

VISOOnto: Semantic and Context-Aware Socialization of Objects in the Social Internet of Things based on Digital Twins

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ABSTRACT

The Social Internet of Things (SIoT) enables heterogeneous devices to autonomously establish social relationships in intelligent environments. Existing relationship recommendation approaches, however, rely predominantly on structural interaction analysis and trust propagation, providing limited support for contextual interpretation and compatibility assessment. This work presents VISOOnto, a semantic-enhanced approach that integrates ontology-based inference, Digital Twins, Organizational Network Analysis (ONA), and graph-based interaction analysis to support context-aware relationship recommendation in SIoT environments. Extending the VISO ecosystem, VISOOnto employs OWL reasoning and SWRL rules to derive compatibility evidence from contextual conditions, device capabilities, operational constraints, trust attributes, and organizational roles, allowing semantic knowledge to actively influence recommendation decisions. VISOOnto was evaluated in a real smart office environment composed of heterogeneous devices operating under continuous interaction conditions. Comparative experiments against VISO demonstrated improvements of 25.3% in Semantic Recommendation Precision and 22.9% in Contextual Consistency Rate, with statistically significant gains in recommendation quality and contextual compatibility. The results demonstrate that semantic inference modifies recommendation outcomes beyond what can be achieved through structural interaction analysis alone. By transforming ontologies from passive knowledge representations into active decision mechanisms, VISOOnto advances adaptive and context-aware relationship management in heterogeneous SIoT environments.

KEYWORDS

Social Internet of Things, Digital Twins, Semantic Web, Ontologies, Relationship Recommendation.

1 INTRODUCTION

The widespread adoption of Internet of Things (IoT) infrastructures has significantly increased the number of interconnected devices operating in smart homes, industrial systems, and ubiquitous computing environments [1]. In this context, the Social Internet of Things (SIoT) extends the IoT paradigm by enabling devices to autonomously establish and manage social relationships that support service discovery, collaboration, and coordination among heterogeneous objects [7, 16].

Relationship recommendation has consequently become a fundamental component of SIoT environments. Most existing approaches rely on graph topology, trust propagation, and interaction metrics to identify influential devices and establish new connections [9]. Although effective in identifying structurally relevant objects, these mechanisms provide limited support for incorporating contextual information and operational constraints into decision-making processes [11]. As a result, devices occupying central positions in the interaction graph are not necessarily the most suitable candidates for collaboration under specific operating conditions.

Ontologies provide a formal mechanism for representing contextual information, device capabilities, and interaction constraints while supporting inference processes capable of identifying implicit relationships and semantic compatibilities [13]. Combined with Digital Twins, which maintain synchronized virtual representations of physical entities [6], semantic reasoning enables relationship establishment decisions to exploit contextual evidence beyond structural interaction analysis. Despite these advances, existing SIoT solutions rarely employ ontology-driven inference as an active component of recommendation generation. From a Semantic Web perspective, this integration transforms semantic representations from interoperability resources into actionable knowledge for context-aware decision making in Web-connected environments.

Earlier work presented a conceptual model for autonomic SIoT relationships [4]. This research line was subsequently instantiated in VISO [3], which integrated Digital Twin virtualization, trust propagation, friendship recommendation, and Organizational Network Analysis (ONA) within a unified ecosystem. Large-scale simulations involving 250 objects showed that approximately 7% of the devices concentrated nearly 60% of the relationships established in

the ecosystem. While these results demonstrated the effectiveness of structural mechanisms for identifying socially influential objects, they also revealed that structural prominence alone does not ensure contextual suitability for collaboration.

To overcome this shortcoming, this work proposes VISOOnto, a semantic-driven approach for relationship management in the Social Internet of Things. VISOOnto extends VISO by incorporating ontology-driven inference into recommendation generation, allowing inferred contextual knowledge to actively influence relationship establishment decisions. The proposed ecosystem combines semantic reasoning, Digital Twin virtualization, structural interaction analysis, and Organizational Network Analysis to support context-aware friendship recommendation. Its effectiveness is evaluated in a real smart office environment composed of heterogeneous devices operating under continuous interaction conditions.

The main contributions of this work are: (i) an ontology-driven recommendation model capable of generating compatibility knowledge from contextual evidence in SIoT environments; (ii) the integration of ontology-based inference with Digital Twin virtualization and Organizational Network Analysis mechanisms; (iii) a recommendation strategy combining structural interaction metrics with inferred semantic compatibility; and (iv) an experimental evaluation demonstrating that ontology-driven inference improves recommendation quality under real operating conditions.

The remainder of this paper is organized as follows. (1) Section 2 presents the related work and research gap; (2) Section 3 describes the VISOOnto approach and recommendation workflow; (3) Section 4 details the experimental methodology and evaluation strategy; (4) Section 5 presents and discusses the experimental results; and (5) Section 6 concludes the paper and outlines future work.

