Pathway to Excellence in Managing Quality Across Complex Systems

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Abstract: Global Quality Management System (G-QMS) within the context of System of Systems (SoS) represents a pioneering research domain critical for addressing the unique needs of SoS G-organizations. These organizations are characterized by vast, intricate technological systems and multi-organizational structures, posing significant challenges in implementing effective Quality Management Systems (QMS) for their operations.This manuscript presents the culmination of research into a novel conceptual model for G-QMSs in the sectors of SoS. The model is grounded in extensive field research conducted within real-world SoS G-organizations, utilizing the Grounded Theory methodology. The proposed model is structured around two foundational supra-entities, with this manuscript focusing on the second supra-entity, termed "G-QMS in SoS." This entity primarily addresses Quality Management for SoS projects. The G-QMS in SoS model is elaborated through an exploration of its structural principles, architectural entities, interrelationships, and complementary components. Moreover, the manuscript details the interconnections between the two segment models that constitute the comprehensive G-QMS framework in SoS sectors, offering an integrated perspective of the overarching model. Developing a robust model for G-QMS in SoS sectors is crucial for understanding the diverse structures of SoS projects and the G-organizations that implement them. The proposed model provides actionable insights into designing and tailoring G-QMS frameworks to enhance the effectiveness of SoS projects, thereby directly influencing their success rates and operational efficiency.

Keywords: quality management system (QMS); global quality management system (G-QMS); system of systems (SoS); global project program; global management; systems theory; systems thinking; field study

1. Introduction:

1.1 Rationale

The implementation of a Quality Management System (QMS) in System of Systems (SoS) organizations is critical for addressing the complexity of highly specialized professional applications. These organizations require adaptable structures to accommodate intricate, large-scale technological solutions that integrate multiple systems and technologies. A SoS is inherently characterized by its complexity, often involving diverse sub-organizations and sub-structures distributed across global locations, creating expansive and interlinked global organizational systems.

Such global organizations (G-organizations) operate in challenging, rapidly evolving environments influenced by continuous technological advancements and varied operational demands. To succeed, they require an efficient and effective QMS framework that can seamlessly manage and support their structural and global operations. As emphasized by Agmon et al. [1] and Agmon and Kordova [2], a QMS for these organizations must address current complexities while also anticipating future demands. It must align with customer expectations, adhere to regulatory and standards requirements, and provide additional value by functioning as a superior, customized QMS.

This research focuses on developing a Global Quality Management System (G-QMS) tailored to organizations functioning within SoS sectors. These G-organizations often operate across multiple global sites, necessitating a QMS that is both adaptive and comprehensive. The study represents a novel academic inquiry into a field of growing importance, addressing unique challenges in quality management faced by G-organizations. Establishing precise terminology is a fundamental step in addressing this complexity and advancing the field.

1.2 Terminology and Definitions

This section provides a detailed explanation of the terminology and definitions central to the research on Global Quality Management Systems (G-QMS) in System of Systems (SoS) sectors. Agmon et al. [1] explored global organizations and their organizational impacts but noted that existing definitions remain broad and underdeveloped. Similarly, the concept of SoS lacks a universally accepted definition, leading the researchers to adopt the Department of Defense (DoD) definition [3].The term "G-QMS in global SoS organizations" was initially introduced to define this research field. However, as Agmon et al. [1] concluded, further refinement of this definition was necessary. In subsequent studies, Agmon and Kordova [2] clarified the terminology to "Global Quality Management System (G-QMS) in the SoS sectors," abbreviated as G-QMS in Sectors of SoS.A System of Systems (SoS) refers to a collection of independent systems that collaborate to achieve overarching objectives, creating capabilities greater than those of any single system [4,5]. For instance, an airport serves as an example of an SoS [2]. Agmon and Kordova [2] emphasized the global deployment of SoS, underscoring the need for a global organizational framework to support intricate integrations beyond individual organizations. Sage and Cuppan [6] further highlighted the multi-organizational structures inherent in SoS, discussing strategies to address their engineering and management challenges.This study defines SoS G-organizations as global entities (G-organizations) with multi-site deployment that require specialized organizational structures. The developed G-QMS model is specifically designed to address the unique requirements of these organizations and is essential for their operations.For SoS, this work adopts the DoD definition [3], focusing on three of its four categories: central management, integration for a special overarching purpose, and consolidation of efforts. Additionally, the term "SoS project" is used to describe a large-scale, comprehensive super-program initiated to realize SoS objectives. SoS projects are governed by a contractual scope and involve multiple agreements among G-organizations. Importantly, these projects conclude with the handover process to the operator organization and do not include the post-delivery operations and maintenance phase.This refined terminology provides a foundation for exploring and developing the G-QMS framework, addressing the specific complexities of SoS G-organizations and enhancing their quality management capabilities.

1.3 Purpose

This innovative research paper introduces a groundbreaking conceptual model for a Global Quality Management System (G-QMS) tailored to the unique challenges of sectors operating within a System of Systems (SoS) framework. The model was meticulously developed through extensive field research conducted within real-world SoS G-organizations. These organizations are characterized by their vast, intricate technological infrastructures and expansive multi-organizational systems.

The proposed model aligns with the requirements and guidelines established by international QMS standards, such as ISO 9001:2015 and ISO 9004:2018, which are widely recognized and implemented across diverse industries. Additionally, the model integrates key Systems Approaches, with a primary focus on Systems Thinking, recognized as a fundamental pillar for the proposed G-QMS architecture.

This research draws on the theoretical foundation laid by Agmon et al. (2022) [1], who identified eight foundational "base anchors" that serve as pivotal elements for this model's development. Through the research process, a two-supra-entity model was conceptualized, each supra-entity encompassing distinct characteristics and functions.

The first supra-entity, termed "G-QMS of G-organization in Sectors of SoS (G-QMS of G-org. of SoS)," was presented in earlier research by Agmon and Kordova (2024) [2] and provided the groundwork for this study. Building upon this foundation, this manuscript introduces a complementary model for the second supra-entity, named "G-QMS in SoS." The interrelationships between these two segment models are explored in detail, offering a holistic view of the overall framework developed for G-QMS in Sectors of SoS.

This model holds significant promise for improving the quality of SoS projects, enhancing operational efficiencies, and fostering collaboration among multiple organizations involved in these complex systems. By addressing the unique quality management challenges posed by SoS, this research aims to contribute to the advancement of both academic knowledge and practical applications in global quality management.

1.4 Literature Review

This literature review synthesizes the evolving and dynamic fields of Quality Management Systems (QMS), Globalization, System of Systems (SoS), and Systems Thinking to establish a foundation for developing a tailored G-QMS model for Sectors of SoS. While Agmon et al. [1] and Agmon and Kordova [2] provided an extensive review in their earlier works, this section narrows the focus to literature pertinent to SoS projects and their unique challenges.

