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Model for Global Quality Management System in System of Systems: Quality Management in System of Systems Project

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Abstract: *Global Quality Management System (G-QMS) in System of Systems (SoS)* is a pioneering field of research essential for SoS G-organizations, which are characterized by their vast and complex technological systems and multi-organizational structures. Consequently, presenting significant challenges in implementing effective QMS for their operations. This manuscript completes the development of a novel conceptual model for *G-QMSs in Sectors of SoS*, drawing from extensive field research conducted within real SoS G-organizations employing the Grounded Theory methodology. This proposed model encompasses two foundational supra-entities, with this manuscript primarily dedicated to the second supra-entity, named "*G-QMS in SoS*", which essentially represents Quality Management for SoS projects. The G-QMS in SoS model image is conceived through a description of its structural principles, entities architecture and interrelationships, alongside its complementary elements. Furthermore, the interrelationships between the two segment models that constitute G-QMS in Sectors of SoS are elucidated, offering a comprehensive view of the overarching model. Establishing a model for G-QMS in Sectors of SoS that describes the various structures of SoS projects and the G-organizations realizing them, as well as understanding the recommended G-QMS model, is vital as it directly impacts the success level of SoS projects and the effectiveness of the tailored G-QMS in these organizations.

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

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1. Introduction

1.1. Rationale

Quality Management System (QMS) in organizations for System of Systems (SoS) is required for highly complex professional applications necessitating adaptation in appropriate organizational structures. A SoS is characterized by highly complex technological solutions, typically on a large scale, based on the synergy of multiple systems and technologies. Correspondingly, its organizational systems exhibit a high degree of complexity, including sub-organizations and sub-structures generally across various geographical locations, thereby constituting global organizational systems. Such organizations require an efficient and effective organizational system capable of operating the structural and global system in a multifaceted, demanding, and continuously evolving landscape, marked by rapid technological advancements and diverse operational environments. Accordingly, as introduced in previous works of Agmon et al. [1] and Agmon and Kordova [2], their QMS must support both the current dynamic complexities and future adaptations. It should align with customer demands and comply with regulatory and standards requirements, all the while also adding value to the organization by being a superlative, customized QMS. This research delves into the Global Quality Management System (G-QMS) for organizations operating within the realms of SoS, often global organizations (G-organizations)—having multi-site deployment across the globe, necessitating a QMS framework that is both adaptive and comprehensive. This is a novel field of academic research that holds substantial relevance for these G-organizations, which are addressing specific challenges in quality management. To address this complexity, it is essential firstly to establish clear terminology.

1.2. Terminology and Definitions

Here, we provide elucidations regarding the outlined field of research for a *Global Quality Management System (G-QMS) in System of Systems (SoS)*, and the terminology and definitions underlying it. Agmon et al. [1] discussed global organizations that still have a highly broad definition and their organizational impacts that are yet to be fully explored. Likewise, they discussed the SoS that lack an agreed definition, and so adopted the definition proposed by DoD [3]. The term "*G-QMS in global SoS organizations*" was named to define the research field, but still, it remains a term that is not fully defined. Agmon et al. [1] concluded in their exploratory study that a more cohesive definition will be needed for further development. Indeed, in further work on the model's development, Agmon and Kordova [2] refined the field of research terminology to be *Global Quality Management System (G-QMS) in the SoS sectors*, and in abbreviated term, ***G-QMS in Sectors of SoS***.

The concept of "System of Systems" (SoS) refers to an ensemble of autonomous systems that collaborate to achieve overarching objectives, generating capabilities that surpass the potential of any individual system [4,5], and an airport is given as an example of SoS [2]. Respectively, Agmon and Kordova [2] emphasize the global deployment of the SoS, necessitating that "*beside the technological solution, a global organizational framework [is needed] to support such intricate integrations. Correspondingly, the multi-organizational structures that are built for the common purpose of the SoS require a reference that goes beyond the organizations*". An expansion is provided by Sage and Cuppan [6], who review aspects with regard to the SoS's multi-organizational structures, noting strategies for their engineering and management challenges. Like Agmon and Kordova [2], we term these *SoS G-organizations*—global organizations (G-organizations) having multi-site deployment across the globe, necessitating an adapted organizational structure. Accordingly, the developed model is defined as a global QMS (G-QMS) which is adapted to such SoS G-organizations, moreover, one that is essential to these organizations. With regard to *SoSs*, which have extensive modes of expression, the DoD definition [3] has been adopted. In this work, we especially relate to three of the definition's four categories, in which the SoS own central management, and it consolidates for a special overarching purpose. Lastly, in addition to the definition phrase with respect to SoS's global deployment and its technological solution, in this work, we use the term *SoS project* to describe a large and comprehensive super-program implemented to realize SoS. The SoS project is initiated to realize SoS in accordance with a contract scope set by its terms and conditions. However, in the SoS project, there is an extensive set of contracts that are signed among the G-organizations. Also, the SoS project does not include the operations and maintenance phase (post-delivery) by the operator but concludes with the completion of the handover process to the operator organization.

1.3. Purpose

This innovative research paper introduces a conceptual model for ***G-QMS in Sectors of SoS*** that has been developed through extensive field research conducted within real-world SoS G-organizations. This endeavor aligns with the established QMS requirements and guidelines, as delineated by international standards, which are widely recognized and implemented across organizations. Additionally, the model integrates pertinent Systems Approaches, chiefly Systems Thinking, identified as vital for the proposed G-QMS structure. Furthermore, it considers the theoretical foundation created by Agmon et al. (2022) [1], which defined eight base anchors pivotal for this model. SoS G-organizations are characterized by their vast and intricate technological systems and expansive multi-organizational structures; consequently, through the research process, a model delineated by two foundational supra-entities was conceptualized, each with its distinct characteristics and functions. The first supra entity, named "***G-QMS of G-organization in Sectors of SoS (G-QMS of G-org. of SoS)***" presented in Agmon and Kordova (2024) [2], laid the groundwork for this study. In this manuscript, we delve into a complementary model for the second supra-entity, termed "***G-QMS in SoS***", and further elucidate the interrelationships between these two segment models, thereby offering a complete portrayal of the model developed for G-QMS in Sectors of SoS. This model has the potential to improve quality in SoS projects and facilitate collaboration among multiple organizations.

1.4. Literature Review

This review, in base the exploration of G-QMS in SoS, integrates the dynamic and evolving disciplines of *QMS*, *Globalization*, *SoS*, and *Systems Thinking*. This emerged amalgamation formulates this pioneering field of research, setting the foundations for the development of a model tailored for G-QMS in Sectors of SoS. A similar and even more extended review was provided by us in Agmon et al. [1] and Agmon and Kordova [2]. However, in this literature review, the relevant literature to the *SoS project* is addressed.

QMS is based on compliance with the international standards requirements, which establish the best global standard for quality management and certification. ISO 9001:2015 [7] stands as a pivotal standard, with ISO 9004:2018 [8] expanding with additional guidance, while both are applicable to a diverse range of organizations. Over recent decades, the emergence of sector-specific standards, built upon ISO 9001, has been notable, particularly relevant to SoS sectors. Notable sectorial QMS standards include AS9100 for Aviation, Space, and Defense (Aerospace) organizations [9]; ISO 13485 tailored for the Medical Device sector [10]; ISO 22163 designed for Rail organizations [11]; and IATF16949 for the Automotive industry [12]. However, these standards, while expansive, typically lack in addressing the complexities of G-organizations within SoS sectors given their intricate QMS.

The ***Process Approach***, which is a foundational principle of the QMS standards [7] and similar standards, faces limitations in addressing the process complexity inherent in global organizations [13], but necessitates a scalable ***System Approach*** to navigate G-organizations in SoS sectors. In addition, methodologies such as *Business Process Orientation (BPO)* [14,15] and *Process Maturity* are incorporated alongside the Process Approach. Schematically, *System Maturity* extends Process Maturity, providing a framework for enhancing organizational maturity and process capability [14]. Yet, a unified methodology for System Maturity remains elusive. ISO 9004 promotes System Maturity [16], with sectorial standards also evolving in this direction, such as AIMM for the Aerospace sector [17]. The second aspect lies in the certification method for the standard.

The prevailing method for QMS certification, based on a binary model (compliance or non-compliance), proves inadequate for capturing the essential elements concerning G-organizations in SoS sectors. Moreover, the current QMS standards lack the detailed references necessary to address the organizational frameworks and the unique attributes and characteristics of SoS, highlighting a gap that this research aims to bridge by developing a comprehensive G-QMS model suited for the complex landscape of SoS sectors.

The concept of **global organizations**, embodying a wide array of structures that continually adapt to organizational objectives and global market demands, despite its emergence in recent decades, remains a subject of extensive exploration [18,19]. These organizations exhibit a dynamic evolution in their structural configurations, reflecting the diverse and shifting nature of global business landscapes.

In parallel, the notion of a G-QMS has surfaced, albeit with limited academic discourse to date. Instances of QMS applications within global settings are noted [20–23], yet a formalized concept of G-QMS remains elusive. Moreover, in the context of QMS international standards this absence is striking since these are also applicable to the global organizations. The burgeoning field of G-QMS research hints at significant untapped potential, marked by a nascent body of work [13,21,24,25]. The challenges inherent in managing quality across geographically dispersed operations underscore the complexity and criticality of developing a coherent G-QMS framework [26]. The lack of a global quality management strategy, including required requirements or guidelines, casts ambiguity on the potential contributions of globalization to the G-QMS model despite the significant impact and importance of globalization. This absence provides a foundation for further exploration and elaboration to better fathom the role globalization plays within the G-QMS paradigm.

The **SoS** domain, recognized for its growing significance, further complicates the global organizational and quality management landscape. The current literature reveals an embryonic understanding of SoS, with ongoing debates surrounding its definition and organizational implications [27–34]. Efforts to formalize SoS concepts can be found in [33,35–38]. Recently, as seen in ISO/IEC/IEEE 21839:2019 [4] and SEBok [5], SoS has been described as a collection of independent constituent systems (CSs), that, when integrated, unveil capabilities, as well behaved, beyond their isolated potential. Especially, these are a global capability and behavior, necessitating a global organizational framework to support such intricate integrations, which this study projects on. The SoS has distinguished attributes and characteristics that require reference to the technological solution and therefore, also the organizational structure. The intersection of Systems Engineering (SE) and the emergent field of System of Systems Engineering (SoSE) introduces a new layer of complexity, challenging the current engineering paradigms to accommodate the expansive scope of SoS [5]. This backdrop of globalization, coupled with the evolving discourse on SoS and the embryonic stage of G-QMS research, presents a compelling canvas for further inquiry.

With regard to ***SoS project*** that refers to a large and comprehensive super-program implemented to realize SoS, the management of SoS projects necessitates distinct methodologies, differing from traditional project management approaches, as these projects often involve heterogeneous systems, diverse stakeholders, multiple objectives, and varied timelines [29]. Moreover, the coordination, interoperability, and seamless integration of CSs are critical for the SoS project engineering and management, and necessitate competent navigation within the complexity obtained by the interactions among independent SCs. Conventional project management methodologies, which typically rely on linear and predictable processes, are inadequate for handling such complexity [39]. Consequently, project managers and engineers are required to employ flexible and adaptive strategies that can address evolving requirements, uncertain interdependencies, and the incorporation of emerging technologies [40]. The integration of these autonomous systems represents a fundamental and pivotal component of SoS program management. This process frequently demands the facilitation of effective communication among systems, necessitating a thorough understanding of interoperability standards and integration protocols [32,41]. Another aspect lies in the alignment of diverse stakeholder objectives, each potentially driven by different priorities and success criteria, which introduces further complexity to the management of SoS projects [29,42].

Expanding the Process Approach foundational to QMS standards necessitates integration with systems theories principles that underpin **Systems Thinking**. This alignment is intrinsic to the SE discipline, from which SoSE evolves. These approaches are based on the Systems Theories that can be traced back to *General Systems Theory (GST)* [43,44], with subsequent developments leading to concepts such as *Open Systems* [45–47] and *Soft Systems* [48]. Each brings valuable insights into the QMS domain, often perceived as Soft Systems due to their inherent characteristics and the nature of their contents. Thus, also *Soft Systems Methodology (SSM)* accentuates holism, adaptability, stakeholder engagement, and continuous learning, thereby offering a pragmatic framework for applying systems principles in complex, real-world contexts [49,50].

