Développement des Systèmes de Systèmes Produits et Services - Approches de Caractérisation, Modélisation, et Analyse : Application dans l'industrie automobile en vue de nouvelles solutions de mobilité

Sarra Fakhfakh

Thèse de doctorat

NNT : 2020UPAST047

Product Service Systems of Systems Development

Characterization, Modeling, and Analysis Approaches

Application in the automotive industry in view of new mobility solutions

Thèse de doctorat de l'université Paris-Saclay

École doctorale n° 573, Interfaces : matériaux, systèmes, usages
Spécialité de doctorat : Ingénierie des Systèmes Complexes
Unité de recherche : Université Paris-Saclay, CentraleSupélec, Laboratoire de Génie Industriel, 91190, Gif-sur-Yvette, France
Référent : CentraleSupélec

Thèse présentée et soutenue à Gif-sur-Yvette, le 14 décembre 2020, par

Sarra FAKHFAKH

Composition du Jury

Michael KOKKOLARAS Professeur, McGill University	Président
Alain BERNARD Professeur, Ecole Centrale de Nantes, LS2N UMR CNRS	Rapporteur & Examinateur
David WYNN Senior Lecturer in Mechanical Engineering, The University of Auckland	Rapporteur & Examinateur
Jakob PUCHINGER Professeur, Université Paris-Saclay, CentraleSupélec, Laboratoire Génie Industriel	Examinateur
Marija JANKOVIC Professeur, Université Paris-Saclay, CentraleSupélec, Laboratoire Génie Industriel	Directrice de thèse
Andreas Makoto HEIN Chercheur, Université Paris-Saclay, CentraleSupélec, Laboratoire Génie Industriel	Co-Encadrant de thèse
Yann CHAZAL Expert Systèmes de Systèmes, Groupe Renault	Invité
Alain DAURON Expert Leader Ingénierie des Systèmes, Groupe Renault	Invité

universite PARIS-SACLAY

ÉCOLE DOCTORALE
Interfaces:
matériaux, systèmes, usages

Titre : Développement des Systèmes de Systèmes Produits et Services - Approches de Caractérisation, Modélisation, et Analyse - Application dans l'industrie automobile en vue de nouvelles solutions de mobilité

Mots clés : Systèmes de produits et services, Systèmes de Systèmes, Systèmes de Systèmes de Produits et Services, Réseaux d'acteurs, Ontologie, Réseaux

Résumé : Les nouvelles solutions de mobilité sont motivées par les progrès technologiques et l'intérêt de répondre aux besoins des individus et de la société. Que ce soit par la connectivité ou l'électrification, la technologie a rendu les véhicules plus complexes à mesure qu'ils interagissaient avec d'autres systèmes de leur environnement. Parallèlement, alors que la société et les individus s'orientent vers des modes de vie plus durables, la possession d'une voiture est remplacée par d'autres solutions (par exemple, les services de location de voitures entre pairs) dont la valeur est accrue en offrant des services en même temps que les produits manufacturés ; un phénomène appelé "servicisation". La complexité croissante et la servicisation des systèmes de mobilité constituent un défi pour l'industrie manufacturière.
Du point de vue de la recherche, la complexité croissante et la servicisation sont étudiées séparément en tant que systèmes de systèmes et systèmes de services de produits, respectivement.
Ce doctorat vise à donner un aperçu des phénomènes concomitants de complexité croissante et de servicisation et porte sur les "systèmes de systèmes produits-services" (PSSoS). Tout d'abord, un cadre de caractérisation des PSSoS a été proposé. Ensuite, une ontologie qui traite des PSSoSa été développée. Troisièmement, approche d'analyser de l'implication et l'influence des parties prenantes des PSSoSs a été proposée. Une autre étude se concentre sur la nature évolutive des PSSoS et analyse les défaillances fonctionnelles et la propagation des changements dans les PSSoSs. Les contributions proposées sont validées par les retours d'experts et des études de cas.