QMS and International Standards

QMS principles are firmly rooted in adherence to international standards, such as ISO 9001:2015 [7] and ISO 9004:2018 [8]. These standards offer a universal benchmark for quality management and certification applicable to diverse organizations. Recent decades have seen the emergence of sector-specific standards, tailored to industries particularly relevant to SoS sectors. Examples include:

- **AS9100** for Aviation, Space, and Defense [9].

- **ISO 13485** for Medical Devices [10].
- **ISO 22163** for Rail organizations [11].
- **IATF 16949** for Automotive [12].

Despite their comprehensive scope, these standards often fall short in addressing the complexities inherent to G-organizations operating within SoS sectors. Specifically, they lack detailed guidance on managing the intricate QMS required for such global entities.

Process Approach and System Maturity

A foundational principle of QMS standards, the Process Approach [7], encounters limitations when applied to the complexity of G-organizations within SoS sectors. To address these limitations, scalable System Approaches are required. Complementary methodologies, such as Business Process Orientation (BPO) [14,15] and Process Maturity, provide frameworks for enhancing process capability and organizational maturity. System Maturity extends these principles further, as promoted by ISO 9004 [16], but a unified methodology for achieving System Maturity remains elusive. Sector-specific standards, such as AIMM for Aerospace [17], are evolving in this direction, yet gaps persist.

Certification Challenges

The prevailing binary certification model—compliance versus non-compliance—proves inadequate for capturing the nuanced requirements of G-organizations in SoS sectors. Furthermore, existing QMS standards lack the necessary specificity to address the organizational structures and unique attributes of SoS projects. This research seeks to bridge these gaps by developing a comprehensive G-QMS model tailored to the complexities of SoS sectors.

Global Organizations and G-QMS

The concept of global organizations, which adapt continuously to meet organizational objectives and global market demands, has evolved significantly over recent decades [18,19]. These entities exhibit dynamic structural configurations reflective of the shifting global business landscape. However, despite its growing relevance, the concept of a Global Quality Management System (G-QMS) remains underexplored in academic discourse.

Instances of QMS applications in global settings are documented [20,21,22,23], but a formalized G-QMS concept has yet to be established. The lack of specific requirements or guidelines for global quality management underscores a critical gap in current standards and research. This absence creates ambiguity regarding the role of globalization in shaping G-QMS frameworks, despite its significant impact on global operations [13,21,24,25].

SoS Projects and G-QMS

SoS projects represent large-scale, comprehensive programs designed to realize SoS objectives. These projects involve extensive contractual arrangements among G-organizations and conclude with the handover process to operator organizations. The challenges associated with managing quality across geographically dispersed operations highlight the need for a cohesive G-QMS framework. This review underscores the complexity and criticality of developing a G-QMS model that addresses the unique demands of SoS sectors. By integrating insights from QMS standards, Systems Thinking, and globalization, this research aims to advance the theoretical and practical understanding of G-QMS in Sectors of SoS. The System of Systems (SoS) domain is increasingly acknowledged for its critical importance, further complicating the landscape of global organizational and quality management. Despite its growing significance, the understanding of SoS remains nascent, as evidenced by ongoing debates regarding its definition, attributes, and implications for organizational frameworks [27-34]. Foundational efforts to formalize SoS concepts are documented in works such as [33,35-38], with recent definitions emerging from ISO/IEC/IEEE 21839:2019 [4] and SEBoK [5]. These describe SoS as a collective of independent constituent systems (CSs) that, when integrated, exhibit capabilities and behaviors surpassing the sum of their isolated potentials. This integration demands a global capability framework and a robust organizational structure, as this study endeavors to explore and project. The distinguishing characteristics of SoS necessitate addressing both technological solutions and the corresponding organizational frameworks. This dual focus has given rise to the intersection of Systems Engineering (SE) and the emergent discipline of System of Systems Engineering (SoSE). SoSE introduces additional complexity, challenging traditional engineering paradigms and necessitating innovative approaches to accommodate the expansive and intricate scope of SoS [5]. Coupled with the backdrop of globalization, these evolving discussions highlight the embryonic stage of research into Global Quality Management Systems (G-QMS), presenting a fertile ground for further inquiry.

SoS Projects and Their Management Challenges

The management of SoS projects—large, comprehensive super-programs designed to realize SoS objectives—requires methodologies distinct from conventional project management approaches. These projects often involve heterogeneous systems, diverse stakeholders, multiple objectives, and varied timelines [29]. Coordination, interoperability, and seamless integration of CSs are critical to SoS project success, requiring navigation of the complexities introduced by interactions among independent CSs. Traditional linear and predictable project management processes are insufficient to address the uncertainties and evolving requirements inherent in SoS projects [39]. Project managers and engineers must adopt adaptive and flexible strategies capable of responding to shifting dependencies, emerging technologies, and dynamic stakeholder demands [40]. Effective integration of autonomous systems is pivotal, demanding robust communication mechanisms, interoperability standards, and integration protocols [32,41]. Furthermore, aligning diverse stakeholder objectives—each potentially driven by unique priorities and success metrics—adds another layer of complexity [29,42].

Systems Approaches and the Evolution of QMS

The foundational Process Approach of QMS standards must expand to incorporate principles from systems theories, particularly those underpinning Systems Thinking. This evolution aligns with the SE discipline, from which SoSE derives its methodologies. Theoretical underpinnings such as General Systems Theory (GST) [43,44], Open Systems [45-47], and Soft Systems [48] provide valuable insights into the QMS domain. QMS, often characterized as a Soft System due to its inherent attributes, benefits from frameworks such as Soft Systems Methodology (SSM), which emphasizes holism, adaptability, stakeholder engagement, and continuous learning [49,50].

For G-QMS in G-organizations within SoS sectors, adopting Systems Approaches is imperative. These perspectives enable navigation through the complexities of SoS by integrating systemic principles into its structures and functionalities. Although SoS is still a relatively new field, limited exploration has been conducted on how Systems Thinking specifically applies to its unique challenges [5]. Systems Thinking, with its holistic view and emphasis on hierarchy, provides a robust framework for addressing the multifaceted nature of global systems [51-58]. This paradigm is particularly relevant for both SoS and G-QMS, as they represent hierarchical systems requiring comprehensive and integrative approaches.

Advancing G-QMS with Systems Thinking

Systems Thinking offers significant potential to enhance G-QMS frameworks by addressing structural, behavioral, dynamic, and relational aspects, including interactions with external environments [59]. By leveraging its interdisciplinary nature, especially within SE, Systems Thinking emerges as a vital contributor to shaping G-QMS structures for SoS sectors [1,2]. The paradigm facilitates the development of encompassing frameworks, advancing the foundational infrastructure required for global quality management.