2 BACKGROUND AND RELATED WORK

An updated literature search was conducted based on the review protocol defined in [15]. The previous systematic review covered publications from 2017 to 2023, identifying 30 studies that met its selection criteria, of which five were directly aligned with its research questions. To avoid overlap and extend that analysis, the present review was restricted to peer-reviewed publications from 2024 to 2026. The search covered ACM, IEEE, Scopus, Springer, and Web of Science through the CAPES CAFE portal, focusing on SIoT relationship recommendation, semantic reasoning, context-aware recommendation, trust management, knowledge graphs, and Digital Twins. The updated search retrieved 200 academic records, from which the studies most directly related to the research problem were selected for comparative analysis.

Recent SIoT recommendation approaches increasingly combine trust, contextual information, and learned representations. Kheloufi et al. [10] combine latent-feature mining and trust aggregation for SIoT recommendation, while recent context-aware approaches incorporate device, service, and interaction information into recommendation models [12]. A recent survey identifies context-dependent information and inference capabilities as open aspects of trust-based SIoT recommendation [2]. These approaches highlight the

importance of trust and context, but generally encode such information through learned features or trust models rather than explicit semantic constraints.

Semantic approaches provide a complementary perspective. Ruta et al. [17] integrate Semantic Web of Things and SIoT through ontology-based representation and reasoning, supporting dynamic social relationships and trust-aware adaptation. Knowledge-graph approaches similarly exploit inferred semantic relations for recommendation and explainability [5, 8]. These results demonstrate that semantic inference can contribute to recommendation and relationship management; however, the reviewed approaches address different decision targets and provide limited evidence of an explicit, auditable mechanism in which inferred semantic facts directly modify SIoT relationship recommendations.

Digital Twins provide persistent representations of physical objects, their states, capabilities, and contextual information. However, the recent literature does not establish a unified mechanism that jointly combines Digital-Twin state, structural relationship relevance, trust, contextual constraints, organizational information, and ontology-derived compatibility.

An important evolution within this research line is represented by VISO [3], OntoVISO [14], and VISOOnto. VISO established the infrastructure for interactions and relationship management among SIoT objects, including friendship recommendation based on structural evidence such as PageRank and Organizational Network Analysis (ONA). OntoVISO subsequently introduced an ontology-based semantic model to represent SIoT entities, relationships, and business rules. VISOOnto advances this progression from semantic representation to semantic inference, incorporating inferred compatibility and constraint information as an active component of the recommendation process.

Thus, the relevant gap is not the isolated use of ontologies, trust, context, or Digital Twins, which are increasingly explored individually or in partial combinations. Rather, comparatively few approaches provide an explicit decision path in which semantic inference derives compatibility or incompatibility facts that directly influence relationship recommendations while structural relevance, trust, contextual constraints, organizational information, and Digital-Twin state are jointly considered. VISOOnto addresses this gap by integrating these evidence sources into a semantic recommendation mechanism, as summarized in Table 1.

Table 1: Comparison of recent approaches for SIoT relationship management and recommendation.

Approach	Year	SL	DT	TM	CA	RR	SDI	ONA
VISO: Autonomous SIoT Interactions [3]	2024	-	✓	✓	△	✓	-	✓
Internet of Conscious Things [17]	2024	✓	-	✓	✓	✓	✓	-
Feature + Trust Recommendation [10]	2024	-	-	✓	△	✓	-	-
Knowledge-Graph Recommendation [5]	2025	✓	-	△	△	✓	✓	-
OntoVISO: Semantic Model for SIoT [14]	2026	✓	✓	-	✓	✓	-	-
Context-Aware SIoT [12]	2026	-	-	-	✓	✓	-	-
VISOOnto (this work)	2026	✓	✓	✓	✓	✓	✓	✓

Legend: ✓: fully supported; △: partially supported; -: not supported. SL: Semantic Layer; DT: Digital Twin; TM: Trust Management; CA: Context-Aware; RR: Relationship Recommendation; IR: Inference-driven Recommendation; ONA: Organizational Network Analysis.

The comparison indicates that recent studies increasingly combine semantic, contextual, trust, and recommendation mechanisms, but their integration remains partial. In contrast, VISOOnto treats

semantic inference as an explicit decision component for refining SIoT relationship recommendations. The next section presents the VISOnto architecture and details how structural, contextual, trust, organizational, and semantic evidence are combined in the recommendation process.

3 VISOONTO APPROACH

This section presents VISOnto, a semantic-driven approach for relationship management in SIoT environments. VISOnto extends the VISO ecosystem by incorporating ontology-driven inference into the recommendation process, allowing contextual knowledge to actively influence relationship establishment decisions.

3.1 Architectural Overview

Figure 1 show the proposed architecture, organized into three integrated layers: *Smart Environment*, *Digital Twin*, and *Data Handling*.

The *Smart Environment* layer comprises heterogeneous devices interconnected through an IoT middleware responsible for communication and event synchronization. In the *Digital Twin* layer, each physical device is represented by a semantic *Virtual Object* encapsulating capabilities, contextual attributes, and interaction information independently of the underlying technology.

