Toward Commitment-Driven Enterprise Digital Twins:
A Socio-Technical Approach to Reflexive Modeling in the Age of Digitalization
The Proof of Concept

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Abstract

Enterprises are drowning in data but starving for insight because they lack a unifying lens to connect digital traces with organizational purpose. This research reframes enterprise modeling as a reflexive practice centered on commitments—intentional, normative relations that bind agents, roles, and services within institutional contexts. Through a dialectical modeling loop grounded in Action Design Research, we integrate conceptual modeling, semantic technologies, and data analytics to transform transactional traces into meaningful representations of organizational life. Applied to air navigation services, this method reveals how commitments emerge, evolve, and align across socio-technical layers. By treating commitments as first-class modeling constructs, we offer a semantic foundation for digital twins that think with, not just about, the enterprise—supporting accountable adaptation, strategic foresight, and institutional learning.

1 Introduction

Digitalization is reshaping the architecture of enterprise life. No longer a peripheral enabler of operational efficiency, digital technologies have become central to the constitution of organizational production agency, socio-economic value creation, and both external and internal organizational coordination. Across industries, data-intensive systems, algorithmic processes, and platform-based infrastructures are transforming how enterprises act, decide, and relate. Yet, despite this profound shift, many organizations remain unable to fully harness the potential of digitalization. The problem lies not in the absence of data or computational power, but in the lack of integrative frameworks that align technological capabilities with the evolving social commitments that underpin enterprise functioning.

This research addresses this gap by proposing a commitment-driven enterprise digital twin—a reflexive, socio-technical modeling approach that unites ontology-driven conceptual modeling with data analytics to capture, represent, and evolve the complex webs of interdependent commitments that define enterprise systems. Commitments—understood as directed, intentional relations among actors, artifacts, and roles—are both the objects of inquiry and the evolving constructs through which enterprises can be understood, designed, and transformed. Rather than modeling enterprises as collections of functions or processes, we focus on them as dynamic networks of commitments situated in regulatory, technological, and organizational contexts.

An illustrative case lies in the domain of air navigation services. Consider the example of budget-based cost decomposition within Air Navigation Services Providers (ANSPs). Here, the cost-based budgeting dataset represents a social commitment from the ANSP to the national supervisory authority, aligning with regulatory requirements under the Single European Sky framework. When interpreted through the lens of commitment modeling, this budgeting data becomes more than a financial record—it serves as a dynamic representation of the enterprise's internal obligations, dependencies, and performance expectations. By coupling conceptual modeling and data mining, the budgeting dataset can uncover an evolving commitment network that supports strategic foresight, performance optimization, and transparent compliance.

This proposal thus advances a dialectical approach to enterprise modeling—one that navigates the tensions between structure and emergence, data and meaning, design and adaptation. Reflexive sensemaking acts as the mediating layer, enabling the iterative co-construction of digital twin representations grounded in empirical realities and ontological clarity. The commitment network becomes the anchor for this modeling process, making explicit the socio-technical relations that govern enterprise viability in the digital age. Through this lens, we aim to contribute a novel, theoretically grounded, and practically actionable foundation for enterprise digital twins that are not merely descriptive but transformative.

The remainder of this paper is structured as follows. Section 2 surveys related work at the intersection of conceptual modeling, data-intensive analytics, and semantic technologies, positioning our contribution within a field shaped by

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methodological tensions and epistemic pluralism. Section 3 outlines the Action Design Research methodology and introduces the dialectical modeling loop that underpins our approach. Section 4 presents findings from a proof-of-concept in the air navigation services domain, illustrating how commitments are surfaced, reinterpreted, and refined through iterative transformations. Section 5 elaborates the distinguishing features of our framework and identifies key avenues for future inquiry. The paper concludes with a synthesis of contributions and their broader implications.

2 Related Works

This section provides a focused review of selected contributions that exemplify the integration of conceptual modeling with data-intensive analytics, digital twin architectures, and semantic technologies. While not exhaustive, the review foregrounds conceptual and methodological orientations most relevant to our reflexive, commitment-based approach. We emphasize not only thematic overlap but also the dialectical tensions that shape the epistemic landscape—between design and sensemaking, representation and interpretation, derivation and integrity, autonomy and institutional accountability. The discussion situates our contribution as a synthetic extension of these prior efforts, grounded in interpretive modeling and operationalized through semantic technologies.

Maass and Storey (2021) propose a bidirectional framework that tightly couples conceptual modeling and machine learning across the data science lifecycle—from problem formulation to analytical decision-making. Their model leverages ontologies and domain models to promote alignment with stakeholder goals, explainability, and ethical oversight. While their contribution emphasizes bidirectionality and lifecycle integration, it remains rooted in aligning business requirements with data-centric workflows. In contrast, our approach foregrounds normative commitments as first-class modeling constructs and embeds them within dialectical loops. Rather than informing machine learning pipelines per se, our method reinterprets operational data—such as budget entries—as dynamic representations of institutional commitments. This recontextualization introduces an epistemic pivot: from workflow alignment to commitment-driven reflexivity.

Nalchigar and Yu (2017) and Nalchigar and Yu (2018) develop a multi-view conceptual modeling framework that connects business objectives with analytical insights through layered views: Business, Analytics Design, and Data Preparation. Their approach supports traceability and stakeholder participation while codifying design knowledge into structured metamodels. Our research shares their ambition to bridge stakeholder intent with analytic execution but diverges in its epistemological stance. Where Nalchigar and Yu rely on goal- and question-driven decomposition, our method employs a dialectical loop where commitments, contradictions, and interpretive gaps are not problems to be resolved but generative tensions that shape iterative modeling. We further extend their representational logic by integrating UML[1] (for structural integrity) and OWL[2] (for inferential derivation) within a reflexive modeling grammar that can surface latent socio-technical tensions across regulatory and semantic layers.