Although foundational research by Agmon et al. [1] and Agmon and Kordova [2] has laid the groundwork for G-QMS in SoS sectors, the full definition and development of this concept remain incomplete. This gap underscores the high potential and urgency for further exploration and refinement of G-QMS models, particularly as they apply to the complex and evolving domain of SoS. This research aims to bridge these gaps, offering a pathway for advancing global quality management strategies tailored to the unique challenges of SoS environments.

2. Methods and Research Design

This research follows the same methodology outlined in Agmon and Kordova [2], with a detailed description of the methods and research design, including illustrations in the accompanying figures. Below, we provide a concise overview of the key components of the methodology used in this study.

The foundational methodology of this research is **Grounded Theory**, a qualitative approach that emphasizes the inductive generation of theoretical constructs through rigorous analysis of data collected from real-world contexts [63,64,65]. Grounded Theory is particularly suited for this study as it allows for the development of a comprehensive framework for Global Quality Management Systems (G-QMS) in Systems of Systems (SoS), based on empirical data drawn from actual SoS Global (G-) organizations. The absence of a formalized G-QMS framework in these organizations underscores the value of investigating the independent applications within each G-organization, as these can provide the insights necessary for developing a robust body of knowledge. The Grounded Theory methodology is rooted in a **bottom-up** approach to theory construction, where the theory evolves alongside the research process, adapting and refining based on the emerging insights and themes as data analysis progresses [66,67,68].

The **research paradigm** combines an analytical review with structured qualitative research. This integration blends analytical, quantitative, and qualitative methods, as shown in the "Research Design" figure in Agmon and Kordova [2]. The qualitative research component relies heavily on **semi-structured interviews**, while the analytical segment extends into **content analysis**, where both the collected data and supplementary sources—such as literature and organizational documents—are critically examined. The quantitative aspect complements the analytical framework by providing numerical measures, which are used to quantify and score the information, enabling cross-content analysis and enhancing the overall analytical process.

Data Collection and Research Design

The qualitative research component is primarily based on **semi-structured interviews**, where participants are carefully selected based on their alignment with the research field. The interviews are structured within a 4-domain square and 3-dimensional framework, as elaborated in the **Data Structure** section of Agmon and Kordova [2]. This structured approach ensures that the data collected is comprehensive and relevant to the study's goals. The data sources, along with their types, quantities, and scopes, are detailed in the **Data Collection** section of Agmon and Kordova [2]. A uniform methodology was applied to analyze all data sources, enabling a nuanced and thorough understanding of the complex relationships and processes within the study's focus area.

Data Analysis Methodology

The data analysis process employed multiple strategies, using a variety of techniques within **content analysis**. The analysis was conducted in several stages to ensure a deep understanding of the data's significance. Techniques such as **analytical induction**, **constant comparison**, and **quantitative methods** were employed to scrutinize the data for consistency and alignment with the study's objectives. The data was structured into five primary clusters, facilitating a focused and in-depth examination of each, and allowing the research team to explore specific aspects with greater detail and insight. This cluster-based approach enhances the learning potential of the content analysis, providing a more robust and nuanced view of the data.

The content analysis process was organized in a matrix format prior to conducting more advanced stages, such as **cross-content analysis** and **triangulation**. This dual-phase methodology allowed for the synthesis of diverse data elements, helping to reveal a comprehensive understanding of the interconnected categories and their interplay. Triangulation, which involves using multiple data sources to validate findings, played a crucial role in ensuring the reliability and validity of the results [69]. By comparing data from various sources, potential biases were minimized, reinforcing the accuracy and trustworthiness of the conclusions drawn.

Quantitative Analysis and Final Results

The quantitative component of the analysis involved counting and scoring the data at various levels, defining specific assessment scale values for each cluster, and facilitating cross-content analysis. Each parameter was quantified individually for each category and aggregated across the entire dataset, contributing to the depth of the **cross-content analysis** and **triangulation**.

The final results of the analysis were distilled into two key parameters:

1. **Significance Index (Si)** – This was calculated as a weighted average of three critical parameters: **Number of Shows**, **Frequency**, and **Strength**. These parameters quantify the findings and provide a measure of their significance within the research.
2. **Maximum Number of Respondents** – This parameter was expressed in relative terms to further enrich the analysis.

A higher value for these parameters indicates greater validity within a given category, reinforcing the reliability of the analysis. Detailed explanations on how these parameters were defined and quantified can be found in the **Data Analysis** section of Agmon and Kordova [2].

The final phase of the data analysis adopted a **quantitative perspective**, building upon the insights gained from content analysis and enriched by the results of cross-content analysis and triangulation. The results were presented in a unified tabular format, which consolidated the individual cluster findings and provided a comprehensive summary of the study's overall results. This format offers a panoramic view of the data, presenting it in a way that facilitates easy comparison and deeper insights.

Development of the G-QMS Model

In line with the **Grounded Theory** methodology [65,66], the study's findings supported the decision to divide the emerging G-QMS model into two distinct parts. This division reflected the way the data naturally grouped into two separate categories, each requiring a different approach for optimal expression. The extensive and complex nature of the research, coupled with the diverse field of study, facilitated the generation of rich findings that were best represented through these two models. This division allows for clearer communication of the insights and provides a more effective framework for understanding the global quality management needs within SoS.

The research methodology, including the Grounded Theory approach, data collection strategies, and analytical techniques, has been instrumental in developing a robust G-QMS model tailored to the complexities of SoS projects.

This approach has allowed for a comprehensive understanding of the subject matter, ensuring that the resulting model is grounded in empirical data and responsive to the unique challenges posed by global quality management in SoS environments.

3. Results

3.1. Introductory Findings Regarding G-QMS in Sectors of SoS Model

3.1.1. G-QMS in Sectors of SoS—Main Conceptual Structure

The development of a model for **G-QMS in Sectors of SoS** is inherently complex, due to the intricate nature of the systems involved and the challenge of capturing these dynamics within a unified framework. Through the research analysis, a conceptual model has emerged that outlines two primary supra-entities: **G-QMS of G-Organization in Sectors of SoS (G-QMS of G-Org. of SoS)** and **G-QMS in SoS**. These entities represent distinct but interrelated components that together form the foundation of the proposed G-QMS model for SoS sectors.

The first supra-entity, **G-QMS of G-Org. of SoS**, refers to the global quality management system implemented within a specific G-organization operating within a SoS environment. This component focuses on the management and optimization of quality standards within the individual organization, ensuring compliance with established frameworks and the integration of best practices for global operations. The second supra-entity, **G-QMS in SoS**, extends beyond the organizational level to encompass the overarching quality management strategies across the entire System of Systems. This entity addresses the collective coordination, interoperability, and integration of multiple G-organizations and their constituent systems, aimed at achieving global performance standards and fostering collaboration across the network of systems.

