Blended SoS: A New Evolutionary Approach for Complex Information Systems

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Abstract. Research Context: *This study investigates complex socio-technical Systems-of-Systems (SoS), focusing on environments where operational technology (OT) and information technology (IT) converge, such as in the domains of Agro 4.0 and eHealth. These domains are at the forefront of digital transformation, requiring innovative approaches to integrate distinct and emerging technologies effectively.* ***Scientific and/or Practical Problem:*** *Existing SoS classifications are insufficient to capture the hybrid and evolutionary nature of real-world systems. Newly designed, legacy, and proprietary systems often coexist and must interoperate within the same ecosystem, creating gaps in understanding emergent behaviors, stakeholder interactions, and technical interoperability. This represents a significant challenge for building resilient and adaptable systems.* ***Proposed Solution and/or Analysis:*** *We introduce the concept of Blended SoS, a novel category of SoS characterized by limited central control, heterogeneous constituents, and adaptive, mission-driven behaviors. We organized this concept within a framework that integrates principles from mission engineering, SoS engineering, and information systems (IS) to guide the design, operation, and evolution of complex systems across various domains.* ***Related IS Theory:*** *The research adopts principles from hermeneutics and grounded theory, providing an interpretive understanding and enabling the emergence of substantial theory within the IS field.* ***Research Method:*** *Qualitative data from interviews and surveys were systematically coded and synthesized into a theoretical framework, validated against existing literature.* ***Summary of Results:*** *Findings highlight the importance of adaptive architectures, stakeholder-centric governance, and technical interoperability to ensure resilience, continuous availability, and alignment with missions.* ***Contributions and Impact to IS area:*** *This study formalizes the Blended SoS category, providing a framework for managing adaptive, multi-domain systems. This framework advances socio-technical understanding of SoS, guides interoperability and governance, and supports decision-making in complex, dynamic IS environments.*

1. Introduction

The increasing digitalization of society has fostered the emergence of highly complex information systems (IS), often structured as Systems-of-Systems (SoS) [Yoo et al. 2012]. Unlike traditional systems, SoS are composed of constituent systems (CS) that are operationally and managerially independent, yet must interoperate while retaining their autonomy [Maier 1998, Dahmann and Baldwin 2008]. This defining characteristic makes SoS particularly suited to critical domains such as agriculture, eHealth, and environmental monitoring, where heterogeneous organizations, technologies, and regulatory frameworks must be effectively coordinated to achieve shared objectives.

Current SoS classifications (i.e., Directed, Collaborative, Acknowledged, Virtual) [Maier 1996, Dahmann and Baldwin 2008] have provided a solid foundation, but they prove insufficient to fully capture the complexity of a hybrid environment. In practice, these ecosystems demand the continuous integration of newly designed systems (greenfield), legacy systems repurposed for novel contexts (brownfield), and proprietary solutions (closed source). The simultaneous need for central guidance (e.g., mission alignment) and constituent autonomy (e.g., technical resilience) creates a theoretical and practical gap in understanding the resulting structure, governance, and technical interoperability mechanisms of such hybrid systems [Kazman et al. 2013].

To address the aforementioned gap, this study proposes a novel conceptual framework by applying a theory-building methodology. We leverage the principles of Grounded Theory (GT) [Corbin and Strauss 2008] combined with systematic literature review [Kitchenham et al. 2010] and empirical data from practitioners and academics in large-scale integration initiatives. The following research question guides our inquiry: *How can a novel SoS type be conceptualized to characterize the hybrid, evolutionary, and mission-driven nature of complex IS?* This approach allows for the emergence of a substantive theory grounded in empirical reality, explicitly connecting the design principles of Mission Engineering [Dahmann and Parasidis 2024] with the technical and organizational challenges of hybrid SoS. Based on the results of this investigation, we introduce Blended SoS, a concept that emphasizes the integration of highly heterogeneous constituents under constraints of limited central control and pervasive awareness of technical interoperability. By framing Blended SoS within the domain of IS, we aim to provide a conceptual foundation that supports dynamic adaptability, resilience, and the continuous evolution of complex socio-technical ecosystems.

This paper makes three main contributions to the field of IS and SoS Engineering: (i) It conceptually defines Blended SoS as a new classification that extends existing SoS typologies by characterizing the dual autonomy and hybrid nature of the integration of OT and IT systems; (ii) It proposes a governance and architectural framework emerging from GT to characterize interoperability and integration mechanisms across these heterogeneous constituents; and (iii) It explores the implications for IS design and engineering, with special attention to requirements, architecture, and stakeholder management in critical application domains.

The remainder of this paper is organized as follows. Section 2 provides context on SoS, classifications, and related work. Section 4 presents details on the GT methodology. Section 5 presents the results, including the specification of Blended SoS. Section 6 describes the discussions of the results. Finally, Section 8 presents the conclusions and future works.

2. Background

The study of SoS has been shaped by seminal taxonomies that classify them according to governance, operational independence, and collaboration among constituent systems. [Maier 1996] identified four main categories: (*i*) Directed SoS, centrally managed by a single authority to achieve a defined mission; (*ii*) Acknowledged SoS, with recognized objectives and central coordination but considerable constituent independence; (*iii*) Collaborative SoS, lacking central authority and relying on voluntary collaboration; and (*iv*) Virtual SoS[1] , highly decentralized, with fluid membership and cooperation without overarching management. Building on Maier's work, [Dahmann and Baldwin 2008] refined these categories, emphasizing governance, stakeholder involvement, and operational constraints. While these classifications remain influential, they portray SoS as relatively stable entities, overlooking the increasing dynamism and heterogeneity of contemporary environments.

In parallel, [Kazman et al. 2013] proposed three development contexts: *greenfield*, in which new systems are intentionally designed to integrate into a SoS; *brownfield*, where existing systems are adapted for interoperation; and *closed source*, where systems participate in a SoS without being accessible for modification. [Madni and Sievers 2014] expanded these ideas, introducing categories of constituent participation such as intentionally projected systems, ad hoc collaborations, and unplanned cooperations. These contexts are particularly relevant in domains where legacy, newly designed, and restricted-access systems coexist, creating interoperability challenges.

Despite the relevance of these classifications, they present limitations when applied to complex IS that demand continuous adaptation and the integration of multiple interoperability modes. Domains such as Agro 4.0 and eHealth often require the coexistence of greenfield, brownfield, and closed-source systems, each operating under distinct regulations, governance models, and ownership structures. These contexts amplify challenges related to interoperability, adaptability, and mission continuity, particularly when systems must evolve dynamically, sustain resilience, and align with heterogeneous stakeholder requirements in multi-organizational environments.