Schuetz and Schrefl (2023) articulate a rich pattern-based framework for embedding conceptual modeling throughout the business intelligence and analytics pipeline. Their approach advocates for lifting analytics development from data wrangling to high-level abstractions using OLAP[3] patterns, ETL[4] models, and domain ontologies. While we share their commitment to conceptual scaffolding, our methodology diverges by framing modeling itself as a dialectical process. Rather than codifying reusable patterns, we problematize the empirical-normative boundary—leveraging contradictions between data practices and institutional commitments to drive model refinement. Our contribution thus reframes the role of conceptual models from stable templates to reflective mediators of organizational sensemaking.

Park et al. (2020) introduce IRIS, a goal-oriented conceptual modeling framework tailored for big data contexts, with a strong focus on managing data variety and ensuring analytical relevance through virtual data modeling. By incorporating diagnostic reasoning and organizational primitives into an extended EER[5] framework, IRIS enables rational construction of big data models despite fragmented sources. Our approach similarly addresses data heterogeneity but through a dialectical modeling lens that emphasizes institutional context and semantic refinement. While IRIS emphasizes completeness and prioritization in model construction, our reflexive loop foregrounds commitment interpretation, allowing for epistemic tensions and normative uncertainties to guide iterative refinement.

Zheng et al. (2022) propose the Cognitive Digital Twin (CDT) as an evolution of digital twin paradigms, underpinned by semantic technologies like ontologies and knowledge graphs. Their architecture supports cognitive functions such as learning and reasoning across lifecycle phases, drawing on frameworks like RAMI4.0[6]. Our study shares the use of semantic web technologies and lifecycle-spanning models but shifts the focus from technical autonomy to dialectical reasoning and institutional sensemaking. Conceptual models, in our case, are not substrates for orchestration but loci of normative contestation—where modeling grammars (UML and OWL) interact to reveal contradictions, justify interpretations, and enable compliance-aware cognition.

[1] Unified Modeling Language
[2] Web Ontology Language
[3] Online Analytical Processing
[4] Extract, Transform, Load
[5] Enhanced Entity-Relationship
[6] Reference Architectural Model Industrie 4.0

Karabulut et al. (2024) explore how ontologies enhance semantic interoperability within digital twin architectures for cyber-physical systems. Their layered model supports heterogeneous data integration and real-time decision-making, with a strong engineering focus. Our research complements this by showing how semantic enrichment—via RDF[7] and SPARQL[8]—also enables reflexive design in socio-technical contexts. Beyond system integration, our contribution advances ontological technologies as instruments of methodological awareness, embedding them in an Action Design Research (ADR) framework that aligns technical modeling with interpretive reconciliation.

Kostova et al. (2020) advocate for methodological pluralism in Information Systems Engineering through systems-thinking heuristics rooted in interpretivist epistemology. Their critique of unified methodologies resonates with our own dialectical orientation, which sees reconciliation not as a terminal state but as a reflective process mediated by ontological, epistemological, and axiological commitments. However, we extend their contribution by formalizing this reconciliation as a computationally tractable dialectical loop. Commitments and contradictions are not merely philosophical constructs but operational inputs to a modeling cycle grounded in UML and OWL grammars—bridging philosophical reflection with executable sensemaking.

Taken together, these contributions map a conceptual terrain where design logics, semantic technologies, and reflexive modeling practices converge—but rarely integrate. Our approach synthesizes these strands into a hybrid methodology that embeds modeling grammars within an ADR cycle structured as a dialectical loop: Conceptual Modeling → Data Mining → Reflexive Sensemaking → Conceptual Refinement. Unlike frameworks that prioritize technical implementation or cognitive autonomy, our method is anchored in institutional accountability and ontological expressiveness. Conceptual models become both the scaffolds of analysis and the sites of contestation—serving as instruments of reflection, negotiation, and transformation.

3 Methodology

The methodological stance adopted in this research is Action Design Research (ADR, see Sein et al., 2011, and Figure 1), underpinned by constructivist epistemology and interpretive methodology. ADR aligns with constructivist principles through iterative cycles of practical engagement and theoretical reflection. Explicit dialectical reasoning helps navigate tensions between conceptual abstraction and empirical grounding, enhanced by Weber's classical interpretivism, which emphasizes explanatory clarity and typological abstraction rather than mere experiential description (Crotty, 1998; Sun, 2024).

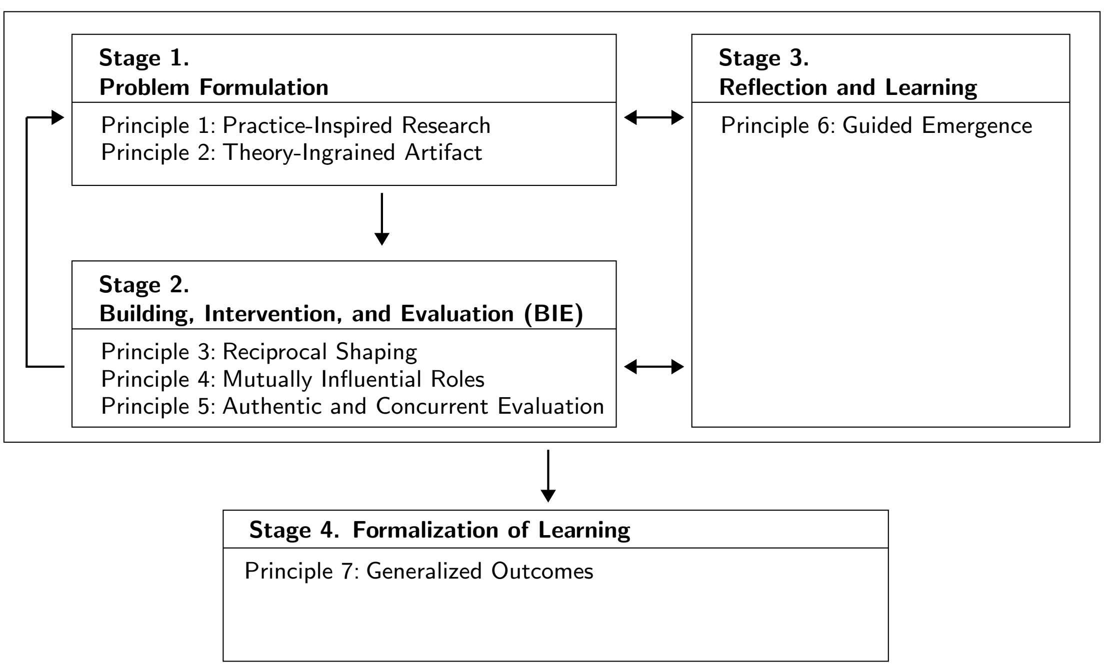

Figure 1: The stages and principles of the Action Design Research showing the iterative alignment between theoretical constructs and real-word empirical data interpretation. Source: based on Sein et al. (2011).