As illustrated in **Figure 1**, these two supra-entities are deeply interconnected through a web of relationships, which span both structural and content-based dimensions. The **G-QMS of G-Org. of SoS** lays the groundwork for the internal quality management processes within each organization, while the **G-QMS in SoS** introduces the necessary framework for managing quality across the collective system, bridging gaps and aligning diverse organizational strategies. Together, they form a dynamic, multilayered structure designed to address the complexity and scope of global quality management within SoS environments.

This model highlights the need for a dual focus: one that prioritizes the internal management of quality within individual G-organizations and another that emphasizes the collective, cross-organizational integration necessary for successful SoS projects. The research indicates that the development of such a model is crucial for enhancing coordination, efficiency, and the overall quality outcomes in global projects that span multiple organizations and systems. The comprehensive interrelationships between these two entities form the core of the model, setting the stage for the development of a robust framework for G-QMS in SoS sectors.

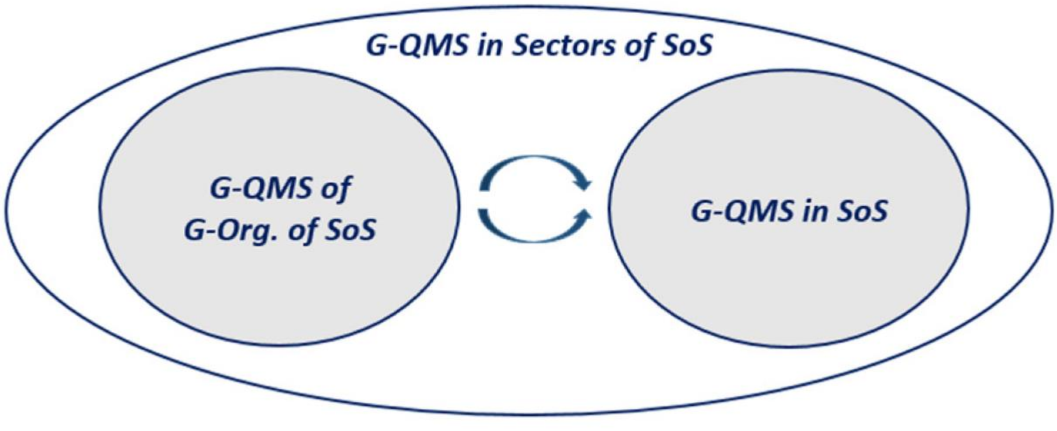

Figure 1. G-QMS in Sectors of SoS model—main conceptual figure. Agmon and Kordova [2].

The **G-QMS of G-Org. of SoS** represents the global quality management system (G-QMS) designed for a G-organization engaged in a System of Systems (SoS) environment. This G-QMS is intricately structured to manage a complex, multi-organizational system, where various G-organizations are coordinated under a unified leadership, responsible for ensuring quality throughout the SoS engagement. This supra-entity encompasses a variety of quality management system (QMS) entities, each addressing distinct aspects of the organization's operations, all aligned under the common framework of global quality standards. The **G-QMS of G-Org. of SoS** provides the foundational infrastructure that supports the overarching G-QMS model within SoS projects. The model presented in **Agmon and Kordova [2]** offers an in-depth exploration of this G-QMS, laying the groundwork for understanding its essential role in ensuring quality across the organization's operations and facilitating the integration of different systems within the SoS.

This foundational model is critical for the development of the **G-QMS in SoS** model, as it provides the necessary structural and content-related components that influence the broader framework. The **G-QMS in SoS** builds upon this infrastructure, incorporating its structural elements to extend quality management practices across the entire system, particularly in the context of multi-organizational collaboration. Understanding the intricacies of the **G-QMS of G-Org. of SoS** is key to navigating the complexities of the G-QMS in SoS model, as both share interrelated components, contributing to the comprehensive approach to quality management across the SoS sector.

The **G-QMS in SoS**, in contrast to the **G-QMS of G-Org. of SoS**, is a temporary supra-entity specifically established for the duration of the SoS project. This model is formed when the SoS project is initiated, structured to reflect the multi-organizational framework required for its execution, and disbands after the project is completed and the system is handed over to the operator organization. Therefore, the scope of the **G-QMS in SoS** does not include post-delivery operations or maintenance processes, which are the responsibility of the operator organization once the SoS project is concluded. Instead, the focus is on ensuring the highest quality standards throughout the project's lifecycle, from its conception to the final delivery.

In practice, the **G-QMS in SoS** often incorporates elements from the **G-QMS of G-Org. of SoS**, with local branches of G-organizations contributing their expertise to the quality management efforts within the SoS project. The **G-QMS in SoS** addresses technological systems relevant to the SoS, requiring specialized quality management knowledge and professionalism tailored to these systems' unique characteristics. Due to the vast scale and complexity of SoS projects, traditional quality management concepts often prove insufficient. As a result, **G-QMS in SoS** must adopt innovative approaches that transcend standard industry practices, forming a higher-order framework that accounts for the multifaceted nature of these projects.

The **G-QMS in SoS** is structured as an independent and expanded entity, encompassing new QMS entities and interfaces. These additional elements are necessary to manage the unique challenges posed by SoS projects, including cross-organizational coordination, system integration, and the management of complex technological infrastructures. This extended QMS structure includes an adaptive set of interfaces, both within the system itself and with external stakeholders, to ensure that quality management processes are not only aligned across organizations but also responsive to the dynamic nature of SoS projects.

Both the **G-QMS of G-Org. of SoS** and the **G-QMS in SoS** adhere to the key principles outlined in **Agmon and Kordova [2]**, which form the foundational basis for the entire model. The integration of these principles ensures a cohesive approach to global quality management within the broader context of SoS sectors, facilitating effective collaboration and quality assurance across all participating organizations. As such, the research presented in this manuscript expands upon the groundwork laid by Agmon and Kordova, offering a comprehensive and cohesive model that spans both the organizational and systemic dimensions of G-QMS in SoS.

2. Discussion: Model for G-QMS in SoS

2.1. Fundamental Principles

2.1.1. A Unique G-Organizational Architecture

The **G-QMS in SoS** operates within a unique organizational architecture that is crafted specifically for each **SoS** project. This architecture is influenced by a variety of factors, including the size and complexity of the systems involved, the specific goals of the **SoS**, and the nature of the stakeholders involved. Since each **SoS** is distinct, the **G-organizational structure** is tailored to meet the specific requirements of that **SoS**, ensuring alignment between the project's objectives and its management structure.

For every **SoS** project, there exists a **chief management structure** that oversees the coordination and alignment of various **CSs** (Constituent Systems). This structure is complemented by various **stakeholder organizations** that influence the project through their expertise, capabilities, and specific roles. These stakeholders include:

- The **client organization**, which sets the project's goals and provides necessary resources.
- **Consulting agencies** that bring in specialized knowledge and expertise.
- **Monitoring and control (M&C) bodies** that ensure compliance with project requirements and standards.