Addressing such challenges requires a clear understanding of the mission, which plays a central role in the design and evolution of SoS. A mission defines the operations and capabilities required to deliver value to stakeholders and customers, serving as a reference point for acquisition, requirements engineering, and architectural refinement [DoD 2018]. In SoS, the mission is analogous to that of traditional systems, but extends across multiple organizational boundaries, involving collaboration between SoS engineers, analysts, architects, and stakeholders.

3. Related Work

Beyond Maier's typology [Maier 1996] (see Section 2), several studies have proposed classifications of SoS to better capture their structure, governance, and emergent behaviors. [Mokhtarpour and Stracener 2017] introduced a conceptual methodology for selecting coalitions of CS based on acquisition requirements. Although not a typology in itself, this approach implicitly recognizes the heterogeneity of governance and control structures that emerge from different combinations of systems, hinting at categories that transcend Maier's rigid classification.

[1] https://osf.io/tqkae/?view_only=3ad3e0c48be94a9290a2c24c73bf5952.

Other researchers have refined SoS characterizations by focusing on internal criteria. [Axelsson 2019] proposed a terminology to describe substructures and CS states, highlighting how subsystem evolution and interdependencies differentiate SoS in terms of adaptability and complexity. Their work offers complementary perspectives to external typologies, supporting the modeling of heterogeneous configurations. [Neto et al. 2021] advanced the notion of Systems-of-Information Systems (SoIS), distinguishing them from Cyber-Physical SoS (CPSoS) and drawing attention to the challenges of interoperability and emergent behavior in digitally intensive environments.

[Papavasiliou et al. 2024] proposed a multidimensional typology that considers constituent attributes such as autonomy, diversity, connectivity, and emergent behavior. By distinguishing categories such as cognitive, social, digital, infrastructure, and political modules, their work highlights the importance of integrating both organizational and technical factors in the analysis of modern SoS. Similarly, [Adesanya et al. 2025] extended SoS theory through the concept of Systems of Twinned Systems (SoTS), merging Digital Twins with SoS paradigms to explore new categories based on coupling, autonomy, and reflexivity. Although SoTS is conceptually distinct, it shares with other extensions the intent of overcoming the limitations of static typologies in capturing hybrid arrangements.

Based on the presented context, the Blended SoS proposed in this paper complements and extends existing approaches by explicitly addressing cases where a single SoS exhibits features of multiple classical categories (i.e., Directed, Acknowledged, Collaborative, and Virtual) simultaneously. While previous work has emphasized domain-specific extensions [Mokhtarpour and Stracener 2017] or hybrid paradigms such as SoTS [Adesanya et al. 2025], the Blended SoS advances a more general conceptual category. Unlike multidimensional classifications [Tekinerdogan 2019, Papavasiliou et al. 2024] or subtypes such as SoIS [Neto et al. 2021], it focuses on the overlap and interplay between types within a single system, recognizing the coexistence of centralized governance, negotiated autonomy, and emergent interoperability requirements. Thus, the Blended SoS represents a practical extension of both classical and contemporary typologies, as it provides theoretical contributions by conceptualizing heterogeneous SoS configurations and practical relevance by supporting the analysis and governance of mission-driven systems where operational and informational layers must be reconciled. Applications such as digital healthcare, intelligent transportation, and defense systems illustrate the value of this category, where neither strict centralization nor complete autonomy suffices, and hybrid governance is necessary for interoperability, resilience, and adaptability.

4. Research Method

This study adopts a qualitative, theory-building research design, following the principles of GT, specifically focused on developing a substantive theory about SoS and their interoperability in hybrid environments. It is particularly suitable for domains that are not formally studied or that benefit from new perspectives [Adolph et al. 2011]. Its application enables faithful representations of the field and supports comprehension by those involved [Charmaz 2014]. The reason for this choice is consistent with considerations in [Benbasat et al. 1987], [Coleman and O'Connor 2007], and [Polacsek et al. 2018].

GT techniques guided the research process. Iterative coding and reflexive analysis supported the gradual emergence of categories and theoretical constructs based on three primary components: (i) Systematic Mapping and Documentary Analysis [Kitchenham et al. 2010] to establish the theoretical baseline and initial analytical categories (sensitizing concepts); (ii) Field Research with practitioners and academics to gather empirical data; and (iii) Constant Comparative Analysis of literature and empirical evidence to construct the theoretical framework. Multiple sources of evidence, including interviews, surveys, and expert discussions, were rigorously triangulated to ensure a comprehensive perspective on interoperability challenges [Remenyi 2014, Araujo et al. 2017]. The methodological process explicitly connected Mission Engineering principles [Dahmann and Parasidis 2024] as a guiding analytical lens with the challenges posed by hybrid and evolutionary SoS, thereby enabling the specification of the Blended SoS conceptual framework.

We follow a four-phase iterative process [Pandit 1996], combining empirical and literature-driven analyses to address the complex, multi-layered nature of SoS as presented in Figure 1). This methodology allowed us to capture stakeholder perspectives and decision-making processes, providing a solid foundation for designing and managing Blended SoS architectures that integrate OT and IT systems. Next, a description of each phase is addressed.

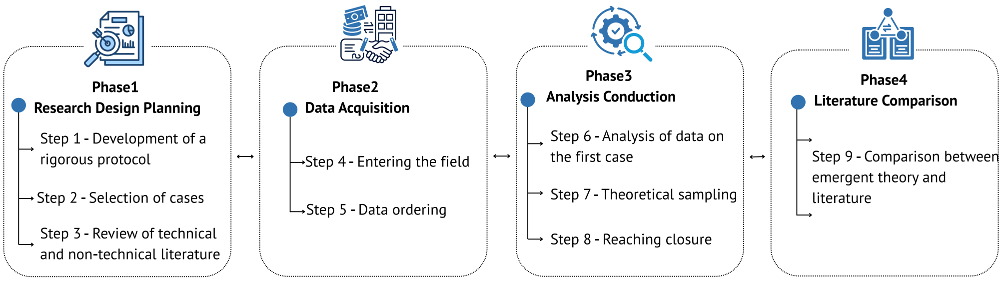


Figure 1. Pandit's grounded theory design process. ***Adapted from [Pandit 1996].***

Phase 1: Research Design Planning. It involved the establishment and validation of the research protocols (i.e., systematic mapping[2]), and interview[3], which encompassed guiding questions, data collection strategies, and analysis criteria, by experts in SoS, interoperability, software architecture, and requirements engineering. Participants provided informed consent and could withdraw at any stage of the study. This phase comprised: (i) defining research questions and strategies, (ii) applying theoretical case selection to maximize insights, and (iii) reviewing technical and non-technical literature as sensitizing material. Data were obtained from four complementary sources to achieve the saturation: (a) technical literature, (b) non-technical literature, (c) empirical evidence (surveys and interviews), and (d) expert meetings. Six best practices were adopted throughout: questioning both data and researchers, comparing concepts, recording memos, taking field notes, engaging experts, and assessing practical applicability [Strauss and Corbin 1990, Glaser and Strauss 1967]. To resolve conceptual ambiguities, ontologies were also consulted [Dolling 1995, Abdalla 2017, Axelsson 2024].