Title: Product Service Systems of Systems Development - Characterization, modeling, and analysis approaches - Application in the automotive industry in view of new mobility solutions

Keywords: Product Service Systems, Systems of Systems, Product Service Systems of Systems, Stakeholders, Ontology, Networks

Abstract: New mobility solutions are driven by technological advances and the interest in meeting individuals' and society's needs. Whether it is through connectivity or electrification, technology made vehicles increasingly complex as they interact with other systems in their environment. Meanwhile, as society and people move towards more sustainable lifestyles, car ownership is being replaced by other solutions (e.g., peer to peer car rental services) where the value is increased by offering services along with manufactured products; a phenomenon referred to as servitization. The increasing complexity and servitization of mobility systems are challenging for the manufacturing industry. From a research perspective, the increasing complexity and servitization are studied separately as Systems of Systems and Product Service Systems, respectively.
This Ph.D. aims to provide insights on the concomitant increasing complexity and servitization phenomena and is concerned with "Product-Service Systems of Systems" (PSSoSs). First, a PSSoS characterization framework has been proposed. Second, an ontology has been developed. Third, an analysis approach has been suggested to analyze PSSoS stakeholder involvement and importance. An additional study focuses on the evolutionary nature of PSSoSs and analyses functional failure and change propagation in PSSoSs. The proposed contributions are validated through experts' feedbacks and case studies.

Université Paris-Saclay
Espace Technologique / Immeuble Discovery
Route de l'Orme aux Merisiers RD 128 / 91190 Saint-Aubin, France

Université Paris-Saclay
Espace Technologique / Immeuble Discovery
Route de l'Orme aux Merisiers RD 128 / 91190 Saint-Aubin, France

Abstract

As cities are continually evolving and becoming bigger and more complex, new urban solutions are being developed under the banner of the "smart cities." Urban solutions are of different natures: administrative, health care, housing, education, transportation, or energy urban solutions. These solutions are driven by technological advances (e.g., Internet of Things, big data) and the interest in meeting individuals' and society's needs. As such, they exhibit increasing complexity and a growing importance of service content.

Among these urban solutions, this thesis focuses on transportation and new mobility solutions. Over the last decades, technological advances allowed to integrate new monitoring, control, optimization, and autonomy capabilities into vehicles, e.g., communication among vehicles and infrastructure systems. Furthermore, vehicle electrification placed cars at the center of a broader ecosystem (e.g., vehicle to grid solutions). Therefore, whether it is through connectivity or electrification, technology made vehicles (systems) increasingly complex as they interact and interoperate with other independent systems in their environment. Meanwhile, as society and people move towards more sustainable lifestyles, car ownership is being replaced by other transportation solutions such as car leasing, shared mobility, or peer to peer car rental services. Hence, the value of a vehicle is increased by offering services along with manufactured products (vehicles), a phenomenon referred to as servitization.

The increasing complexity and servitization of transportation and mobility systems are challenging for the manufacturing industry. For instance, car manufacturers need to incorporate new capabilities into vehicles, envision car interactions and interoperations with systems developed and managed by other stakeholders, and collaborate with these stakeholders to provide service value to the user. From a research perspective, the increasing complexity of systems and servitization are studied separately as Systems of Systems and Product Service Systems, respectively.

This Ph.D. aims to provide insights for both academics and automotive practitioners on the concomitant increasing complexity and servitization phenomena. Therefore, within the design engineering field, this thesis is concerned with "Product-Service Systems of Systems" (PSSoSs).

Several contributions have been made during this research work. First, to understand and characterize PSSoSs, a PSSoS characterization framework has been proposed. This framework has been used to differentiate PSSoSs examples and identify challenges for their development. Second, an ontology that addresses PSSoSs, and more specifically, collaborative, use-and result-oriented PSSoSs, has been

developed. Third, a modeling approach as well as adapted analysis approaches, have been suggested to analyze stakeholder involvement and importance in the PSSoS development and support its management. An additional study focuses on the evolutionary nature of PSSoSs and analyses functional failure and change propagation in PSSoSs. Given that this PhD has been conducted in collaboration with the car manufacturer "Renault," several automotive case studies were considered, and expert feedbacks solicited to evaluate and validate the PhD contributions. In this manuscript, the electric vehicle plug and charge example illustrates the possible deployment of proposed approaches.

This thesis opens up the perspective of refining and complementing the proposed approaches towards a PSSoS design methodology for new mobility solutions. Another research avenue is to study the applicability of the proposed approaches to other urban solutions such as energy or health care services.