During Problem Formulation, we identified that the core challenge lies not in the scarcity of data or analytical tools, but in the absence of integrative, reflexive modeling frameworks that can bridge transactional data and institutional purpose

[7]Resource Description Framework
[8]SPARQL Protocol and RDF Query Language

by making explicit the evolving networks of social commitments that underpin enterprise functioning. Weber's ideal type concept here acts as a heuristic, positioning commitments as simplified, normative constructs offering explanatory power (Sun, 2024). This normative idealization serves as a theoretical baseline, enabling dialectical interpretation of transactional and trace enterprise data, initially generated for compliance or operational purposes. However, the repurposing of such data for conceptual reinterpretation can raise ethical considerations within critical data studies, necessitating explicit mitigation strategies.

In the Building, Intervention, and Evaluation (BIE) phase, our approach integrates three dialectically interconnected activities: conceptual modeling, data mining, and reflexive interpretation, mediated through explicit machine-interpretable knowledge representation. The commitment-driven enterprise digital twin is conceptualized as both a conceptual modeling script and an enterprise knowledge graph. UML (Unified Modeling Language) and OWL (Web Ontology Language) form our methodological foundation, acknowledging their convergent yet distinct epistemological roots and purposes. UML, grounded in software engineering practice, emphasizes structural and behavioral integrity constraints central to internal consistency and system implementation. Conversely, OWL, rooted in formal logic and semantic web methodologies, prioritizes derivation constraints through formal axioms designed to support logical inference and automated reasoning (Guarino et al., 2019). This epistemological divergence between integrity and derivation constraints becomes methodologically significant in facilitating dialectical interplay between abstraction and empirical validation.

Reflection and Learning iteratively leverages dialectical tensions between ideal-typical abstraction, empirical data validation, and knowledge representation languages. By comparing enterprise realities against idealized commitments through UML and OWL-based representations, we systematically identify critical socio-technical tensions, inconsistencies, and opportunities for improvement—of the model as a semantic scaffold, of the modeled original as a dynamic web of social commitments, and of modeling itself as a reflexive practice that mediates between abstraction and situated organizational meaning. Reflexivity ensures theoretical abstractions remain grounded in practical relevance, while explicit methodological awareness addresses potential ethical concerns associated with transactional data reuse.

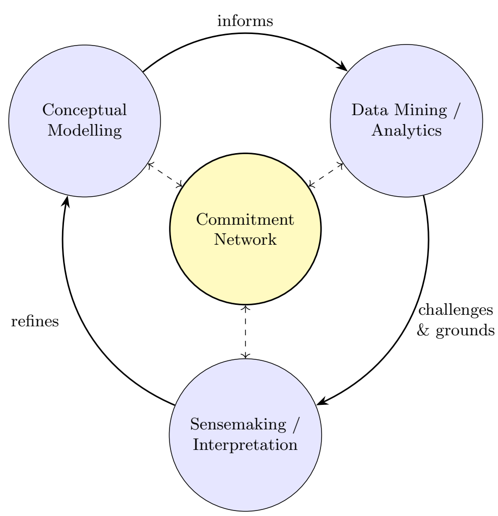

Figure 2: Conceptual modeling framework underpinning the commitment-driven digital twin. The dialectical loop enables progression from modeling to actionable insights, bridging design-time abstraction with runtime interpretability. Source: authors.

The Formalization of Learning phase crystallizes the dialectical process into a generalized conceptual modeling framework structured explicitly as a dialectical loop: Conceptual Modeling → Data Mining → Reflexive Sensemaking → Conceptual Refinement, as Figure 2 illustrates. This loop can employ both integrity and derivation constraints, exploiting strengths from UML and OWL to ensure explanatory clarity, normative precision, and logical consistency. Thus, the framework becomes a robust, ethically conscious tool, enabling practitioners and researchers in business informatics to comparatively evaluate, deliberately shape, and responsibly leverage enterprise commitment networks across diverse organizational contexts.

4 Findings

Imagine turning reporting tables on unit costs of air navigation services into more than a spreadsheet—into a living map of commitments between regulators, providers, and organizational units. Our research does exactly that. By modeling enterprises as dynamic networks of commitments and using data to trace and update those commitments, we create digital twins that make enterprise systems understandable, transparent, and reflexively improbable.

This section reports the core insights of the proof-of-concept through the lens of the proposed dialectical modeling loop: Conceptual Modeling → Data Mining → Reflexive Sensemaking → Conceptual Refinement. We begin by situating the empirical and regulatory context, then trace how evolving representations—UML, OntoUML, RDF, and SPARQL—mediate our understanding of enterprise commitments. Each modeling layer contributes to surfacing latent coordination structures, informing both epistemic and practical insights. All underlying research data and modeling artifacts are publicly accessible in accordance with the FAIR principles, curated at https://lustraka.github.io/resources/pechar/, ensuring transparency, reusability, and alignment with open science practices.

4.1 Empirical and Regulatory Context

This research builds upon a constructed exemplar dataset based on regulatory structures defined in Implementing Regulation 2019/317 (IR317), which governs air navigation services across the European Union (European Commission, 2019; European Commission, 2024). The dataset simulates a fiscal-year cost base for a fictional Air Navigation Service Provider (ANSP), covering 125 budget entries across multiple organizational units, service domains, and cost types. While grounded in practical experience, the dataset is abstracted from any specific provider and serves as a modeling scaffold rather than a comprehensive empirical study. This study deliberately repurposes compliance-driven financial data for conceptual modeling and reflexive interpretation. This raises questions of scope, generalizability, and ethical reuse—all acknowledged here as part of a bounded, exploratory intervention.