The research population was incrementally selected to address the research questions and achieve theoretical saturation. The survey sample comprised academics and practitioners

[2] `https://osf.io/tqkae/?view_only=3ad3e0c48be94a9290a2c24c73bf5952`.
[3] `https://osf.io/tqkae/?view_only=3ad3e0c48be94a9290a2c24c73bf5952`.

from conferences, journals, research projects, industry, and government organizations. From an initial pool of 658 individuals, 432 valid participants remained after filtering (see Section 4). To complement saturation, two rounds of semi-structured and unstructured interviews were conducted with 27 participants across Germany, the United States, Spain, and Brazil (see Section 4). Semi-structured interviews balanced consistency and comparability, while unstructured interviews encouraged novel insights and experiences, supporting the iterative refinement of theory [Seaman 2008].

In parallel, a systematic mapping of the literature was conducted. GT concepts [Charmaz 2014, Strauss and Corbin 1998] guided the construction of search strings, while snowballing [Wohlin 2014] ensured comprehensive coverage [Kitchenham et al. 2010]. Iterative comparison of empirical data and literature enabled refinement of the research questions and alignment of findings with mission-driven interoperability needs [Remenyi 2014]. Mapping revealed that few studies explicitly addressed technical interoperability requirements derived from SoS missions, underscoring a critical theoretical and practical gap. The methodology therefore supported incremental engagement with data, systematic questioning, and iterative theory development, while revisiting previous steps to mitigate bias and enhance reliability [Glaser and Strauss 1967, Strauss and Corbin 1990, Charmaz 2005].

Phase 2: Data Acquisition. It adopted a flexible process that allowed simultaneous collection and preliminary analysis, enabling real-time adaptation. Data collection followed a research protocol, guided by methodological triangulation [Strauss and Corbin 1990, Charmaz 2005], combining systematic mapping of technical and non-technical literature (e.g., dissertations, reports, gray literature), snowballing, surveys, and interviews. Field notes, observations, and memos were systematically recorded to ensure rigor.

The mapping of SoS development processes occurred in three cycles: April-October 2015, September-December 2018, and August 2024-July 2025, involving several researchers, including four experts. In 2015, 493 studies were retrieved; 88 were selected for full reading, yielding 33 inclusions. The 2018 update added 225 studies, 183 analyzed after duplicates, with 12 new inclusions. The 2024–2025 update retrieved 4,262 studies, 3,679 analyzed after duplicates, with 71 new inclusions. In total, 116 primary studies were selected[4]. Memos captured critical insights and research questions, supporting theory development. For example, one memo (established May 10th, 2015; updated June 15th, 2025) questioned how SoS architectures address requirements, how missions align with constituent systems, and how requirements evolve across heterogeneous systems at design and runtime. Successive memo writing and mapping notes facilitated abstraction and productivity [Charmaz 2005], while expert discussions emphasized the importance of requirements analysis and specification. This ensured incremental refinement and deepened understanding of requirements activities beyond elicitation and validation.

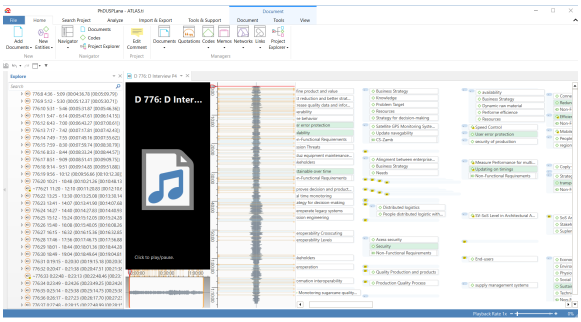
Complementing the mapping, empirical data were collected through surveys and interviews. The survey was distributed to 432 potential respondents via the Survey Anyplace platform[5], obtaining 51 valid responses (11.81% response rate). The questionnaire addressed (i) architectural analysis practices for interoperability, (ii) the landscape of SoS interoperability, and (iii) demographics. Responses were first analyzed by the authors and later reviewed by a statistician from the Núcleo de Estatística Aplicada (NEA – USP).

[4] https://osf.io/tqkae/?view_only=3ad3e0c48be94a9290a2c24c73bf5952.
[5] https://www.surveyanyplace.com

The interview phase comprised 27 participants (13 industry professionals, 14 researchers) from Germany, the United States, Spain, and Brazil[6] ; ensuring diverse perspectives on SoS missions and interoperability challenges. Interviews, held online or face-to-face, ranged from semi-structured to unstructured formats and generated 57h40m of recorded material. Ten participants were consulted multiple times for validation. Participants' experience ranged from 5 to over 40 years, covering roles such as SoS architects, requirements engineers, and system designers. Cases were incrementally incorporated until theoretical saturation was achieved.

Phase 3: Analysis Conduction. It involved a systematic and iterative process of coding and theory building. Data were analyzed using open, axial, selective, and color coding to identify categories, establish relationships, and progressively refine theoretical constructs. Theoretical sampling was applied throughout, allowing replication, expansion, and critical examination of categories. Closure was achieved once theoretical saturation was reached, when no additional data contributed new insights [Glaser and Strauss 1967, Strauss and Corbin 1990].

All coding was analyzed in ATLAS.ti 8.0[7], with data extraction conducted by the primary researcher and subsequent discussions with interviewees and domain experts to validate interpretations. The procedure followed the four-step framework proposed by [Freitas 2009]. Consistent with grounded theory principles, coding was designed to remain flexible, interactive, and problem-oriented, ensuring close alignment with the research question [Charmaz 2005]. Low-level coding ensured that higher-level categories and abstractions emerged directly from the data [Corbin and Strauss 2008]. Open and color coding were applied from the earliest data, progressively refining concepts and assigning meaning to words, sentences, and interactions. Figure 2 illustrates the coding process: (a) an excerpt of interview transcript analysis (D776) and (b) examples of color-coded categories, such as `communication channel` and its subcategory `network`, from interviews IT_8 and IT_22.



