Supplementary Materials

Examples of External Knowledge Representations

EKRs are explicit, structured, formal or semi-formal artifacts that encode domain knowledge relevant for machine learning. For each type of EKR, seminal (commonly, the original publication) and additional, widely used, sources are identified to trace the intellectual lineage of the approach and outline how initial formulations have evolved into today's practices.

Table 1 provides a sample list of External Knowledge Representations (EKRs) spanning a wide range of applications, such as engineering, design, communication, business, policy and science. As EKRs have been shown to be effective in a wide range of tasks, many modeling techniques have been developed to support specific uses (Fowler 2004; Olivé 2007; Storey et al. 2023). These representations commonly facilitate problem solving, design, reasoning, interoperability, compliance, and decision making (Guizzardi and Proper 2021; Halpin 2015; Hirschheim et al. 1995; Recker et al. 2021; Siau and Rossi 2011; Thalheim 2024; Wand and Weber 2002). This Supplementary Table extends Table 1 (Section 3.4) by providing citations and historical background on each EKR.

To prepare the list, we consulted seminal papers and textbooks about EKRs used in practice and research (Buede and Miller 2024; Dobing and Parsons 2006; Fettke 2009; McDaniel and Storey 2019; Michael et al. 2023; Olivé 2007; Storey et al. 2023; Thalheim 2024; Zott et al. 2011). We focused on most recent surveys to identify those EKRs that are in use today. Some publications offered tables of most popular EKRs (e.g., Dobing and Parsons (2006); Storey et al. (2023)). From these sources, the popular EKRs were extracted and presented in Table 1. Some EKRs (e.g., process models, knowledge graphs, causal diagrams) can address multiple knowledge deficiencies.

Table 1. Popular External Knowledge Representations

EKR	**Citations**
Ontologies (OWL, Protégé)	**OWL - Web Ontology Language:** McGuinness, D. L., & Van Harmelen, F. (2004). OWL Web Ontology Language Overview. W3C. https://www.w3.org/TR/owl-features/ Bechhofer, S. (2018). *OWL: Web Ontology Language*. https://dblp.uni-trier.de/db/reference/db/o2.html#Bechhofer18 **Protégé**: Mark A. Musen. (2015). The protégé project: a look back and a look forward. AI Matters 1, 4 (June 2015), 4–12. https://doi.org/10.1145/2757001.2757003
Conceptual data models (ER, UML	**ER - Entity-Relationship Model**:

Class Diagram, Object-Role Models)	Chen, P. P. S. (1976). The entity-relationship model—toward a unified view of data. *ACM transactions on database systems (TODS)*, *1*(1), 9-36. Elmasri, R., & Navathe, S. B. (2014). Fundamentals of database systems (7th ed.). Pearson **UML - Unified Model Language:** Booch, G. (2005). The unified modeling language user guide. Pearson Education. **UML Class Diagram - Unified Modeling Language Class Diagram**: Booch, G., Rumbaugh, J., & Jacobson, I. (2005). Unified modeling language user guide (the 2nd edition). Addison-Wesley Object Technology Series. Tegarden, D. P., Samuel, B., Lukyanenko, R., Dennis, A., & Wixom, B. H. (2025). Systems Analysis and Design, with EEPUB Access: An Object-Oriented Approach with UML. John Wiley & Sons. **Object-Role Modeling**: Halpin, T. (2006). Object-role modeling (ORM/NIAM). In Handbook on architectures of information systems (pp. 81-103). Berlin, Heidelberg: Springer Berlin Heidelberg. Halpin, T. (2015). Object-role modeling fundamentals: a practical guide to data modeling with ORM. Technics Publications.
UML Activity Diagrams	**UML Activity Diagrams:** Booch, Grady & Rumbaugh, James & Jacobson, Ivar. (2005). Unified Modeling Language User Guide, The (2nd Edition) (Addison-Wesley Object Technology Series). J. Database Manag.. 10. Ahmad, T., Iqbal, J., Ashraf, A., Truscan, D., & Porres, I. (2019). Model-based testing using UML activity diagrams: A systematic mapping study. Computer Science Review, 33, 98-112 Tegarden, D. P., Samuel, B., Lukyanenko, R., Dennis, A., & Wixom, B. H. (2025). Systems Analysis and Design, with EEPUB Access: An Object-Oriented Approach with UML. John Wiley & Sons.
Instance-based models (UML Object Diagram,	**UML Object Diagram - Unified Modeling Language Object Diagram:** Booch, G., Rumbaugh, J., & Jacobson, I. (2005). *The unified modeling*

