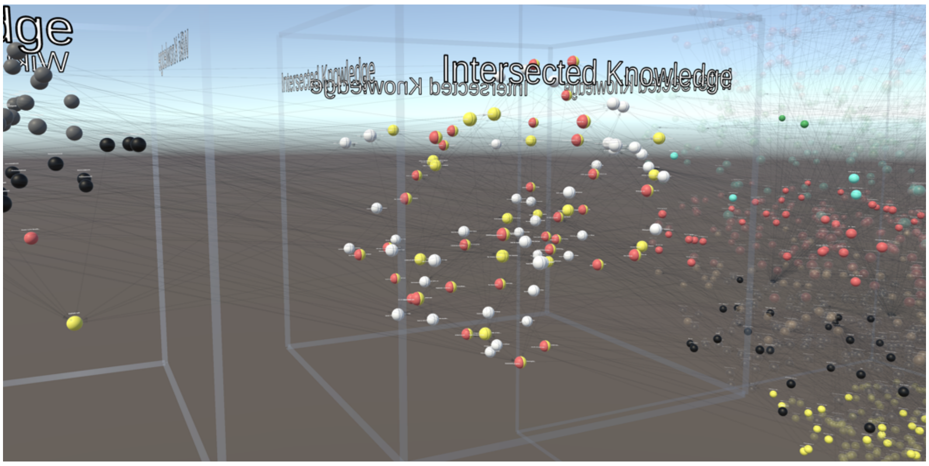

Fig. 13. Intersected Knowledge Nexus: relations from Atlas on the right, from Wiki on the left.

6.2 Business Process Scenario

As to analyzing business processes (BP), the models (in BPMN or another notation) typically only include primary participants as shown in Fig. 14. With VR-EA+TCK, the BP elements in a BP blueprint in Atlas can be highlighted and the BP analyzed for 1) first degree related neighbor nodes (actors, knowledge, etc.) that may influence or be influenced by this BP, or 2) dynamic access to (potentially live system) information associated with any of the associated BP nodes.

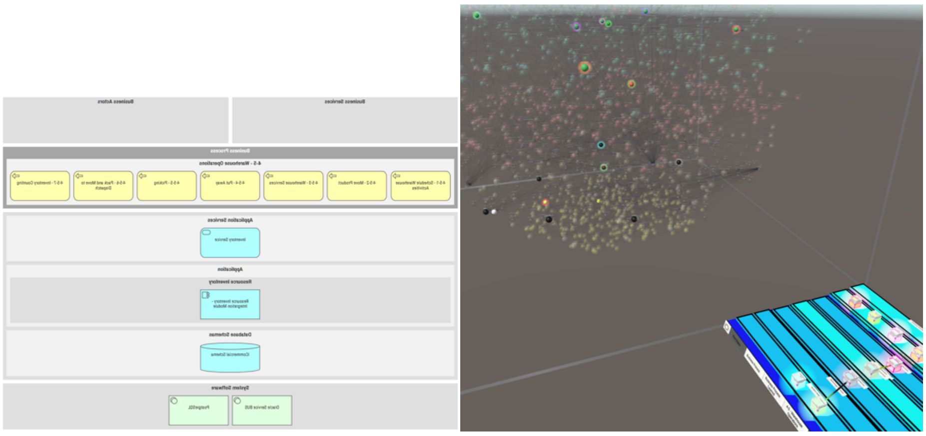

Fig. 14. Business Process Layered Warehouse Operations: a) Atlas (left); b) VR nexus (right).

6.3 Knowledge Chain Scenario

For knowledge-driven enterprises, modeling and analyzing knowledge utilization (e.g., strengths, needs) will become imperative. While KMDL® provides a notation for modeling knowledge-intensive BPs, not all knowledge or its use may be associated with BPs, and non-notation enterprise types may be involved. We thus generalize our solution to *knowledge chains* containing an open set of nodes and relations.

To demonstrate support and knowledge chain capability, we adapted a Modelangelo KMDL sample model from [30] to entities within our Atlas model (Fig. 15, Fig. 16a). Activating KMDL mode via the VR-Tablet, KMDL nodes (11 types for our example denoted via name prefix) and chains are seen in the nexus, ghosting the rest (Fig. 16b). Available KMDL 3.0 perspectives (process, knowledge) are dynamically listed in the VR-Tablet and a subset of interest can be selected. Halo color indicates the KMDL type: white = Actor, yellow = Role, red = Information Object, green = Task/Conversion, pink/purple = Knowledge Object, orange = Requirement. As to relations (lines): green = Socialization, blue = Externalization, red = Internalization. For 2D analysis, the chain can be moved to the front glass box pane (nodes remain connected to the nexus) (Fig. 16c). This visualization offers insights into enterprise *knowledge chains*, any related elements, and how they interact and relate.