The *Data Handling* layer integrates persistence, semantic processing, and recommendation mechanisms. Interaction histories, trust values, contextual attributes, and recommendation outcomes are maintained by the *VISO-Based API for Structured Storage* (VISO-BASS), while the *VISOnto* ontology formalizes contextual entities, trust relationships, social circles, operational constraints, and recommendation rules.

Unlike VISO, where recommendations rely primarily on structural interaction evidence, VISOnto incorporates ontology-driven inference into the *Relationship Recommendation Engine*. Structural relevance derived from interaction analysis is therefore complemented by semantic evidence obtained from contextual reasoning. Consequently, recommendation decisions consider not only social relevance but also contextual coherence and operational feasibility.

3.2 Ontology Engineering Process

The VISOnto ontology was designed to support recommendation decisions in situations where structural interaction evidence alone is insufficient to determine contextual suitability. Its specification was guided by Competency Questions derived from the research objectives, including the identification of contextually compatible devices, verification of operational constraints, detection of complementary capabilities, validation of trust requirements, and exclusion of semantically incompatible recommendations.

The conceptual model formalizes the entities required for SIoT relationship management, including *VirtualObject*, *Interaction*, *Skill*, *Constraint*, *Environment*, *SocialCircle*, *TrustMetric*, *ONARole*, and *Recommendation*. These concepts are connected through semantic properties describing capabilities, environmental restrictions, trust relationships, and organizational characteristics.

Unlike purely descriptive semantic models, VISOnto employs OWL reasoning and SWRL rules to derive implicit knowledge from explicitly asserted facts. Devices sharing contextual conditions and

complementary capabilities can therefore be automatically identified as semantically compatible, even when such relationships are not directly observable from interaction data.

The following rule exemplifies compatibility inference during recommendation generation. The trust threshold employed by the ontology is domain-dependent and may vary according to the characteristics, risk tolerance, and interaction policies of each SIoT environment. In the smart office scenario evaluated in this work, a threshold of 0.7 was adopted to represent sufficiently reliable interaction histories, as defined by the environment manager, enabling the distinction between highly trusted candidates and weakly supported associations.

$$\begin{aligned}
 &VirtualObject(?i) \wedge VirtualObject(?j) \wedge \\
 &hasEnvironment(?i, ?e) \wedge hasEnvironment(?j, ?e) \wedge \\
 &requiresSkill(?i, ?s) \wedge hasSkill(?j, ?s) \wedge \\
 &hasTrustValue(?j, ?t) \wedge swrlb:greaterThan(?t, 0.7) \wedge \\
 ¬ConflictingConstraint(?i, ?j) \\
 &\rightarrow CompatibleWith(?i, ?j)
 \end{aligned} \tag{1}$$

In Eq. 1, $?i$ denotes the requester *VirtualObject* and $?j$ the potential provider. The variable $?e$ represents the environment in which both objects operate, $?s$ corresponds to a skill or capability required by the requester and offered by the provider, thereby expressing operational complementarity, and $?t$ denotes the trust score associated with the candidate provider. The trust threshold is domain-dependent and may be adjusted by the environment manager according to local interaction policies and risk tolerance.

The rule infers compatibility from four complementary dimensions: shared environments, operational complementarity, configurable trust requirements, and the absence of conflicting constraints. As a result, VISOnto derives compatibility evidence that is not explicitly represented in the interaction graph.

This inferred evidence actively influences recommendation generation. Structurally prominent candidates may be discarded when contextual restrictions invalidate potential collaborations, whereas devices with moderate structural relevance may be recommended when semantic reasoning reveals compatible capabilities and conditions. Therefore, VISOnto operationalizes ontology-driven inference as a decision mechanism capable of modifying recommendation outcomes, providing the semantic basis for the improvements reported in Section 5.

3.3 Semantic Model

The VISOnto semantic model operationalizes the concepts identified during ontology specification by representing the entities, relationships, and constraints required for recommendation generation. The model captures contextual, social, and operational knowledge that cannot be fully represented through interaction graphs alone.

VISOnto formalizes *VirtualObjects*, *Interactions*, *Skills*, *Constraints*, *Environments*, *SocialCircles*, *TrustMetrics*, *ONARoles*, and *Recommendations*. These concepts are linked through semantic properties describing capabilities, contextual dependencies, operational restrictions, trust relationships, and organizational characteristics.