Résumé

Comme les villes sont en constante évolution et deviennent plus grandes et plus complexes, de nouvelles solutions urbaines sont développées sous la désignation de "villes intelligentes". Les solutions urbaines sont de différentes natures : solutions urbaines administratives, de santé, de logement, d'éducation, de transport, ou d'énergie. Ces solutions sont motivées par les progrès technologiques (par exemple, l'Internet des objets, les grandes données) et l'intérêt de répondre aux besoins des individus et de la société. En tant que telles, elles présentent une complexité croissante et une importance grandissante des offres de service.

Parmi ces solutions urbaines, cette thèse s'intéresse au transport et aux nouvelles solutions de mobilité. Au cours des dernières décennies, les progrès technologiques ont permis d'intégrer de nouvelles capacités de surveillance, de contrôle, d'optimisation et d'autonomie dans les véhicules, par exemple la communication entre les véhicules et avec les systèmes d'infrastructure. En outre, l'électrification des véhicules a placé les voitures au centre d'un écosystème plus large, par exemple, grâce à des solutions de connexion des véhicules au réseau électrique. Par conséquent, que ce soit par la connectivité ou l'électrification, la technologie a rendu les véhicules (systèmes) de plus en plus complexes à mesure qu'ils interagissent et inter opèrent avec d'autres systèmes indépendants dans leur environnement. Parallèlement, alors que la société et les gens s'orientent vers des modes de vie plus durables, la possession d'une voiture est remplacée par d'autres solutions de transport telles que la location de voitures, la mobilité partagée ou les services de location de voitures entre pairs. Ainsi, la valeur est augmentée en offrant des services en même temps que les produits manufacturés (véhicules), un phénomène appelé "servicisation".

La complexité et la servicisation croissantes des systèmes de transport et de mobilité constituent un défi pour l'industrie manufacturière. Par exemple, les constructeurs automobiles doivent intégrer de nouvelles capacités dans les véhicules, envisager les interactions et l'interopérabilité de la voiture avec des systèmes développés et gérés par d'autres parties prenantes, et collaborer avec ces dernières pour offrir une valeur de service à l'utilisateur. Du point de vue de la recherche, la complexité croissante des systèmes et la servicisation sont étudiées séparément sous les appellations respectives de systèmes de systèmes et de systèmes de produits et services.

Cette thèse de doctorat a pour objectif de fournir aux universitaires et aux praticiens de l'automobile un aperçu des phénomènes concomitants de complexité croissante et de servicisation. Par conséquent, dans le domaine de l'ingénierie de conception, cette thèse porte sur les "systèmes de systèmes produits-services" (PSSoSs).

Plusieurs contributions ont été apportées au cours de ce travail de recherche. Tout d'abord, pour comprendre et caractériser les PSSoS, un cadre de caractérisation des PSSoS a été proposé. Ce cadre a été utilisé pour différencier les exemples de PSSoS et identifier les défis pour leur développement. Deuxièmement, une ontologie qui traite des PSSoSs, et plus spécifiquement des PSSoSs collaboratifs, orientés vers l'utilisation et les résultats, a été développée. Troisièmement, une approche de modélisation ainsi que des approches d'analyse adaptées ont été proposées pour analyser l'implication et de l'importance des parties prenantes dans le développement des PSSoSs et soutenir leur gestion. Une autre étude se concentre sur la nature évolutive des PSSoSs et analyse les défaillances fonctionnelles et la propagation des changements dans les PSSoSs. Étant donné que cette thèse de doctorat a été menée en collaboration avec le constructeur automobile "Renault", plusieurs études de cas dans le secteur automobile ont été prises en compte et les commentaires des experts ont été sollicités pour évaluer et valider les contributions du travail de recherche. Dans ce manuscrit, l'exemple de la charge d'un véhicule électrique (solution Plug&Charge) illustre le déploiement possible des approches proposées.

Cette thèse ouvre la perspective d'affiner et de compléter les approches proposées vers une méthodologie de conception de PSSoS pour les nouvelles solutions de mobilité. Une autre piste de recherche consiste à étudier l'applicabilité des approches proposées à d'autres solutions urbaines telles que l'énergie ou les services de soins de santé.

Acknowledgement

I would like to express my gratitude to my academic and industrial supervisors. First, I sincerely thank my PhD. supervisor and mentor, Prof. Marija Jankovic, for her guidance, motivation, and numerous enlightening discussions. I am also thankful to Dr. Andreas Makoto Hein for sharing his knowledge and craft of conducting research work. Then, I thank Yann Chazal for his insights on the industrial context and stakes, advice, patience, and trust. I thank Dr. Alain Dauron for following this research work with great interest and care.