When dealing with G-QMS in G-organizations for SoS, it is vital to include Systems Approaches. This integration necessitates the adoption of these systemic perspectives and tools into the structures and characteristics of SoS to effectively navigate the complexities inherent in SoS. However, since SoS is a relatively new area, the exploration of how Systems Thinking might extend to SoS-specific issues remains limited [5] although imperative. With this regard, Systems Thinking is an approach to handling global systems, which considers the components of the system as an ensemble, as a *whole* in a *holistic* way, but also using the principle of *hierarchy* [51–58]. Respectively, the concept and principles of Systems Thinking can be applied within both SoS and G-QMS since they should also be considered as a hierarchical system that requires a holistic view. The Systems Thinking paradigm has the potential to significantly enhance the foundational infrastructure for developing encompassing frameworks by addressing aspects such as structure, motion, behavior, dynamics, and interrelations, including those with the external environment [59]. This approach harbors the potential to advance global quality management exploration [60–62], and due to its interdisciplinary nature, especially within SE, it positions itself as a vital contributor to shaping G-QMS frameworks for SoS sectors [1,2]. Although the foundational research by Agmon et al. [1] and Agmon and Kordova [2] has laid the groundwork for G-QMS in SoS sectors, its full definition and development have not yet been completed, while it harbors a high incentive for further exploration and advancement.

2. Methods and Research Design

This manuscript is subjected to the same methodology detailed in Agmon and Kordova [2], where the methods and research design are fully described, including illustration through figures. Hereinafter, we provide a concise summary of their main points.

The Grounded Theory, a prominent methodology in qualitative research, facilitates the inductive derivation of theoretical constructs through a meticulous analysis of data gleaned from the field [63–65]. This methodology underpinning the development of this model is rooted in comprehensive field research conducted within actual SoS G-organizations. The lack of a formalized G-QMS framework within such organizations underscores the importance of the independent applications unique to each G-organization for developing the body of knowledge. This methodology is committed to a bottom-up methodical explication of phenomena, aimed at theory construction, while it evolves in tandem with the research process and analysis phases, allowing for adjustments and refinements into the theory that is being built based on the insights and themes that emerge during the analytical phases [66–68].

The research paradigm combines *analytical review* and *structured qualitative research*, by integrating *analytical*, *quantitative*, and *qualitative* methods, as depicted in the "Research Design" figure of Agmon and Kordova [2]. The qualitative research segment is anchored in semi-structured interviews, while the analytical component extends to content analysis, examining both the collected data and supplementary sources like the relevant literature and internal organizational documents. The quantitative facet enhances the analytical framework by counting and scoring the obtained information, establishing assessment scales, and facilitating cross-content analysis. The structured qualitative research is primarily based on semi-structured interviews, with interviewees meticulously selected in alignment with the research field, structured within a **4-domain square and 3-dimensional structure** (as explained and illustrated in the Data Structure sub-chapter of Agmon and Kordova [2]). The data sources, their type, quantity, and scope are detailed in the data collection sub-chapter of Agmon and Kordova [2]. All the sources were analyzed with a uniform methodology that facilitated a thorough exploration of the research subject and allowed for a nuanced understanding of the intricate interrelations and processes at play.

Data analysis employed various strategies that leveraged a range of data analysis techniques using *content analysis*. Methods such as *analytical induction*, *constant comparison*, and *counting and quantitative methods* were utilized to scrutinize the collected data's criteria and consistency. On top of that, to structure the content analysis process, the data sources were organized into five primary clusters. That facilitated a focused and in-depth analysis within each cluster, enabling a more detailed examination of specific aspects and nuances, thereby augmenting the learning potential from the content analysis. The content analysis was employed in a matrix structure prior to the advanced content analysis of *cross-content analysis* and *triangulation*. Through this dual-stage approach, the study effectively synthesized the disparate elements of the data, unveiling a holistic understanding of the intricate web of categories and their interplay, thereby enriching the overall insights derived from the research. The triangulation employed also mitigated potential biases as it relies on multiple data sources, thereby establishing the validity and trustworthiness of the analysis [69]. The quantitative analysis that counted and scored the obtained information throughout the content analysis levels, defined the assessment scale values, and facilitated cross-content analysis, used measurable parameters that were defined. Each parameter that was quantified individually for each cluster category and then collectively for the entire dataset contributed to the depth of cross-content analysis and triangulation employed.

For the final results, those parameters were formulated into two final parameters. The first and pivotal is the ***Significance Index (Si)***, obtained by a weighted average of three key parameters which were defined to quantify the findings: *Number of Shows*, *Frequency*, and *Strength*. The second is the ***Maximum Number of Respondents***, presented in relative terms, further enriching the analysis. A higher value across these parameters suggests a greater validity of the category. (An explanation of how the parameters are defined and quantified is given in the data analysis sub-chapter of Agmon and Kordova [3]). The concluding phase of data analysis adopted a quantitative perspective, building upon the four levels of content analysis and further enrichment by the insights gained from cross-content analysis and triangulation. The final view of this analytical process was consolidated in a unified tabular format, encapsulating the individual cluster results and a consolidated summary. This display offers a panoramic view of the final results obtained from the multifaceted and multidimensional analysis.

In accordance with the theoretical and methodological framework of the Grounded Theory [65,66] adopted in this research, practically during the content analyses, we realized that the developing model deserves to be presented through two separate model parts. The obtained research findings fully supported this division in the way they were distinctly divided into the first part of the model or its second. Furthermore, rich and extensive findings were obtained due to the extensive research that was carried out, alongside the extensive and complex field of research itself, with their optimal expression proposed through these two separate models.

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

A model for ***G-QMS in Sectors of SoS*** encompasses a high degree of complexity, posing a challenge in its articulation and depiction. However, the research analysis revealed that a proposed model encapsulates two bases supra-entities designated as follows: ***G-QMS of G-Organization in Sectors of SoS (G-QMS of G-Org. of SoS)*** and ***G-QMS in SoS***, as is illustrated in Figure 1. These are distinct entities that encompass extensive interrelationships in both content and structure.

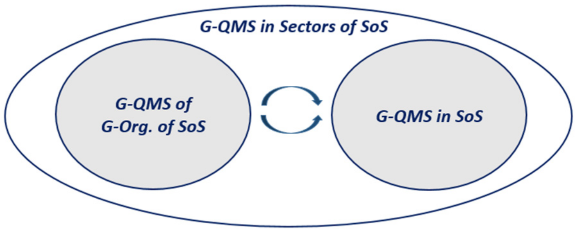

Figure 1. G-QMS in Sectors of SoS model—main conceptual figure. Agmon and Kordova [2].

The *G-QMS of G-Org. of SoS* is the G-QMS for a G-organization, embodying a complex multi-organizational structure, based on the multi-organizational structures organized under unified chief management for the SoS engagement. This G-QMS encompasses multiple and diverse QMS entities. This supra-entity with the model developed for it is presented in Agmon and Kordova [2]. This infrastructural entity model forms the foundational infrastructure of the overarching model, with the *G-QMS in SoS* incorporating structural elements from it. Moreover, a thorough understanding of it is pivotal for engaging effectively with the G-QMS in SoS model. Building on the groundwork laid by Agmon and Kordova [2], this manuscript introduces the model developed for G-QMS in SoS, including the profound mutual interplay of content and structure that exists between the two supra-entities, and consequently, completes revealing the comprehensive model for *G-QMS in Sectors of SoS*.

The supra-entity G-QMS in SoS represents the QMS for the SoS project. Unlike the first supra-entity, this is a temporary entity established for the *special purpose* of providing quality management throughout the SoS project. It comes into existence with the initiation of the SoS project, structured to mirror the multi-organizational layout required for the project's execution, and concludes its role following the project's completion upon concluding the *handing-over* process to the operator organization. Therefore, in this work, this entity's scope does not include quality processes for the SoS operational phase (post-delivery) by the operator, nor the maintenance and technical support processes for this phase. The G-organizational arrangement, usually tailored in special purpose to the SoS project's execution, is typically structured from the local branches of G-organizations. Similarly, G-QMS in SoS is often comprise the local branches of G-QMS of G-organizations. Quality management in G-QMS in SoS addresses the technological systems areas relevant to SoS, and thus should include the unique quality management expertise and professionalism for these areas. Furthermore, the extremely high complexity and large scale of SoS projects require a quality concept *different* from all those in the industry. These projects demand innovative quality concepts that transcend industry norms, requiring the development of designated approaches within G-QMS in SoS that are from a higher order in scope and complexity. G-QMS in SoS has an independent, expanded structure, encompassing additional and unique QMS entities, and an adapted, unique set of interfaces, both within its structure and in front of the environment.

G-QMS in SoS model, like the second distinct model segment, is subjected to the same foundational key principles specified in Agmon and Kordova [2]. Also, the overarching model for G-QMS in Sectors of SoS, defined by these two, is subjected to these same principles.

3.1.2. Affinity Between G-QMS of G-Org. of SoS Model and G-QMS in SoS Model

The relationship between the G-QMS of G-Org. of SoS model and the G-QMS in SoS model is defined by a complex network of interfaces, with several key elements emerging from the research findings:

(a) The G-QMS in SoS model is infrastructurally dependent on the G-QMS of G-Org. of SoS model, allowing for the support of the G-QMS in the SoS model.

(b) The G-QMS of G-Org of SoS model inherently includes QMS entities of Quality Project Management for such and other systems (denoted by QMS_{pro_x}), while unlike them, the supra entity G-QMS in SoS requires an adapted, separate model. However, these entities share common elements in terms of content and structure, which are placed within each of the two models or in their external environments. These shared elements are linked by specific, unique interrelationships.

(c) The diverse structural nature of both the G-QMS of G-Org. of SoS and the G-QMS in SoS models—particularly influenced by the specific structure of the SoS project—results in a variety of interrelationship forms between the two models. The G-QMS in Sectors of SoS model must, therefore, be flexible enough to accommodate such variability.

(d) SoS projects are realized within G-organizations capable of accommodating such projects and capabilities. These G-organizations typically maintain a G-QMS in Sectors of SoS that encompasses these two supra-entities. The G-QMS of G-Org. of SoS not only interacts with the G-QMS in SoS but also plays a vital role in its formation and operational support, ensuring its successful integration and functionality.

3.2. Content Analysis Final Results

The outcomes obtained from the content analysis were clearly organized according to the two models in base of the overarching G-QMS in Sectors of SoS model developed in this research. Employing the Grounded Theory methodology enables themes to emerge from the field data through content analysis, led to this bifurcation of results in accordance with the two explored supra entities, thus contributing to the overall development of the proposed model. This manuscript showcases in Figure 2 the final results pertinent to the supra entity G-QMS in SoS, offering a preliminary view of its structure and the interrelated elements that define it.

The five main clusters that clustered from the research's data sources as part of the content analysis implementation are presented in the final result table: (1) G-QMS CORE, (2) QMS of organizations (QMSs), (3) Light Rails sector, (4) SoSE, and (5) Accreditation bodies. The content categories in their final wording are displayed, with the numerical results of the two final formulated parameters: Significance Index (Si) and relative Maximum Number of Respondents. The quantification result obtained for each of the five main clusters and the total result are shown to them both. A higher score across these parameters suggests a greater validity of the category. For instance, the parent category [5], named "G-QMS structure", consists of three categories: [5.2], [5.3], and [5.4], e.g., category [5.2] is named "G-QMS in SoS Concept". These categories obtained, respectively, Si_{Total} = 10.04, 7.82, and 3.30, while the parent category [5] is the sum of these three, so it is Si_{Total} = 21.16. In addition, e.g., with regard to category [5.2] with a Si_{Total} = 10.04, the participants from the Accreditation bodies cluster (with Si = 8.14) contribute 81.1% of the Si_{Total}, and the participants from the QMSs cluster (with Si = 1.25), 12% of it. Likewise, the participants from the SoSE cluster did not relate at all to this category topic. With regard to the second parameter, 67% of the participants from the Accreditation bodies cluster referred to this category [5.2], while only 11% of the participants from the QMSs cluster.