Datish diagram)	*language user guide* (2nd ed.). Addison-Wesley Professional. Fowler, M. (2004). UML distilled: A brief guide to the standard object modeling language (3rd ed.). Addison-Wesley Professional. Tegarden, D. P., Samuel, B., Lukyanenko, R., Dennis, A., & Wixom, B. H. (2025). Systems Analysis and Design, with EEPUB Access: An Object-Oriented Approach with UML. John Wiley & Sons. Lukyanenko, R., Samuel, B. M., Parsons, J., Storey, V. C., Pastor, O., & Jabbari, A. (2024). Universal conceptual modeling: principles, benefits, and an agenda for conceptual modeling research. *Software and Systems Modeling*, *23*(5), 1077-1100.
BPMN and DMN (Decision Model & Notation)	**BPMN - Business process model and notation**: Object Management Group. (2011). Business process model and notation (BPMN) version 2.0.2. OMG Standard. https://www.omg.org/spec/BPMN/2.0.2/PDF Chinosi, M., & Trombetta, A. (2012). BPMN: An introduction to the standard. Computer Standards & Interfaces, 34(1), 124-134. **DMN - Decision model and notation:** Object Management Group. (2025). Decision model and notation (DMN) version 1.5. https://www.omg.org/spec/DMN Figl, K., Mendling, J., Tokdemir, G., & Vanthienen, J. (2018). What we know and what we do not know about DMN. Enterprise Modeling and Information Systems Architectures (EMISAJ), 13, 2-1.
Enterprise Models (ArchiMate, TOGAF ADM, SysML, C4)	**Enterprise Models**: Fox, M. S., & Gruninger, M. (1998). Enterprise modeling. AI magazine, 19(3), 109-109. Sandkuhl, Kurt, Janis Stirna, Anne Persson, and Matthias Wißotzki. Enterprise modeling. Heidelberg: Springer, (2014). **ArchiMate**: The Open Group. (2022a). *ArchiMate® 3.2 specification.* https://pubs.opengroup.org/architecture/archimate32-doc/ **TOGAF ADM - The Open Group Architecture Framework Architecture**

	Development Method : The Open Group. (2022b). *The TOGAF® standard, version 10.* https://pubs.opengroup.org/architecture/togaf-standard/ **SysML - OMG Systems Modeling Language**: Object Management Group. (2007). *OMG systems modeling language (SysML®), version 1.5.* https://www.omg.org/spec/SysML/1.5/PDF **C4 Model - Context, Containers, Components, and Code Model:** Brown, Simon (2018). "The C4 Model for Software Architecture". InfoQ. https://c4model.com/ Archived from the original on 2018-12-12.
Motivation Models (Business Motivation Model)	**Business Motivation Model**: Object Management Group. (2015). *Business motivation model (BMM), version 1.3*. OMG Standard. https://www.omg.org/spec/BMM/1.3/PDF
Policy and Legal Ontologies (GDPR, LKIF Core)	**GDPR - General Data Protection Regulation:** Voigt, Paul & Bussche, Axel. (2017). The EU General Data Protection Regulation (GDPR): A Practical Guide. 10.1007/978-3-319-57959-7. Li, H., Yu, L., & He, W. (2019). The impact of GDPR on global technology development. Journal of Global Information Technology Management, 22(1), 1-6. **LKIF Core - Legal Knowledge Interchange Format core**: Hoekstra, Rinke & Breuker, Joost & Di Bello, Marcello & Boer, Alexander (2007). The LKIF Core ontology of basic legal concepts. International Journal of High Performance Computing Applications - IJHPCA. 43-63. Casanovas, P., Palmirani, M., Peroni, S., Van Engers, T., & Vitali, F. (2016). Semantic web for the legal domain: the next step. *Semantic web*, *7*(3), 213-227. Peroni, S., Van Engers, T., & Vitali, F. (2016). Semantic web for the legal domain: the next step. *Semantic web*, *7*(3), 213-227.
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Policy manuals/models (e.g., XACML, data contracts)	**Policy Models**: Hu, V. C., Ferraiolo, D., Kuhn, R., Schnitzer, A., Sandlin, K., Miller, R., & Scarfone, K. (2014). *Guide to attribute based access control (ABAC) definition and considerations*. NIST Special Publication 800-162. Coyne, Ed & Weil, Tim. (2013). ABAC and RBAC: Scalable, flexible, and auditable access management. IT Professional. 15. 14-16. 10.1109/MITP.2013.37. **XACML - eXtensible Access Control Markup Language**: OASIS. (2013). *eXtensible Access Control Markup Language (XACML) Version 3.0*. OASIS Standard. https://docs.oasis-open.org/xacml/3.0/xacml-3.0-core-spec-os-en.html Ramli, C. D. P. K., Nielson, H. R., & Nielson, F. (2014). The logic of XACML. *Science of Computer Programming*, *83*, 80–105. https://doi.org/10.1016/j.scico.2013.05.003