Reflexive Note 1: The constructed nature of the dataset necessitates careful boundary-setting. It is neither a generalizable empirical corpus nor an artificial testbed but a practice-inspired scaffold for modeling inquiry.

4.2 Conceptual Modeling: From Data Structure to Ontological Commitment

To unpack the commitment-laden structure of the budgeting data, we first present two Unified Modeling Language (UML) scripts that differ in structural orientation in Figure 3. Model (a) integrates service, cost type, and organizational unit attributes directly into a single `BudgetEntry` class—reflecting a pragmatic, spreadsheet-compatible structure used in many internal budgeting workflows. Model (b), by contrast, decomposes these attributes into separate classes with explicitly modeled associations, prioritizing clarity and semantic separation over immediate operational convenience.

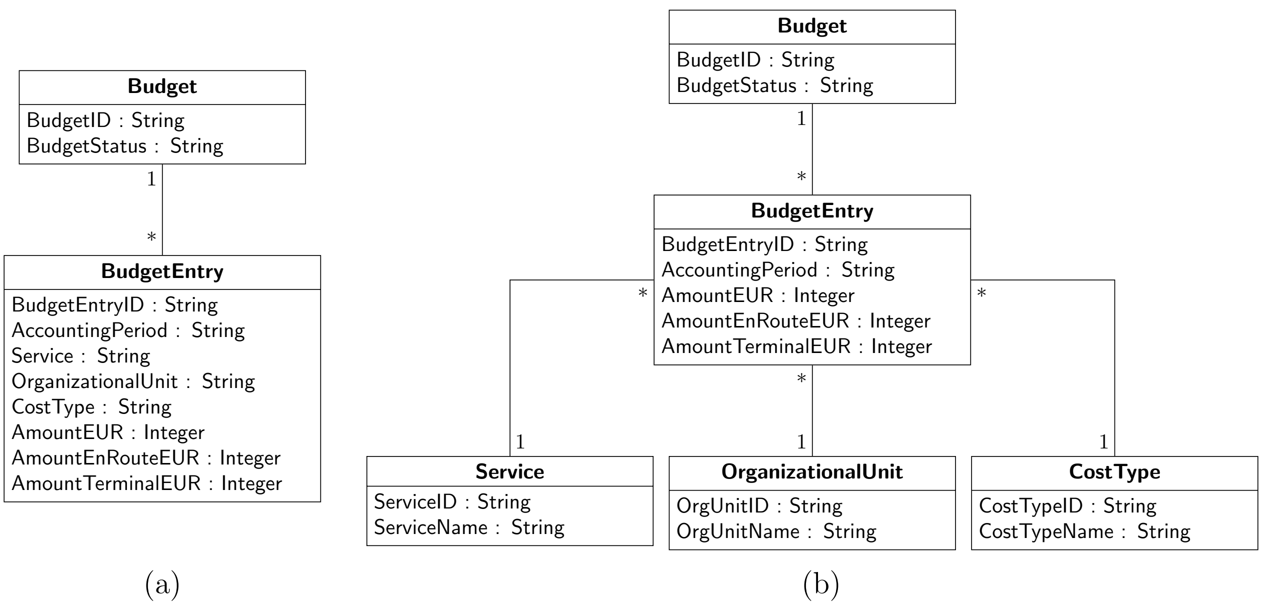

Figure 3: Alternative representations of budgeting entities through UML modeling scripts, contrasting an attribute-integrated approach (a) with a structurally decomposed and semantically richer relational approach (b). Source: authors.

This contrast exemplifies different modeling grammars in practice: the former privileges simplicity and system alignment, the latter supports data consistency and normalization. Yet both fall short of full conceptual modeling: neither script externalizes domain semantics beyond naming conventions or captures underlying commitments among roles, resources, and services. To address these limitations and deepen the analytical lens, we transition from structural data modeling to ontology-driven conceptual modeling. We introduce OntoUML as a foundation for formalizing institutional roles, relators, and modalities, offering expressive power beyond traditional structural models (Guizzardi et al., 2018). The OntoUML script in Figure 4 reinterprets the budget entries not merely as data containers but as manifestations of institutionalized commitments. Here, each `BudgetEntry` connects an `OrganizationalUnit` (as agent) to a Service (as intentional output), within the context of a given `AccountingPeriod`. A Service contributes to a Chargeable Service and requires human effort, subservices, and infrastructure captured through a `CostType`.

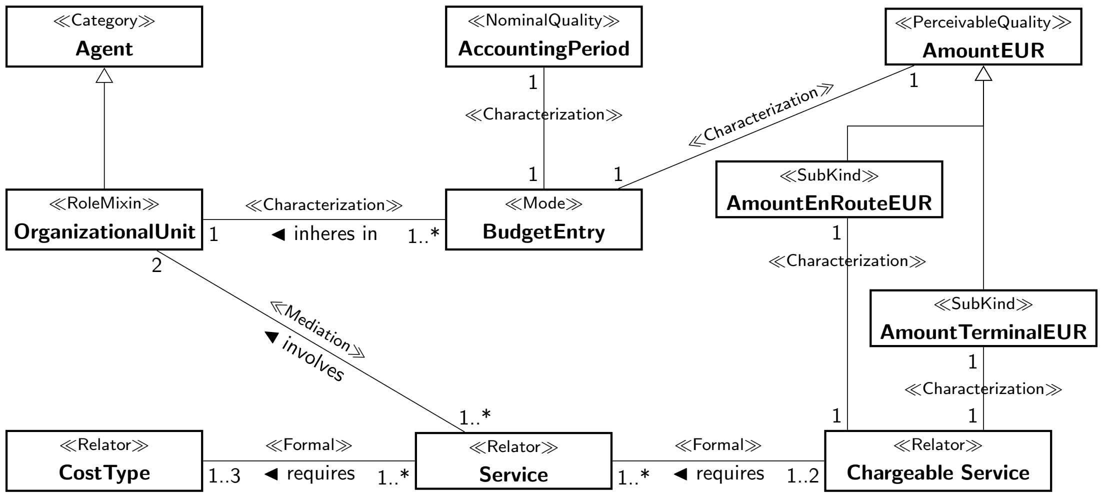

Figure 4: Conceptual model in OntoUML showing how budget entries, services, and cost types interrelate to reflect enterprise operations. Source: authors.

