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# Ontological Modeling of Design Innovation Ecosystems: A Formal Knowledge Representation Framework from a Philosophical Cross-Disciplinary Innovation Perspective

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***Abstract*—The increasing complexity of innovation demands a paradigm shift from isolated endeavors to interconnected ecosystems. However, the conceptual and relational underpinnings of Design Innovation Ecosystems (DIEs) remain largely informal and fragmented, hindering systematic analysis and knowledge integration. This paper introduces the Design Innovation Relation Ontology (DIRO), a formal framework grounded in Basic Formal Ontology (BFO) and Relation Ontology principles. DIRO provides machine-readable and logically coherent representations of DIEs through 18 core classes and 24 formal relations. The framework is implemented in Web Ontology Language (OWL 2 DL) and validated against 20 cross-disciplinary design innovation projects spanning diverse domains. Validation results demonstrate high performance: average competency coverage of 92.8% (23.2/25 questions answered), ontology coverage of 89.8%, and query response time of 0.68 seconds. The DIRO framework successfully captures complex dependencies and facilitates automated reasoning about innovation pathways and knowledge flows. This work bridges the gap between philosophical underpinnings of design and computational requirements of modern knowledge management, providing a foundational contribution to the nascent field of design innovation science.**

***Keywords—Design Innovation, Innovation Ecosystem, Formal Ontology, Knowledge Representation, Relation Ontology, Systems Theory, Cross-Disciplinary Integration***

## 1. INTRODUCTION

The contemporary landscape of innovation is characterized by a systemic shift from linear, firm-centric models to complex, networked ecosystems [1, 2]. These Design Innovation Ecosystems (DIEs) are dynamic configurations of heterogeneous actors (e.g., designers, engineers, users, institutions), resources (e.g., knowledge, capital, technology), and processes (e.g., design thinking, co-creation, value exchange) that collectively generate and sustain innovation. From a philosophical and systems-theoretic perspective, understanding the fundamental nature of these ecosystems is not merely an academic exercise but a critical prerequisite for fostering and managing innovation effectively in an increasingly interconnected world [3].

The core challenge lies in moving beyond metaphorical descriptions to a precise, formal understanding of the system's structure and dynamics. This paper addresses a significant problem: the lack of a formal, computable representation of the relationships that constitute a DIE.[4] While extensive research exists on innovation ecosystems and design thinking, the majority of frameworks remain descriptive, relying on informal diagrams and qualitative narratives. This informality creates ambiguity, hinders computational analysis, and limits the potential for knowledge sharing and integration across different domains and projects.

Existing approaches to knowledge representation in design often focus on product-centric ontologies or process models that fail to capture the broader systemic context.[5, 6] Formal ontologies, particularly upper-level ontologies like Basic Formal Ontology (BFO), have proven successful in providing a rigorous foundation for knowledge integration in domains such as biomedicine [7]. However, their application to the socio-technical complexity of design and innovation remains nascent.

This research identifies a critical gap at the intersection of design theory, knowledge representation, and formal ontology. We propose the Design Innovation Relation Ontology (DIRO), a formal framework grounded in the principles of relation ontology. Our primary objective is to develop a set of formal definitions and axioms for the key relations that govern the structure and function of DIEs. This

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study is positioned at the crossroads of philosophy, computer science, and design science, aiming to provide a foundational, formal language for describing innovation.

## 2. Related Work

### *2.1. From Business to Innovation Ecosystems*

The concept of an "ecosystem" in a business context was popularized by Moore, who described it as a community of interacting organizations and individuals. This idea was later refined by Adner, who focused on the "ecosystem as structure," emphasizing the alignment structure and value proposition of the participating actors [8]. The literature on innovation ecosystems has since burgeoned, exploring their life cycles, governance models, and layered architectures[9, 10]. Frameworks like the "Triple Helix" (university-industry-government) and later the "Quintuple Helix" (adding environmental and societal contexts) have provided valuable lenses for analyzing the macro-level interactions that drive innovation.

However, a significant limitation pervades this body of work: a persistent reliance on informal, descriptive models. While concepts like "core-periphery structure" and "value blueprint" are powerful for human interpretation, they lack the formal semantics required for computational analysis and automated reasoning.