Next, I would like to express my gratitude to Prof. Alain Bernard, Dr. David Wynn, Prof. Michael Kokkolaras, and Prof. Jakob Puchinger for giving me the privilege of discussing my research work with them.

My gratitude also goes to my colleagues at Renault. I thank all those who gave feedback on my research work and discussed its applicability within the industrial context.

All the members of the Industrial Engineering Lab, CentraleSupélec, made this journey particularly rich and enjoyable. I am grateful to my fellow PhD students, in alphabetic order, Adam, Lara, Naouress, Timothé, and the others. I have learned so much from them. I particularly acknowledge Youssef Damak for being a great companion in debating and challenging ideas. Together, we discovered the immense joy and bearable pain of research.

My deepest thoughts go to my dear friends, family, and all those who are a helping hand and strong support at all stages of my life. They will recognize themselves.

I would like to express my heartfelt thanks to Raphaël for his unconditional support and for making life sweet and painless.

Above all, I am deeply and sincerely grateful to my mother. Without you, nothing, including this PhD, would have been achievable, not even conceivable. I dedicate this PhD as well as all my past and future “successes” to you!

TABLE OF CONTENTS

List of Tables

List of Figures

Foreword

This PhD dissertation results from a collaboration between CentraleSupélec and Renault Group under the CIFRE (Conventions Industrielles de Formation par la Recherche) contract n° 2017/0830 between November 2017 and January 2021. It is partially supported by the French National Association for Research & Technology (ANRT). Chapter 1 introduces the research work and gives an overview of it. Chapters two, three, and four present the background research, including a background literature and an industrial diagnosis, and describe the research methodology. The following chapters, from five to eight, are scientific papers published or submitted for publication in international journals and conferences. Finally, chapter nine concludes the dissertation with a discussion on the advantages and limits of the contributions and the implications of the research work. It also opens up on future research perspectives.

The following papers included in the dissertation have been published:

- Fakhfakh, S., Hein, A. M., Jankovic, M., & Chazal, Y. (2019, July). Towards an uncertainty framework for Product Service Systems of Systems. In *Proceedings of the Design Society: International Conference on Engineering Design* (Vol. 1, No. 1, pp. 3121-3130). Cambridge University Press.
- Fakhfakh, S., Hein, A. M., Jankovic, M., & Chazal, Y. (2020, October). Characterizing Systems of Systems change and Failure via network-based metrics. In Proceedings of the International Dependency and Structure Modelling conference (DSM)

The following paper included in the dissertation has been submitted for publication:

- Fakhfakh, S., Jankovic, M., Hein, A.M., Chazal, Y., 2020. An ontology to support Product Service Systems of Systems Engineering, submitted to the Systems Engineering

The following paper included in the dissertation is a working paper to be submitted for a journal publication:

- Fakhfakh, S., Jankovic, M., Hein, A.M., Chazal, Y., 2020. An analysis of Stakeholders importance and influence in Product Service Systems of Systems business partnerships and development, to be submitted to IEEE Transactions on Engineering Management
- Fakhfakh, S., Jankovic, M., Kokkolaras, M., Hein, A.M., Chazal, Y., 2020. A review of Product Service Systems (PSS) modeling approaches using the Function-Structure-Behavior framework, a working paper

The dissertation by paper style may produce some repetitions between the Chapter 2, 5, 6 ,7 and 8.

1 Introduction

1.1 Context and motivation

1.1.1 Smart cities

Cities are constantly evolving. Over the last decades, they became bigger and more complex, facing new challenges. For instance, the environment is a significant concern of urban cities due to the increasing pollution and greenhouse gas emission. Other concerns of urban cities are society and people, such as the aging population and the inclusiveness of people with disabilities. Cities holistically addressing these challenges have been referred to by different countries, organizations, and research as “smart cities” (OECD, 2020). According to the report of the 1st OECD Roundtable on Smart Cities and Inclusive Growth (OECD, 2020), different definitions have been given to smart cities. Based on the definitions cited in the OECD report, we retain that technological advances in communication and information technology and digital solutions are at the core of smart city development. However, the use of technology is intended to provide urban solutions and services that are more efficient, sustainable, and inclusive. As such, improving the lives and wellbeing of people, places, and the planet is also at the center of the concept of smart cities (Marrone and Hammerle, 2018). In essence, smart cities rely on technological advances to improve the quality of life of citizens, society, and businesses by enhancing the efficiency, reliability, resilience, and sustainability (social, economic and environmental) of urban services (in design and operation) (Elshenawy et al., 2018; Katina et al., 2016). Building smart cities also involves different stakeholders: public and private organizations, as well as citizens, collaborating and co-creating urban services (OECD, 2020). These urban services include administration, safety, transportation, energy, economy, healthcare, education, housing, and welfare urban services (Heppelmann, 2014, 2015; Marrone and Hammerle, 2018; OECD, 2020).