Significance Index						Maximum Number of Respondents							
TOTAL	Accreditation badies	SoSE	Light-Rails	QMSs	G-QMS CORE	TOTAL	Accreditation badies	SoSE	Light-Rails	QMSs	G-QMS CORE	Category	No.
17.33	0.98	12.44	2.40	0.02	1.50	0.57	1	1	0.67	0.11	0.50	SoS, term & attributes	1
21.16	11.44	7.82	0.25	1.25	0.40	0.37	0.67	0.17	0.33	0.22	0.67	G-QMS Structure	5
10.04	8.14		0.25	1.25	0.40	0.13	0.67		0.17	0.11	0.17	G-QMS in SoS Concept	5.2
7.82		7.82				0.07		0.17				Additions & extensions for G-QMS in SoS	5.3
3.30	3.30					0.03	0.33					Maturity levels in G-QMS for SoS	5.5
10.81		1.16	8.07	1.01	0.57	0.37		0.17	0.83	0.22	0.17	SoS, project structure	7
95.35	5.20	28.07	28.95	19.74	13.39	0.47	0.33	0.67	0.67	0.33	0.33	G-QMS in SoS	8
2.78			2.25	0.53		0.10			0.33	0.11		General	8.1
18.78	1.53	10.70	2.29	3.17	1.10	0.40	0.33	0.67	0.17	0.22	0.17	SoS, project management	8.2
5.66		3.15		2.47	0.05	0.20		0.67		0.11	0.17	SoS, project management	8.2.1
2.57	0.54	1.95			0.08	0.07	0.33	0.17			0.17	Horizontal blocks design	8.2.2
9.28	0.98	4.95	2.29	0.53	0.52	0.33	0.33	0.67	0.17	0.22	0.17	SoS, integration	8.2.3
1.27		0.64		0.17	0.45	0.17		0.33		0.11	0.17	SoS, validation	8.2.3.1
10.49	1.25	0.34	1.68	2.51	4.73	0.27	0.33	0.17	0.17	0.33	0.33	SoS G-QMS CORE	8.3
9.54		2.19	4.31		3.04	0.20		0.33	0.33		0.33	G-QMS in SoS, entities	8.4
8.27		0.30	7.29	0.46	0.22	0.13		0.17	0.33	0.11	0.17	G-QMS in SoS, interfaces	8.5
7.91		1.38	0.91	2.81	2.81	0.20		0.17	0.17	0.22	0.33	Affinity between project QM and System	8.6
6.46		0.66	4.56	0.73	0.51	0.23		0.17	0.67	0.11	0.17	Customer requirements through contract	8.7
5.43	2.42		0.10	1.72	1.17	0.20	0.33		0.17	0.22	0.33	SoS, subcontractors management	8.8
26.96		13.15	5.56	7.98	0.27	0.30		0.33	0.50	0.33	0.17	SoS, Quality tools and processes	8.9

Figure 2. The final results which form the base for the G-QMS in SoS model.

These final result table offers a coherent depiction of the model components for G-QMS in SoS, as will be discussed in Section 4.

4. Discussion: Model for G-QMS in SoS

4.1. Fundamental Principles

4.1.1. A Unique G-Organizational Architecture

The architecture of G-QMS in SoS is inherently diverse, with each SoS project featuring a unique hierarchical structure and management tailored to its specific G-organizational architecture. This uniqueness is a direct response to the supra common purpose of the SoS, consequently crafting a G-organizational architecture specifically designed to fulfill the SoS objectives. As such, the G-QMS structure for each SoS project is distinctly shaped by its own G-organizational configuration, influenced by a combination of global and local constraints as well. Furthermore, each SoS is characterized by its own set of stakeholders, including the client organization with its specific capabilities, and the consulting agencies and monitoring and control (M&C) bodies engaged by the client. The G-QMS in SoS architecture is, therefore, determined by the dynamic interplay between the SoS project's chief management structure, the stakeholders' organizations, the infrastructure entities within the overarching G-organization, and the management teams of the CSs organizations. This set of forces moves across a continuum from a dominant, centralized SoS project's chief management to a more consequential—almost imperceptible—one, where the CSs significantly influence the project's content and interfaces [41]. Similarly, this set of forces also dominates the interrelationships between the internal QMS entities of the G-QMS in SoS. It is crucial to define the structural concept of the SoS project and the corresponding one of the G-QMS in SoS, as they have a direct bearing on the project's success. Consequently, there is a significant need to develop a structural conceptual model for G-QMS in SoS that can aptly represent these varied architectures, alongside providing guidelines for an optimal model structure that aligns with the project's goals and contributes to its successful execution.

4.1.2. SoS—Term and Attributes

The SoS term and its defining attributes emerged as significant themes within the research, as evidenced by the results presented in Figure 2. This category [1] stands as one of the eight primary categories identified in the study, with Si_{Total} = 17.33. The SoSE cluster is notably prominent in this category, contributing a robust 71.8% of the Si. In addition, the Maximum Number of Respondents index for this category is the highest among the eight parent categories, comprising 57% of the total respondents and 100% of the respondents within the SoSE cluster. Despite the increasing use of the term SoS, there is still no consensus regarding its definition. This finding rose with a high frequency and by 23.3% of the respondents. The SoS definition distinguishes it from a highly complex system, yet the boundary between the two is not clearly defined. The differentiation is often influenced by the associated SoS aspects related to the specific sector, organization, project, or situation in question. Furthermore, SoS encompasses many types and classes [29,35,41] and others. SoS is characterized by a set of unique attributes that not only set it apart from complex systems but also contribute to its definition. The SoS definition does not rely on the mere existence of these characteristic attributes, but on the level of each of these attributes (e.g., [29]). Therefore, the dominant attributes according to their levels play a crucial role in defining the SoS and its various configurations.

This study is based on the SoS characteristic attributes presented in [27,29,52,70]. However, the focus here is not to provide an exhaustive analysis of SoS attributes but to highlight those identified as central by study participants and those that have practical implications in real-world SoS efforts, especially in the context of quality management. The attributes considered in this discussion, ordered by their obtained significance level, are as follows: ***Emergence property*** is the most significant attribute, presented at one level or another across all the SoS configurations. Since emergence is an inherent characteristic of SoS that cannot be completely eliminated, quality management tools and processes must be incorporated to mitigate its effects as much as possible. ***Scale, Size, and Black-Box-Character***; in that the SoS projects often do not delve into the detailed design level of the CSs, treating some of the mature and professional CSs as black boxes within an assessment of calculated and acceptable risk. Additionally, the vast scale of SoS projects means that they may include CSs that are themselves extremely complex systems, each possibly embodying SoS attributes at a lower level. ***Connectivity***: The management of SoS prioritizes *interoperability*, the management of interfaces among the systems, and determining specific interface requirements for the CSs [5,71–74]. Moreover, SoS is characterized by *dynamic interoperability*, allowing for the integration of new CSs and the adaptation of connections and interfaces as needed. ***Autonomy***: SoS often lacks full control over the design and configuration of CSs, as these systems are not always developed specially for a dedicated project. This necessitates a definition of the requirements that most CSs already meet or, occasionally, compromises are required. The autonomy characteristic is expressed in the Configuration Management (CM) of each CS, where the more the CSs are autonomic to each other, the more the relevance of their individual CM to the SoS level CM is diminished. The above attributes are joined by the ***Different Product Lifecycles***, including the integration of CSs considered as a *legacy*, which were developed in the past without documented specifications. This is a factor that poses significant challenges to the quality management of the SoS project, including compliance with standards and regulatory requirements.

The G-QMS in SoS is required to address the distinct attributes characteristic of SoS to ensure the SoS quality. This entails incorporating specific additions and extensions that transcend the conventional QMS frameworks aligned with QMS international standards. Moreover, a shift in mindset is essential to adeptly navigate the SoS landscape, embracing the principles of *complexity thinking* such as those highlighted in [5], grounded in Systems Thinking. Key principles include as examples, firstly, an evolution in quality management approaches from traditional *control* and *design* paradigms, typical at the CS levels, to strategies focused on *influence* and *intervention* (also [2]). Secondly, quality management that recognizes *patterns* and operates according to them becomes pivotal. Understanding systems, their behaviors, and interrelationships is fundamental in SoS; therefore, patterns can be an effective approach in G-QMS in SoS modeling. By identifying and modeling these patterns, they can be leveraged as opportunities for enhancing the G-QMS in SoS, facilitating more nuanced and effective quality management strategies. Incorporating these advanced principles, alongside the necessary additions and extensions, is vital for structuring an effective G-QMS in SoS.

4.1.3. A 3-Dimensional Quality Concept

In Figure 2, the independent category [5.2] identified for this concept scored Si_{Total} = 10.04, comprising 47.4% of the parent category [5]. The Accreditation bodies cluster was the predominant contributor to this category's significance, contributing 81.1% of its Si. The quality management concept proposed for G-QMS in SoS model is identified by three dimensions, and each of them is essential to ensure the required quality level: **Quality first dimension** focuses on the quality level inherent to each CS based on the QMS specific to its organization (denoted by QMS_{CS}). **Quality second dimension** addresses the quality level of interfaces between each CS and the overarching SoS, including the comprehensive interface structure of the SoS ($QMS_{[integ\_CS]}$ entities and other QMS_{int} entities). **Quality third dimension** adds a layer of quality concerning systemic attributes that manifest uniquely when specific CM configurations of CSs converge for a collective systemic feature (QMS_{integ} entity and others, as well as additional and extended special quality tools and processes). Figure 3 presents a graphic illustration of this conceptual structure.

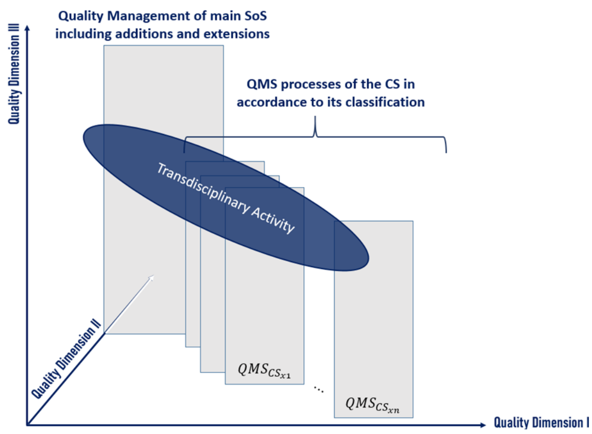

Figure 3. Conceptual structure diagram of G-QMS in SoS.

4.1.4. Shared Principles Underlying the G-QMS in Sectors of SoS Model

The foundational principles outlined for the G-QMS of G-Org. of SoS model, as detailed by Agmon and Kordova [2], are equally applicable to the G-QMS in SoS model, albeit with necessary modifications to suit the specific context. These principles not only underpin these two supra models underlying the G-QMS in Sectors of SoS model, but also serve as a cornerstone for the overarching model of G-QMS in Sectors of SoS.

4.1.5. Encompassing of Unique Additions and Extensions

The independent category [5.3] with Si_{Total} = 7.82 was identified to this principle which is most distinctly associated with the SoSE cluster (Figure 2). This category, along with insights from other result categories, highlights the necessity for additions and expansions within the G-QMS in SoS model, akin to those discussed in previous studies by Agmon et al. [1] and Agmon and Kordova [2]. However, some of these are particular to this G-QMS model, among them:

(a) **Unique QMS entities** are identified that are crucial for further development and focus. These QMSs align with the **three-dimensional quality concept** (Section 4.1.3) and the intricate and extended process structure of project management for SoS (Section 4.2.2). For example, the QMS_{integ} entity designated for the Combination and Integration (C&I) stage is not currently recognized in the QMS standards nor explicitly identified within organizations yet is deemed essential for this model (refer to Section 4.1.3, *third quality dimension*, and Section 4.2.2(d)). Another example includes the (QMS_{CS} refer to Section 4.1.3, *first quality dimension*, and Section 4.4.2(1)). Further additions and extensions are found in the management of SoS, encompassing QMSs for organizational functions, typically considered as *external* QMSs but not marginal, for instance, the *QMS Client* and *QMS M&C* $Local_{SoS_x}$ entities (Section 4.3.1). These aspects are reflected in the program management structure for SoS and are also embodied in expanded quality management tools.

(b) **Interface as an entity:** The concept of treating interfaces as distinct entities is emphasized in principle 4 of the model discussed in Agmon and Kordova [2] and is closely related to the *second quality dimension* outlined in Section 4.1.3. In the context of SoS projects, explicit emphasis must be given to the interface aspects by defining the relevant QMS_{int} entities. This model specifically recognizes the technological system QMS_{int} entities (Section 4.3.2(1)). As efforts are made to develop various QMS_{int} entities, the inclusion of a *classification* structural element is necessary, which is the implementation of the **Balance component**, as explained in Agmon et al. [1] and further expanded by the term **Balance point (Bp)** in Agmon and Kordova [2].