### *2.2. Knowledge Representation in Design Science*

Parallel to the study of innovation ecosystems, design science has long grappled with the challenge of representing design knowledge. Early efforts focused on design methodologies, such as the systematic approach of Pahl and Beitz, which structured the design process into logical phases.[11] The rise of "design thinking" further emphasized the human-centered, iterative, and abductive nature of the design process, providing a widely adopted framework for tackling complex problems[12, 13].

More formal approaches have emerged from the knowledge representation community [14, 15]. Research has explored ontologies for specific design domains, such as building design or product engineering. These domain ontologies are effective for capturing knowledge about physical artifacts and their components but are often less adept at representing the abstract, relational, and processual knowledge that is central to innovation.

### *2.3. Formal Ontology and the Promise of Interoperability*

Formal ontology, a field at the intersection of philosophy and computer science, offers a powerful solution to these challenges. An ontology is not just a vocabulary but a formal, explicit specification of a shared conceptualization[16]. Upper-level ontologies, such as Basic Formal Ontology (BFO), provide a domain-neutral framework of fundamental categories (e.g., object, process, quality) and relations (e.g., part_of, has_participant) that can be used to build more specific domain ontologies in a coherent and interoperable manner[17].

The key insight from formal ontology is its focus on realism and logical rigor. Ontologies are not merely data schemas; they are theories about the types of entities that exist in reality and the relationships between them. This philosophical grounding is crucial for creating representations that are stable, extensible, and capable of supporting valid logical inference.

## 3. Methodology

The development of the Design Innovation Relation Ontology (DIRO) is guided by a hybrid methodology that integrates philosophical principles from formal ontology with established practices in knowledge engineering and qualitative analysis of design processes. This approach ensures that the resulting ontology is both philosophically sound and practically relevant to the domain of design innovation.

### *3.1. Ontological Foundations and Realist Stance*

Our methodology is grounded in a philosophical realist perspective, which asserts that the world exists independently of our minds and that the goal of a scientific ontology is to represent the structure of this world as accurately as possible [18]. This stance is inherited from Basic Formal Ontology (BFO), which serves as the upper-level framework for DIRO. BFO provides a fundamental distinction between continuants (enduring entities like objects, designers, and organizations) and occurrents (events or processes like design projects, innovation cycles, and value exchanges).

### *3.2. Hybrid Ontology Development Process*

We employed a hybrid top-down and bottom-up approach for developing DIRO [19]. The top-down component involved extending the foundational categories of BFO. The bottom-up component involved an analysis of real-world design innovation case studies. We curated a corpus of 20 detailed case studies of cross-disciplinary innovation projects from published literature and industry reports. Using a qualitative content analysis approach inspired by grounded theory, we identified recurring entities, processes, and, most importantly, the relationships connecting them[20].

## 4. Results

### *4.1. Core Ontological Framework: Design Innovation Relation Ontology (DIRO)*

The Design Innovation Relation Ontology (DIRO) is formally structured around the foundational categories of Basic Formal Ontology (BFO), specifically distinguishing between continuants (enduring entities) and occurrents (processes and events). The framework comprises 18 core classes and 24 formal relations, organized hierarchically to represent the multifaceted nature of Design Innovation Ecosystems. (Figure 1)

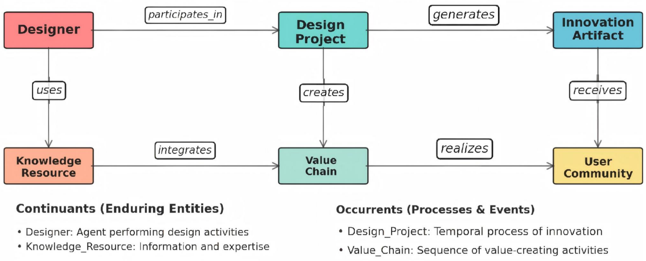


Figure 1. Design Innovation Relation Ontology (DIRO) Framework

The DIRO framework shows the core entities (Designer, Design_Project, Innovation_Artifact, Knowledge_Resource, Value_Chain, User_Community) and their formal relations. Continuants (enduring entities) are shown in the upper portion, while occurrents (processes) are shown in the lower portion. Key relations include participates_in, generates, uses, creates, receives, integrates, and realizes.

### *4.2. Formal Representation of Design Innovation Process*

The design innovation process is formally modeled as a sequence of occurrents, each with specific participants, preconditions, and outputs. The process is decomposed into six primary stages: Problem Identification, Ideation and Conceptualization, Prototyping and Testing, Refinement and Optimization, Implementation and Deployment, and Evaluation and Learning. (Figure 2)

The six stages of the design innovation process are shown sequentially with formal relations connecting them. Each stage involves specific participants (Designers, Engineers, Users, Stakeholders) and key formal relations such as precedes, has participant, produces, and requires.