The architecture of the **G-QMS in SoS** is dynamic, with the chief management structure often at the core, exercising a dominant influence over the overall direction of the project. However, as the project progresses, the **CSs** and their management teams increasingly influence the content and interface of the **SoS**. This evolving balance between a central authority and distributed entities makes the **G-QMS** unique to each project.

This interplay between the different entities that form part of the **SoS** project highlights the need for a **structural conceptual model** that can represent the different architectures of **SoS** projects. Such a model would serve as a guide, ensuring that the **G-QMS in SoS** is structured optimally to align with the project's goals and enhance its likelihood of success. The **model** would focus on flexibility and adaptability, allowing for different forms of governance depending on the project's specific needs.

2.1.2. SoS—Term and Attributes

The term **SoS** (System of Systems) is commonly used but lacks a universally agreed-upon definition, as highlighted by the research findings. **SoS** projects are often distinguished from complex systems due to their broader, more dynamic scope, but the line between the two is not always clear. The definition of **SoS** is highly contextual and often depends on the specific sector, organization, or project under consideration. While **SoS** has many forms, it is generally recognized by a unique set of characteristics that set it apart from traditional systems.

The attributes of **SoS** play a critical role in shaping the project and its quality management approach. These attributes include:

- **Emergence**: One of the defining features of **SoS** is the **emergent behavior** that arises from the interaction of different systems. This phenomenon makes it difficult to predict the system's behavior solely based on its individual components. As emergence cannot be fully eliminated, **quality management tools** within the **G-QMS in SoS** must specifically account for its effects. Strategies such as **adaptive management** and **feedback loops** are essential in mitigating the risks posed by emergent behaviors.
- **Scale, Size, and Black-Box Nature**: **SoS** projects are often massive in scale, incorporating multiple **CSs** that are sometimes treated as **black boxes**. This means that the details of certain **CSs**, particularly those that are mature or legacy systems, may not be fully understood or assessed in detail. Instead, these systems are often managed based on predefined risk assessments, with quality measures applied to ensure their integration into the larger **SoS**. The size and scale of the project add to its complexity, as the interactions between numerous systems create intricate interdependencies that must be managed effectively.
- **Connectivity and Interoperability**: Effective management of interfaces between **CSs** is critical for the success of any **SoS** project. This involves ensuring that different systems can communicate and operate together seamlessly. Given that **SoS** projects may involve the integration of new **CSs** or the modification of existing ones, maintaining **dynamic interoperability** is essential. This includes managing **interface requirements** for each **CS** and ensuring that the **SoS** as a whole can function cohesively despite its diverse components.
- **Autonomy**: Many **CSs** in an **SoS** project are not designed specifically for the project but are instead pre-existing systems that must be adapted to meet project requirements. This creates a level of **autonomy** for each system, which means the **SoS** project may have limited control over the design and configuration of each **CS**. This autonomy can create challenges in defining the project's requirements for each **CS**, as they must often be tailored to meet the capabilities and constraints of systems that were not designed with the **SoS** in mind.
- **Different Product Lifecycles**: Another challenge in managing **SoS** projects is the presence of systems that have different lifecycles. Some **CSs** may have been developed many years ago, with outdated or incomplete documentation. This presents a significant challenge for **quality management**, as older systems may not comply with modern standards or regulatory requirements. The **G-QMS in SoS** must incorporate tools and processes to ensure that legacy systems are integrated effectively into the **SoS** while still maintaining the required quality standards.

The **G-QMS in SoS** must be designed to address these unique attributes. This means that traditional quality management frameworks, which are based on standardized systems and processes, will need to be adapted to suit the highly dynamic and complex nature of **SoS** projects. Furthermore, the **G-QMS** will need to embrace new strategies and principles that reflect the complexity and uncertainty inherent in **SoS**.

2.1.3. A 3-Dimensional Quality Concept

The **3-Dimensional Quality Concept** for **G-QMS in SoS**, as illustrated in **Figure 3**, is essential for managing the quality across the various components and interfaces of a **SoS**. Each dimension focuses on a different aspect of quality management, ensuring that the overall system functions as intended while maintaining high standards across the entire project.

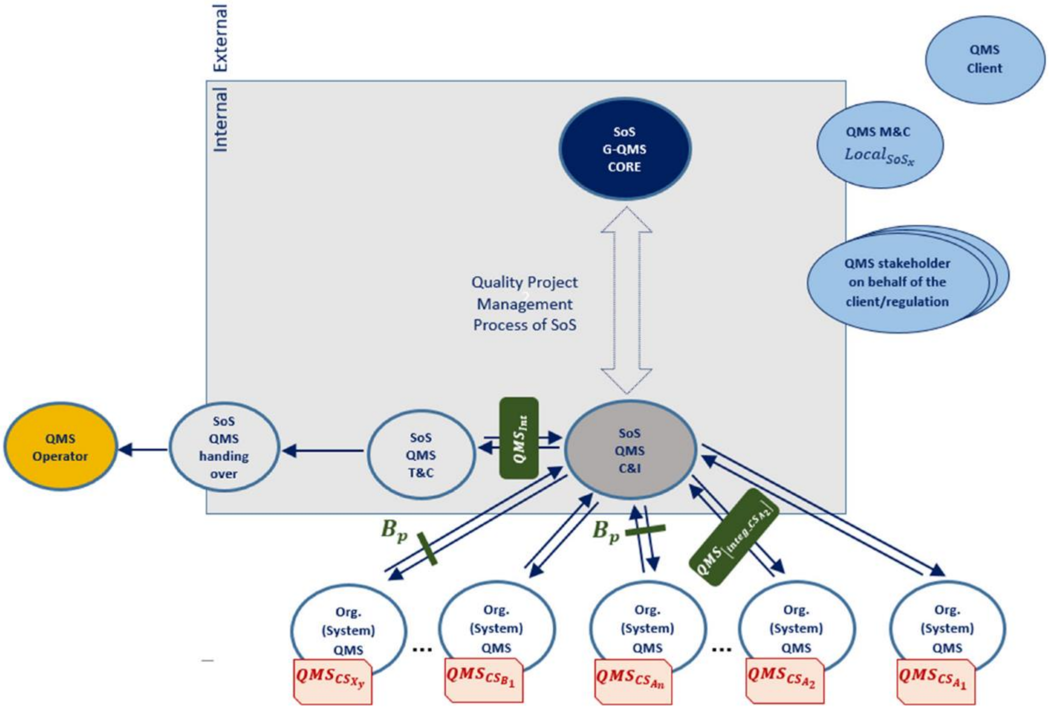

Figure 4. Graphical structure of main QMS entities in G-QMS in SoS.