This shift elevates modeling from data alignment to ontological interpretation, surfacing the teleological dimensions of budgeting structures. OntoUML's rich ontological distinctions—between relators, roles, events, and agents—support finer-grained insights into how enterprises coordinate internal capacities under regulatory constraints.

Reflexive Note 2: OntoUML enables ontological commitment articulation but increases representational complexity. The trade-off between analytical clarity and operational usability must be managed deliberately.

4.3 Data Mining: Semantic Representation and Query-Based Insight

To support automated reasoning and semantic interoperability, the conceptual model and its instantiation (data) are serialized into RDF using the Turtle syntax. Figure 5 presents two alternative RDF Turtle representations of budget entries, corresponding to the structural models introduced in Figure 3. These examples illustrate how conceptual modeling choices—whether attribute-integrated or semantically decomposed—directly shape the structure, granularity, and inferential potential of the resulting knowledge graph. This transition preserves ontological distinctions while translating them into a graph-based format suited for semantic querying. Automated bi-directional transformation between UML and OWL are feasible (Suchanek and Pergl, 2020), although not demonstrated in this study.

In the process of transforming tabular budgeting data into semantically enriched RDF graphs, several methodological tensions emerge. A particularly illustrative case involves identifying, for each service, the organizational unit with the highest financial contribution. This task requires computing the maximum `AmountEUR` grouped by `Service`, and subsequently asserting RDF triples such as `pechar:ServiceX pechar:hasTopContributor pechar:OrgUnitY`, thereby enabling downstream reasoning over organizational units' relations. Figure 6(a) presents a Python script fragment that computes these maxima prior to RDF serialization, embedding the derived triples into the graph structure. This approach externalizes computational logic from the RDF layer, privileging operational control, algorithmic clarity, and performance transparency over declarative purity.

Figure 6(b), by contrast, introduces a SPARQL construct that derives `pechar:OrgUnitX pechar:deliversTo pechar:OrgUnitY` triples based on the previously established `pechar:hasTopContributor` relations. This transition re-internalizes semantic inference into the graph model, enhancing queryability, fostering inter-resource interoperability, and supporting scalable reasoning across heterogeneous datasets. However, it also abstracts away the underlying quantitative justifications, thus attenuating their interpretive utility in subsequent analysis.

Reflexive Note 3: This dialectic—between externalized computation and internalized semantics—illustrates a broader modeling tension: whether to prioritize operational pragmatics or ontological expressiveness. Navigating this trade-off is not merely a technical design decision but a reflexive moment that shapes how commitment networks are rendered intelligible, accountable, and analytically tractable within enterprise digital twins.

To infer inter-organizational relationships in the absence of explicit linkage data, we adopted the simplifying assumption that the organizational unit with the highest financial contribution to a given service could serve as a proxy for that service in the coordination network. This heuristic enables the construction of inferred `deliversTo` relations, thereby revealing a latent graph of operational coordination, as illustrated in Figure 7.

```turtle
@prefix pechar: <https://lustraka.github.io/resources
    /pechar/> .
@prefix schema: <http://schema.org/> .
@prefix ses: <https://eur-lex.europa.eu/eli/reg
    /2024/2803/oj/> .
@prefix skos: <http://www.w3.org/2004/02/skos/core#>
    .

pechar:bYYe001 a pechar:BudgetEntry ;
    pechar:AccountingPeriod "YYYY" ;
    pechar:AmountEUR 8752200 ;
    pechar:AmountEnRouteEUR 6867900 ;
    pechar:AmountTerminalEUR 1884300 ;
    pechar:CostType "a Staff Costs" ;
    pechar:OrganizationalUnit "1000 Corporate Services
        " ;
    pechar:Service "201 Air Traffic Management" .
```

(a)

```turtle
pechar:aStaffCosts a schema:DefinedTerm ;
    schema:inDefinedTermSet pechar:CostsByNature ;
    schema:name "a Staff Costs" .
pechar:1000_CS a schema:DefinedTerm ;
    schema:inDefinedTermSet pechar:OrgUnits ;
    schema:name "1000 Corporate Services" .
pechar:201AirTrafficManagement a schema:DefinedTerm ;
    schema:inDefinedTermSet pechar:CostsByService ;
    schema:name "201 Air Traffic Management" ;
    skos:related ses:AirTrafficManagement ;
    pechar:hasTopContributor pechar:2111_ACC .

pechar:bYYe001 a pechar:BudgetEntry ;
    pechar:AccountingPeriod "YYYY" ;
    pechar:AmountEUR 8752200 ;
    pechar:AmountEnRouteEUR 6867900 ;
    pechar:AmountTerminalEUR 1884300 ;
    pechar:CostType pechar:aStaffCosts ;
    pechar:OrganizationalUnit pechar:1000_CS ;
    pechar:Service pechar:201AirTrafficManagement .
```

(b)

Figure 5: Fragmentary RDF Turtle representations of budgeting entities, contrasting a literal attribute approach (a) with a structurally decomposed and semantically enriched relational approach (b) that affords greater reasoning capabilities via SPARQL. Source: authors.

```python
# Add pechar:hasTopContributor triples based on
    AmountEUR
grouped = bYYe.groupby("Service")["AmountEUR"].idxmax
    ()

for service_label, top_index in grouped.items():
    service_uri = get_uri_by_label(service_label)
    org_label = bYYe.loc[top_index]["
        OrganizationalUnit"]
    org_uri = get_uri_by_label(org_label)

    if service_uri and org_uri:
        g.add((service_uri, pechar.hasTopContributor,
            org_uri))
```

(a)

```sparql
PREFIX schema: <http://schema.org/>
PREFIX pechar: <https://lustraka.github.io/resources/
    pechar/>

CONSTRUCT {
  ?OU_a pechar:deliversTo ?OU_b .
}
WHERE {
  ?be a pechar:BudgetEntry ;
      pechar:OrganizationalUnit ?OU_a ;
      pechar:Service ?service .
  ?service pechar:hasTopContributor ?OU_b .
  FILTER (?OU_a != ?OU_b)
}
```

(b)

Figure 6: Illustrating a modeling trade-off between procedural computation and semantic inference: (a) scripted maxima computation foregrounds control and traceability; (b) graph-native SPARQL construction enhances semantic expressiveness but abstracts quantitative grounding. Source: authors.