Urban transportation services are considered critical in the context of smart cities (Elshenawy et al., 2018). Therefore, this research work proposes to focus on transportation and mobility systems in future smart cities.

1.1.2 Transportation and mobility solutions within smart cities

As an integral part of smart cities, transportation and new mobility systems can be viewed from two perspectives technology and people (including individuals and society) (Marrone and Hammerle, 2018). As for the **technology**, advances in information and communication technology have made it possible to develop connected and smart cars referred to in a more general sense as Intelligent Transportation Systems

(Elshenawy et al., 2018). These systems enhance the efficiency of the transportation and show new capabilities of monitoring, control, optimization, and autonomy (Heppelmann, 2014) permitting, for example, the communication between vehicles or vehicle smart parking management. Future autonomous vehicles are another example of Intelligent Transportation Systems that will be an essential component of smart cities (Maurer et al., 2016; OECD, 2015; Talebpour and Mahmassani, 2016). Technology also allows for addressing climate change and energy efficiency issues (Plassat, 2010) through vehicles' electrification. By definition, electric vehicles are at the center of a broader ecosystem, including among others energy infrastructure and grids (Chen et al., 2016; Katina et al., 2016; Laurischkat and Viertelhausen, 2017). Therefore, whether it is by the connectivity or electrification, technology is making vehicles (systems) **increasingly complex** as they interact and interoperate with other systems in their environment.

From a **people** perspective, smart cities are not designed for cars but rather for citizens (Plassat, 2010). Smart city development promotes more efficient, sustainable, and human-centered mobility solutions (OECD, 2020). For instance, moving towards more low-carbon lifestyles people and society start replacing car ownership by other transportation solutions such as car leasing, shared mobility, or peer to peer car rental services (Plassat, 2010). Such mobility solutions also constitute support to traditional public transportation and help to relieve congestion in the transport network and road infrastructure. Hence, new mobility solutions and services can contribute to reducing the costs related to public transportation and reduce greenhouse gas emissions. Furthermore, we note that new mobility solutions tend not to focus on the vehicles and systems themselves. Instead, they focus on the **services** these systems can help provide to individuals and society.

In summary, technological advances, along with new societal and individual concerns (e.g., sustainability), drive the development of new mobility solutions. These new mobility solutions render the vehicles and systems more complex and switch the focus from the product (or vehicle) to the services vehicles help achieve.

1.1.3 New mobility solutions and shifts in the automotive industry

The automotive industry is, therefore, impacted by such transformations in the transportation area and mobility solutions. For instance, advances in information and communication technology as well as the development of services, are not necessarily at the core of the competencies of the automotive industry (Mahut et al., 2015). Hence, it moves towards more collaboration with other business partners (e.g., mobility operators and energy providers) to develop and operate mobility services such as "pay as you drive", plug and charge, navigation services, and smart route planner (Chazal, 2018; Hein, Chazal, et al., 2018).

Therefore, the automotive industry shifts from being seen as an industrial chain to being a part of a larger ecosystem where the development management and operation of mobility services and connected services are shared with other stakeholders (Mahut et al., 2015).

1.1.4 New mobility solutions as Product Service Systems of Systems

The previous sections showed that new mobility solutions **(1)** rely on information and communication technology, **(2)** increase the complexity of vehicles and systems, **(3)** focus on the services supported by vehicles and systems, and **(4)** involve multiple stakeholders.

In the literature, systems with an increasing software content **(1)** are referred to as **"Cyber Physical Systems"** (CPS) (Biff et al., 2017; Bondavalli et al., 2016; Broy, 2012). CPSs are defined as "open, ubiquitous systems of coordinated computing and physical elements which interactively adapt to their context, are capable of learning, dynamically and automatically reconfigure themselves and cooperate with other CPS (resulting in a compound CPS), possess an adequate man-machine interface, and fulfill stringent safety, security and private data protection regulations" (Broy et al., 2012).

