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Recent developments in software engineering for systems-of-systems and software ecosystems

Francesca Lonetti ^{a,*}, Antonia Bertolino ^b, Pablo Antonino ^c, Doo-Hwan Bae ^d^a *ISTI-CNR, Pisa, Italy*^b *GSSI, L'Aquila, Italy*^c *Fraunhofer-IESE, Kaiserslautern, Germany*^d *KAIST, Daejeon, South Korea*

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ABSTRACT

The increasing scale, distribution, and interconnection of software-intensive systems continue to change the landscape of software engineering research and practice, bringing the diffusion of two similar paradigms: Systems-of-Systems (SoS) and Software Ecosystems (SECO). SoS are characterized by the integration of operationally and managerially independent systems that join together to accomplish a common mission. SoS are central to domains such as transportation, healthcare, defense, smart cities, and industrial automation where heterogeneous systems must cooperate, exchange information, and adapt to evolving missions. On the other hand, SECO describe environments in which a platform and its surrounding network of developers, partners, and organizations co-create software offerings. In SECO, technical artifacts interact with economic and social processes. Modern digital platforms, mobile operating systems, cloud services, and enterprise platforms leverage the capabilities of their ecosystems. This editorial brings together perspectives that explore the shared challenges and complementary insights of SoS and SECO research, aiming to foster a richer understanding of complex software-intensive systems and highlight new opportunities for collaboration across communities. From the long-running, successful series of the International Workshop on Software Engineering for Systems-of-Systems and Software Ecosystems (SESoS), co-located with the IEEE/ACM International Conference on Software Engineering (ICSE), we present this special issue of the Journal of Systems and Software on the topics of SESoS 2024 in Lisbon, Portugal. From a total of 18 submissions, 7 articles were accepted in this special issue. The articles in this collection address fundamental questions of SoS and SECO, including the evolution of functional relations and experimentation practices, the key factors affecting developer experience, also related to women's inclusion, as well as the adoption of GenAI-driven approaches for vulnerability fixing. These articles offer updates on current advances of SoS and SECO engineering to researchers and practitioners, highlighting opportunities for future research.

1. Selected studies

Most of the papers in this special issue address the challenges of using SECO in different contexts, such as cyber-physical systems, open source environments, business-to-business, or industrial domains.

The paper titled "Experiences and challenges from a software ecosystem for cyber-physical systems development: An empirical study on industry-academia collaboration" [Muttillio et al. \(2025\)](#), by Vittoriano Muttillio, Romina Eramo, Johan Cederbladh, Per Erik Strandberg and Adnan Ashraf, investigates the role of SECO in the development of Cyber-Physical Systems (CPSs). The authors examine the challenges arising in industry-academia collaboration within the AIDOoRt European

project by combining the findings of a systematic literature review of 24 primary studies with the results of an opinion survey conducted among project stakeholders. The study identifies 14 potential challenges associated with developing CPSs using SECO, spanning system design, quality attributes, development processes, data management, and interoperability. It also highlights key insights and lessons learned from the collaboration between academia and industry, particularly regarding: i) establishing a shared understanding through a common framework; ii) defining security and safety standards and ensuring their compliance with practical regulations; and iii) organizing hackathons to promote collaboration, innovation, and rapid prototyping, as well as to nurture long-term partnerships and open-source contributions. Finally, the authors argue

* Corresponding author.

E-mail addresses: francesca.lonetti@isti.cnr.it (F. Lonetti), antonia.bertolino@gssi.it (A. Bertolino), pablo.antonino@iese.fraunhofer.de (P. Antonino), bae@se.kaist.ac.kr (D.-H. Bae).<https://doi.org/10.1016/j.jss.2026.112819>

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that the main benefits of adopting SECO for CPS development include modular and scalable architectures that support reuse and third-party integration, enhanced handling of heterogeneity through standardized interfaces and components, and more robust engineering processes.

The paper titled “Extension decisions in open source software ecosystem” [Onagh and Nayebe \(2025\)](#) by Elmira Onagh and Maleknaz Nayebe, analyzes the GitHub Marketplace to deeply understand the SECO evolution, leveraging LLM-based feature extraction methods. This study analyzes the functionalities of GitHub Actions, identifying functional relations and their evolution over time in SECO. A highly connected network of functionalities related to continuous integration is presented using a graph-based model. Moreover, the characteristics of providers and their role in SECO evolution, as well as the inter-category migrations in GitHub marketplace, are investigated. Finally, this paper discusses the results based on features extracted from a dataset of 5006 Actions of the GitHub Marketplace.