Rather than serving solely as a representation layer, the semantic model provides the evidence required by the recommendation process. Explicit assertions describing environments, capabilities, trust values, and operational constraints are combined through

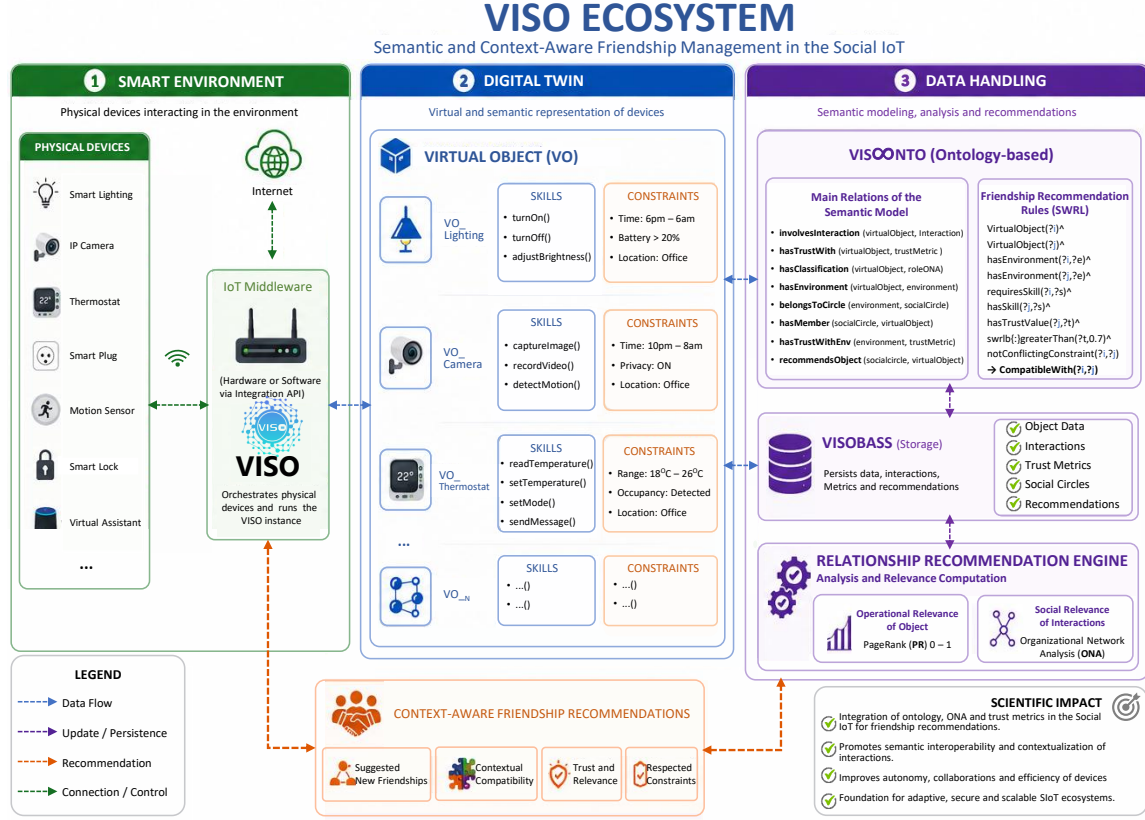


Figure 1: VISOnto architecture integrating semantic reasoning, Digital Twins, and ONA.

OWL reasoning and SWRL rules to infer compatibility relationships among devices. Consequently, recommendation decisions are guided not only by structural interaction relevance but also by contextual evidence derived from the semantic model.

This distinction is central to VISOnto: while interaction graphs reveal how devices are connected, the ontology explains whether these relationships are contextually appropriate for collaboration.

3.4 Recommendation Workflow

Relationship recommendation in VISOnto follows a three-stage process. First, interaction graphs are analyzed using PageRank and Organizational Network Analysis to identify socially relevant devices according to their structural roles and interaction patterns.

Second, candidate relationships are evaluated through ontology-driven inference. Structural evidence obtained from interaction analysis is combined with compatibility evidence inferred from the ontology, allowing recommendation decisions to simultaneously consider social relevance and contextual suitability. Contextual restrictions, operational capabilities, environmental conditions, trust attributes, and organizational roles are processed through OWL reasoning and SWRL rules to infer compatibility relationships among devices. The recommendation process can be expressed as:

$$R(d_i, d_j) = f(S(d_i, d_j), C(d_i, d_j)), \quad (2)$$

where $S(d_i, d_j)$ represents the structural evidence obtained from interaction analysis, including PageRank, Organizational Network Analysis indicators, and trust propagation, whereas $C(d_i, d_j)$ denotes the compatibility evidence inferred through semantic reasoning over the contextual knowledge represented in VISOnto.

VISOnto operates as a semantic refinement mechanism over structurally generated candidates. Recommendations are generated according to:

$$R(d_i, d_j) = \begin{cases} 1, & S(d_i, d_j) > \tau_s \wedge C(d_i, d_j) = \text{true}, \\ 0, & \text{otherwise}, \end{cases} \quad (3)$$

where τ_s denotes the minimum structural relevance threshold.

A practical example from the smart office environment illustrates this decision process. The relationship between the *Notebook* and the *SmartTV* satisfies both conditions in Eq. 3: the pair exhibits high structural relevance ($S > \tau_s$), shares the same environment, presents complementary multimedia capabilities, and satisfies the trust requirements represented in the ontology ($\text{Trust} = 0.86$). Consequently, VISOnto preserves the recommendation.