(a) Excerpt of interview analysis in ATLAS.ti

Subcategory	Network
Codes:	Formal Data
	Meaning
	Application
	Transmitter/Receiver
	Interface description
	Transmission procotols
	Transmission rates
	Timelines or data latency
	Command (executable instruction)
	Standards

Interview

IT_8 : The systems can adapt to different interfaces and reconfigurations of several devices for the same vehicle. Interoperation is required, since it is used in several environments or domains.

Interview

IT_22: Interoperability uses various technologies that enable several systems to communicate with our organizations. However, it must support the decision-making process at all levels. Data are processed at runtime and made available at runtime or online, depending on the situation. Their performance must be assessed, since they cannot be maintained offline for a long time.

(b) Excerpt from codification by color coding

Figure 2. Examples of codification using ATLAS.ti and Microsoft Excel 2019.

In the initial phase, 315 codes were identified from nine interviews and 51 survey responses. A further 293 codes emerged from 17 additional interviews, resulting in 608 codes overall. These were consolidated into concepts, reduced for redundancy, and refined to 386 codes. Successive validation rounds narrowed this set to 271

[6] `https://osf.io/tqkae/overview?view_only=3ad3e0c48be94a9290a2c24c73bf5952`
[7] `https://atlasti.com`

codes. Categories such as `communication channel` were then established, supporting the delineation of actions, conditions, and consequences essential to theory development [Charmaz 2014, Strauss and Corbin 1998, Corbin and Strauss 2008]. Constant comparison across literature and empirical data guided the refinement process, with iterative feedback from participants ensuring validity. Axial coding was employed to link categories and subcategories, facilitating higher-level abstractions and enabling the construction of a paradigm model [Halaweh 2011]. Finally, selective coding integrated and synthesized the emerging categories, culminating in the core category, *Technical Interoperability Awareness*. This construct served as the central axis, organizing all other categories around the convergence of OT and IT systems.

Phase 4: Literature Comparison. The emergent theory was systematically compared with prior frameworks, aligning categories and relationships while refining constructs, highlighting original contributions, and identifying theoretical gaps. This constituted the final stage in constructing the Blended Category, which integrates OT and IT systems[8]. To ensure rigor, the literature was revisited to contrast empirical findings with the emerging category. Consistent with the constant comparison principle of theory development, this process enabled the identification of both convergences and contradictions with prior studies [Glaser and Strauss 1967]. Initial validations enhanced the reliability of the Blended Category, while subsequent validations incorporated diverse perspectives, providing a critical basis for refinement and ensuring alignment with established knowledge. The literature review followed a systematic approach, grounding all comparisons in primary studies. When necessary, supplementary searches in academic and gray literature were conducted to guarantee comprehensive coverage and contextual robustness.

5. Results

In this section, we present the constitutive element of the substantive theory derived from empirical and literature-driven analysis. It introduces the Blended SoS category, integrating behaviors that are both centrally controlled and negotiated with CS owners. The findings also highlight the convergence of OT and IT, showing how complex, adaptive systems emerge from the interaction of operational and informational layers.

5.1. Convergence between OT and IT

The convergence of OT and IT has emerged as a critical driver in the evolution of complex IS and digital transformation initiatives such as Industry 4.0. OT traditionally focuses on monitoring and controlling physical processes[9], including embedded systems, cyber-physical systems, smart transportation, healthcare management solutions, Agro 4.0, and IoT infrastructures, while IT emphasizes information processing, data management, communication, and application integration across organizational contexts[10]. Historically, these domains evolved separately, with OT prioritizing reliability, real-time responsiveness, and safety, and IT prioritizing information quality, interoperability, and scalability.

The convergence of OT and IT involves not only the technical integration of protocols, standards, and communication channels, but also the alignment of organizational processes, managerial practices, and IS strategies. As one interviewee noted: *"OT was built for*

[8] `https://osf.io/tqkae/overview?view_only=3ad3e0c48be94a9290a2c24c73bf5952`
[9] Adapted from `https://csrc.nist.gov/glossary/term/operational_technology`
[10] Adapted from `https://csrc.nist.gov/glossary/term/information_technology`

control and stability, IT for flexibility and integration. Now, we have to combine both in the same environment" (INTERVIEWEE ID9). This convergence has significant contributions and implications for both theory and practice. From an IS perspective, it enables the creation of hybrid ecosystems that combine operational data with enterprise-level systems, enhancing decision support, business intelligence, and process optimization. Empirically, it highlights the challenges of maintaining scalability, modularity, privacy, and composability in mission-critical environments, emphasizing the importance of continuous monitoring and adaptive management. For example, interoperability between two devices caused unexpected temperature increases, temporarily degrading system performance until adaptive measures were implemented (INTERVIEWEES IT_02 and IT_22), illustrating the emergence of runtime dependencies that must be managed proactively.

In practice, organizations operate both controllable systems and independent third-party systems, creating dual governance structures. The convergence of OT and IT motivates the definition of the Blended SoS category, which integrates technological domains while accommodating managerial independence and evolving interoperability requirements. This category advances the field of IS by providing a framework to understand and manage complex, adaptive infrastructures that extend beyond traditional enterprise boundaries into cyber-physical and cross-organizational environments, offering practical guidance for designing resilient, flexible, and interoperable systems.

5.2. Establishment of a Blended Category for SoS

Figure 3 shows a data-based solution, called Blended category, which is a deliberative SoS with a central control and a mission and SoS engineering team that builds the SoS to fulfill specific purposes. Therefore, central control is intended to maximize the success towards achieving emergent behaviors, ensuring conditions for the continuous operation of the system. The owner (i.e., `O2`) and the central entity (i.e., `O1`) must establish a contractual relationship with guarantees and demands to meet business objectives and the supply of capabilities necessary for the accomplishment of the overall mission. `S1` and `S2` are constituents of operational and managerial independence, since their behavior is not subordinated to `01`; however, they contribute to the achievement of the overall mission. On the other hand, `S3` and `S4` are subordinate to owner `O3` and to the central control `O1`.