1. **Quality First Dimension**: This dimension focuses on ensuring that each **CS** adheres to quality standards set by its individual organization's **QMS**. It emphasizes that the **quality** of each component system must be assessed and managed based on the existing **QMS** for that system. This ensures that the foundational quality of each system is in place before addressing the interactions and overall performance of the entire **SoS**.
2. **Quality Second Dimension**: This dimension deals with the **interfaces** between **CSs** and the **SoS**. Effective interface management is essential to ensure that the systems within the **SoS** can interact seamlessly, and that any issues in interoperability are addressed. This dimension involves the **QMS** for managing these interfaces and ensuring that the structure of the **SoS** is robust enough to accommodate these interactions without introducing new risks or inefficiencies.
3. **Quality Third Dimension**: This dimension adds a layer of quality focused on the **systemic attributes** that emerge when multiple **CSs** are integrated into the **SoS**. It addresses the **configuration management (CM)** of each **CS**, as well as the overall **CM** of the **SoS**. In this dimension, the goal is to ensure that the collective behavior of the **SoS** does not introduce systemic risks and that quality is maintained through the management of configurations, system interactions, and overall design.

Together, these three dimensions provide a comprehensive framework for managing quality in **SoS** projects. Each dimension focuses on a different layer of quality management, from individual components to the overall system, ensuring that quality is maintained at every level of the project.

3. Conclusions and Contributions

This manuscript introduces a comprehensive **conceptual model** for **G-QMS in SoS** (Global Quality Management System in Systems of Systems), providing a thorough exploration of its core principles and **QMS entity structures**. It emphasizes the dynamic interactions between these entities, along with their relationship to external elements, including the client commissioning the **SoS** and the broader **global organizational structure** associated with the **SoS** project. The model is framed within the context of **transdisciplinary management**, requiring high levels of **expertise in quality management** and an **independent organizational structure**.

A key feature of the model is the proposed method for operationalizing quality management through the creation of an **Integrated Project Team (IPT)** work concept, offering a practical approach to managing quality across multiple, interconnected systems. Additionally, the **QMS entities**, which include **QMSCSs** (Quality Management Systems for Constituent Systems), are integral to the model, with the classification key serving as an essential quality management tool.

The model extends traditional **QMS frameworks**—which are generally aligned with international **QMS standards**—by incorporating necessary adjustments that are specific to **SoS** projects. It integrates processes from **Systems Engineering** and **Systems Thinking** methodologies, reflecting the complex and evolving nature of **SoS** environments. The outcome is a cohesive framework for implementing **G-QMS in SoS**, which is crucial for the success of **SoS** projects and makes meaningful contributions to the field of quality management in **SoS** projects.

This conceptual model serves as a guide for **quality management bodies** seeking to establish a **G-QMS** for **SoS** projects. It highlights critical, yet often underexplored, domains of **quality management** that, if further developed, could significantly enhance the quality contributions in **SoS** initiatives. The model also provides insights into structuring the **G-organizational** and **functional architecture** of **SoS** projects, with particular emphasis on the role of the **SoS G-QMS CORE leader** within the project's **chief management trio**.

With the completion of this model and its connections to the **G-QMS of the G-organization of SoS** model, we now have a well-defined conceptual framework for **G-QMS in Sectors of SoS**.

Research Limitations and Directions for Future Research

The development of this pioneering **conceptual model** for **G-QMS in Sectors of SoS** marks the beginning of an exciting new avenue for research. Several areas warrant further exploration to expand on the foundation laid in this study.

1. **Further Exploration of Model Elements**: Future research could delve deeper into the various components of the model. This would provide detailed guidance for relevant **organizational quality bodies**, contributing to the establishment of **updated QMS standards**. For instance, further work could focus on the development of **QMSinteg** and its associated **QMSint** entities. Tools from **Systems Thinking**, such as **Causal Loop Diagrams (CLD)** or **Systemigrams**, could provide valuable insights into these aspects.
2. **Development of Specialized Tools**: The model introduces several **extended quality management tools** specific to the **SoS** domain, as well as an illustration of a **conceptual quality process structure** for **SoS** projects. Future studies could focus on identifying and developing additional quality tools that can enhance the model's applicability. These advancements could not only benefit **G-QMS in Sectors of SoS** but also extend to other sectors that implement similar **G-QMS** frameworks.
3. **Case Studies and Sector-Specific Models**: Given the **adaptability** of the **G-QMS in SoS** model to various **G-organizations** and **SoS projects**, future research could include case studies of specific projects, organizations, or sectors. These case studies could enrich the model by tailoring it to the unique characteristics and challenges of individual projects or industries. Insights from these cases could lead to refinements of the model, improving its effectiveness across different contexts.
4. **Quantitative Validation**: While the current model was developed through qualitative research methods, future studies could build on this work by validating the model using **quantitative** approaches. Techniques such as **Bayesian machine learning models** and **Bayesian algorithms** could be utilized to enhance the accuracy of quality management systems and data analysis. These models would provide more precise insights into the functioning of the **G-QMS in SoS** and could support decision-making with greater confidence.
5. **Artificial Intelligence (AI) Integration**: With the rapid advancements in **Artificial Intelligence (AI)**, future research could explore the integration of **AI technologies** into the **quality management process** for **SoS** projects. AI could assist in managing and analyzing large volumes of qualitative data, improving the efficiency and accuracy of data collection and analysis. Moreover, AI could be employed to enhance the quality of research methodologies themselves, leading to more robust findings and further advancing the field.

In conclusion, while this work lays the groundwork for a robust **G-QMS in SoS** model, future research will be instrumental in refining the model and broadening its applicability across various sectors and organizational contexts. The integration of new tools, methodologies, and technologies will likely play a crucial role in the evolution of this emerging field of study.

References

1. Agmon, N.; Kordova, S.; Shoval, S. Global Quality Management System (G-QMS) in Systems of Systems (SoS)—Aspects of Definition, Structure and Model. *Systems* 2022, *10*, 99.
2. Agmon, N.; Kordova, S. Model for Global Quality Management System in System of Systems. *Appl. Syst. Innov.* 2024, *7*, 72. [] []