Conversely, a candidate relationship involving the *Webcam* and the *SmartTV* may also satisfy the structural relevance threshold and trust requirements ($\text{Trust} = 0.81$), leading VISO to recommend the relationship. However, VISOnto rejects this recommendation because ontology-driven inference identifies operational restrictions associated with video capture and privacy constraints that

invalidate the contextual compatibility conditions required for collaboration.

These examples illustrate that inferred semantic evidence serves both to preserve contextually coherent recommendations and to prevent structurally relevant but operationally inappropriate relationships. The resulting workflow combines graph-based relevance and ontology-driven inference to refine recommendation outcomes beyond what can be achieved through structural interaction analysis alone, thereby operationalizing contextual knowledge as an active decision component in SIoT relationship management.

4 EXPERIMENTAL METHODOLOGY

This section describes the methodology adopted to evaluate VISOnto under real operating conditions. The evaluation investigates the impact of ontology-driven reasoning on recommendation quality, contextual consistency, and social organization in SIoT environments.

4.1 Experimental Setup

The evaluation was conducted in a physical smart-office testbed under continuous operating conditions, composed of 13 interconnected devices distributed across four functional categories: *Lighting*, *Computing*, *Audio and Video*, and *Printing*. The infrastructure includes laptops, smartphones, webcams, microphones, smart TVs, soundbars, printers, smart lighting devices, and virtual assistants interconnected through heterogeneous communication services. The environment extends the infrastructure adopted in VISO, enabling a controlled comparison between structural and ontology-driven recommendation strategies [3].

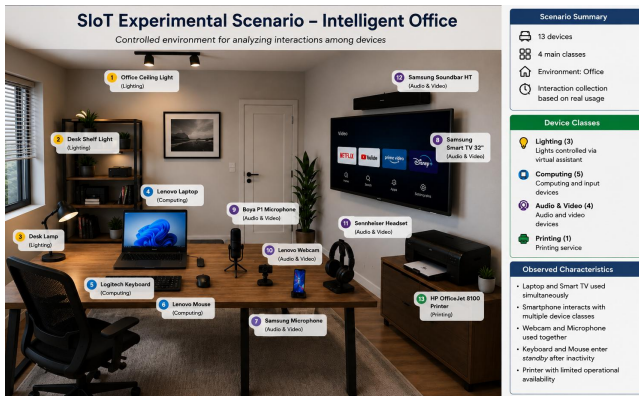


Figure 2: Heterogeneous smart office SIoT environment.

Figure 2 illustrates the experimental environment. The scenario includes devices with distinct operational roles supporting multimedia sharing, sensing, environmental control, user assistance, and peripheral services.

Interaction events were continuously monitored and persisted through VISO-BASS. The collected dataset includes device identifiers, timestamps, interaction categories, service requests, trust evaluations, contextual constraints, and recommendation outcomes.

Contextual information describing capabilities, environmental conditions, operational restrictions, organizational roles, and trust relationships was instantiated in the ontology and processed through OWL reasoning and SWRL rules.

The experimental design compares two recommendation scenarios executed under identical operating conditions. The baseline scenario employs the original VISO recommendation strategy, which relies on structural interaction analysis, trust propagation, and Organizational Network Analysis. The second scenario incorporates the ontology-driven reasoning mechanisms introduced by VISOnto. Consequently, the primary experimental variable corresponds to the inclusion of inferred semantic evidence during recommendation generation, while the underlying infrastructure, interaction traces, trust propagation mechanisms, and communication conditions remain unchanged.

Recommendations generated by both approaches were derived from the same interaction histories and evaluated using identical execution windows. In practical terms, VISO establishes relationships according to structural relevance and trust evidence, whereas VISOnto applies an additional semantic validation stage capable of preserving, refining, or rejecting candidate relationships based on contextual compatibility inferred from the ontology. This design enables the observed differences to be attributed specifically to ontology-driven inference rather than to variations in device behavior or environmental conditions.

Unlike simulation-based evaluations commonly adopted in SIoT research, all experiments were conducted under real operating conditions through repeated interaction cycles. This configuration enables the observation of recommendation behavior, contextual compatibility, trust propagation, and social organization dynamics while assessing the contribution of ontology-driven reasoning to relationship management.

It is important to note that the real-world experiments complement previous large-scale simulation studies conducted during the development of VISO using the SeSAM agent-based simulation platform. Those simulations involved 250 objects exhibiting heterogeneous interaction volumes and random interaction patterns over time, providing evidence regarding the structural behavior and scalability of the original ecosystem. In contrast, the present study focuses on validating whether ontology-driven inference improves recommendation outcomes under realistic operating conditions, thereby strengthening the ecological validity of the proposed approach.

4.2 Evaluation Metrics

The evaluation considers structural, semantic, and trust-oriented dimensions of relationship management in SIoT environments. Structural metrics characterize interaction relevance and network organization, semantic metrics assess contextual compatibility and recommendation quality, and trust-oriented indicators evaluate the reliability of established relationships. Table 2 summarizes the research questions and their corresponding evaluation metrics.