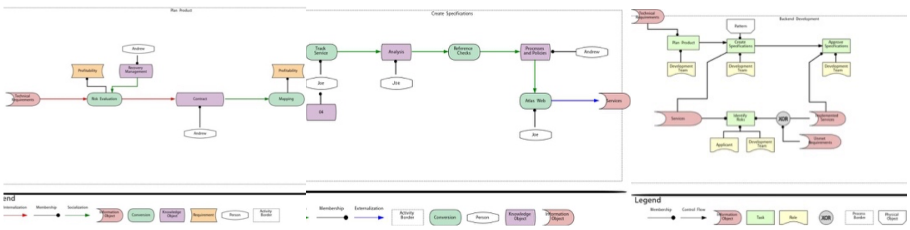

Fig. 15. Adapted KMDL sample model in Modelangelo: Plan Product (left), Create Specfication (center), and Backend Development (right).

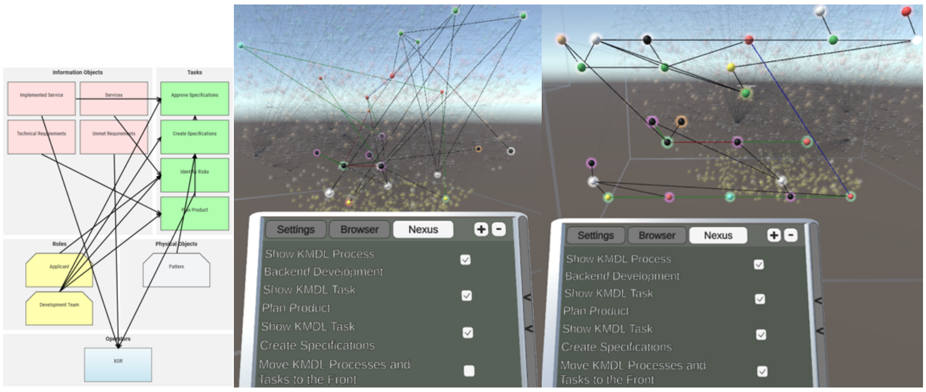

Fig. 16. Knowledge chain: a) Atlas (left), b) nexus (center), c) moved to the front glass (right).

6.4 Wardley Map Value Chain Scenario

A Wardley Map [31] is a business strategy method that maps the business landscape in the form of a value chain. In 2D, two object properties *evolution* and *visibility* are mapped to each axis. For VR visualization, we mapped these to a 3D chain in a nexus: *evolution* has a four-level scale mapped to a halo color: 0..1 (Genesis = yellow), 1..2 (Custom Built = blue), 2..3 (Product = pink), 3..4 (Commodity = green); *visibility* has a scale 0..1 which we mapped to sphere size. After setting Wardley mode in the VR-Tablet, Wardley virtual nodes (chains or objects denoted by a string prefix and referencing Atlas nodes) are shown in the nexus, while other nodes are ghosted (Fig. 17a). If 2D analysis is preferred, the chain can be moved to the front glass box pane (nodes remain connected to the nexus) (Fig. 17b). This visualization offers insight into enterprise *value chains*, all related elements, and potential impacts.

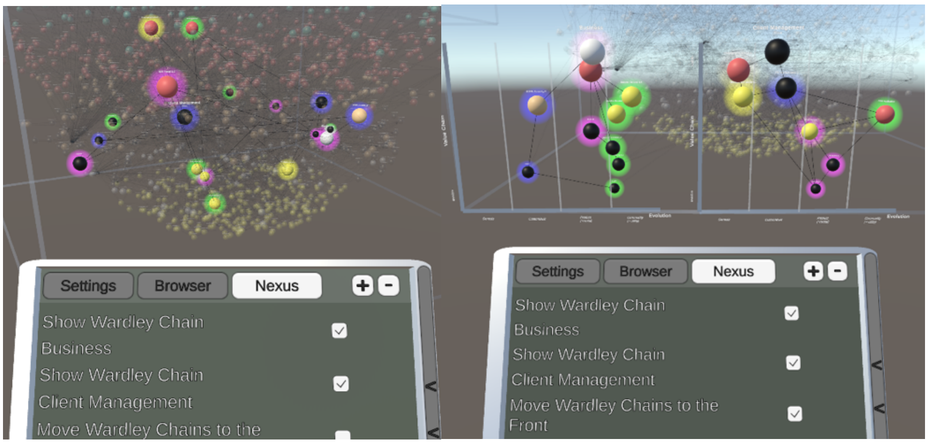

Fig. 17. Wardley Map Value Chains: a) in nexus (left) and b) moved to the front glass (right).