3. Office of the Director, Defense Research and Engineering, Director of Systems Engineering. *Systems Engineering Guide for Systems of Systems: Summary*; Defense Pentagon: Washington, DC, USA, 2010. []
4. *ISO/IEC/IEEE 21839:2019*; Systems and Software Engineering—System of Systems (SoS) Considerations in Life Cycle Stages of a System. ISO: Geneva, Switzerland, 2019.
5. Guide to the Systems Engineering Body of Knowledge (SEBoK), Version 2.8. 2023. Available online: www.sebokwiki.org (accessed on 10 September 2023).
6. Sage, A.P.; Cuppan, C.D. On the Systems Engineering and Management of Systems of Systems and Federations of Systems. *Inf. Knowl. Syst. Manag.* 2001, *2*, 325–345. []
7. *ISO 9001:201*; Quality Management Systems—Requirements. International Organization of Standardization: Geneva, Switzerland, 2015.
8. *ISO 9004:201*; Quality Management—Quality of an Organization—Guidance to Achieve Sustained Success. International Organization of Standardization: Geneva, Switzerland, 2018.
9. *AS9100*; Aerospace Standard, Management Systems—Requirements for Aviation, Space, and Defense Organizations. SAE International: Warrendale, PA, USA, 2016.
10. *ISO 13485:2016*; Medical Devices—Quality Management Systems—Requirements for Regulatory Purposes. International Organization of Standardization: Geneva, Switzerland, 2016.
11. *ISO/TS 22163:2017*; Railway Applications—Quality Management System—Business Management System Requirements for Rail Organizations: ISO 9001:2015 and Particular Requirements for Application in the Rail Sector. International Organization of Standardization: Geneva, Switzerland, 2017.
12. *IATF16949:2016*; Quality Management Systems Standard for the Automotive Industry. IATF-International Automotive Task Force: Sydney, NSW, Australia, 2016.
13. Bashan, A.; Notea, A. A hierarchical model for quality management systems in global organizations. *Int. J. Qual. Reliab. Manag.* 2018, *35*, 1380–1398. []
14. Farazmand, E.; Moeini, A.; Sohrabi, B. Main Categories of Information Technologies Systems Regarding Process Orientation and Knowledge Orientation. In Proceedings of the 6th WSEAS International Conference on Mathematics and Computers in Business and Economics (MCBE'05), Buenos Aires, Argentina, 1–3 March 2005; D'Attelis, C., Saint-Nom, R., Mastorakis, N., Eds.; WSEAS Press: Athens, Greece, 2005. []
15. McCormack, K. Business Process Orientation: Do you Have It! *Qual. Prog.* 2001, *34*, 51–58. []
16. Chrissis, M.B.; Konrad, M.; Shrum, S. *CMMI for Development: Guidelines for Process Integration and Product Improvement*, 3rd ed.; Addison-Wesley: Westford, MA, USA, 2012. []
17. IAQG. AIMM. 2021. Available online: https://iaqg.org/ (accessed on 20 November 2023).
18. Demeter, K. Research in Global Operations Management: Some Highlights and Potential Future Trends. *J. Manuf. Technol. Manag.* 2017, *28*, 324–333. [] []
19. Sambharya, R.B.; Contractor, F.J.; Rasheed, A.A. Industry globalization: Construct, measurement and variation across industries. *Multinatl. Bus. Rev.* 2022, *30*, 453–470. [] []
20. Bashan, A.; Armon, B. Quality management challenges in a dynamic reality of mergers, acquisitions and global expansion. *Int. J. Qual. Reliab. Manag.* 2019, *36*, 1192–1211. [] []
21. Kim, K.Y.; Chang, D.R. Global Quality Management: A Research Focus. *Decis. Sci.* 1995, *26*, 561–568. [] []
22. Mehra, S.; Agrawal, S.P. Total quality as a new global competitive strategy. *Int. J. Qual. Reliab. Manag.* 2003, *20*, 1009–1025. [] []
23. Srinivasan, A.; Kurey, B. Creating a culture of quality. *Harv. Bus. Rev.* 2014, *92*, 23–25. [] [PubMed]
24. Barabasi, A.L.; Frangos, J. *The New Science of Networks Science of Networks*; Basic Books: New York, NY, USA, 2014. []
25. Troshkova, E.V.; Levshina, V.V. Quality Management System of Complex Economic Entity as Organizational Innovation. *Int. J. Qual. Res.* 2018, *12*, 193–208. []
26. Steven, A.B.; Dong, Y.; Corsi, T. Global sourcing and quality recalls: An empirical study of outsourcing supplier concentration-product recalls linkages. *J. Oper. Manag.* 2014, *32*, 241–253. [] []
27. Albers, A.; Mandel, C.; Yan, S.; Behrendt, M. System of Systems Approach for the Description and Characterization of Validation Environments. In Proceedings of the DESIGN 2018 15th International Design Conference, Dubrovnik, Croatia, 21–24 May 2018. [] []

28. Azarnoush, H.; Horan, B.; Sridhar, P.; Madni, A.M.; Jamshidi, M. Towards optimization of a real-world robotic-sensor system of systems. In Proceedings of the World Automation Congress (WAC), Budapest, Hungary, 24–26 July 2006. []
29. Gorod, A.; Sauser, B.; Boardman, J. System-of-Systems Engineering Management: A Review of Modern History and a Path Forward. *IEEE Syst. J.* 2008, *2*, 484–499. [] []
30. Keating, C.; Rogers, R.; Unal, R.; Dryer, D.; Sousa-Poza, A.; Safford, R.; Peterson, W.; Rabaldi, G. Systems of Systems Engineering. *Eng. Manag. J.* 2003, *15*, 36–45. [] []
31. Kotov, V. *Systems of Systems as Communicating Structures*; Hewlett Packard: Palo Alto, CA, USA, 1997. []
32. Maier, M.W. Architecting Principles for Systems-of-Systems. *Syst. Eng.* 1999, *1*, 267–284. [] []
33. Shenhar, A.J.; Sauser, B. Systems engineering management: The multidisciplinary discipline. In *Handbook of Systems Engineering and Management*, 2nd ed.; Wiley: New York, NY, USA, 2008. []
34. Vargas, I.G.; Braga, R.T.V. Understanding System of Systems Management: A systematic Review and Key Concepts. *IEEE Syst. J.* 2022, *16*, 510–519. [] []
35. Department of Defense. *System of Systems, Systems Engineering Guide: Considerations for Systems Engineering in System of Systems Environment*; Department of Defense: Washington, DC, USA, 2017. []
36. Eisner, H.; Marciniak, J.; McMillan, R. Computer-aided system of systems (C2) engineering. In Proceedings of the IEEE International Conference on Systems, Man, and Cybernetics, Charlottesville, VA, USA, 13–16 October 1991. []
37. Eisner, H.; McMillan, R.; Marciniak, J.; Pragluski, W. RCASSE: Rapid computer-aided systems of systems (S2) engineering. In Proceedings of the INCOSE 3rd International Symposium Engineering, Crystal City, VA, USA, 26–28 July 1993. []
38. Shenhar, A.J. A new systems engineering taxonomy. In Proceedings of the 4th International Council on Systems Engineering, St. Louis, MO, USA, 22–26 July 1995; pp. 723–732. []
39. DeLaurentis, D.; Callaway, R. A System-of-Systems Perspective for Public Policy Decisions. *Rev. Policy Res.* 2004, *21*, 829–837. [] []
40. Nielsen, C.B.; Larsen, P.G.; Fitzgerald, J.; Woodcock, J.; Peleska, J. Systems of Systems Engineering: Basic Concepts, Model-Based Techniques, and Research Directions. *ACM Comput. Surv.* 2015, *5*, 1–41. [] []
41. Weiler, M.; Siton, M.; Reuvani, E. *A Critical Examination of Work Methodology for Systems Engineering Processes in Unsynchronized System of Systems, Version 8.0*; Gordon Center for Systems Engineering, Technion: Haifa, Israel, 2012. []
42. Sousa-Poza, A.; Kovacic, S.; Keating, C.B. System of systems engineering: An emerging multidiscipline. *Int. J. Syst. Syst. Eng.* 2008, *1*, 1–17. [] []
43. Von Bertalanffy, L. *General System Theory*; George Brazilier: New York, NY, USA, 1968. []
44. Von Bertalanffy, L. The Meaning of General System Theory. In *General System Theory: Foundations, Development, Applications*; George Brazilier: New York, NY, USA, 1973; pp. 30–53. []
45. Azani, C. *A Multi-Criteria Decision Model for Migrating Legacy System Architectures into Open Systems and Systems-of-Systems Architectures*; Defense Acquisition University: Washington, DC, USA, 2009. []
46. Hitchins, D. What are the general principles applicable to systems? *INCOSE Insight* 2009, *12*, 59–63. [] []
47. Wells, G.D.; Sage, A.P. Engineering of a System of Systems. In *Systems of Systems Engineering—Principles and Applications*; CRC Press: Boca Raton, FL, USA, 2009. []
48. Wilson, B. *Soft Systems Methodology Conceptual Model Building and Its Contribution*; Wiley: Hoboken, NJ, USA, 2001; ISBN 471-89489-3. []
49. Checkland, P. *Systems Thinking, Systems Practice*; Wiley: Hoboken, NJ, USA, 1999; ISBN 0-471-98606-2. []
50. Burge, H. An Overview of the Soft Systems Methodology, System Thinking: Approaches and Methodologies. 2015. Available online: https://eindhovenengine.nl/wp-content/uploads/2023/01/Soft-Systems-Methodology-source-2.pdf (accessed on 20 November 2023).
51. Anderson, V.; Johnson, L. *Systems Thinking Basics from Concepts to Causal Loops*; Pegasus Communications, Inc.: Cambridge, UK, 1997. []
52. Boardman, J.; Sauser, B. *Systems Thinking: Coping with 21st Century Problems*; Taylor & Francis: Boca Raton, FL, USA, 2008. []