The paper “Overcoming experimentation challenges in software ecosystems of large product and service organizations: A participatory action research study” [Hegazy et al. \(2025\)](#) by Shady Hegazy, Christoph Elsner, Jan Bosch and Helena Holmström-Olsson, presents an action research study on the topic of introducing experimentation practices, such as A/B testing, into ecosystems within large organizations, especially in business-to-business or industrial domains. Data are obtained through a systematic literature review and analysis of 63 primary studies, expert interviews with 25 participants across 17 software ecosystems, and collaborative workshops with internal stakeholders. The paper identifies and discusses the main organizational, technical, and cultural challenges to experimentation in the organization’s software ecosystems. The main factors limiting experimentation include: i) difficulty in reaching statistical significance in experiments; ii) critical or sensitive applications; iii) perceived instability and high costs of the applications; iv) regulations and contractual requirements; v) decisions driven by strategic factors rather than performance or user experience. Other factors that complicate the experimentation are: data integration and data availability issues, lack of experimentation infrastructures, experimentation skill and expertise constraints, and low awareness of experimentation benefits. Finally, the paper provides a roadmap for iteratively addressing such challenges.

The paper “Exploring developer experience factors in software ecosystems” [Zacarias et al. \(2025\)](#) by Rodrigo Oliveira Zacarias, Léo Carvalho Ramos Antunes, Márcio de Oliveira Barros, Rodrigo Pereira dos Santos and Patrícia Lago, presents a systematic mapping study that analyzes 29 papers and identifies 27 key factors affecting developer experience in SECO. Then, the paper presents a Delphi study with 21 third-party developers to evaluate how these factors influence their adoption and contribution to an SECO. These factors are classified in four categories: i) Common Technological Platform; ii) Projects and Applications; iii) Community Interaction; and iv) Expectations and Value of Contribution.

Two papers of this special issue focus on Proprietary Software Ecosystems (PSECO), a type of SECO in which the core platform, its interfaces, and the rules governing participation are owned and controlled by a single company. Specifically, the paper “An actionable framework to investigate and foster women inclusion in software development teams in proprietary software ecosystems” [Outão et al. \(2025\)](#) by Juliana Carvalho Outão, Luiz Alexandre Costa, Eleni Constantinou, Rodrigo Pereira dos Santos and Alexander Serebrenik, investigates how to enhance the inclusion of women in software development teams operating within PSECO. Building on a prior multivocal literature review on gender-related barriers and on 21 semi-structured interviews with women working in PSECO keystone organizations in Brazil, the authors introduce the PSECO-GDI framework as an actionable tool to both analyze and foster women’s inclusion in such environments. The study identifies 15 barriers to women’s participation, including well-known challenges from the literature, such as non-inclusive communication, stereotypes, lack of parity between peers, and family-related issues, as

well as two PSECO-specific barriers: client resistance to working with women and lack of collaboration between business partners. The paper also discusses strategies to mitigate these barriers through interventions targeting organizational processes, culture, hiring practices, and leadership. These strategies include creating and raising awareness of diversity policies, amplifying women’s voices, avoiding task stereotyping, increasing the visibility of women’s achievements, promoting women-focused events, and supporting women’s career progression.

The paper “Applying generative artificial intelligence for vulnerability fixing in a proprietary software ecosystem” [Costa et al. \(2025\)](#) by Luiz Alexandre Costa, Awdren Fontão, Rodrigo Pereira dos Santos and Alexander Serebrenik, introduces PSECO-SafePatch, a GenAI-driven approach designed to accelerate vulnerability fixing while adhering to enterprise security, governance, and DevOps practices. Building on insights from a participative case study conducted within a large global organization in the financial and insurance domain, the authors present a web-based tool that retrieves or generates patches for detected vulnerabilities, offers side-by-side code comparisons, and ensures traceability and compliance in regulated environments. To evaluate the approach, the authors conducted a two-month participative case study comparing manual vulnerability fixing with the PSECO-SafePatch workflow. The results show an 84% reduction in mean remediation time and an 89% patch success rate, indicating that most AI-generated patches required no rework. Additionally, the approach reduced developer cognitive load and achieved high acceptance and perceived usefulness among both developers and IT managers.

Finally, one paper of this special issue addresses Systems-of-Information Systems (SoIS) that represent an evolution of the System-of-Systems concept, specifically focusing on information-intensive systems such as enterprise platforms, government systems, cloud services, and digital infrastructures. The paper titled “An accountability evaluation model for systems-of-information systems” [Cordeiro et al. \(2025\)](#) by Felipe Cordeiro, Aline Pires Vasconcelos, Rodrigo Pereira dos Santos and Patrícia Lago, explores the challenge of evaluating accountability in SoIS. Based on a manual review of 32 primary studies, the authors propose both a definition of accountability and a conceptual model intended to support the systematic assessment of accountability in SoIS. The model is evaluated through a survey of 21 industry professionals and academic researchers. Using the participants’ assessments of the model’s propositions, the authors derive a refined version that incorporates obligations, sanctions, and conditions. This final model emphasizes the need for evaluation strategies and countermeasures to ensure responsibility fulfillment in the face of interdependence, evolution, and emergent behaviors inherent to SoIS.

CRediT authorship contribution statement

Francesca Lonetti: Conceptualization, Writing – original draft, Writing – review & editing; **Antonia Bertolino:** Conceptualization, Writing – original draft, Writing – review & editing; **Pablo Antonino:** Conceptualization, Writing – original draft, Writing – review & editing; **Doo-Hwan Bae:** Writing – original draft, Writing – review & editing.

Data availability

No data was used for the research described in the article.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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