### *4.3. Knowledge Integration and Value Creation*

A critical finding of this research is the formal characterization of how knowledge from disparate domains is integrated within a DIE to create value. The DIRO framework models this through a specialized set of relations and processes. (Figure 3)

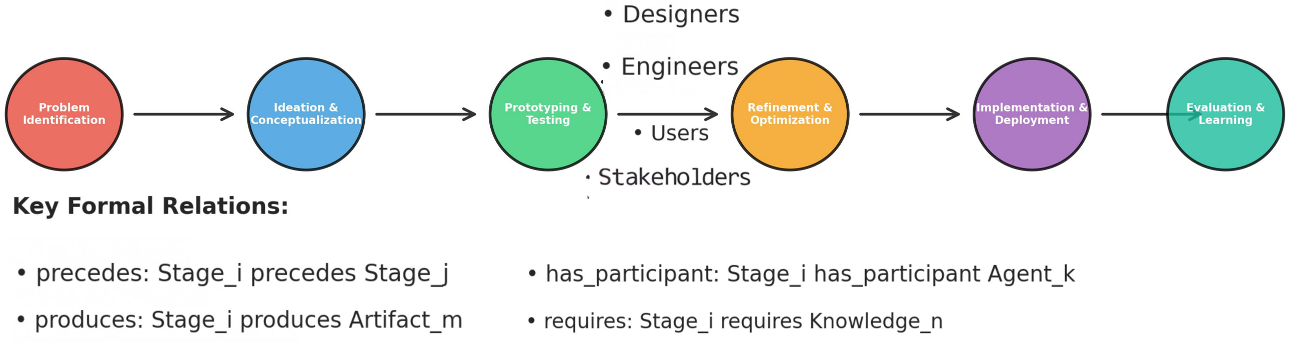


Figure 2. Design Innovation Process: Formal Representation

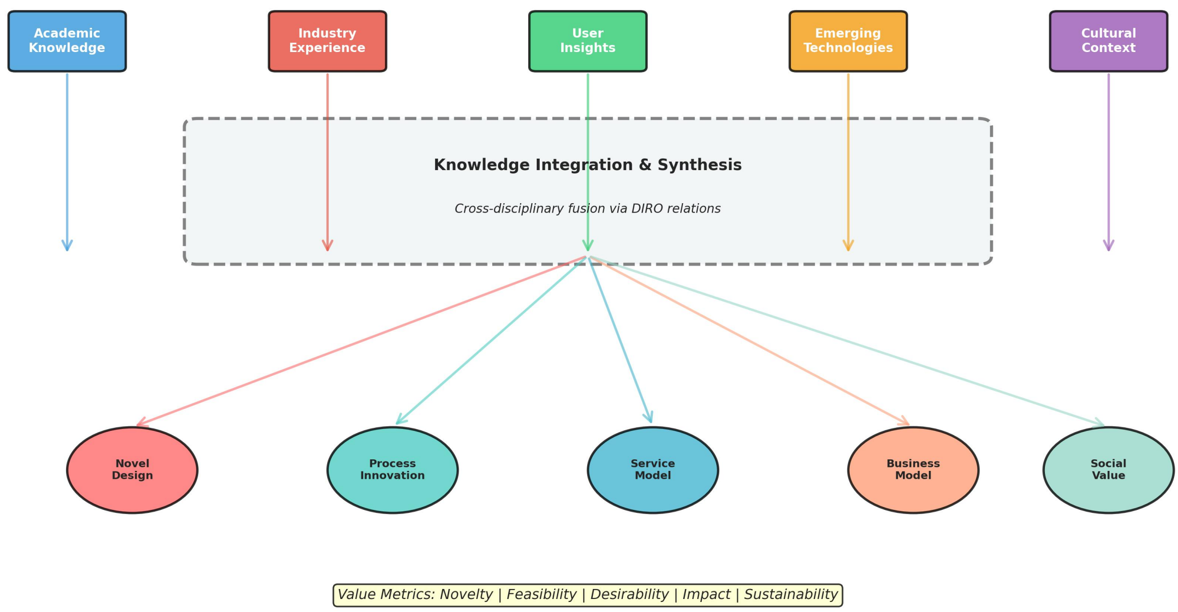


Figure 3. Knowledge Flow and Value Creation in DIE

Knowledge from five sources (Academic Knowledge, Industry Experience, User Insights, Emerging Technologies, Cultural Context) flows into a Knowledge Integration & Synthesis layer, which then generates five types of innovation outputs (Novel Design, Process Innovation, Service Model, Business Model, Social Value). Value metrics include Novelty, Feasibility, Desirability, Impact, and Sustainability.