(c) **Additions or extensions to the current QMS international standards** in accordance with base anchors 5 and 6 of Agmon et al. [1]. For example, the AS9100 standard expands by introducing special terms into the required application such as *Critical Items (CIs)*, *Key Characteristics (KCs)*, and *Product Safety (PS)*. These terms become more important as the level of system complexity increases; therefore, their proper application can contribute to G-QMS in SoS. These components can be integrated within each of the **three G-QMS in SoS model concept dimensions** (Section 4.1.3). For instance, within the *first dimension*, an idea of the *CS classification* emerges from the identification and classification of CI and PS (Section 4.4.2(1)). Within the *second dimension*, it refers to the classification of the interface levels through the identification and classification of CI and PS for the interface. On this basis, those $QMS_{[integ\_CS]}$ (Section 4.3.2(1)) can be identified, defined, and classed.

(d) **Additional or extensional quality management tools** specifically designed for SoS projects are integral, such as a comprehensive set of forums, advanced communication systems, and robust documentation and control systems (Section 4.4.7).

4.1.6. Balance Principle

The **balance principle** in the model architecture is fundamental in the architecture of the G-QMS in SoS model, underpinning its structural integrity and enabling it to achieve its objectives. G-QMS in SoS model bases its structural robustness on the balancing components scattered along the length, width, and depth of the model, as these are detailed in

Agmon et al. [1], and Agmon and Kordova [2]. The complex nature of these projects and the corresponding G-organizational layouts they necessitate, along with the intricate environments in which they operate, amplify the necessity for maintaining balance throughout the model's structure.

4.2. G-QMS in SoS Structure Supports the SoS Project Structure

The management landscape for SoS undergoes significant transformations, posing significant challenges to the successful execution of SoS projects. Gorod et al. [29] emphasize the importance of recognizing the unique types of SoS, their special strategic purposes, and the distinct challenges they pose in terms of engineering, management, and structure. As a result, no single method can address these evolving challenges, indicating that no universal strategy fits all SoS projects. This diversity in SoS projects and their managerial processes is well established. Consequently, each G-organization tends to adopt specific project forms and management frameworks, whether explicitly or impliedly [75,76]. To delve into the structure of the G-QMS in SoS model, it is essential to first explore the main aspects of SoS project structure, especially those related to the project management process, as highlighted by the research findings.

4.2.1. SoS Project Structure Prism

As can be seen from the research results in Figure 2, the parent category [7] with a Si_{Total} = 10.81 was identified to this circumferential topic, with 16.7% of it dedicated to the project stakeholders. The G-QMS in SoS structure is built in accordance with the SoS project structure to provide the most congruous support to the project's objectives. This alignment is underscored by the diversity in SoS project structures, which vary significantly based on factors such as the field of occupation; the project's scope; the characteristics of the client organization that commissions the project, including how the project is financed; and the influence of global, geopolitical, and local constraints. This diversity necessitates a G-QMS in SoS model that is inherently flexible; however, there are shared principles among SoS project structures that have direct implications for quality management and the structuring of the G-QMS in SoS.

One of the foundational principles of structuring a QMS involves the identification and mapping of **stakeholders to the system**, assessing their needs and expectations as instructed by QMS standards, e.g., ISO9001:2015 [7], ISO9004:2018 [8], and ISO13485:2016 [10]. This principle is integral to the G-QMS in SoS model, necessitating a **balance** in addressing the diverse needs and expectations of *all* the stakeholders involved. Given the uniqueness of each SoS project, the constellation of stakeholders and their specific needs and expectations also vary distinctly, directly influencing the structure of the G-QMS in SoS. Key unique stakeholders in SoS projects typically include the following: First, the *client (owner)* who orders the SoS, and for whom it is designed and built, often a core organization, including a state or an association of states. SoS projects are characterized by a comprehensive contract from the client, detailing stringent requirements, including process outputs throughout the project lifecycle. Furthermore, the client, through a designated local organizational unit (one or more), usually actively participates in all phases of the project including the actual approval of process milestones. Second, *consulting, monitoring, and control (M&C) organizations*. Specialized agencies representing the client's interests are involved in various responsibilities according to the nature of the client and its capabilities, from drafting requirements in tenders and contracts to supervising and controlling project execution. These are usually several designated organizations depending on their specialization. Third, *regulatory bodies*, since SoS projects typically need to demonstrate adherence to regulatory requirements, which may span multiple jurisdictions, e.g., FAA and EASA regulations in the aviation sector. Fourth, *certification bodies for standardization.* These bodies are pivotal in the QMS landscape, with G-QMS in SoS often engaging with multiple certification entities (instead of with a single) to ensure comprehensive compliance with quality standards. Fifth, *the CS organizations* which are unique stakeholders with a vested interest in the G-QMS in SoS. Typically, some CSs are provided by the main contractor of the SoS project, thus fostering a deeper connection between the G-QMS in SoS and the other supra-entity of the G-QMS in Sectors of SoS model. Besides these primary stakeholders, SoS projects encompass *a wide array of additional stakeholders*, both external and internal, each contributing to the project's complexity and necessitating a nuanced approach to quality management within the G-QMS in SoS structure.

The G-organizational structure of SoS projects is characterized by contractual agreements between the participating organizations alongside legal communication. Typically, the client initiates the structure by issuing contracts to selected participating organizations. This is further expanded by the SoS project's main contractor, who issues additional contracts to other participating organizations beyond those designated by the client, including various CS organizations. A unique characteristic of SoS projects is the client's directive role in specifying certain organizations for the main contractor to engage with, including M&C organizations appointed to supervise the project on the client's behalf at all stages. This arrangement results in a complex web of inter-organizational relationships where many of the entities involved operate independently. This independence can pose challenges for the SoS project's main contractor tasked with unifying and managing all the G-organization bodies, including those that have entered into direct contractual agreements with the client.

SoS projects, given their complexity and extensive scale, are often marked by prolonged durations and are typically executed in a modular fashion. This approach involves completing a segment of the project, delivering it to the client, and then embarking on a subsequent project phase that either complements or expands upon the previously delivered component. This modular approach inherently leads to a dynamic environment where organizations involved in a project under contract with the client may find their roles evolving or changing within a subsequent project. The light rail sector, developed from the railway sector, is characterized by highly complex G-organizational structures. However, since this is a traditional, experienced sector, these are proven, well-known, and accepted structures, with each participating organization clear about its role and responsibilities. From a quality management perspective, a distinctive feature of this sector project is the adoption of a dual-system structure initiated by the client through the contractual process. The client concurrently engages both the control (or oversight) organizations and the implementation ones, setting up a dual pathway where both sets of organizations operate in parallel and report back to the client. This dual structure inherently embeds controls across every facet and phase of the project, ensuring comprehensive oversight and quality assurance throughout the project lifecycle.

Furthermore, the G-organizational structure is established specifically as a *G-organization for a special purpose*, for the purpose of realizing the particular project. This structure predominantly comprises organizations that are recognized experts in their respective fields and possess a global operational footprint. These G-organizations are involved in multiple projects worldwide, each managed by local organizational units dedicated to the specific contractual obligations of the project at hand. A local organizational unit typically includes a project manager along with the relevant professional management functions, including QMS. For example, such a G-organization establishes a local organizational unit for the role of M&C (denoted by $M\&C\ Local_{SoS_x}$). This unit is composed of a highly specialized team, with one of its core functions being quality management (QMS M&C

$Local_{SoS_x}$). The M&C $Local_{SoS_x}$ is positioned between the client organization and the SoS project main contractor and operates throughout all the project phases.

Finally, the SoS project structure is a critical factor influencing the project's potential success, and so is the G-QMS in SoS structure. SoS projects often face challenges stemming from structural weaknesses within the architecture of participating organizations. These challenges can include issues related to the distribution of power and authority among organizations and ambiguities in the roles and responsibilities of the various entities within the G-organization architecture. Given these complexities, the model for G-QMS in SoS proposed in this study not only aims to address the quality management requirements of such intricate projects but also has the potential to influence the overall structure devised for the SoS project.

4.2.2. SoS Project Management Prism

In Figure 2, the results for SoS project management are abundant in the independent category [8.2] with Si_{Total} = 18.78. All five clusters referred to it, with the SoSE cluster notably contributing 57% of the Si. The management process of a SoS project encompasses distinct features that necessitate corresponding support from the G-QMS in SoS. These key features of the SoS project management process directly influence the design and function of the G-QMS in SoS, underlining the need for a QMS that is adaptable and robust enough to cater to the unique demands of managing SoS projects.

(a) ***SoS project management process structure is longer and extended:*** The structure of the SoS project management process is notably more extensive and prolonged, diverging from conventional models by incorporating additional stages (along the longitudinal axis) and expansions (on the transverse axis). In Figure 2, subcategory [8.2.1] with Si_{Total} = 5.66 was identified for this process, with the SoSE cluster contributing 55.7%. On top of it, this special process structure is further elucidated through other related subcategories.

(b) ***SoS design process through horizontal blocks***: A strategy aimed at managing the high complexity inherent in these systems. This is an example of expansion (on the horizontal axis) that allows for the segmentation of the design phase into manageable sections. It is highlighted in Figure 2 in subcategory [8.2.2] with a Si_{Total} = 2.57 and predominantly contributed by the SoSE cluster (75.9%). This is an essential, necessary concept in SoS, starting from the planning stage, and aims to obtain design outputs along the defined milestones through the project development and not only at its end, thereby reducing the risk level in the development. Each horizontal design block encompasses a set of CSs along with their specific designed contents. This method not only aims for the design planning of the blocks in a *balanced way* among the CSs but also strives to plan these blocks as *independently* as possible. The significance of quality management within this design stage emerged prominently in the research findings, underlining the critical notion that a system's quality is fundamentally rooted in its design. Despite its importance, quality management in the design phase is observed to be less advanced compared to other project areas, indicating a potential area for further development and focus in SoS projects.

(c) ***Expanded quality assurance mechanisms for approving entry of CSs to SoS C&I stage***: An entire quality management area that involves diverse quality processes (see Section 4.4.2) and relies on the QMS_{CS}. QMS_{CS} is responsible for providing each CS with an extended Certificate of Compliance (COC) along with additional extended quality references, denoted as a process extension. In addition, in accordance with CS classification, a modular (multi-stages) control process structure is implemented, starting with the CS approval at the CS organizational site through to its final validation approval, obtained by the successful completion of the SoS validation experiments.

(d) ***Combinations and Integration (C&I) stage***: This represents a critical and highly complex phase in SoS projects, carried out in an elaborate and multi-phased manner. This stage is particularly notable for its final integrated phase, which involves comprehensive testing at the level of the fully integrated SoS. The C&I process is found at the core of the SoS, a pivotal feature of SoS project management. In Figure 2, subcategory [8.2.3] is identified for this process stage with a Si_{Total} = 9.28. This was noted across all five clusters, specifically by 67% of the respondents in the SoSE cluster, contributing 53.3% of the Si. The C&I process unfolds in three phases after a *preliminary phase* of the SCs installations. The *first phase* involves thorough testing of each CS in isolation to ensure full and systematic verification of its functionalities. The *second phase* focuses on the testing of interfaces, initially between individual CSs and the SoS, gradually expanding to include as many interfaces as possible to test the interoperability between multiple CSs. The *third phase* entails testing the fully integrated SoS as a whole, ensuring that all systems function together as intended. In SoS projects, the C&I process is significant since most of the problems are found in the interfaces (connections). As more systems are connected, interface complexity increases exponentially. The research results highlighted that this structured approach to the C&I process is instrumental in addressing the challenges posed by the *emergence property*, which is particularly dominant in SoS projects. The more the emergence phenomenon is revealed in the fully integrated SoS testing—the final phase, the more complicated and expensive it is to solve, and therefore, a modular multi-phase process makes it possible to reduce it as much as possible. A lot of resources are found to be invested in the C&I process, including the testing's application in extensive laboratories and using specialized simulators designed to simulate the fully integrated SoS as much as possible. The responsibility for the C&I process, including the conduction of tests, falls to specialized SoS engineers. In highly complex and large-scale SoS projects involving expansive G-organization structures, a dedicated Integration organizational body, sometimes a specialized organization, may assume this responsibility on behalf of the SoS project's chief management. Beyond the planning and execution of C&I tests, the Integration body ensures that the project's process structure, which involves multiple partners, operates as intended. This is the technical owner that integrates all the systems of the SoS in the project, whose primary objective is to guarantee the successful completion of the C&I process. Structurally, the Integration body oversees the Interfaces management and the Testing and Commissioning (T&C) management, each led by a manager and supported by technical staff. Quality management during the C&I stage entails an assurance process C&I process itself, culminating in the confirmation of the owner at the end of the process, before proceeding to the validation stage through experiments. This assurance utilizes quality tools, common also in the previous project stages, but suitably adjusted for the C&I stage. However, like the design processes, quality management in the C&I stage is often found to be under-defined or underdeveloped, highlighting a clear need for its advancement. This research contributes to advancing quality management in these critical areas by identifying relevant quality management entities within the model: QMS_{integ}, *SoS QMS T&C*, *SoS QMS handing over*, and the contents required within these entities.