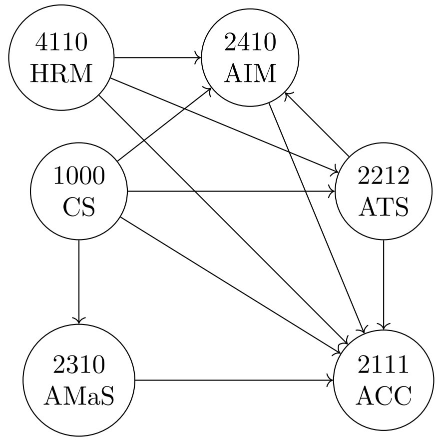

Figure 7: A fragment of an organizational unit's network derived from the exemplar dataset. Legend: 1000 Corporate Services (ADM), 2111 Area Control Centre (ACC), 2212 Aeronautical Telecommunications Services, 2310 ATM/ANS Methodology and Standards, 2410 ATM Information Management, and 4110 Human Resources Management. Source: authors.

While methodologically expedient for this proof-of-concept, the approach rests on strong assumptions: that financial dominance equates to operational responsibility, and that service delivery can be reasonably imputed from cost allocation patterns alone. These assumptions—grounded in management accounting logic and shaped by organizational structure and controlling methodology—necessarily introduce epistemic uncertainty. As such, they should be treated as provisional abstractions and simplifications rather than definitive mappings. Future research (see Section 5) will pursue comparative analysis of commitment modeling methodologies and develop more robust inferential strategies that integrate transactional data with formal representations of social commitments. The goal is to enhance the modeling of coordination pathways with greater semantic precision, institutional nuance, and support for ethical and organizational accountability.

4.4 Reflexive Sensemaking: From Data to Commitments

Reflexive sensemaking in the modeling cycle is a methodological intervention that transforms inferred data into structured understanding, enabling enterprise phenomena to be interpreted as dynamic networks of social commitments. It does not merely explain existing structures but actively interrogates how enterprises coordinate, account, and adapt. This phase hinges on dialectical interplay between data representations—such as RDF graphs derived from budgeting data—and conceptual abstractions formalized in ontologies. Inferred relations between organizational units act as proxies for commitments, turning operational data into diagnostic tools that reveal latent coordination structures and institutional accountabilities.

While the current analysis centers on financial commitments, derived from cost allocations and dominance patterns, a more granular investigation of cost types could expose additional dimensions—such as labor distribution, infrastructure reliance, or service integration—that reflect deeper layers of organizational obligation. Crucially, modeling heuristics are entangled with managerial logics: conventions like cost center hierarchies are treated as ontological anchors, yet they originate from institutionalized practices. Reflexivity here becomes a method of inquiry, foregrounding how modeling decisions both reflect and reshape what becomes visible and meaningful in enterprise analysis.

In sum, reflexive sensemaking is not a lens applied post hoc, but a constitutive method that fuses conceptual modeling, semantic representation, and institutional critique—rendering commitments not only visible, but contestable and actionable within digital twin infrastructures.

Reflexive Note 4: The methodology involves a shift along the intension/extension axis. Inferred relations (e.g., `OrgUnitX deliversTo OrgUnitY`) begin as instances of commitments but may be elevated to analytical (ideal) types of transactions, informing future cycles of modeling and analyzing. This recursive reframing enables both retrospective understanding and prospective design.

4.5 Conceptual Refinement: Methodological Deepening

Building on the interpretive insights surfaced during reflexive sensemaking, conceptual refinement anchors provisional understandings in formal ontological structures. Rather than extending analysis, this phase consolidates it—elevating heuristics into semantically precise, reusable constructs. To support this transition, we employ the Unified Foundational Ontology (UFO, Guizzardi et al., 2022) and its OWL representation gUFO (Almeida et al., 2019), which provide a principled semantic scaffold for modeling commitments as relators connecting agents through roles and normative modalities.

As shown in Figure 8, the commitment-based reference ontology for services (Nardi et al., 2015) operationalizes this structure, enabling commitments to be rendered as institutional facts within logically coherent digital twin models.

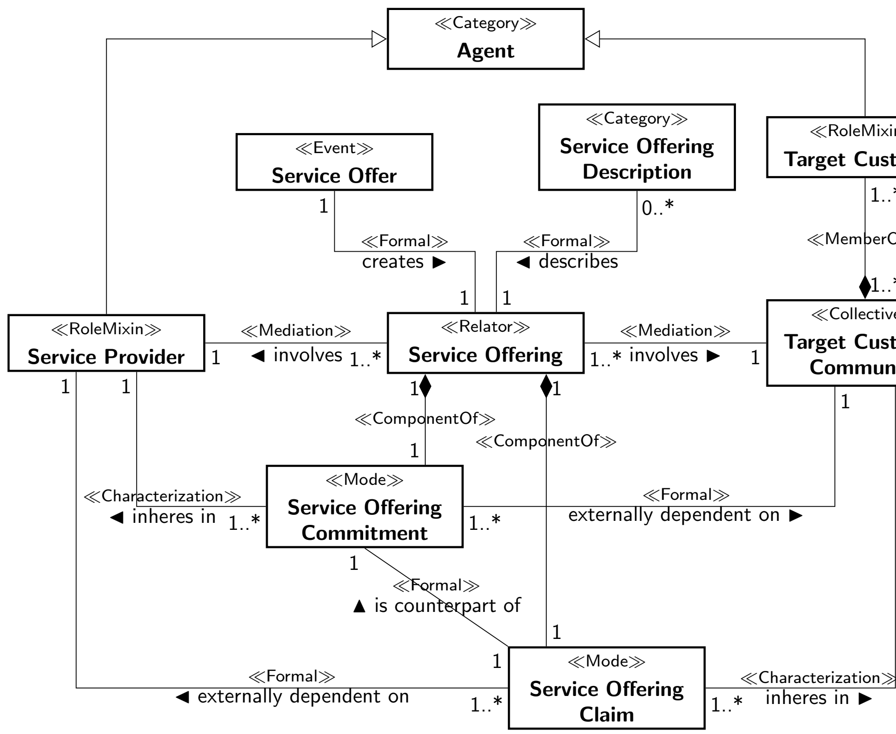

Figure 8: Ontology-driven representation of service commitments based on the Unified Foundational Ontology and the commitment-based reference ontology for services. Source: based on Nardi et al. (2015).