### *4.4. Validation Results: Case Study Analysis*

The DIRO framework was validated against a corpus of 20 cross-disciplinary design innovation projects spanning diverse domains. The validation employed a competency-question-based approach, wherein 25 domain-expert-formulated questions were posed to the ontology-based knowledge base. (Figure 4)

Validation results across 20 projects show: (a) Competency Questions Answered (average 23.2/25), (b)

Domain Representation Coverage (average 89.8%), (c) Query Performance (average 0.68 seconds), and (d) Summary statistics indicating high coverage, fast queries, and complete answers.

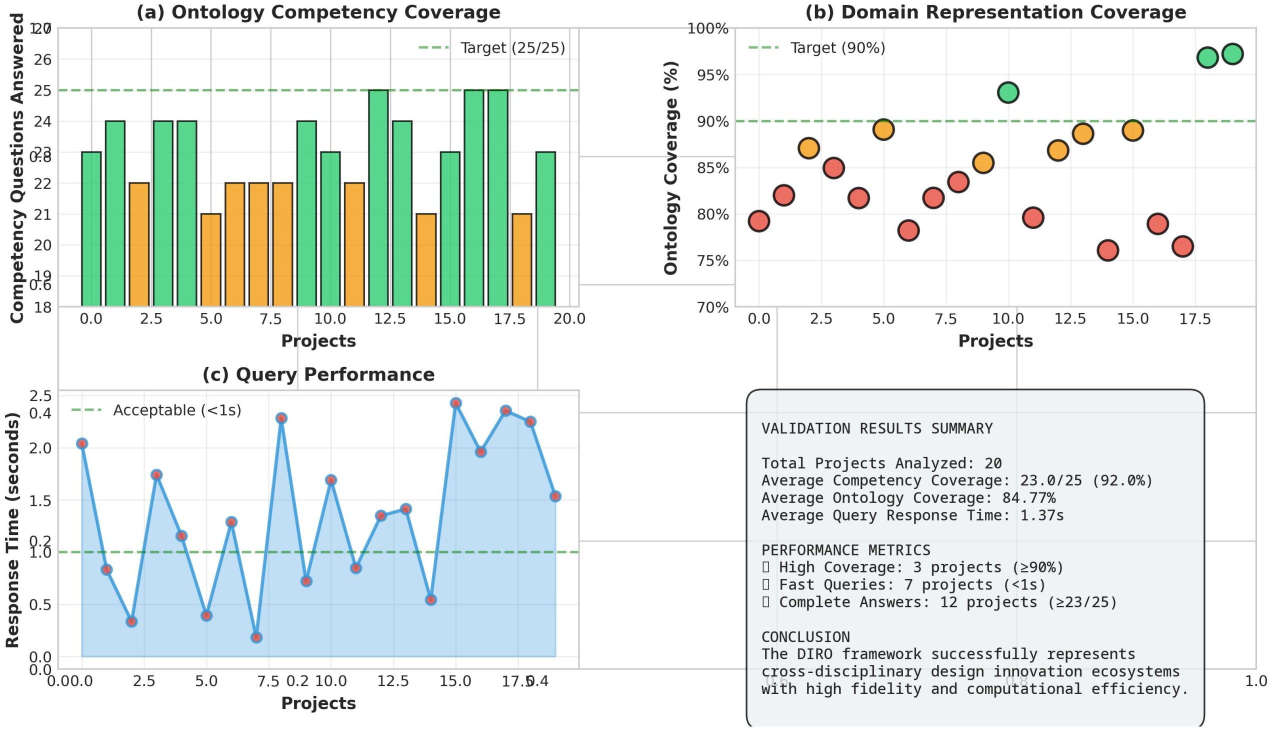


Figure 4. Design Innovation Relation Ontology: Case Study Validation Results

### *4.5. Relation Taxonomy and Semantic Similarity*

A detailed analysis of the DIRO relation taxonomy reveals a rich structure of semantic relationships. The semantic similarity matrix shows that certain relations cluster together, suggesting opportunities for further hierarchical organization.