Semantic Recommendation Precision (SRP), Contextual Consistency Rate (CCR), and Semantic Relationship Accuracy (SRA) directly evaluate the contribution of ontology-driven inference by measuring the extent to which inferred compatibility knowledge is

Table 2: Research questions and evaluation metrics.

RQ	Research Question	Metrics
RQ1	Does ontology-driven reasoning improve relationship recommendation consistency in SIoT environments?	SRP, CCR
RQ2	Can ontology-driven inference reduce semantically incompatible recommendations compared with purely structural interaction analysis?	SRA, Recommendation Acceptance Rate, Interaction Success Rate
RQ3	How does semantic contextualization influence social organization and interaction relevance among SIoT devices?	Degree Cent., Betweenness Cent., PageRank, Interaction Density, Trust Consistency

reflected in recommendation outcomes. These metrics were operationalized as follows:

$$SRP = \frac{\#CompatibleRecommendations}{\#GeneratedRecommendations} \quad (4)$$

$$CCR = \frac{\#ContextuallyConsistentRelationships}{\#EstablishedRelationships} \quad (5)$$

$$SRA = \frac{\#CorrectCompatibilityInferences}{\#ObservedInteractions} \quad (6)$$

SRP quantifies the proportion of generated recommendations satisfying semantic compatibility constraints. CCR measures the alignment between established relationships and contextual requirements observed during execution. SRA evaluates the agreement between ontology-driven compatibility inferences and the interactions effectively observed in the environment. In this study, a compatibility inference was considered correct when a recommendation supported by inferred semantic evidence resulted in a successful interaction without violating contextual restrictions during the corresponding execution cycle. Higher values therefore indicate that inferred contextual knowledge is effectively incorporated into recommendation decisions.

Statistical validation included descriptive measures (mean, median, standard deviation, and confidence intervals) and comparative analyses between VISO and VISOOnto. Data normality was assessed using the Shapiro–Wilk test. Depending on the observed distribution, paired Student’s *t*-tests or Wilcoxon signed-rank tests were applied using a significance level of $\alpha = 0.05$. Effect sizes were estimated using Cohen’s *d* and rank-biserial correlation, while Spearman coefficients were employed to investigate associations between structural relevance and semantic recommendation quality.

4.3 Experimental Configuration

The evaluation compares two recommendation scenarios executed under identical operating conditions. The baseline scenario employs the original VISO strategy, which combines structural interaction analysis, trust propagation, and Organizational Network Analysis [4]. The second scenario incorporates the ontology-driven reasoning mechanisms introduced by VISOOnto. Therefore, the primary experimental variable corresponds to the inclusion of inferred semantic evidence during recommendation generation.

Interaction events generated in the smart office environment were continuously monitored and transformed into interaction graphs enriched with relationship categories, trust evaluations, service requests, and contextual information. In the VISOOnto scenario, contextual knowledge was processed through OWL reasoning and

SWRL rules to infer compatibility relationships subsequently incorporated into recommendation decisions.

To minimize experimental bias, both scenarios were executed using the same infrastructure, communication conditions, interaction policies, device configurations, and interaction traces. Data were collected across repeated execution cycles to reduce the influence of transient events and short-term interaction fluctuations.

Statistical validation was performed using the Wilcoxon signed-rank test applied to 30 paired observations obtained from repeated execution cycles under equivalent conditions. Each execution cycle corresponded to a complete recommendation process using the same interaction conditions, differing only in the inclusion of ontology-driven inference. In each cycle, recommendations were independently generated using VISO and VISOOnto, producing paired measurements for Semantic Recommendation Precision (SRP), Contextual Consistency Rate (CCR), Semantic Relationship Accuracy (SRA), Recommendation Acceptance Rate, Interaction Success Rate, and Trust Consistency.

This design enables the observed differences to be attributed specifically to ontology-driven inference while controlling for environmental and operational variations. The resulting datasets were analyzed using the structural, semantic, and statistical procedures previously described to assess the impact of inferred semantic evidence on recommendation quality, contextual consistency, trust reliability, and social organization in SIoT environments.

5 RESULTS

This section presents the results obtained from the evaluation of VISOOnto in the smart office environment. The analysis investigates interaction organization, ontology-driven inference, and recommendation performance through comparative experiments involving the original VISO approach and the semantic mechanisms introduced in VISOOnto.

5.1 Structural and Semantic Inference Analysis

The monitored interactions generated a heterogeneous graph comprising computing devices, multimedia infrastructure, smart lighting systems, virtual assistants, and peripheral equipment. Structural analysis revealed a non-uniform interaction distribution in which a limited subset of devices concentrated most communication flows. Devices responsible for coordination and information exchange achieved the highest *Degree Centrality* and *PageRank* values, while *Betweenness Centrality* identified devices acting as bridges between otherwise disconnected interaction communities. Table 3 summarizes the structural metrics obtained across repeated execution cycles.

Table 3: Structural metrics of the interaction graph.