Crucially, refinement also enables meta-modeling shifts: relations initially inferred as instance-level patterns are reclassified as analytical (ideal) types, guiding future modeling and reasoning (see Reflexive Note 4). This recursive elevation of modeling elements strengthens the loop's epistemic depth and methodological portability. Rather than closing the loop in a conclusive sense, conceptual refinement amplifies its generativity—transforming models into reflexive infrastructures capable of supporting institutional learning, semantic traceability, and adaptive redesign.

Reflexive Note 5: Underpinned by constructivist epistemology, the use of Weberian ideal types grounds our models as heuristic constructs—normative, selective, and explanatory rather than descriptive. In socio-technical settings, this aligns with a shift from validating truth claims (accuracy) to assessing the sensemaking fitness (adequacy) of models in institutional contexts.

5 Discussion and Future Research

This section elaborates on the theoretical positioning and methodological implications of the commitment-driven enterprise digital twin (CoEDiT), contributing to its precise articulation within conceptual modeling and digital twin scholarship.

What exactly characterizes CoEDiT as a conceptual model? Employing Delcambre's reference framework for conceptual modeling (Delcambre et al., 2018), we define CoEDiT as a multi-purpose, multi-language, multi-level conceptual script continuously evolving in response to socio-technical phenomena within enterprise settings. Unlike conventional static representational models, CoEDiT employs a reflexive method to mediate effectively between formal abstraction and the fluid dynamics of institutional practices. Within the broader taxonomy of digital twins, CoEDiT aligns conceptually with cognitive digital twins (Zheng et al., 2022). However, it significantly departs from typical applications oriented towards physical systems by explicitly targeting institutional commitments as the foundational ontological elements of enterprise cognition.

Crucially, CoEDiT rejects fragmented lifecycle views that separate modeling from reality. Instead, it advocates for continuous co-evolution, aiming to enable real-time comprehension, analysis, and refinement of organizational commitments. Thus, it uniquely integrates descriptive accuracy with prescriptive actionable insights. While extending towards broader socio-technical ecosystems, CoEDiT intentionally avoids the overly generalized scope found in the "universal digital twin" concept (Akroyd et al., 2021), privileging context-sensitive accountability over universal abstraction.

To further delineate CoEDiT's distinctive characteristics, we apply Mayr and Thalheim (2021) schema for conceptual model (CM) attributes, with slight adjustments to attribute names for clarity and terminological consistency:

(CM1) Modeled Original: Because commitments inhere in social agents—as internal, social, and collective commitments (Castelfranchi, 1995)—they are not objective features of the world but interpretive constructs. Accordingly, our methodological foundation is rooted in a constructivist epistemology and interpretive research tradition, diverging from scientific realism and other dominant paradigms in conceptual modeling. The emergent, situated, and often tacit character of commitments calls for a careful balance: between formalization, which ensures ontological clarity, and representational flexibility, which reflects semantic fluidity. This methodological tension underpins our approach, demanding reflexivity in how commitments are elicited, represented, and refined.

(CM2) Modeling Intention: CoEDiT shares with other conceptual models the intentions of retrospective understanding, perspective communication, and prospective design. However, in our case, 'design' is neither temporally decoupled from use nor limited to computational specification. Instead, it involves the dynamic shaping of commitment networks at runtime—such as through the inclusion of parallel worlds that enable intelligent exploration of alternative organizational trajectories without disrupting the base world (Akroyd et al., 2021).

(CM3) Model Affordances: Built upon a machine-interpretable knowledge graph, CoEDiT is operable not only by human agents but also by artificial agents. This enables novel applications such as compliance monitoring, semantic querying, constraint-based validation, and the execution of formal specifications. Crucially, CoEDiT's commitment-oriented foundation allows it to engage with ethical and accountability challenges associated with embedding artificial agents within enterprise systems. However, the inherent tension between automated affordances—rooted in formal rules—and the interpretive, often tacit nature of commitments must be carefully navigated.

(CM4) Model Environment: CoEDiT's multidisciplinary grounding—at the intersection of software engineering, data analytics, and business process modeling—yields both opportunities and challenges. At the individual level, it leverages diverse disciplinary advancements but demands cross-domain expertise, making professional engagement intellectually demanding and coordination-intensive. At the enterprise level, it must reconcile digital abstractions (e.g., models, logs) with the fluid realities of organizational life, including human practices, power dynamics, and institutional norms. At the industry level, particularly in regulated domains such as air navigation services, CoEDiT offers the potential to support systemic reconfiguration and strategic insight—akin to modeling economies as service-based networks (Telesca et al., 2020; Telesca et al., 2021).

(CM5) Model Focus: Although centered on commitments, a defining feature of CoEDiT is data repurposing—transforming compliance-driven, transactional data into meaningful signals of evolving commitments. This process requires careful navigation of the tension between the original intent of the data (e.g., budgeting, accounting, performance planning) and its reinterpretation through conceptual modeling for insight, foresight, and strategic alignment. As with any model, CoEDiT reflects selected aspects of its source data relevant to its purpose, rather than attempting comprehensive representation.