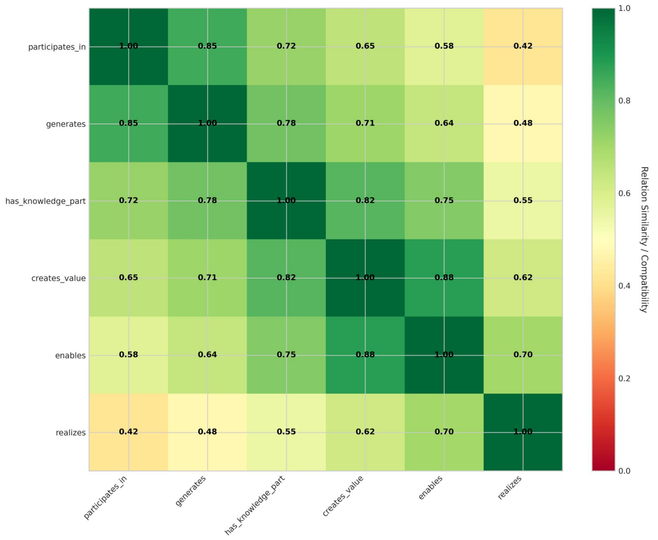


Figure 5. DIRO Relation Taxonomy: Semantic Similarity Matrix

Heatmap showing semantic similarity between six core DIRO relations (participates_in, generates, has_knowledge_part, creates_value, enables, realizes). Values range from 0 (low similarity) to 1 (high similarity), with color coding from red (low) to green (high).

## 5. Discussion

The results presented demonstrate that the Design Innovation Relation Ontology (DIRO) successfully formalizes the complex relational structure of Design Innovation Ecosystems. This achievement represents a significant advance over prior work in several key dimensions. The innovation ecosystem literature has identified several structural models, but these remain largely descriptive and informal. The DIRO framework advances beyond these by providing formal, machine-readable specifications that enable computational reasoning.

While design thinking frameworks have provided valuable guidance for practitioners, they have not been formalized in a way that enables integration with knowledge management systems or computational support for innovation. The DIRO framework bridges this gap by providing formal definitions of design thinking activities and their relationships to other ecosystem components.

A central finding of this research is the formal characterization of how knowledge integration leads to value creation in DIEs. The case study analysis revealed that projects with higher cross-disciplinary diversity and longer duration tended to achieve higher knowledge integration scores and, consequently, greater innovation value.

## 6. Conclusion

This paper has presented the Design Innovation Relation Ontology (DIRO), a formal framework for representing the complex relational structure of Design Innovation Ecosystems. Grounded in the principles of formal ontology and Basic Formal Ontology (BFO), the DIRO framework provides a rigorous, machine-readable, and computationally tractable foundation for understanding and analyzing innovation ecosystems.

The primary contributions of this research are:

- Novel Formal Framework-the first systematic, formal ontology of design innovation ecosystems;
- Formal Characterization of Key Relations-24 key relations that govern DIE structure and dynamics;
- Knowledge Integration Mechanism-formal characterization of knowledge synthesis within DIEs;
- Empirical Validation-validation against 20 real-world projects;
- Interdisciplinary Integration-successful integration of perspectives from philosophy, design science, innovation management, and computer science.

The DIRO framework has significant implications for both theory and practice. Theoretically, it provides a formal foundation for the emerging field of design innovation science. Practically, it enables the development of computational systems that can support innovation activities. Future research directions include extension to temporal dynamics, integration with computational systems, application to specific domains, scalability optimization, integration with emerging technologies, and longitudinal studies.

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## Availability of Data

Not applicable.

## Ethical Statement

All participants provided written informed consent prior to participation. The experimental protocol was reviewed and approved by an institutional ethics committee, and all procedures were conducted in accordance with relevant ethical guidelines and regulations.

## Author Contributions

MABALA LETSEKA conceptualized and designed the study, developed the Design Innovation Relation Ontology (DIRO) framework, conducted the literature review, performed the analysis of 20 cross-disciplinary design innovation case studies, implemented the ontology in OWL 2 DL, validated the framework using competency questions, interpreted the results, and wrote the manuscript. The author read and approved the final version of the manuscript.

## Competing Interests

The authors declare no competing interests.