(e) ***Validation stage experiments***: Another example of longitudinal expansion. In Figure 2, a second-order subcategory [8.2.3.1] is identified for this topic with Si_{Total} = 1.27. The validation stage in SoS projects involves a series of critical experiments designed to verify the SoS's functionality and performance. For instance, in the rail sector, this stage includes dynamic tests when a train is operational on the track, and similarly, in the aviation sector, it encompasses experimental flights. The more complex the SoS project, its scope of experiments is greater, and it is carried out through a longer multi-phase process to ensure that each system of the SoS functions as expected in real-world conditions, and the entire SoS meets the required standards and specifications.

(f) ***Handing Over phase***: Another example of longitudinal expansion. In SoS projects, the transition from project completion to operational use involves a structured handing over phase, where the SoS is formally transferred to the client or an appointed operator. This phase goes beyond mere delivery, encompassing a series of organized steps and procedures to ensure that the fully functional SoS meets all the contractual requirements, and is ready for use as intended.

(g) ***After Sale (delivery) phase***: SoS projects are known for their requirement of continuous service in the field, often necessitating round-the-clock availability. Modern contracts for SoS not only cover the initial delivery of the system but also emphasize ongoing service and support, reflecting a shift from focusing on the sale of a new product to ensuring its sustained operational effectiveness. One of the quality management aspects of this phase relates to knowledge retention required for decades after the SoS initial delivery, and to the highly extensive scope of the maintained materials.

4.3. G-QMS in SoS, Sturcure

The structure of G-QMS in SoS encompasses a network of QMS entities tailored specifically for SoS projects, including a core entity designated as the *SoS G-QMS CORE*. This arrangement features both the internal QMS entities that are integral to the project management framework and the external ones that are embedded within the broader G-organizational structure of the project. The architecture facilitates a complex web of connections and interrelationships among these entities, ensuring comprehensive quality management tailored to the unique demands of SoS projects.

4.3.1. G-QMS in SoS Entities

In Figure 2, an independent category [8.3] with a Si_{Total} = 9.54 was identified for the QMS entities. These key structural entities are elaborated below, beginning with the internal and continuing with external ones, while Figure 4 presents a graphical view of them.

- ***SoS G-QMS CORE***: In accordance with base anchor number 1 [1], and the main principles already identified for the model [2], G-QMS in SoS requires a CORE entity, which functions as the headquarters of the G-QMS in SoS. The CORE chief reports to the SoS project chief manager and is a member of the SoS project chief management team.
- ***SoS-QMS-C&I*** **(*QMS*$_{Integ.}$)**: Refers to the QMS for the integrated SoS engineering function at the C&I stage. This QMS entity is recognized for its paramount importance, with a recognized need for enhancement in its quality management capabilities (Section 4.2.2(d)). It serves as a central hub for multiple interfaces among all the CSs involved in the SoS, necessitating its definition from the project's planning phase. $QMS_{Integ.}$ maintains an active interface with the SoS G-QMS CORE. It is recommended that the $QMS_{Integ.}$ head has both a *direct* reporting line to the SoS G-QMS CORE chief and an *indirect* one to the Integration body head. This structural arrangement underscores the importance of $QMS_{Integ.}$ within the SoS project's quality management framework, with its effectiveness contingent upon the professional caliber of the SoS G-QMS CORE entity.
- ***SoS QMS T&C***: Denotes the quality management functions during the validation stage. The research highlights a strong motivation to enhance the role of quality engineering in the field of tests and experiments, acknowledging that quality engineers, typically

in this field, possess specialized knowledge and skills that can greatly contribute to the success of this phase.

- ***SoS QMS handing over***: Refers to the quality management functions during the handing over phase, which includes a distinct role for quality management.
- ***QMS entities and other areas***, such as PS and RAMST, need to be integrated under an independent quality management framework specific to the project. Typically, these entities are branches of the QMS entities belonging to the G-QMS of G-org. of SoS model, combined locally in the SoS project management program.

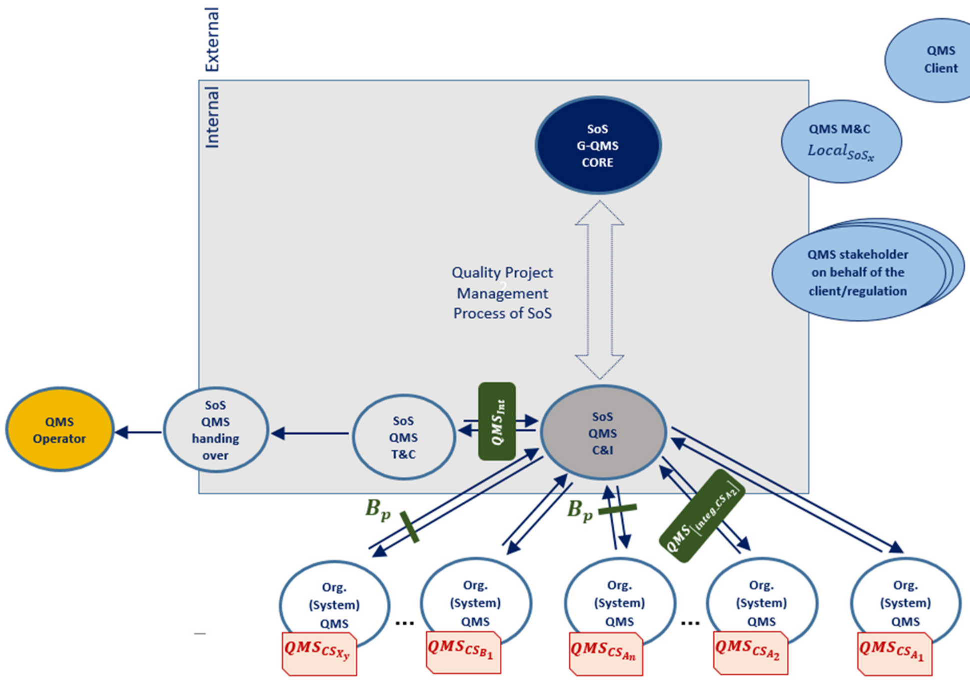

Figure 4. Graphical structure of main QMS entities in G-QMS in SoS.

The main external QMS entities comprise the following:

- ***QMS Client***: The typical client (or *owner*) of SoS is itself a large and significant organization, sometimes a government or military authority. Similarly to other G-organizations, the client typically establishes a local organization unit specifically tasked with overseeing the SoS project in order to successfully ensure its ordered asset. The client effectively becomes an integral component of the overarching G-organization architecture built for the SoS project. As part of this structure, the client entity also incorporates its own QMS.
- ***QMS M&C*** $\boldsymbol{Local_{SoS_x}}$: The QMS entity of the M&C $Local_{SoS_x}$ for a specific SoS project (denoted by *X*). This M&C $Local_{SoS_x}$ aims to ensure the project's adherence to its scheduled timelines, content delivery, and required quality level. It is composed of expert leadership teams that parallel the main contractor's organizational structure, effectively serving as a "mirror image" to monitor and control the project's execution. Within the M&C $Local_{SoS_x}$, there exists a dedicated team focused on quality management, known as the QMS M&C $Local_{SoS_x}$ entity. The broader M&C $Local_{SoS_x}$, encompassing various functional areas *beyond* just quality management, is *fundamentally* a quality management function in itself. Its comprehensive monitoring and control mechanisms contribute significantly to the strength of the *control structure* within the entire global organizational framework established for the SoS project.
- ***QMS entity of an additional stakeholder on behalf of the client or regulation***: Additional QMS M&C $Local_{SoS_x}$ exist when more than one is involved in the project,

including M&C $Local_{SoS_x}$ of additional stakeholders such as regulatory, standardization, and other authorities.
- ***QMS_{CS}***: QMS entities of the CSs of the SoS based on the QMS of the CS organization. Elaborated in Section 4.4.2.
- ***QMS Operator***: The QMS for the operator organization. The operator, specified early by the client within the contract, is integrated into the project from its inception to ensure that all the developments align with its specific operational requirements. The operator assumes responsibility for operating the SoS with the *formal* conclusion of the handing-over process.

4.3.2. G-QMS in SoS Interfaces

In Figure 2, an independent category [8.5] was identified for this topic with a Si_{Total} = 8.27, recognized across all five clusters, notably by the Light-Rails cluster, contributing 88.1% of the Si. The G-QMS in SoS interfaces are elaborated in the following sections.

1. **Interface entities**

Within G-QMS in SoS model, QMS_{int} entities assume a significant role, especially since they encompass *technological system QMS_{int}* entities as well. These entities participate in facilitating interoperability within the SoS, enabling effective communication and integration among the various constituent systems to form a more complex, higher-order system. The notable example is the identification of the unique QMS_{int} located between the $QMS_{Integ.}$ and the QMS_{CS} (denoted by $QMS_{[integ\_CS]}$). Moreover, the development and enhancement of interoperability are critical across all entities within the G-QMS in SoS, ensuring effective coordination and communication throughout the system.

2. **Professional expertise and transdisciplinary management**

The G-QMS in SoS model demands a high level of professional expertise and transdisciplinary management. This complexity and deepness transcend the capabilities of traditional quality management, necessitating professionals in quality fields and QMS entity leaders—who are conceived as persona—to exude validity and professional authority (See also Agmon and Kordova [2]). Additionally, the model requires a systemic, holistic, and transdisciplinary view, echoing the necessities identified in the G-QMS of Org. of SoS model [2]. Both are necessary conditions, without which the G-QMS in SoS will not be able to provide the added value for the SoS projects, which are naturally complex and integrate advanced technologies and span large scales and scopes. This lays on two pivotal elements: The first is ***a strong emphasis on interface management***. A critical aspect of this model is the emphasis on managing interfaces, which includes not only the interactions among QMS entities within the organizational structure, seen also in G-QMS of Org. of SoS model [2], but also, importantly, the technological interfaces or interoperability among the CSs of the SoS. Given the large scale and complexity of SoS, managing these interfaces becomes increasingly significant. The focus should be on characterizing and implementing these interfaces effectively, particularly the interoperability among the CSs, as these points are *potential weaknesses* but also *opportunities for enhancing* the SoS's success. Furthermore, the model must consider the SoS project's interfaces with the client, the other stakeholders on his behalf, and the operational environment, such as regulatory bodies and municipal regulations in the case of sectors like light rail. Managing these interfaces is central to SoS project management, necessitating dedicated executive methods and specialized teams equipped with the needed expertise, including these for defining interoperability among the CSs and the SoS that combines aspects of which the CSs are completely unaware. Thus, the G-QMS in SoS should include functions specifically designed for comprehensive interface management, ensuring effective communication and coordination across all levels of the project.

The second crucial element is the capability to ***coordinate and combine activities within the G-QMS in SoS framework***. This model acts as a management entity that undertakes the coordination and combination of efforts in a transdisciplinary manner, leveraging the quality work carried out by the various responsible QMS entities. This requires a transdisciplinary approach to manage the diverse outputs originating from multiple sources across the breadth and depth of the entire structure, including both external and internal QMS entities. Moreover, this transdisciplinary quality management activity needs to be manifested across the three quality dimensions identified in the G-QMS in SoS concept (Section 4.1.3). For example, the capability to coordinate and combine is particularly crucial when dealing with the diversity and volume of the CSs, which includes establishing coordination and combination mechanisms in accordance with the class (type) definitions of the CSs (see Section 4.4.2). The motivation of the G-QMS in SoS is to rely on the QMS_{CS} as much as possible, and by this classification, delineating clear responsibilities among the various organizations involved and reducing the use of management resources.

3. **Interface structure among the local G-organizations**

The G-QMS in SoS framework is structured to include a network of interfaces that connects the various local G-organizations involved in the SoS project, each with specific responsibilities. This is a quality management structure based on a *chain-down of control and reporting levels*, starting from the client through the structure levels and reaching down to each CS. Figure 5 gives a graphical illustration of this structure.

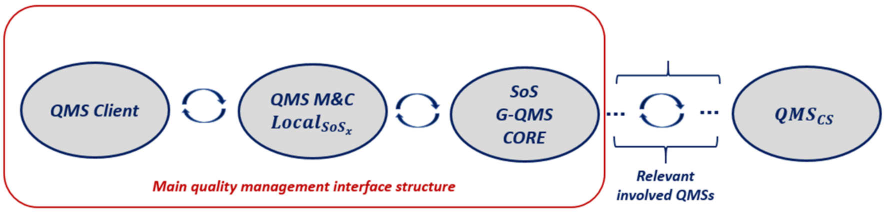

Figure 5. Interface structure of local G-organizations QMSs based on a chain-down of control and reporting levels.