The greatest benefit of the Blended category is increased flexibility to meet the expectations and needs of businesses that comply with mission needs, requirements, and capabilities that emerge at runtime, environmental changes, and legal regulations for both OT and IT. However, the mission and SoS team will face significant challenges of adaptation for supporting converged architecture, open-ended sustainability, evolvability, scalability, availability, reliability, and dependability. Moreover, the structure and analyses of technical infrastructure and technical interoperability requirements of OT and IT are even more challenging due to the trade-offs from the increase in complexity. We identify properties to differentiate Blended SoS from directed and acknowledged SoS:

1. *SoS Mission*: the Blended type concerns the end-to-end and the mission threat detected in the SoS development lifecycle, which can hinder the achievement of the SoS mission over time. Mission engineering concepts were applied to its planning.
2. *Stakeholders*: stakeholders in Blended SoS are considered according to their decision power and influence capabilities under SoS. Such property is related to the number of

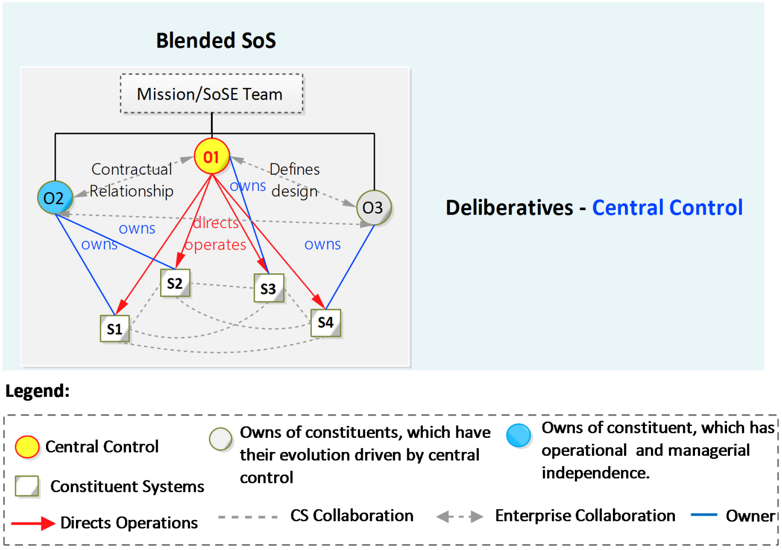


Figure 3. Blended Systems-of-Systems: a theoretical SoS category.

stakeholders of a Blended SoS during its lifecycle. Therefore, they can be changed, and those that contribute to the development are maintained even if the roles are changed. Roles and responsibilities of stakeholders should be changed in the development lifecycle to improve contributions.

3. *Constituent Systems*: these architectural elements represent systems that integrate a SoS. Constituents that compose this SoS can also be other SoS (e.g., satellite constellations, smart vehicles) or even OT, such as an Internet of Things (e.g., wireless sensor networks (WSN) with sink nodes). Each constituent can be described in terms of its interfaces, i.e., the interaction points exposed to the environment. According to the interviewees, the interactions of those that comprise other SoS are much more critical and costly to interoperate.
4. *SoS Central*: the central control of a Blended SoS does not have complete authority over the behavior of all constituents. Blended SoS was designed by a combination of constituents whose behavior is subordinated to the central entity and others that evolve independently.
5. *Interaction between Platforms*: Blended SoS can facilitate the interaction between different platforms, since they enable more than one SoS as a constituent.

Although the literature acknowledges overlapping category boundaries [Dahmann 2015, Ncube and Lim 2018]. To the best of our knowledge, this is the first study that characterizes, describes, and designs a Blended SoS with interoperability requirements derived from mission engineering. The Blended SoS can be defined as a hybrid category characterized by interdependent management, where some degree of central coordination exists but without full authority over CSs. It occupies an intermediate position between the deliberative SoS types (Directed and Acknowledged), which emphasize centralization and structured coordination, and the spontaneous SoS types (Collaborative and Virtual), which rely on autonomy and decentralized cooperation. In this sense, the Blended SoS represents a balance between control and autonomy, enabling flexibility and adaptability while maintaining alignment with common mission objectives.

Blended SoS typically emerge incrementally from the interoperation of heterogeneous CSs that share a mission orientation. Development contexts may involve *greenfield* systems specifically designed for integration, *brownfield* systems adapted from legacy infrastructures, or *closed-source* systems over which no direct modification is possible [Kazman et al. 2013, Madni and Sievers 2014]. This diversity introduces significant heterogeneity in governance and interoperability mechanisms, reinforcing the hybrid nature of the Blended category.

Figure 4 compares the Blended with Maier's original categories [Maier 1996, Dahmann and Baldwin 2008] and the Table 7 extends the framework proposed by [Ki-Aries et al. 2018], adding eight aspects for the Blended category (i.e. White and yellows cells) and six new dimensions to five categories (i.e. Blue cells), providing a more detailed characterization.

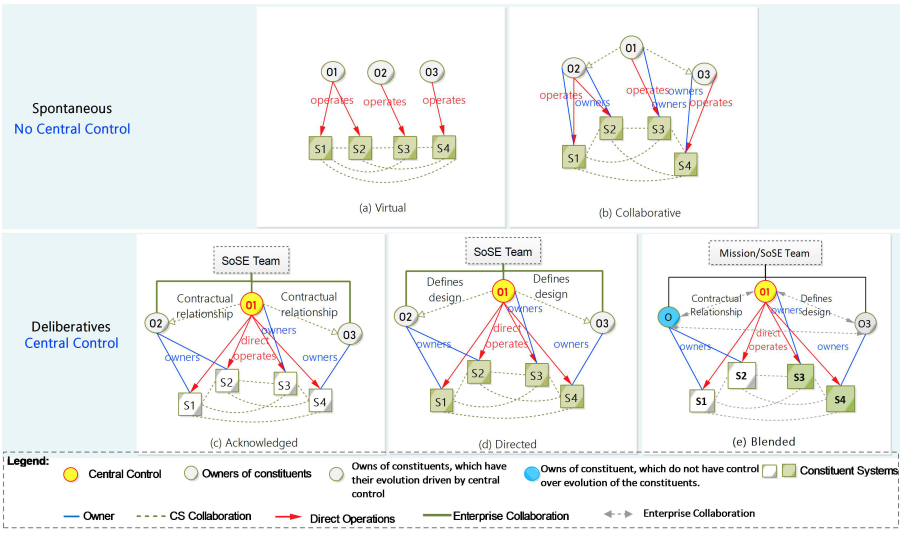


Figure 4. Systems-of-Systems types.

The framework presented in Table 7 is organized into five major information groups: (i) SoS Categories - classifies the SoS according to Maier's typology and the Blended category. (ii) Management and Oversight - covers governance structures, requirement allocation, stakeholder roles, and coordination mechanisms. (iii) Operational Environment - describes the contextual factors in which the SoS operates, including heterogeneity, dynamics, and regulatory constraints. (iv) SoS Design - addresses architectural patterns, interoperability strategies, and mechanisms for achieving mission and goal alignment; and (v) Engineering and Design Considerations - includes change management, resilience, evaluation processes, and emergent behavior handling. Each information group is further subdivided into specific subcategories to provide a detailed characterization. The color coding in the table indicates the source and nature of definitions: white cells correspond to the original definitions proposed by [Ki-Aries et al. 2018]. Yellow cells indicate updated definitions that refine or extend previous concepts, and blue cells present new definitions, introduced specifically to capture the characteristics of the Blended SoS.