(CM6) Model Grammar: CoEDiT is grounded in a conceptual grammar ensemble, prominently comprising OntoUML (ontology-driven conceptual modeling), RDF (serialization), OWL (inferencing), SHACL[9] (validation), and SPARQL (reasoning and querying). The method involves translating, mapping, and aligning across these diverse modeling grammars. A central challenge is balancing coherence, through shared semantic anchors, with pluralism, by respecting the epistemological and functional differences among grammars. Rather than enforcing full unification, CoEDiT adopts dialectical synthesis as a methodological stance—preserving heterogeneity while enabling integrated, reflexive modeling across layers and purposes (Kostova et al., 2020).

(CM7) Concept Space: Conceptual modeling is modeling with concepts drawn from an associated concept space (Mayr and Thalheim, 2021). In CoEDiT, this space is shaped by commitments as ontological primitives—relators linking agents, roles, and normative modalities. Unlike models rooted in functional or structural abstractions, CoEDiT's concept space foregrounds institutional meaning, intentionality, and accountability. It spans both formal constructs (e.g., service commitments, organizational roles) and inferred proxies (e.g., budget allocations as signals of coordination). The space evolves dialectically through modeling cycles, where conceptual refinement feeds back into the concept space itself—rendering it not static, but reflexively extensible.

(CM8) Concept Relationships: CoEDiT engages a spectrum of concept relationships fundamental to conceptual modeling, including mereology (aggregation and decomposition), generalization–specialization (ontological hierarchies), and most critically, the intension–extension relationship. As a multi-level model, CoEDiT systematically links intensional constructs—ideal-typical representations of commitments—with extensional traces drawn from transactional data. This dynamic is central to its reflexive methodology: as articulated in Reflexive Note 4, inferred relations (e.g., `OrgUnitX deliversTo OrgUnitY`) initially function as instance-level extensions, yet through iterative cycles of modeling and interpretation, they may be abstracted into intensional, analytical types. This recursive shift enables

[9] Shapes Constraint Language

the model to support both retrospective understanding and prospective design, transforming concept relationships into pathways of cumulative insight and adaptive learning.

From a broader disciplinary perspective, CoEDiT contributes meaningfully to current scholarly debates regarding the scope and identity of Information Systems (IS) and Business Informatics (BI). As digitalization increasingly permeates organizational life, prominent researchers call for integrative frameworks that reconcile technical artifacts, organizational contexts, and economic constraints (Schütte et al., 2022). In response, CoEDiT offers a socio-technical modeling framework that integrates formal abstraction, empirical data mining, and reflexive interpretation—recasting enterprise modeling as a dynamic practice attuned to institutional meaning, ethical accountability, and semantic plurality. By elevating commitments to primary analytical constructs, CoEDiT transcends the boundaries of technical design, advancing enterprise modeling as a normative inquiry into how obligations are structured, enacted, and transformed across organizational contexts. This repositioning marks a conceptual shift: from modeling systems as they function to modeling enterprises as they evolve—ethically, socially, and semantically.

Future research should begin with a comparative inquiry into commitment modeling methodologies, which span a diverse spectrum of conceptualizations. Some frameworks, such as DEMO[10] and CBMAS[11], treat commitments as explicit ontological primitives, while others—like BPM[12], SOA[13], or REA[14]—encode them implicitly within structural or procedural constructs. This heterogeneity reflects a deeper epistemological tension between static, design-time formalization and dynamic, reflexive emergence of commitments in situated practice. CoEDiT contributes a unifying lens by operationalizing a dialectical modeling loop that enables systematic comparison across methodologies. Such comparative research should examine how different approaches account for the temporal evolution of commitments, their semantic and organizational alignment, and the formalization of soft commitments—including ethical responsibilities and cultural expectations—that often evade rigid codification. The Unified Foundational Ontology offers a promising basis for reconciling these grammars at a meta-ontological level.

Beyond methodological comparison, several complementary research trajectories arise. First, semantic expansion is needed to extend modeling grammars to accommodate normative constraints, drawing on legal ontologies such as UFO-L[15] or ELTS[16] to incorporate ethical and institutional dimensions. Second, design interventions in the form of longitudinal Action Design Research cycles could embed CoEDiT into live organizational settings, enabling real-time institutional learning and adaptive governance. Finally, the rise of human–AI collaboration demands exploration into how artificial and human agents co-construct and interpret commitment networks via shared ontologies—offering a fertile intersection between explainable AI, organizational theory, and modeling ethics. Together, these avenues aim to deepen CoEDiT's role not only as a conceptual artifact but as a living, reflexive infrastructure for socio-technical transformation.

6 Conclusion

This research reconceptualizes enterprise digital twins not as static mirrors of operations but as reflexive infrastructures for institutional sensemaking. By foregrounding commitments—understood as intentional, normative relations among agents, roles, and artifacts—we articulate a socio-technical modeling paradigm capable of rendering enterprise realities not only intelligible but transformable. Through a dialectical loop that integrates conceptual modeling, data analytics, reflexive interpretation, and ontological refinement, we operationalize a commitment-based digital twin methodology attuned to the tensions between structure and emergence, formalism and context, automation and accountability.

Our findings demonstrate that transactional data, when semantically enriched and ontologically recontextualized, can illuminate latent networks of organizational coordination and obligation. By elevating commitments from implicit traces to analytical constructs, this approach enables new forms of compliance-aware reasoning, strategic foresight, and adaptive enterprise design. Ontological tools such as OntoUML, OWL, and UFO do not merely support representation—they mediate a reflexive discourse in which the meaning, relevance, and ethical implications of enterprise behavior are continuously interrogated.

This contribution positions conceptual modeling as an epistemic infrastructure for digital transformation, expanding its role from system specification to institutional critique and redesign. The proposed approach invites a rethinking of enterprise modeling as a normative endeavor, one that treats socio-technical commitments not as incidental byproducts of design but as foundational elements of enterprise viability and ethical coherence.

[10]Design and Engineering Methodology for Organizations
[11]Commitment-Based Multi-Agent Systems
[12]Business Process Modeling
[13]Service Oriented Architecture
[14]Resource-Event-Agent
[15]Unified Foundational Ontology for legal domain
[16]European Legal Taxonomy Syllabus

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