This chained interface structure includes a main quality management interface structure, connecting the client and the project's main contractor, facilitated through one or more M&C local G-organizations. The client delineates quality requirements and ensures their enforcement via a contractual agreement with the project's main contractor and establishing a *control and reporting* interface throughout all the project stages. The M&C local G-organization details the client's quality demands and allocates resources to operate control and reporting tasks across the project's lifecycle. The SoS G-QMS CORE is responsible for implementation, adhering to the stipulated reporting obligations towards both the client and the M&C local G-organizations representing the client. For this purpose, SoS G-QMS CORE is tasked with setting the quality requirements for the internal QMS entities within the G-QMS in SoS framework and ensuring these are met throughout the project, providing balanced feedback. This setup exemplifies a Causal Loop Diagram (CLD), one of the primary structural tools of Systems Thinking [58,77–79]. In particular, the SoS G-QMS CORE chains down a level of control and reporting vis-a-vis QMS_{CS} and other subcontractors. From the QMS_{CS} perspective, it must meet both the requirements of the SoS G-QMS CORE (typically its "customer") and of its own organizational QMS.

Main quality management interface structure: *"If we are not with each other, we will not be able to work with each other. And here in the project, we are with each other, and this is* *a point of success—an advantage in the project"* (research respondent). The G-QMS in SoS, in accordance with the SoS project, features an actively participating client who outlines contractual requirements and takes an active part in project management. This is a pivotal factor in the quality management for the SoS project, leading to the formation of the main quality management interface structure, which includes the following key components: First, ***a dual interface structure for QMS M&C Local*** $_{SoS_x}$ embedded in the G-organizational layout structure of the SoS project, which acts as "*a bridge between East and West*". The dual interface behavior of the QMS M&C Local$_{SoS_x}$ is founded on a couple of main principles. Firstly, it aims to ensure that the project aligns with contractual obligations and adheres to professional standards, reflecting the primary objective of its operation. Secondly, its nature is influenced significantly by the "project's DNA" or the organizational culture of the specific SoS project. The dynamics at these interfaces are largely shaped by the professional relationships established between the organizational QMS entities. The typically expansive scope of the project allows officials considerable latitude in fostering these relationships, which in turn shapes the structure of activities and execution priorities. These dynamics are substantially influenced by the personalities involved, particularly the professional expertise and authoritative standing of the heads of the QMS entities, underscoring the human factor in the effective management of quality within the SoS project framework.

Second, ***the level of cooperation among the three entities is a pivotal factor in enhancing the project's quality***. Effective collaboration and partnership in the two interfaces that add up the three QMS entities of the main structure are a lever for quality improvement within the project. Therefore, it is essential to find the conditions for creating high and full cooperativeness in each of the pairs of interfaces existing in it. Third, the ***QMS Client plays a vital role in driving quality across the project***. Particularly, the interface between the QMS Client and the QMS M&C Local$_{SoS_x}$ is dominant, given that the latter serves as the client's operational arm within the project, wielding considerable sway over the SoS G-QMS CORE. The extent to which the QMS Client supports and promotes the QMS M&C Local$_{SoS_x}$ can significantly enhance its effectiveness and, by extension, contribute to the overall quality management efforts. Conversely, projects that lack a robust and active QMS Client presence often experience diminished quality management activities, underscoring the importance of a strong and engaged client role in the G-QMS in SoS structure.

4.3.3. G-QMS in SoS Structure, Aspects

The quality management field typically lacks specific references for SoS projects, highlighting the need for its development and promotion within this context. Several aspects to consider in advancing the G-QMS in SoS include the following: First, quality management practices were found active within traditional quality management frameworks as outlined by QMS standards. However, these practices are not adequately extended to areas relevant to SoS projects. For example, the pivotal area of the C&I stage, crucial in SoS project management, may not always recognize the need for a dedicated QMS$_{Integ.}$ entity. Yet, the research underscores a significant demand for enhancing quality management in such a pivotal area. As can be seen in Figure 2, the C&I processes [8.2.3] emerge as the most significant subcategory of the SoS project management category [8.2], contributing 49.4% of its total Si. In addition, the most effective ***quality management approach*** for managing a SoS project remains unclearly defined. Drawing from the research findings, current trends in quality management [2], and Systems Thinking principles, we propose defining the G-QMS in SoS as a *supporting* entity for the project, which *advises*, *assists*, *participates*, and also *reports* in some instances. This *approach* necessitates identifying critical focus areas for quality management within each SoS project, considering the specific project's resource limitations, professionalism level, and the degree of independence of the G-QMS in SoS within the overall project structure. In general, achieving the right *balance* between the various constraints and the ability of the G-QMS in SoS to contribute to the project is crucial.

In the G-QMS in SoS structure, a novel approach to quality management involves the establishment of a ***designated Integrative Project Team (IPT) work concept for quality management***. This concept mirrors the IPT model used for overall project management in SoS projects, where a chief IPT, typically the SoS chief management team, coordinates project execution. For quality management, the proposed *IPT for quality* would be led by the SoS G-QMS CORE head and include heads of various QMS entities within the G-QMS in SoS structure, including the QMS_{CS} heads of these classified as main, and representatives from QMS_{int} entities. It is also crucial to ensure the participation of QMS heads from stakeholder organizations, such as QMS M&C $Local_{SoS_x}$. In large-scale and high-technology SoS projects, this IPT for quality could be structured by several specialized IPTs that all together provide the required quality management solution.

Another aspect refers to the ***degree of autonomy within the G-QMS in SoS***. The G-QMS in SoS is established as an integral part of the SoS project's management framework, orchestrated by the main contractor of the project. The unique nature of each SoS project, consequently, shapes the unique structure and operational dynamics of its corresponding G-QMS in SoS, which is influenced by various factors, including the directives of the project's chief management, the interplay with the G-QMS of G-Org. of SoS, contractual obligations towards the client, and sector-specific regulatory demands. When setting up the G-QMS in SoS, careful consideration must be given to its level of independence. This involves determining the extent to which the various QMS entities should have *direct* reporting lines to the SoS G-QMS CORE and *indirect* to the project functions, in front of the opposite. Generally, a higher degree of independence for the G-QMS in SoS is associated with a more robust and effective quality management regime within the SoS project. Nevertheless, achieving such independence hinges on the presence of profound professional expertise within the G-QMS in SoS, particularly within its core management entity, the SoS G-QMS CORE. Furthermore, this aspect is also contingent upon organizational attributes such as the organization's maturity level, its cultural predispositions, and its overall capability to support an autonomous quality management system.

4.4. G-QMS in SoS Model, Key Aspects

4.4.1. G-QMS Subject to Client Quality Requirements Dictated by a Contract

In Figure 2, an independent category [8.7] with Si_{Total} = 6.46 was identified for this aspect. In the SoS project, the relationship between the client and the organizations that form the project's G-organization, especially the main contractor responsible for project management, is fundamentally governed by contractual agreements, which are central, binding documents. In SoS projects, this is an extensive series of documents, including thousands of requirements, and encompasses all the project topics and areas, including the quality management requirements. In practice, the G-organization configuration for the project and its structure of responsibilities is determined at the stage of defining the contract requirements. In particular, the quality contractual requirements (including those received from the supervisory bodies) directly affect the G-QMS in SoS configuration, its structure of responsibility, and its contents. Contractual quality management requirements are the client's direct *special requirements*, and typically go beyond the standards requirements, to which the SoS project chief management is obligated under the contract. These requirements have a pivotal validity to assure quality; therefore, they are highly important for all QMS entities within the G-QMS in SoS. To ensure that the quality management aspects of the project are comprehensively and accurately addressed within the contract, it is imperative that relevant quality management bodies are involved right from the initial stages of client engagement. This includes participation in the tendering process and subsequent contract formulation phases. For this purpose, those quality bodies should be identified and defined already during these early stages both by the relevant G-organization bodies, particularly the main contractor, and by the client. As presented in Agmon and Kordova [2], the research results indicate the growing trend of expanding and deepening of contractual quality requirements within SoS projects.

The responsibility for the contract quality requirements primarily lies with the QMS Client entity. However, if it fails to do so, a typically weak G-QMS in SoS will be built, which may lead to a poor project quality level. In the light rail sector, the contract quality requirements were found to be usually poor and insufficient; however, they include a mechanism in purpose to refine and consolidate them. The essence of this practice lies in the refinement and deepening of quality requirements after the contract has been finalized, which involves a collaborative approval mechanism that engages both the QMS Client and the QMS M&C $\text{Local}_{\text{SoS}_x}$. This mechanism is designed to review and approve project documents, which include quality requirements, produced by the main contractor with the signed approval of SoS G-QMS CORE. The G-QMS in Sectors of SoS model is characterized by a mature, impressive G-QMS, which includes advanced internal requirements originating from the G-QMS CORE of the G-QMS of G-Org. of SoS, including the requirements for QMS standard certifications and other relevant standards. However, the G-QMS in SoS foremost is committed to the quality requirements outlined in the contract. In instances where there is a discrepancy between a contractual quality requirement and the internal policies, procedures, or directives of the G-QMS of G-Org. of SoS, the contractual requirement takes precedence.

Beyond the direct quality management requirements for the project for which the G-QMS is responsible, the relevant quality bodies participate already in the initial engagement processes with the client to ensure thorough *contract review processes* for all the contract requirements. In the SoS project, due to its complexity and large scale, the volume and complexity of these requirements are substantial and thus necessitate contract review processes that include *special processes*, while their implementation must be thoroughly assured.

4.4.2. Subcontractor's Management

In Figure 2, an independent category [8.8] with a Si_{Total} = 5.43 was identified for this aspect. Managing subcontractors is a critical aspect in managing complex systems, especially in SoS projects that particularly involve those providing CSs. Correspondingly, quality management for assuring the integrated systems compliance becomes crucial. Historically, the largest industrial companies, which heavily depend on subcontractors for their products, have developed this area of quality management. With this regard, ISO9001 initially served as a means to standardize the quality expectations for subcontractors, aiming to replace the inspection activity of the organizations themselves with a complied subcontractors' QMS. For example, this is also how the AS9100 standard began, which significantly expanded upon ISO9001's requirements concerning subcontracting by placing a strong emphasis on the management of subcontractors and suppliers, including a chain-down of requirements (Section 8.4, AS9100:2016 [9]). This emphasis is driven by the modular nature of industries that rely on subcontractors with established a recognized QMS with a consistently acceptable quality level, typically certified to one or more QMS standards.

With regard to G-QMS in Sectors of SoS, a $QMS_{S\&P}$ entity responsible for managing the intricate quality processes for subcontractors and suppliers on a global scale, including the expert knowledge and the required resources, is typically placed within the G-QMS of G-Org. of SoS model [2]. The G-QMS in SoS model has been supported by this quality infrastructure through a dual work interface, primarily interacting with *approved* QMS_{CS}s validated by $QMS_{S\&P}$ and meeting the higher standards set by the G-QMS of G-Org. of SoS. The $QMS_{S\&P}$ requirements from the QMS_{CS}s, are often beyond the QMS standards requirements and are determined according to the CS classification. However, the SoS project typically involves a client who often mandates several CS subcontractors and even engages with them directly through contracts. In such scenarios, the G-QMS in SoS is required to work with the QMS_{CS} of the dictated CS, and despite having the support of $QMS_{S\&P}$ infrastructures, this situation presents numerous challenges.

1. **Classification key for CSs**

SoS involves an integrated configuration of CSs, typically characterized by the architecture of a large number and technological diversity of CSs. Effective quality management within a SoS demands the systematic mapping and classification of these CSs. This classification serves as the basis for tailoring specific quality management mechanisms to each CS, facilitating organized prioritization and resource management. This strategy represents an elaboration and extension of the foundational principle outlined as base anchor 4 in the research by Agmon et al. [1]. This study introduces a classification key for CSs within a SoS project, serving as a strategic tool for quality management. This framework, depicted in Figure 6, utilizes four defined primary parameters, each parameter spanning a continuum. CS classification is, thus, determined by its position on these continuums, rather than the mere presence or absence of certain parameters. The decision on the number of distinct classes into which CSs are organized is an administrative decision of the G-QMS in SoS.