A feature of the Blended SoS is its operation within a dynamic Blended context, where multiple interoperation types coexist under diverse regulatory and managerial conditions. Domains such as Agro 4.0 and eHealth exemplify this context, combining newly

Table 7. Characterising the Blended category (Part 1). White cells: original definitions from [Ki-Aries et al. 2018]. Yellow cells: Update definitions Blue cells: new definitions.

Adapted from [Ki-Aries et al. 2018]

Types	Aspects	Deliberatives			Spontaneous	
		Directed SoS	Acknowledged SoS	Blended SoS	Collaborative SoS	Virtual SoS
SoS Categories	Description	A Directed SoS can be described as developing "interrelated collaboration with central control management, operation and control over the SoS as a whole".	An Acknowledged SoS has "designated management, but limited control over the independent collaboration of the SoS".	A Blended SoS has an interdesigned management with a central control, but no complete authority over constituents.	A Collaborative SoS has "no central management , therefore, operational and control must be formed and agreed as mutual independent collaboration".	A Virtual SoS develops "individual independent collaboration with no central management, operation or control of the SoS as a whole".
Management and Oversight	Stakeholders Engagement	•Stakeholders are at system and SoS levels; •Interrelated independent system owners; •Some competing interests and priorities; •May have limited interest in the SoS; •Most stakeholders are likely to be recognized.	• Stakeholders are at system and SoS levels; • independent systems owners; • Competing interests and priorities; •Possible interest in the SoS; • Some stakeholders may not be recognized.	• Stakeholders are at system and SoS levels; • Interrelated and independent systems owners; • Some competing interests and priorities; •Possible interest in the SoS; • Some stakeholders may not be recognized.	• Stakeholders are at system level and collaborate mutually at the SoS levels; • independent systems owners; • Competing interests and priorities; Possible interest in the SoS; • Some stakeholders may not be recognized.	• Stakeholders are at system and SoS levels; • Independent systems owners may not develop direct interactive collaboration; • May show no interest in the SoS or Constituents; •Many stakeholders may not be recognized -
	Management	•Some levels of complexity with central management and funding for both SoS and interrelated collaboration of constituents. •SoS exerts authority over all constituents.	• Adds level of complexity due management and funding designated for both SoS and individual systems. •With independent collaboration, the SoS does not have authority over the whole system.	•Increased levels of complexity due to interdesigned management and funding for the interrelated collaboration of SoS and individual systems. •SoS is comprised of constituents it controls to evolving and others it does not control.	• Further levels of complexity due to the mutual independent collaboration of SoS management with funding only at or from individual system level. • SoS exerts no authority over the systems.	•Increased levels of complexity and uncertainty due to the lack of a central management and funding for SoS limited to individual system level. • System do not have authority over the SoS as a whole.
Operational Environment	Operational Focus	•Directed collaboration toowards the meeting of a set of operational objectives.	• Designated collaboration towards the meeting of a set of operational objectives.	•Interdesigned collaboration for the meeting of a set of operational objectives	• Mutually agreed collaboration towards the meeting of a set of operational objectives.	• Individually aligned towards the meeting of a set of operational objectives.
	Purpose	• Constituents' purpose is usually further aligned with the SoS' purpose.	• Constituents' purpose may not be known and aligned with the SoS' purpose.	• Some constituents' purpose are usually more align with those of SoS; and constituents' purpose may not be known and neither align with the SoS' purpose.	• Constituents' purpose are aligned with the SoS' purpose.	• Constituents' purpose are not known and the SoS level lacks agreement.
	Mission	•Constituents' missions may or may not align with the SoS' mission.	•Constituents' missions are not aligned with the SoS' mission.	•Constituents' missions may or may not align with the SoS' mission.	•Constituents' missions are generally not aligned with the SoS' mission, but they share it.	•Constituents' missions are generally not aligned with the SoS' mission.
	Goal	•SoS' goals and constituents' goals are not clearly defined.	•The goals of SoS level and constituent level are not clearly recognized.	•High-level goals are vaguely stated for SoS and constituents levels.	•No clear goal statement.	No clear goal statement.
	Objectives	•Both SoS level and constituent level have clearly defined objectives	• There are recognize objectives	•A combination of recognized and clear objectives is designed for the SoS level.	•No clear objectives.	No clear objectives.

Table 7. Characterising the Blended category (Part 2). White cells: original definitions from [Ki-Aries et al. 2018]. Blue cells: new definitions.

Adapted from [Ki-Aries et al. 2018]