Metric	Mean	Std. Dev.	Max
Degree Centrality	0.42	0.18	0.87
Betweenness Centrality	0.27	0.11	0.64
PageRank Score	0.31	0.09	0.71
Interaction Density	0.58	0.07	0.73
Trust Consistency	0.81	0.05	0.93

The relatively low standard deviations indicate stable interaction behavior across repeated executions. Interaction Density and Trust Consistency further suggest a cohesive and reliable collaboration structure among participating devices. Together, these findings provide evidence for RQ3 by showing that social organization emerges around structurally influential devices and reinforce the relevance of Organizational Network Analysis for identifying distinct collaboration roles within SIoT environments.

However, structural relevance alone does not guarantee contextual suitability. Devices occupying central positions in the interaction graph may remain inappropriate candidates for collaboration due to incompatible capabilities, operational constraints, or service objectives.

To address this limitation, VISOnto incorporates ontology-driven inference during recommendation generation. Contextual knowledge describing device capabilities, environmental conditions, trust requirements, organizational roles, and interaction constraints is processed through OWL reasoning and SWRL rules to derive compatibility relationships that are not explicitly represented in the interaction graph. This inferred knowledge produced two complementary effects: structurally relevant but contextually incompatible relationships were discarded, while additional collaboration opportunities were identified from compatibility evidence. Table 4 summarizes the semantic evaluation results.

Table 4: Semantic metrics obtained during the evaluation.

Metric	Mean	Std. Dev.	Max
Semantic Recommendation Precision	0.89	0.04	0.96
Contextual Consistency Rate	0.91	0.03	0.97
Semantic Relationship Accuracy	0.87	0.05	0.95
Recommendation Acceptance Rate	0.84	0.06	0.93
Interaction Success Rate	0.88	0.04	0.94

The results indicate that ontology-driven inference contributed substantially to recommendation quality. Semantic Recommendation Precision reached 0.89, indicating that nearly nine out of ten generated recommendations satisfied the compatibility conditions represented in the ontology. Similarly, the Contextual Consistency Rate of 0.91 demonstrates strong alignment between established relationships and the contextual requirements during execution.

Semantic Relationship Accuracy reached 0.87, indicating substantial agreement between inferred compatibility relationships and the interactions effectively observed in the environment. In other words, most recommendations supported by semantic evidence were subsequently validated through successful interactions without violating operational restrictions.

Recommendation Acceptance Rate (0.84) and Interaction Success Rate (0.88) indicate that recommendations supported by semantic compatibility remained operationally coherent after relationship establishment. These results provide initial evidence for the role of semantic contextualization and motivate the comparative evaluation against VISO presented in Section 5.2.

In response to RQ3, semantic contextualization complements the structural organization mechanisms inherited from VISO. Degree Centrality, Betweenness Centrality, and PageRank identify socially prominent or gateway objects from interaction patterns, whereas

ontology-driven inference evaluates whether candidate relationships satisfy contextual requirements and operational constraints. Thus, semantic inference does not replace structural relevance; it refines it by distinguishing structurally relevant candidates from those that are also contextually compatible. The observed successful interactions without violations of the evaluated constraints indicate that semantic contextualization provides decision evidence beyond structural ranking alone.

5.2 Recommendation Performance

To quantify the impact of ontology-driven inference, VISOnto was compared with the original VISO recommendation strategy. While VISO prioritizes structurally relevant devices based on interaction patterns and trust propagation, VISOnto additionally incorporates inferred semantic compatibility during relationship establishment. Figure 3 presents the comparative performance obtained for both approaches.

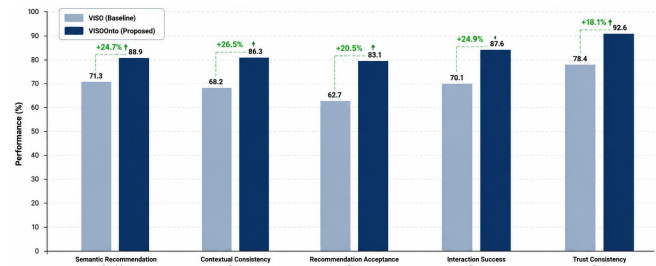


Figure 3: VISO and VISOnto recommendation performance.

Statistical validation was performed using paired observations collected during repeated execution cycles. The Shapiro-Wilk test indicated non-normal distributions for part of the dataset, motivating the adoption of the Wilcoxon signed-rank test. Table 5 summarizes the comparative results.

Table 5: Recommendation results for VISO and VISOnto.

Metric	VISO	VISO Onto	Improve-ment(%)	p-value
Semantic Recommendation Precision	0.71	0.89	25.35	0.012
Contextual Consistency Rate	0.74	0.91	22.97	0.009
Recommendation Acceptance Rate	0.77	0.84	9.09	0.031
Interaction Success Rate	0.79	0.88	11.39	0.018
Trust Consistency	0.78	0.81	3.84	0.072

The comparative results provide evidence for RQ1 and RQ2 indicate that ontology-driven inference significantly improved recommendation quality and contextual consistency. The largest gains were observed for Semantic Recommendation Precision (25.35%) and Contextual Consistency Rate (22.97%), demonstrating the effectiveness of incorporating inferred compatibility evidence into relationship establishment decisions.