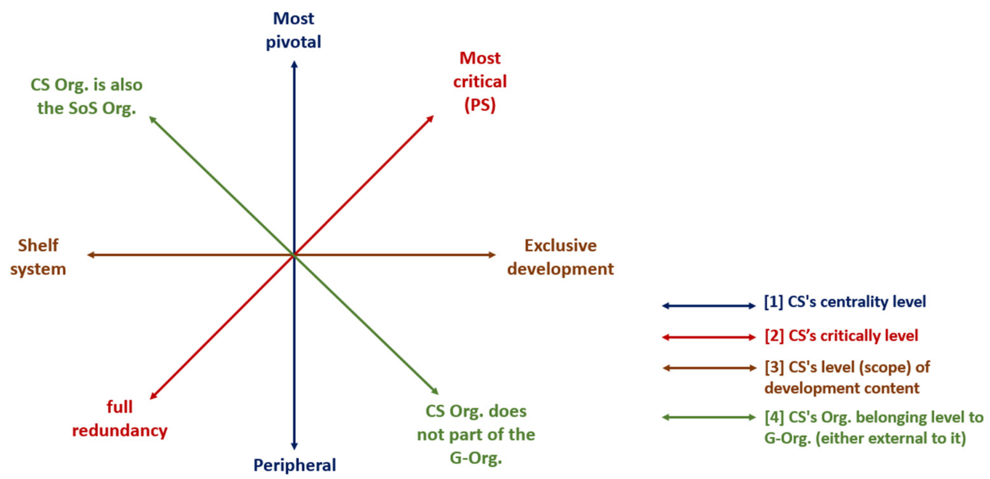

Figure 6. Classification key for CSs.

With regard to base anchors 5 and 6 of Agmon et al. [1], this CS classification is an extension of the QMS standards. AS9100 introduces particular concepts like CI and PS, which can be integral within a feature that characterizes CSs within a SoS. As such, a CS that encompasses numerous CIs, or has significant safety implications, would likely score higher on the classification parameters 1-3. This nuanced approach to classification draws from the literature on SoS attributes [27,29,52,70], suggesting that the distinction of SoS configurations depends on the degree of certain attributes rather than their mere presence. However, this study focuses on mapping and classifying individual CSs, aiming to tailor quality management practices to each CS's unique role and complexity within the SoS. The classification framework, determined by a set of several classes (types), ranks CSs into types based on a calculated score from the levels of the four main parameters. As the CS is classified in a higher type, then *additional unique quality requirements* shall be defined for it, and the monitoring and control operations by the G-QMS will be *tightened*.

According to this key and the base definition given by Agmon et al. [1]: "$S_X - Dimension$ *of Classification according to the classification of the constituent systems (SoS*$_\mathbf{X}$*)*". Here, we suggest an extended notation: $S_X - QMS_{CS-typeX}$, or in short, QMS_{CS_x}. Here, X designates the classed type, and the number of types can differ from one SoS project to another. For example, CS type A will be symbolized as follows: $S_A - QMS_{CS-typeA}$ or QMS_{CS_A}. To complete the notation, we added the letter Y to identify the specific system, resulting in the following: $S_{X_y} - QMS_{CS-typeX_y}$ ($QMS_{CS_{xy}}$). For example, CS specific 1, classified as type A, will be referred to as follows: $S_{A_1} - QMS_{CS-typeA_1}$ ($QMS_{CS_{A_1}}$). Furthermore, the CSs classification projects directly on the interface entity $QMS_{[integ\_CS]}$, and so characterizes these entities with classification levels as follows: $QMS_{[integ\_CS_{xy}]}$.

4.4.3. Maturity Level of QMS Entities

In Figure 2, within the parent category [5] that refers to the main model G-QMS in Sectors of SoS, among the categories that focus on the analysis relevant to the G-QMS in SoS model, category [5.5] was identified with a Si_{Total} = 3.3. Although this category also corresponds to the first supra entity, it is presented in this analysis due to its applicability to the QMS_{CS_x} as it is related to *quality first dimension* in the model concept of G-QMS in SoS (Section 4.1.3). Another dimensional aspect within that G-QMS in SoS concept is obtained by suggesting the parameter ***System Maturity Level*** for the QMS entities of the model, thereby offering a nuanced approach to assessing the capability and readiness of these entities, particularly the QMS of individual CSs. This parameter drawing from System Maturity model approaches, such as ISO9004 [8], CMMI [16], AIMM [17], as well as from G-QMS that internally develop such evaluation bars. It can serve as a comparative tool for the SoS G-QMS CORE, and thus aid in defining precise interface requirements between the CORE and various QMS entities. This parameter is less recommended for application for (internal) QMS entities since some of them are new evolving entities and some have partial (open) QMS structures. However, it proves more valuable for QMS_{CS_x} entities based on the QMS of independent external organizations located in the *quality first dimension* of the G-QMS in SoS concept. The System Maturity model classifies the maturity level of the CS organization's QMS, reflecting their proficiency in handling complex system deliveries based on an objective and acceptable level rating (according to the standard or acceptable guides). This additional layer of classification, when combined with the CS classification outlined in Section 4.4.2(1), enriches the management toolkit of the SoS G-QMS CORE, enabling a more tailored and effective quality management strategy for SoS projects.

4.4.4. SoS G-QMS CORE

In the results presented in Figure 2, the independent category [8.3] with Si_{Total} = 10.49 underscores the pivotal role of the SoS G-QMS CORE entity within the G-QMS in SoS model. This high index value underscores the entity's central importance and its recognition across all the clusters, particularly by the G-QMS CORE and QMSs clusters, which contribute at a rate of 45.1% and 23.9%, respectively. This parallels the emphasis placed in the G-QMS CORE category as well as in the second model [2]. The SoS G-QMS CORE head is the chief quality manager for the SoS project and a member of the SoS project chief management team. The main aspects identified for this entity are as follows:

(a) ***SoS G-QMS CORE head shall be a persona with high professionalism and authority***: This is a necessary condition, aligning with findings related to the G-QMS CORE in the model of the first supra entity [2]. This position demands not only expertise in quality management but also a deep understanding of the product and technology. Field data suggests a scarcity of professionals with the requisite expertise for such roles even at the lower levels of systems, particularly at the level required for leading the SoS

G-QMS CORE. In addition to these, the added value of the SoS G-QMS CORE is in being a comprehensive ensuring management factor, necessitating a broad systems perspective and the ability to manage transdisciplinary systems effectively.

(b) ***SoS G-QMS CORE role perception***: The role of the SoS G-QMS CORE lacks clear guidelines within the current QMS standards and literature, leading to varying perceptions of its responsibilities across different projects. This field study points out the existence of different perceptions, shaped by the unique characteristics and factors of each SoS project, and by the influence, often limited, from the infrastructural G-QMS CORE of the G-QMS of Org. of SoS model. This study proposes a role perception for the SoS G-QMS CORE as an integral part of the SoS project's chief core management team. Similarly to the chief project manager and SoS engineering, this position is *comprehensive and systemic*. However, unlike the comprehensive implementing role of SoS engineering, the SoS G-QMS CORE is a *comprehensive ensuring* role that does not in the execution functions. The scope of this assurance role can vary widely, subject to interpretation. This research suggests viewing the SoS G-QMS CORE and generally the G-QMS in SoS as a support and assistance body, particularly with the authority to approve exceptions within the bounds of regulatory, standard, and client requirements. It emphasizes the promotion of quality management principles such as risk-based thinking (see ISO9001 [5] and other standards), especially a body that should be seen as a resource that *contributes* to the project's success rather than hindering progress.

(c) ***SoS G-QMS CORE role positioning***: Quality management in SoS projects needs further enhancement, and it is suggested that the SoS G-QMS CORE be posited as a core element of the SoS project's chief management trio. The Positioning of the comprehensive systemic management that consists of the Chief SoS Project Manager, who oversees the overall project management; the Chief SoS Engineering, responsible for product and technology aspects; and the Head of SoS G-QMS CORE, who focuses on assurance and control, is depicted in the proposed structure in Figure 7.

(d) ***SoS G-QMS CORE main functions***: Primarily, the SoS G-QMS CORE is the focal point for quality management interactions with the client, stakeholders on his behalf, SoS project administration, and its chief project manager. It is tasked with overseeing all the aspects of quality management dictated by client contract requirements, regulations, and standardization norms. Additionally, it is responsible for formulating the policy and strategy for all the quality management processes within the G-QMS in SoS. The operational roles of the G-QMS in SoS are bifurcated into role routines, which persist throughout the project, and specific routines, which are phase-dependent according to the project's life cycle. Both are run with particular attention to the unique extensions typical for SoS projects. Moreover, the G-QMS in SoS drives a *transversal systemic* activity of quality management tools, *extended* QMS framework tools for internal audits, failure analysis, risk management, etc. The effectiveness and scope of G-QMS in SoS activities are conditioned to the availability of resources and personnel allocated to this system. The research results indicate an inherent lack of these functions across many projects, limiting the potential impact of G-QMS in SoS. However, this work contributes by offering a structured model for establishing a G-QMS in SoS tailored to such projects, thereby ensuring that the requisite support and resources are in place.

Figure 7. SoS project's chief management trio—comprehensive systemic management.

4.4.5. Interface of SoS G-QMS CORE and G-QMS CORE

SoS G-QMS CORE has a main interface with the SoS project's chief management team, alongside direct, strong connections with the client and the stakeholders on his behalf. However, the interface with the G-QMS CORE is often underdeveloped and considered a secondary one. This finding, highlighted by various cross-group respondents, underpins the delineation of the G-QMS in Sectors of SoS model into two distinct models, reflecting the unique and separate operational spheres of the SoS G-QMS CORE and the G-QMS CORE. A key distinction lies in the SoS G-QMS CORE focus on product technological quality management, a domain generally absent from the G-QMS CORE, which lacks direct interfaces with specialized entities like $QMS_{Integ.}$ and SoS-QMS-T&C that are integral to SoS project management. Given that the G-QMS of G-Org. of SoS is engaged with numerous projects, predominantly at the CS level rather than the SoS level, the specialized expertise required for managing quality in SoS projects is centralized within the SoS G-QMS CORE. The SoS G-QMS CORE is appointed by the SoS project chief management, often necessitating client approval in line with contract stipulations. It is crucial that this appointment also secures a recommendation from the G-QMS CORE, ensuring alignment and support. Geographically, the G-QMS in SoS is frequently positioned in proximity to, or even within, the client's premises, facilitating extensive interactions with the client's professional functions more than with the G-QMS of G-Org. of SoS, as depicted in Figure 8. SoS projects that establish a robust interface between the QMS Client or the QMS of the stakeholders on its behalf (such as QMS M&C $Local_{SoS_x}$) and the SoS G-QMS CORE lay a foundation for elevating the project's quality level. Conversely, a scenario where these interfaces are weak will lead to a weakened SoS G-QMS CORE that needs support from the G-QMS CORE, but such support cannot compensate for the lack of those direct engagements.

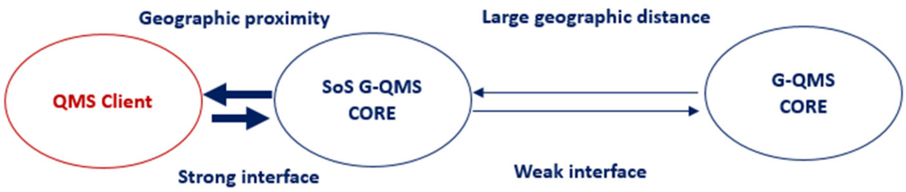

Figure 8. Geographical layout element of the global and the local focus.

The G-QMS CORE, recognized for its transdisciplinary perspective, management seniority, and expertise [2], presents a valuable resource from which the SoS G-QMS CORE can benefit significantly. The G-QMS CORE is motivated to enhance quality functions across the board, including within the G-QMS in SoS structure. It practices embedding personnel across various roles within QMS entities of the G-QMS in SoS, facilitating a matrix of quality expertise. Additionally, the involvement of G-QMS CORE with the SoS G-QMS CORE becomes crucial in exceptional situations, such as critical failures or extensive system issues, often triggered by client demands. In such scenarios, the SoS G-QMS CORE is required to have the active involvement and support of the G-QMS CORE to address and resolve the issues effectively. Given all these structural dynamics, it is crucial to ensure the independence of the G-QMS in SoS within the SoS project's structural framework, and simultaneously, strengthen the interfaces with the G-QMS CORE.