Types	Aspects	Deliberatives			Spontaneous	
		Directed SoS	Acknowledged SoS	Blended SoS	Collaborative SoS	Virtual SoS
SoS Design	Acquisition	• Complexity from multiple systems lifecycles, new developments, technologies, acquisition programs, development, and legacy systems.	• Complexity from multiple systems' lifecycles, new developments, technologies, acquisition programs, developmental, and legacy systems.	• Complexity from multiple systems' lifecycles, new developments, technologies, acquisition programs, developmental, and legacy systems.	• Complexity from multiple systems' lifecycles, new developments, technologies, acquisition programs, developmental, and legacy systems.	• Complexity from multiple systems' lifecycles, new developments, technologies, acquisition programs, developmental, and legacy systems.
		• Stated capability objectives up-front, which may provide basis for requirements.	• Stated capability objectives up-front, which may provide basis for requirements.	•Mission objectives continually determined upfront and updated continually, which may provide basis for requirements end-to-end.	• Stated capability objectives up-front towards the supply of basis for requirements.	• Stated capability objectives based on limited needs may be noted up-front, which may provide basis for requirements.
		• Benefits from the central control for the establishment, integration and interoperation of constituents' needs.	• Designated management and independent system needs are established.	•Interdesigned management with benefits from central control to establish, integrate and interoperate independent systems' needs.	• Mutually agreed independent system needs are established.	• Individual independent system needs may not establish needs of other systems.
	Requirements	• A single, large, and dominant organisation must play a requirements engineering leadership role and define both SoS-Level requirements and constituent Systems Level requirements.	•Constituents are owned and operated by different organizations, and requirements engineering to SoS' level is performed by a central authority and addresses requirements across the SoS.	•Requirements engineering is performed by mission/Sos team which defines both SoS level requirements and some constituents systems level requirements.	•No single dominant organisation performs the leading role for SoS' level requirements engineering.	•SoS purposes are dynamic and requirements requently change. There is no central requirement engineering authority.
		• The central SoS authority must support the controls and mandates and direct the lifecycles of the constituent systems.	•Requirements engineering for each constituent is performed independently and addresses requirements from their owner's perspective with independent life cycles.	•The central control exerts authority only over some constituents. Therfore, some constituents have an independent lifecycle of requirements engineering.	•Requirements engineering is performed by each constituent independently.	•Informal and irregular, if at all, requirements engineering at constituents level.
		• The requirements evolution of both, SoS and constituents levels are controlled and coordinated by the central authority. Classical requirements engineering approaches, methods, techniques, and tools may apply.	•Requirements engineering is performed independently by the SoS owner and constituents with minimal collaboration.	•The evolution of a Blended SoS is controlled and managed by a central control for SoS level and by some constituents level. To constituents managerially and operationally independents the new implementation to SoS level need be negotiated, but minimal structure are provided to achievement of the global mission.	•There are not one group owners the SoS, there is no obvious group that owners its requirements.	•SoS will be composed and the participating constituents cannot be known in advance. Requirements engineering at design time cannot be applied.
	Test & Evaluation	• Constituents of a same SoS often have asynchronous lifecycles.	• More challenging due to the difficult of synchronization of multiple' life cycles.	•The challenge is great and complex, since constituents have several lifecycle difficult to be synchronized.	• Complete testing is more challenging due to the difficult synchronization of multiples system's lifecycles.	• Testing cannot be completed and is challenge due to the difficult of synchronization across multiples system´life cycles.
		• Complexity of all moving parts and potential for unintended consequences.	• Complexity of all moving parts and potential for unintended consequences.	• Complexity of all moving parts and potential for unintended consequences.	• Complexity of all moving parts and potential for unintended consequences.	• Limited access and complexity of all the moving parts and potential for unintended consequences.
	Maintenance & Change mechanism	• Constituents continue operating independently, but each one is subordinated to the central authority.	• Changes in the systems are based on collaboration between SoS and constituents.	• Changes are based on two principles: (i) subordinated to central control or (ii) collaboration between SoS and constituents.	• Enforcement and maintenance of standards.	• Constituents are relatively invisible to one another.
Engineering and Design Consideration	Boundaries & Interface	• Focus is on identifying constituents within direct management and control that contribute to the SoS mission, functionality and data flow.	• Focus is on identifying the constituents within designated management and control that contribute to the SoS mission, functionality and data flow.	• Focus is on identifying the constituents within interdesigned management and control that contribute to the SoS mission, functionality and data flow.	• Focus is on identifying constituents and mutually agreed management and control that contribute to the SoS mission, functionality and data flow.	• Focus is on identifying constituents and expected indirect collaboration and control that contribute to the SoS mission, functionality and data flow.
	Performance & Behavior	• Directly managed and monitored at SoS level to satisfying SoS use needs.	• Designated management and monitoring at SoS level and system levels to satisfying SoS use needs.	• Interdesigned management and monitoring at SoS level and constituent level to satisfying SoS use needs.	• Mutually agreed management and monitoring at systems level to satisfying SoS use needs.	• Direct and indirect management and monitoring at system levels to satisfying SoS use needs.
		• Balancing needs of the systems benefits from direct co-ordination.	• Balancing needs of the systems benefits from designated co-ordination.	• Balancing needs of the systems benefits from interdesigned co-ordination.	• Balancing needs of all systems is reliant to mutual co-ordination.	• Balancing needs of the systems and indirect systems may not be achieved.

designed systems, legacy adaptations, and externally owned platforms. These environments require solutions capable of handling both top-down mission requirements and emergent runtime needs, enabling the system to integrate new constituents, adapt to unforeseen behaviors, and support evolutionary development [Jamshidi 2009].

The benefits of the Blended category stem from its hybrid nature. By combining central coordination with negotiated autonomy, this SoS provides resilience, adaptability, and mission alignment in contexts where neither strict centralization nor complete decentralization suffices. Architectures often incorporate self-healing properties, robustness, and survivability, enabling the system to restore stability amid cascading failures [AL-Nashif and Mythili 2007]. Adaptation occurs both proactively (anticipated changes) and reactively (responses to unforeseen events), addressing epistemological emergence (incompletely specified) and ontological emergence (unforeseen) [Tolk 2019].

From a governance and requirements perspective, Blended SoS operate through dual dynamics: requirements are partly defined at the SoS level by a central authority, but their evolution depends on negotiation with constituent owners. This contrasts with Directed SoS, where requirements are strictly imposed, and with Collaborative or Virtual SoS, where requirements emerge in a more ad hoc manner. The Blended type provides a structured yet flexible mechanism for aligning system evolution with overarching missions, reducing risks of misalignment while accommodating stakeholder diversity.

Similarly, testing and evaluation in Blended SoS is complex but highly informative. Unlike Directed SoS, where evaluation follows standard engineering practices, or Collaborative/Virtual SoS, where assessment is limited, Blended SoS requires multidimensional evaluation processes that reconcile central oversight with constituent autonomy, ensuring both mission-level performance and local adaptability.

In terms of maintenance and change management, the Blended category integrates structured change principles with negotiated collaboration. While Directed and Acknowledged SoS follow centralized or largely independent mechanisms, and Collaborative/Virtual SoS rely on emergent coordination, Blended SoS apply hybrid adaptation mechanisms, allowing continuous evolution without undermining system stability and ensuring sustained mission achievement under changing operational conditions.

Finally, stakeholder and operational perspectives further illustrate the distinctiveness of the Blended type. Stakeholders exist at both SoS and constituent levels, often with diverging priorities and ownership structures. Centralized control provides strategic direction, yet mission accomplishment depends on recognizing independent actors and their decision-making influence [Chung and Crawford 2016]. Operationally, Blended SoS combines clear mission-driven objectives with flexibility for constituent negotiation, situating them between the rigid mandates of Directed SoS and the undefined goals of Virtual SoS.

5.3. Evaluation of the Theory

This section discusses the validity and reliability of the emergent theory, based on [Charmaz 2005], [Wohlin et al. 2012], and [Merriam and Tisdell 2015], as it balances methodological rigor with the creativity required to ensure quality in qualitative research.

Credibility or Internal Validity concerns the alignment between theory and empirical analysis, ensuring that findings accurately reflect observed phenomena. In this study, credibility was ensured through methodological rigor and triangulation of data sources. Categories emerged directly from surveys and interviews, systematically coded using open, axial, and selective coding. Relationships among categories were synthesized into a generic model, linked to the core category and technical interoperability requirements, and validated against relevant literature to ensure contextual alignment.