Table 6 provides a detailed view of how semantic inference modified recommendation outcomes. While VISO generated 132 recommendations, VISOnto discarded 13 structurally relevant candidates due to inferred contextual incompatibilities and identified 18 additional recommendations through compatibility inference.

Table 6: Recommendation outcomes after inference.

Outcome	Count
Recommendations generated by VISO	132
Recommendations preserved by VISOnto	119
Recommendations rejected by semantic inference	13
New recommendations inferred by VISOnto	18
Successful inferred relationships	15
Unsuccessful inferred relationships	3

Among the inferred recommendations, 15 resulted in successful interactions, corresponding to an effectiveness rate of 83.3%. These findings indicate that semantic inference contributes not only to filtering unsuitable candidates but also to discovering effective collaboration opportunities that remain undetected through structural interaction analysis alone.

Improvements were also observed for Recommendation Acceptance Rate and Interaction Success Rate, whereas Trust Consistency did not exhibit statistically significant variation ($p = 0.072$). This result is also consistent with the experimental design, in which the trust propagation mechanism was kept unchanged between VISO and VISOnto; therefore, changes in Trust Consistency were not expected to constitute the primary effect of the intervention.

Overall, the results provide direct evidence that ontology-driven inference actively refines structurally generated recommendations, explaining the improvements observed in recommendation quality and contextual consistency.

5.3 Discussion

The results indicate that structural interaction relevance alone is insufficient for adaptive relationship management in SIoT environments. Although graph-based metrics and trust propagation identify influential devices, they provide limited evidence of contextual suitability. VISOnto addresses this limitation by using OWL reasoning and SWRL rules to derive compatibility relationships from device capabilities, environmental conditions, trust requirements, and organizational roles.

The gains in Semantic Recommendation Precision and Contextual Consistency Rate indicate that semantic inference provides decision evidence not directly available from interaction topology. The statistical significance of the main recommendation metrics and their low variability across repeated execution cycles further support semantic inference as an active decision component rather than merely a representation mechanism.

More broadly, the results provide evidence that ontology use in SIoT can extend beyond semantic interoperability toward adaptive relationship management. By integrating semantic inference with structural relevance, trust, Digital Twins, and Organizational Network Analysis, VISOnto enables contextual knowledge to refine relationship recommendations under real operating conditions.

The evaluation is limited to 13 devices in a single smart-office scenario and uses VISO as the baseline, isolating the contribution

of ontology-driven inference but not establishing superiority over alternative SIoT approaches. The ontology and SWRL rules were manually specified, and the 0.7 trust threshold was selected for the evaluated environment. Sensitivity to alternative thresholds and semantic inference overhead was not assessed. Moreover, SRP, CCR, and SRA partially depend on ontology-defined compatibility criteria and should therefore be interpreted as semantic consistency indicators rather than independent ground-truth measures. Future work should evaluate larger and more heterogeneous environments, alternative baselines, threshold sensitivity, computational overhead, and independent validation criteria.

6 CONCLUSION AND FUTURE WORK

This work presented VISOnto, a semantic-driven approach for SIoT relationship management that integrates ontology-based inference, Digital Twins, Organizational Network Analysis, trust propagation, and interaction-based recommendation.

Under real operating conditions, VISOnto improved Semantic Recommendation Precision by 25.35%, Contextual Consistency Rate by 22.97%, Recommendation Acceptance Rate by 9.09%, and Interaction Success Rate by 11.39% compared with VISO. These results indicate that ontology-derived semantic compatibility can effectively refine relationship recommendations beyond structural interaction analysis alone.

The main contribution is the operationalization of semantic inference as a decision component within the VISO ecosystem, extending its interaction, trust, Digital Twin, and ONA mechanisms with ontology-based representation, SWRL rules, and semantic recommendation refinement.

Future work will evaluate VISOnto in larger and more heterogeneous environments, including smart campuses, industrial IoT, and urban-scale scenarios, while investigating distributed semantic reasoning, explainable recommendations, ontology evolution, and the integration of knowledge graphs and machine learning.

Artifact availability

The interaction dataset, source code, ontology, SWRL rules, and analysis scripts will be made available upon publication, subject to applicable institutional, licensing, and data protection requirements, to support reproducibility and independent verification.

Ethical considerations

This study did not involve human participants or human subjects. Experiments used only heterogeneous IoT devices and device-level interaction records, including identifiers, timestamps, interaction categories, trust evaluations, contextual constraints, and recommendation outcomes. No participant-level data, images, recordings, questionnaires, or interviews were collected or analyzed.

Declaration on the use of generative AI

Generative Artificial Intelligence were used solely for language revision and minor editorial support. The authors retain full responsibility for the research design, implementation, data, analysis, results, interpretations, and conclusions presented in this work.

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