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Prompt Engineering in MWF

Symbolic and structured EKRs encode verified domain knowledge, preserving explicit relationships and constraints that can be audited and validated by domain experts. Implicit or emergent representations, by contrast, internalize such knowledge within model parameters; MWF treats them as complementary components that require external EKRs for grounding. Our framework augments LLMs with explicit and verifiable domain knowledge through EKRs.

Implementation of Retrieval Augmented Generation (RAG)

Recent industry developments such as OpenAI's GPTs with Custom Actions, Anthropic's Claude with Model Context Protocol (MCP), and LangChain's tool integrations all represent attempts to bridge implicit neural knowledge with explicit external knowledge. The MWF framework provides theoretical grounding and systematic guidance for how such augmentations can preserve representational fidelity and transparency across the stages of machine learning.

The illustration was implemented using OpenAI GPT-5 (Enterprise) within the Projects environment, which provides a managed retrieval-augmented generation (RAG) setup. The uploaded External Knowledge Representations (EKRs) include the entity-relationship diagram, process diagram, and policy manuals, which served as the project's knowledge base. This configuration automatically handles document indexing and contextual retrieval, allowing the model to ground reasoning in domain artifacts without manual parameter tuning.

The managed environment builds on the same representational principles tested in an open-source RAG implementation (available at https://github.com/ragapp/ragapp or https://github.com/infiniflow/ragflow), where parameters such as embedding models, retrieval depth, model, temperature, and chunk size, among others, can be adjusted. Together these implementations demonstrate that MWF concepts can be applied across both open-source and enterprise-grade infrastructures.

Generic Template for EKR-Guided Prompting

[Describe Context]
Provide Context, Summarize the prediction task, outcome of interest, and available domain materials (e.g., sample data, handbooks, procedures, manuals, and other relevant organizational data).

Task:
Propose candidate engineered features for **[Outcome_of_interest]** using only the provided EKRs and contextual documents.

EKRs:
Describe the EKRs that ground the model-world fit process. For example:

EKR_ERD

- Entities: (e.g., Child, Placement, Case, ...)
- Key relationships and keys
- Attributes available at decision time

EKR_ProcessDiagram

- Valid event sequence and gateways
- Decision point and allowable inputs at prediction time

Requirements (Model–World Fit Constraints)

- Respect temporal validity: do not use information after the decision point.
- Map each feature to its source EKR element(s) and document span(s).
- Use terminology and constructs consistent with EKRs and case practice.
- Prefer interpretable transformations (counts, durations, gaps, rates).
- Provide calculations/definitions that are robust to missing or incomplete data.

Output Format per Feature

Field	Description
Feature Name	Descriptive title
Description	What the feature measures
Domain Justification	Why it matters in the domain

Calculation	How to compute it
Provenance	EKR element references + citations from knowledge base

[Files included as Context]

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