4.4.6. Affinity Between Quality Project Management and System Engineering

In Figure 2, an independent category [8.6] with a Si_{Total} = 7.91 was identified, pointing to its prominence in the research findings. Systems Engineering and Quality Engineering share similar characteristics, in both fields; these are areas of *systems engineering* where professionals typically transition into after gaining experience and professional maturity in more specific engineering roles. In SoS environments, systems engineering is at a higher level encompassing SoS engineering (SoSE), and quality engineering adopts a comprehensive, systemic approach. The parallels between these two fields are more pronounced than may initially be apparent. The thinking of a system engineer requires the systems view, a capability that disciplinary engineers might not naturally possess [57,80], which is *similar* to that of a quality engineer. In project management areas such as risk management, information management, client interaction, monitoring and evaluating, and decision making, the responsibilities are less distinctly defined. The works of Confronto et al. [81] and Kordova et al. [82] support these findings, although they focus on the affinity between project management and system engineering and involve projects that are not necessarily SoS projects. For a quality management engineer, while deep technical proficiency in a specific discipline may not be a prerequisite, possessing a solid understanding of the product technological aspects can significantly advance his position and enhance his work effectiveness.

The broad systems view, often transdisciplinary in nature, is indeed a pivotal advantage for those involved in the SoS projects. There are dedicated areas such as interface management, C&I process management, and T&C process management, in which strong, multidisciplinary expertise acquired through professional experience is essential. The roles of system engineering and SoS engineering indeed share significant similarities with quality management, particularly in their strategic and oversight functions rather than direct execution. These responsibilities include requirement definition, monitoring and supervision, troubleshooting, and compliance and complete control by providing approval signatures. Thus, there are various overlapping activities between the two roles, such as failure analysis and corrective action, process and product risk management, and the monitoring and control of outputs/products.

Quality management deals with highly *comprehensive systemic management* that includes process management, as well as processes such as for prevention and organizational learning, and operates from positions of *influence* within the project's hierarchy. The ultimate goal of the G-QMS in SoS is to provide significant added value to the SoS project by ensuring high-quality standards across all the functions and phases of the project. However, when the G-QMS in SoS is weakened or under-resourced, its ability to influence and ensure quality across the project diminishes. In such cases, there is not an organizational vacuum; rather, the responsibilities and activities related to quality management tend to be absorbed by other functions within the project, most notably system engineering and SoS engineering. In order to enhance G-QMS in SoS as an influential and contributing leader for a high-quality level in the SoS project, a great advantage in promoting system engineers to positions of quality managers was recognized. They hold a natural affinity for quality management roles and even a high potential to leverage these positions.

4.4.7. Quality Processes and Tools Promoted by G-QMS in SoS

In Figure 2, an independent category [8.9] with Si_{Total} = 26.96 was identified for this topic, the largest among the categories for the parent category [8]. As described by one of the respondents from the SoSE cluster, "*Quality is one of the most important things in the organization and the SoS project, so alongside the technology it is important to build supporting organizational processes*". The quality management processes for the SoS project are designed to define and maintain the desired quality level, adhering to established quality management principles for these processes. Based on base anchor 5 (internal extension) [1], these processes incorporate standard QMS tools, with necessary special extensions for the unique complexities of SoS. In addition, based on base anchor 6 (external extension) [1], considering the diverse complexity and importance of the CSs, SoS projects require additional specialized infrastructures, tools, and processes. The design of these processes follows a comprehensive structure that combines both longitudinal (horizontal) and cross-sectional (vertical) processes, ensuring they work together to uphold the required quality level. This conceptual process structure is depicted in Figure 9, highlighting the multi-dimensional approach needed to manage quality in SoS projects effectively.

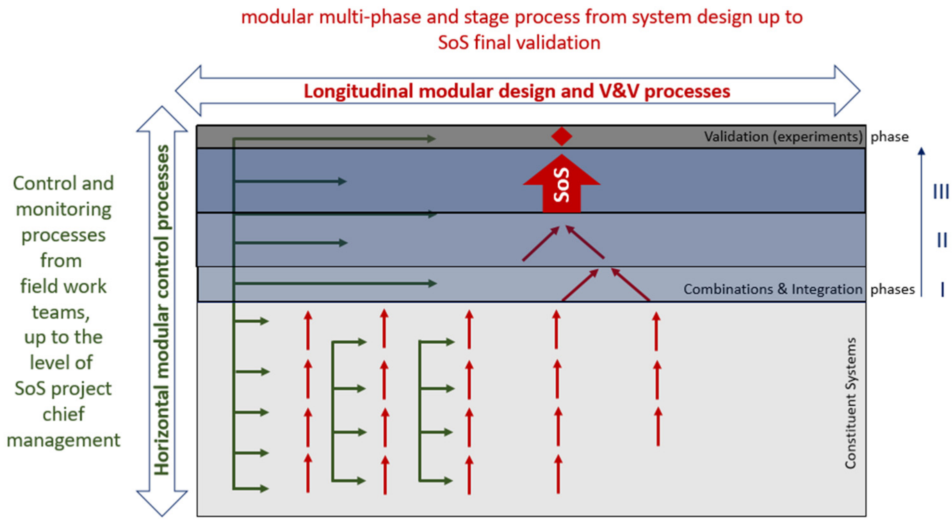

Figure 9. A horizontal–vertical conceptual quality process structure in SoS project.

The study collected data on quality management tools used in SoS projects, identifying 17 specialized tools from a longitudinal project management perspective and an additional 11 tools from a horizontal perspective. This comprehensive collection of tools forms a broad and detailed landscape of quality management resources suitable for SoS projects, from which it is possible to create a refined and exhaustive set of recommended tools tailored for SoS projects in general and for specific SoS projects as needed.

5. Conclusions and Contributions

This manuscript introduces a comprehensive conceptual model for G-QMS in SoS, thoroughly detailing its core principles and QMS entity structures, emphasizing the dynamics of their interactions, as well as those between other structural elements, including relationships with external elements like the client commissioning the SoS and the global organizational structure established for the SoS project. The model is completed with a detailed description of its key aspects, such as the management method approach integral to G-QMS in SoS, characterized by transdisciplinary management with a high level of expertise in quality management and with an independent organizational structure. It proposes an example of how quality management could be effectively operationalized through a designated IPT work concept. Another example of a notable aspect of this model is QMS entities which contain QMS_{CS}s as an essential component, offering for that benefit a classification key as a quality management tool. The conceptual model for G-QMS in SoS extends the common QMS, usually aligned with QMS international standards by incorporating necessary adjustments for SoS projects, integrating Systems Engineering processes and Systems Thinking methodologies. The outcome created is a cohesive framework essential for the successful G-QMS in SoS implementation with meaningful contributions to SoS projects.

The model can serve as a guide for quality management bodies in establishing G-QMS for SoS projects, highlighting critical but underexplored domains in quality management that, if developed, could significantly enhance the quality contribution to SoS projects. Additionally, the G-QMS in SoS model provides insights into structuring the G-organizational and functional architecture for SoS projects, particularly emphasizing the role of the SoS G-QMS CORE leader within the project's chief management trio.

The completion of this model, along with its interconnections with the G-QMS of G-org. of SoS model, culminates in a well-defined conceptual model for G-QMS in Sectors of SoS.

Research Limitations and Directions for Future Research

The creation of this pioneering conceptual model for G-QMS in Sectors of SoS opens a new avenue for research, marking just the beginning of exploration in this field. Future studies could focus on several areas. Future research could explore the elements or aspects of this model in greater detail. These kinds of works could provide in-depth guidance for relevant organizational quality bodies and contribute to the literature as a source for periodically updated QMS standards. One of these could be, e.g., further development of the QMS_{integ} alongside the layout of its unique QMS_{int} entities. Tools from Systems Thinking, such as CLD or Systemigrams, could be instrumental in these investigations. Secondly, the current model introduces some examples of extended or additional quality management tools specialized for the SoS arena, along with an illustration of the conceptual quality process structure for SoS projects. Future studies could identify and develop additional tools, enhancing the body of knowledge and potentially offering practical benefits not only to G-QMS in Sectors of SoS but to G-QMS of other sectors as well. Thirdly, given the model's adaptability to various G-organizations and to various SoS projects, future research could include case studies analyzing specific models tailored to particular organizations or projects, or even specific sectors. These case studies could enrich the knowledge base for each such model, and further contribute to the general model developed in this work. Fourthly, the qualitative methodology employed in this research contributed crucially to the conceptualization of this novel model. However, future research can continue developing this model, and even further validate it or parts of it using other research methods, including quantitative ones. Future research may consider examining Bayesian machine learning models and Bayesian algorithms as tools for enhancing quality management systems and data analysis. Such models could potentially increase accuracy and resilience in managing complex quality data, offering new insights and methodologies in conjunction with the development of this innovative field of research. Finally, with the rapid advancements in Artificial Intelligence (AI), future research could integrate AI technologies to improve the application of qualitative methodologies in research like this. AI could assist in managing and analyzing large volumes of qualitative data, enhancing the efficiency and accuracy of data collection and analysis processes; moreover, it can improve the effectiveness of methodological processes themselves, thus even leading to more robust research outcomes.

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Nomenclature and Definitions

G-organization	a global multi-organizational system, encompassing organizations distributed geographically across one or more countries. It features corporate senior management overseeing activities that go beyond national borders.
SoS	System of Systems is a conglomerate of independent constituent systems (CSs) integrated into a larger system to deliver unique capabilities and behaviors unattainable individually. Typically, this is global capability and behavior, whose realization necessitates a corresponding global organizational structure. SoS carries distinct attributes and characteristics necessitating technological and organizational addressable.
CS	Constituent System is an autonomous system with its development, management goals, and resources, contributing to the unique capability of the SoS through interaction. A CS can be a part of one or more SoS. ISO/IEC/IEEE 21839:2019 [4].
G-QMS	Global Quality Management System, which refers to QMS tailored for a G-organization.
G-QMS in Sectors of SoS	refers to G-QMS in G-organizations operating in the field of occupations (sectors) of SoS.
G-QMS of G-organization in Sectors of SoS (G-QMS of G-Org. of SoS)	refers to the first supra entity of G-QMS in Sectors of SoS, rooted in the multi-organizational structures of the G-organization. The G-organization could either be a main-contractor (or concessionaire) of a SoS project or a contractor of one or more CSs in a SoS project, functioning as a global company in one of the SoS sectors.
G-QMS in SoS	refers to the second supra entity of G-QMS in Sectors of SoS, a designated definition that represents the G-QMS for the SoS project, a temporary entity established with a special purpose to provide the quality management for the SoS project. It is of higher order in both scope and complexity and, consequently, integrates new quality management concepts.
G-QMS CORE	denotes the corporate senior management entity of the G-QMS. Named for the G-QMS CORE of the G-QMS of G-Org. of SoS.
SoS G-QMS CORE	denotes the corporate senior management entity of the G-QMS in SoS.
$\mathbf{QMS_{pro_x}}$	denotes a QMS entity of Quality Project Management of project X, located in G-QMS of G-Org. of SoS.
$\mathbf{QMS_{S\&P}}$	denotes a QMS entity for domain-wide Subcontracting and Procurement, located in G-QMS of G-Org. of SoS.
$\mathbf{QMS_{int}}$	denotes a QMS entity serving as an interface entity, defined by quality management principles, and aligned with the local functionality where it is situated in the G-QMS structure.
$\mathbf{QMS_{CS}}$	denotes the QMS of the CS, which is based on the QMS of its organization, located in G-QMS in SoS. Each CS in a specific SoS is traceable, when for a certain CS_{x_y} it is $QMS_{CS_{x_y}}$.
SoS QMS C&I or $\mathbf{QMS_{integ}}$	denotes a QMS entity, located in G-QMS in SoS, for the integrated SoS engineering function of the Combination and Integration (C&I) stage, and acts as a multi-interfaces hub among all the CSs.
$\mathbf{QMS_{[integ\_CS]}}$	designates a QMS_{int} located in G-QMS in SoS, which represents the QMS interface between the QMS_{CS} and the QMS_{integ}. For the particular CS_{x_y} it is $QMS_{[integ\_CS_{x_y}]}$.
QMS Client	denotes a QMS entity of local organization unit of the SoS project client, located in G-QMS in SoS.
QMS M&CLocal$_{\mathbf{SoS_x}}$	denotes a QMS entity of local organization unit for expert role of M&C in a certain SoS project X, located in G-QMS in SoS.

SoS QMS T&C	denotes a QMS entity for the SoS project validation stage, located in G-QMS in SoS.
Balance point (B_p)	a structural element in the model referring to the equilibrium position between two interface entities. The proximity of B_p to one of the two interfacing entities denotes the dominance of that entity in influencing the common interface. The variable locations of B_p across the scale continuum are a factor producing heterogeneity in the G-QMS structure.

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