Supporting Systems Modeling Using Semantic Cues for Concept Development

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Motivation

- In high-tech industrial environments with low systems engineering capability [1], systems life cycle processes are often executed in an ad hoc manner, with **inadequate initial planning** and **limited stakeholder engagement** during the early phases.
- As a result, customer needs are prematurely translated into design activities without sufficient analysis, violating prescribed practices of ISO/IEC/IEEE 24748-1:2024.
- Systems engineering traditionally addresses this through **model-based approaches** for early-phase analysis [2]. *Yet, time and resource constraints limit tradespace exploration*, leading to **overlooked design alternatives** [3] and **critical gaps** in system definition [4].

Approach

- We reviewed literature on cognitive processes in engineering design, relevant systems engineering standards, and existing methods, tools, and potential solutions for addressing identified limitations. The goal was to **augment systems capability during modeling**.
- Based on our engineering objectives, we formulated the following null hypothesis (H_o):

  "The identification of system constructs that require extended cognitive processing has no significant effect on the completeness or the level of detail in system models."
- To test the hypothesis, we implemented a **knowledge graph search strategy** to extract semantically related terms from those used in the model, and **developed a tool** that presents them as interactive word cloud to support **concept exploration** and **refinement**.

Background

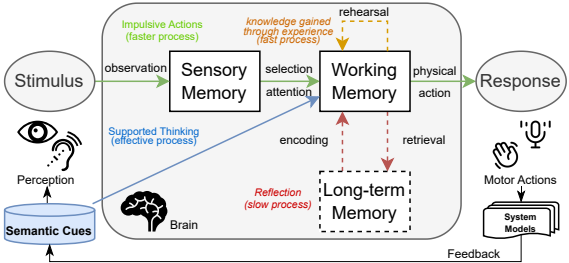

Figure: The role of semantic cues in information processing based on multi-store memory model [5].

Time Order of retrieval: 1) Recollecting Entities-Relationships, 2) Industry-specific Knowledge, 3) Acting without reflection, and 4) Semantic Cues.

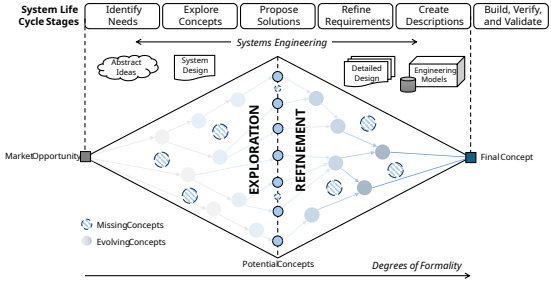

Figure: Systems engineering development lifecycle mapped with concept exploration and refinement.

Graph Search Strategy

Instead of relying on distributional models for semantic similarity, the proposed approach employs semantic networks grounded in lexical relationships between concepts to enhance traceability, interoperability, and predictability, essential for engineering design decisions.

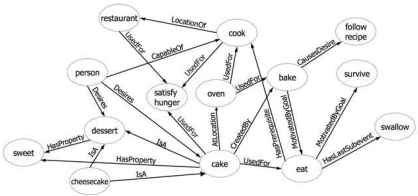

Figure: A visual representation of a sample query from ConceptNet knowledge base [6].

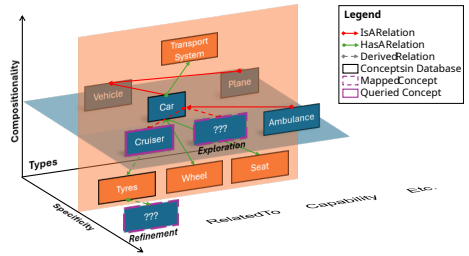

Figure: The organization of the concepts in a semantic network based on their degrees of compositionality and specificity.

Operational Definitions

Concept Exploration

Concept exploration is the phase in system development where candidate solutions evolve from low-level components toward higher-level system constructs, characterized by low specificity and an emphasis on identifying homologous components to inform architecture-level decisions.

Types: *holonyms, meronyms, hyponyms, hypernyms, polysemy, retronym, troponym, and synonym.*

Concept Refinement

Concept refinement is the phase in system development where system components are progressively detailed, with increased emphasis on specificity and the evaluation of quality attributes derived from analogous system constructs to support informed design decisions.

Types: *meronyms, hyponyms of meronyms, meronyms of hyponyms of meronyms, and other qualities.*

Examples

Demonstration: `https://draw.io/`

Analysis

- We **validate** the proposed approach using **25 soft system models** from different industries available through literature that **employ natural language** to informally structure concepts and highlight entities and relationships within complex systems.
- Each system model was recreated in draw.io, and its words and phrases were **processed** using the developed tool. This was followed by **manual selection** of candidate entities for potential inclusion in the model, categorized as either for **Expansion** or **Upscaling**.
- **Expansion** was defined as the proportion of context-relevant entities identified by the prototype that were absent from the original model but deemed important to the study's conclusions. **Upscaling** referred to the proportion of additional entities that could be inserted between existing nodes to **enhance structural clarity** and **reduce ambiguity**.

Results

We aggregated the data by year published, paper title, industry, entities, relationships, new entities, intermediate additions, graph sparsity, relative expansion, relative upscaling, and relative upscaling per edge, calculating the mean and standard deviation for each.

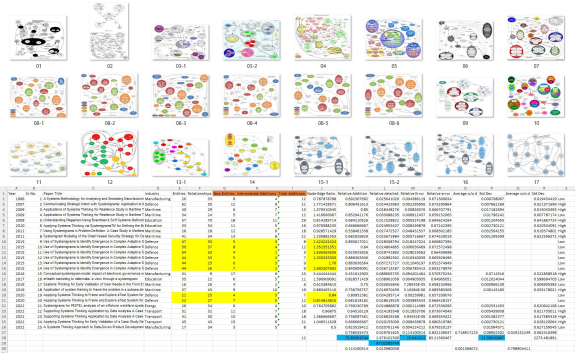

Figure: Screenshots of recreated system models in Draw.io with aggregated data in Excel.

Conclusion

- An **average addition of 24.15% entities** was observed with the application of the tool to the existing system models. The tool also enhanced edge detail by adding intermediate entities, resulting in a *15.5% overall increase*, with *average 2.98% more entities per edge*.
- An independent samples t-test yielded a low p-value (0.00137) for expansion criteria, leading to rejection of the null hypothesis and confirming *a significant effect of cognitive processing on model completeness*. Conversely, a high p-value (0.799) for upscaling means the null hypothesis cannot be rejected, indicating *no significant impact on level of detail*.
- Excluding defense industry data, which heavily used abbreviations, **reduced the relative standard deviation to 12.38%**, indicating improved precision, including for upscaling.
- Graph sparsity significantly affects the methodology's effectiveness, implying it **struggles to replicate human cognitive ability** on connections rather than entity listing. As a result, expert systems engineers may find the tool less useful than beginners.

Future Work

- Systems engineering has traditionally emphasized technical challenges, with **limited attention to human factor**. As intelligent methods integrate with MBSE, exploring solutions that **bridge engineering and cognitive processes** grows increasingly critical.
- The tool's semantic support is limited by ConceptNet's **lack of engineering-specific vocabulary**. Integrating **structured ontologies** and **domain-specific knowledge** bases is essential to improve semantic accuracy and model usability for engineering workflows.
- **Real-world validation** with industry professionals in organizational settings, along with **enhancements** like collaborative tagging and retrieval-augmented generation, will improve interpretability, domain adaptation, and scalability. **Aligning with user cognition** and supporting problem-solving and workflow efficiency remain essential.

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Thank you!