53. Cabrera, D.; Colosi, L.; Lobdell, C. Systems Thinking. *Eval. Program Plan.* 2008, *31*, 299–310. [] []
54. Checkland, P.B. *Systems Thinking, Systems Practice*; John Wiley & Sons: Chichester, UK, 1981. []
55. McDermott, T.; Freeman, D. Systems Thinking in the Systems Engineering Process: New Methods and Tools. In *Systems Thinking: Foundation, Uses and Challenges*; Nova Science Publishers: New York, NY, USA, 2016. []
56. Monat, J.P.; Gannon, T.F. What is Systems Thinking? A Review of Selected Literature Plus Recommendations. *Am. J. Syst. Sci.* 2015, *4*, 11–26. []
57. Richmond, B. Systems thinking: Critical thinking skills for the 1990s and beyond. *Syst. Dyn. Rev.* 1993, *9*, 113–133. [] []
58. Senge, P.M. *The Art and Practice of the Learning Organization*; Doubleday: New York, NY, USA, 1990. [] []
59. Ackoff, R.L.; Addison, H.J.; Carey, A. *Systems Thinking for Curious Managers*; Triarchy Press Limited: Axminster, UK, 2010. []
60. Bashan, A.; Kordova, S. Globalization, quality and systems thinking: Integrating global quality Management and a systems view. *Heliyon* 2021, *7*, e06161. [] [] [PubMed]
61. Nagahi, M.; Hossain, N.U.I.; Jaradat, R.; Goerger, S.R.; Abutabenjeh, S.; Kerr, C. Do the Practitioners Level of Systems-Thinking Skills Differ Across Sector Types? In Proceedings of the 14th Annual IEEE International Systems Conference, Montreal, QC, Canada, 24–27 August 2020. []
62. Valerdi, R.; Rouse, W.B. When Systems Thinking Is Not a Natural Act. In Proceedings of the 2010 IEEE International Systems Conference, San Diego, CA, USA, 5–8 April 2010. [] []
63. Creswell, J.W. *Research Design: Qualitative, Quantitative, and Mixed Methods Approaches*, 4th ed.; SAGE: Thousand Oaks, CA, USA, 2013. []
64. Glaser, B. *Theoretical Sensitivity: Advances in the Methodology of Grounded Theory*; Sociological Press: Mill Valley, CA, USA, 1978. []
65. Glaser, B.G.; Strauss, A.L. *The Discovery of Grounded Theory: Strategies for Qualitative Research*; Transaction Publishers: Piscataway, NJ, USA, 2009. []
66. Yehoshua, N.S.B. *Qualitative Research in Teaching and Learning*; Modan: Ben Shemen, Israel, 1995. []
67. Yehoshua, N.S.B. *Traditions and Genres in Qualitative Research. Philosophies, Strategies and Advanced Tools*; Mofet Institution: Tel Aviv, Israel, 2016. []
68. Strauss, A.; Corbin, J.M. *Basics of Qualitative Research: Grounded Theory Procedures and Techniques*; Sage: Newbury Park, CA, USA, 1990. []
69. Patton, M.Q. Two decades of developments in qualitative inquiry: A personal, experiential perspective. *Qual. Soc. Work* 2002, *1*, 261–283. [] []
70. Dahmann, J. System of Systems Pain Points. In *INCOSE International Symposium*; INCOSE: Las Vegas, NV, USA, 2014; Volume 24, pp. 108–121. [] []
71. Billaud, S.; Daclin, N.; Chapurlat, V. Interoperability as a Key Concept for the Control and Evolution of the System of Systems (SoS). In Proceedings of the 6th International IFIP Working Conference, Nîmes, France, 28–29 May 2015; Volume 213, pp. 53–63. [] []
72. Ford, T.C.; Colombi, J.M.; Graham, S.R.; Jacques, D.R. The interoperability score. In Proceedings of the Fifth Annual Conference on System Engineering Research, Hoboken, NJ, USA, 14 March 2007; pp. 1–10. []
73. Sahin, F.; Jamshidi, M.; Sridhar, P. A Discrete Event XML based Simulation Framework for System of Systems Architectures. In Proceedings of the IEEE International Conference on System of Systems, San Antonio, TX, USA, 16–18 April 2007. []
74. Abel, A.; Sukkarieh, S. The Coordination of Multiple Autonomous Systems using Information Theoretic Political Science Voting Models. In Proceedings of the IEEE International Conference on System of Systems Engineering, Los Angeles, CA, USA, 24–26 April 2006. []