On the other hand, **Originality and Construct Validity** address whether categories provide novel insights and whether findings are replicable under stable conditions. The study offers theoretical expressiveness by linking enterprise objectives to technological implementation at runtime, guided by mission engineering principles. While qualitative research acknowledges multiple interpretations, adherence to systematic coding and methodological procedures ensures consistency with empirical evidence, even if contextual replication yields variations.

The **Resonance or Conclusion Validity** evaluates whether categories meaningfully reflect participants' experiences. The theory was grounded in empirical data from practitioners and academics in an industrial project, refined through iterative analysis and at least two rounds of feedback. Consultations with ten interviewees during category finalization helped resolve ambiguities and ensured interpretability for participants.

Finally, **Usefulness (External Validity)** concerns the practical applicability and transferability of the Blended category. For SoS with limited central control and heterogeneous constituents, the proposed guidelines support integration and coordination while preserving mission alignment. However, further empirical validation is required to assess applicability in contexts such as virtual or fully distributed SoS, particularly regarding resilience, operational continuity, and adaptive interoperability.

6. Discussion of the Results

The results highlight the originality of the Blended SoS as a novel category that extends Maier's taxonomy by explicitly addressing scenarios where constituents operate under hybrid governance, combining directed and acknowledged logics. Unlike existing categories, the Blended type captures contexts in which central control exists but lacks full authority over constituents, requiring coordination across autonomous CSs, OT, IT, and IS. This innovation provides a theoretical lens for understanding SoS configurations that are increasingly common in domains such as eHealth, Agro 4.0, and smart infrastructure, but which have remained under-explored in prior classifications.

The distinctive contribution of the Blended category lies in recognizing adaptability as the product of both proactive mission engineering and reactive responses to unforeseen runtime behaviors. By explicitly linking ontological (unexpected) and epistemological (design-time but knowledge-limited) emergence to mission fulfillment, the framework advances current discussions of adaptability and evolution in SoS. This perspective clarifies how emergent requirements should be identified, classified, and partitioned for negotiation with constituent owners, ensuring alignment between operational continuity and business objectives [Jamshidi 2009, Tolk 2019].

Another original aspect concerns the integration of IS as a structural element in Blended SoS. While IS have traditionally been considered supportive, our results demonstrate their centrality in enabling interoperability, decision-making, and requirements management across heterogeneous and autonomous constituents. IS provides the mechanisms for capturing diverse requirements, maintaining traceability, and resolving conflicts across organizational boundaries [Nuseibeh et al. 1994, Daun et al. 2012]. This emphasis on IS reframes their role from passive enablers to active mediators of governance, data flows, and stakeholder negotiation.

From an architectural viewpoint, the Blended type advances SoS engineering by advocating open, mediator-based frameworks where hardware, software, and IS components evolve independently but interoperate seamlessly. The deliberate use of redundancy, mediator overlap, and distributed data management is shown to improve reliability, availability, and decision-making quality under conditions of high autonomy and complexity [Vassalos and Papakonstantinou 1998, Stevens 2008]. This approach strengthens SoS resilience and enables the effective use of analytics and business intelligence for anticipating emergent behaviors, adapting interventions, and responding to regulatory or environmental changes.

At the end, the Blended SoS should be understood as a socio-technical and informational ecosystem rather than merely a technical or operational construct. Its effective design and management depend on harmonizing OT, IT, and IS capabilities with organizational governance, stakeholder engagement, and mission-oriented coordination. By embedding IS perspectives, Blended SoS moves beyond data integration: they enable data-driven decision-making, strengthen resilience and evolvability, and maximize value creation in complex, multi-organizational environments.

7. Implications for IS Research and Practice

The conceptualization of Blended SoS carries significant implications for both IS research and practice. By framing SoS as evolutionary, adaptive, and hybrid socio-technical systems, this perspective opens novel pathways for managing highly dynamic IS environments while directly addressing the Grand Challenges of IS 2016–2026 [Maciel et al. 2017], particularly adaptability, heterogeneous integration, resilience, and multi-stakeholder coordination.

From a *research perspective*, the Blended category advances the field in four ways: (i) it extends SoS theory by explicitly incorporating greenfield, brownfield, closed source, and *ad hoc* constituents, supporting the analysis of systems under diverse ownership, governance, and operational constraints; (ii) it fosters deeper investigation into emergent behavior, adaptive architectures, and self-healing mechanisms, strengthening understanding of resilience and runtime evolution in uncertain contexts; (iii) it refines the comparison among SoS categories by adding new characteristics to Maier's types [Maier 1998, Baldwin 2008], enhancing their descriptive and analytical power; and (iv) it informs IS methodologies by guiding requirements engineering, architectural design, and evaluation processes in domains where interoperability and mission alignment are essential. From a *practical perspective*, Blended SoS highlight four implications. **First**, they promote adaptive IS architectures that integrate heterogeneous technologies and evolve with business or operational demands. **Second**, they emphasize operational resilience through fault tolerance, redundancy, and rapid recovery in mission-critical environments. **Third**, they reinforce governance and requirements processes capable of balancing diverse stakeholder needs while sustaining mission objectives. **Fourth**, their cross-domain applicability,demonstrates the potential to integrate heterogeneous systems without compromising adaptability, performance, or regulatory compliance, thereby supporting the design of resilient IS ecosystems.

8. Conclusion and Future Works

This study proposed and conceptualized the Blended SoS as a novel category characterized by limited central control, heterogeneous constituents, and mission-driven adaptability. By integrating principles from mission engineering, SoS engineering, and IS, it advances a comprehensive framework to guide the design, operation, and evolution of complex socio-technical systems across domains. In addition, the study contributes by defining the operational environment applicable to all SoS types, strengthening the theoretical foundations of SoS classification.

The findings highlight the critical role of adaptive architectures, stakeholder-centered governance, and technical interoperability in ensuring resilience, availability, and mission alignment. Methodological rigor was ensured through credibility, originality, resonance, and usefulness, demonstrating that the framework is both theoretically expressive and practically relevant. By adopting GT principles and aligning them with interpretive perspectives akin to hermeneutics in IS, the study establishes a robust foundation for understanding the dynamics of Blended SoS and their interactions with OT and IT infrastructures in real-world contexts.

Future research will involve conducting case studies across diverse SoS contexts to evaluate the effects of adaptive interoperability and transformation properties on mission performance and stakeholder engagement. This work aims to expand the theoretical framework to include cross-domain interactions in Blended SoS, increasing its generalizability and providing guidance for the design, coordination, and governance of large-scale adaptive socio-technical systems.

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