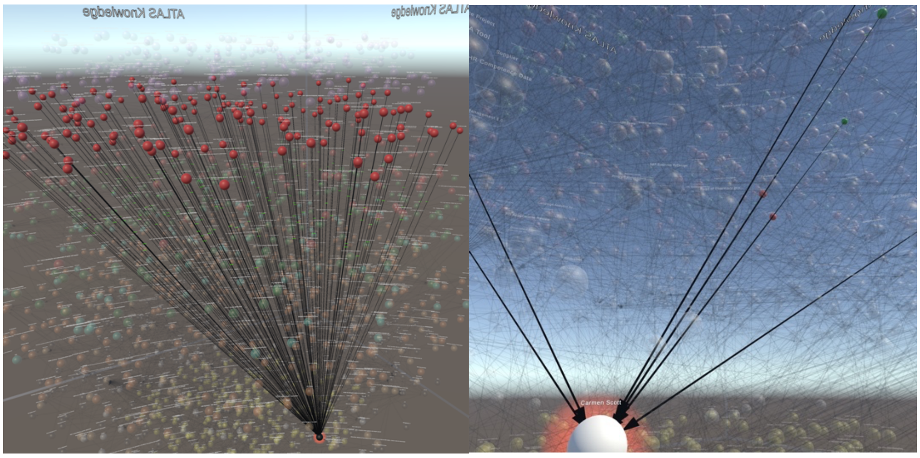

Fig. 18. Risk analysis: a) standard: ISO 27001/2 (security techniques) (left); b) person (right).

6.5 Risk and Governance Analysis Scenario

As the nexus displays all modeled enterprise element instances simultaneously, various analyses can be performed. In one scenario, detecting to what degree a standard such as the ISO/IEC 27005 Information Security Risk Management standards are referenced, applied, or overlooked within the enterprise (and documentation can be directly referenced via KMS) (Fig. 18a). Here we see that the standard and associated risk controls are modeled but isolated, not referenced by any other elements in the enterprise. In Fig. 18b, an employee is selected, which can be used to analyze associated roles, authority, system and physical access, teams, BPs, knowledge, Responsible Accountable Consulted Informed (RACI), and any other dependencies and influences.

6.6 Discussion

Growing enterprise complexity and digitalization creates inherent visualization, synchronization, and documentation challenges affecting EAM analysis, decision-making, and collaboration. VR-EA+TCK brings advantageous VR factors to the EA and ECMS/KMS space. Our VR-Tablet concept provides settings to help address certain challenges or liabilities unique to VR, including limiting visual clutter and cognitive overload or ascertaining user intentions. Our evaluation demonstrated that integrating EA with ECMS/KMS in VR is viable and can support various practical EAM analysis scenarios: 1) EA-KMS Coverage via an intersection nexus showed EA elements associated with ECMS/KMS documentation and can be used to explicitly visualize and associate enterprise knowledge, 2)Business Processes exemplified how when analyzing a BP, depicted in a diagram from an EA tool such as Atlas, it can be visualized in 3D in VR, and by highlighting the involved elements in the EA nexus, additional supporting relationships, elements, and documentation and knowledge can be discovered, 3) Knowledge Chains showed how related chains of knowledge can be viewed in a nexus and comprehended in an overall enterprise context 4) Wardley Maps Value Chains illustrated how a value chain in the enterprise can be visualized within the enterprise nexus and associated elements considered, while 5) Risk and Governance Analysis showed how enterprise-wide risk-associated aspects might be discovered, such as important standards not applied, forgotten, undocumented, risk controls missing, unclarified RACI, roles, authorities, authorizations, employees, and other governance aspects depicted and analyzed.

7 Conclusion

Enterprise information, knowledge, documentation, content, and views in their various forms play an essential part in EA for gaining insights into the real digital structures and, in turn, into the digital enterprise. VR-EA+TCK contributes a unique nexus-based VR visualization solution concept, providing comprehensive integration, visualization, and synthesis of heterogenous enterprise entities and their relations, models, and diagrams simultaneously. VR-EA+TCK enhances our original heterogeneous multi-model VR-EA concept, integrating additional enterprise tool, content, and knowledge repositories (exemplified with Atlas and the Semantic MediaWiki) and including additional diagram support (Wardley and knowledge chains). Leveraging the vast VR space, it provides direct access within VR to valuable relevant related enterprise content via the browser-capable VR-Tablet and hyperplanes for Atlas-based EA diagrams. The VR implementation demonstrated its feasibility, while the evaluation case study showed its potential to support various practical EAM analysis scenarios, including ECMS/KMS knowledge intersection coverage, business processes, knowledge chains, Wardley Map value chains, and risk and governance analysis. With our solution concept, EAM activities including analysis, discovery, inquiry, reasoning, decision-making, synthesis, and assessment via VR can become accessible and included for various stakeholder groups in their daily work, towards supporting the grander enterprise modeling vision [4] with "grass-roots modeling".

The benefits of VR-EA+TCK include: comprehensive full 3D view in a nexus of all EA enterprise elements and type classifications with all relationships, ECMS/KMS integrated as a nexus to visualize knowledge elements and their relations, intersection nexus generation to support cross-nexus analysis, unlimited simultaneous EA diagrams in 3D from the Atlas tool, automatic stack-based depiction of all diagrams containing an element of interest, and simultaneous heterogeneous multi-model visualization (e.g., with VR-EA ArchiMate, VR-BPMN, or VR-UML models) in the limitless space offered by VR.

Future work includes enhancing the interactive, informational, analytical, and modeling capabilities of VR-EA+TCK, including chronological analysis, gap analysis, force-directed layout and additional visualization alternatives, and a comprehensive empirical study.

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