Another concept of the literature pertains to the characteristics of new mobility solutions **(2)** and **(4)** and is referred to as **"System of Systems"** (Baldwin et al., 2011; Maier, 1996). Systems of Systems are "a class of systems built from components that are large scale systems in their own right. Systems-of-systems should be distinguished from large but monolithic systems by the independence (managerial & operational) of their components, their evolutionary nature, emergent behaviors, and a geographic extent that limits the interaction of their components to information exchange."(Maier, 1996)

Finally, the **(3)rd** characteristic pertains to the shift from selling products to selling services. This phenomenon has been referred to as **"servitization"**. And the solutions are named **"Product Service Systems"** (PSS) and defined as "system of products, services, supporting networks and infrastructure that is designed to be competitive, satisfy customers' needs and have a lower environmental impact than traditional business models." (Mont, 2002)

This thesis falls within the design engineering research and focuses on the increasing complexity and servitization phenomena. Hence, this research work is interested in systems that are Systems of Systems and Product Service Systems. We name such systems Product Service Systems of Systems (PSSoS) and define them as "sets of products, services, infrastructures, and networks where its constituent elements exhibit operational and managerial independence" (Hein, Poulain, et al., 2018).

1.2 Problem statement

1.2.1 Industrial issues and stakes

In the context of Product Service Systems of Systems, independent organization and enterprises involved in the development and operation of the PSSoS act on various levels: **1)** Collaborative Product-Service System business models and portfolio development **2)** Collaborative PSS concept and value proposition, and **3)** Heterogeneous products and services architecture (Hein, Chazal, et al., 2018) (Figure 1.1). For example, a car manufacturer, an energy provider, and a service provider collaborate to offer a vehicle to grid services to customers (Chazal, 2018).

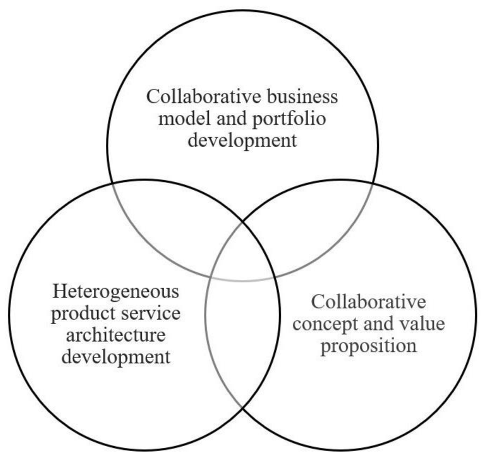

Figure 1.1: Product Service Systems of Systems research concerns

PSSoS development requires enterprises and organizations to adapt partnership frameworks and business models (Chazal, 2018; Hein, Chazal, et al., 2018). For the automotive industry, and more generally, the manufacturing industry, the development of such collaborative business models is rather new as these industries traditionally treat with suppliers rather than independent business partners (Weiller and Neely, 2013). Enterprises and organizations also need to cooperate to fix service definition and operation conditions (Muller, 2016; Pinho, 2015; Sahin et al., 2007; Zine et al., 2014) and operate products and services continuously (Boardman and Sauser, 2006). In this respect, the main difficulties of the automotive industry are designing services along with products and defining the operational conditions of products and services, including the involvement of the enterprise during the use phase of the product and service. Compared to conventional car maintenance services, which may require the car to be returned to the garage periodically, mobility services such as navigation require a continuous service provision. Furthermore, new mobility solutions require the enterprises and organizations to respect user needs for mobility (Mahut et al., 2015) and involve users so that they bring their contribution to the design and developments of mobility services (Boukhris et al., 2017; Kimita et al., 2016; Pezzotta et al., 2018; Yip et al., 2012). If the automotive industry is used to get customer feedback to develop new car lines (products), involving users in the design of mobility solutions, including a service content is fairly new and implies changes in the design process.

As it offers services along with the manufactured products (cars), the automotive industry is further involved during the operation of the product and the delivery of the service. Because the vehicle interoperates with other systems (e.g., energy grids) and services are continuously adapted to operational conditions and user's needs, the car's technical behavior is to be adapted. And new capabilities are to be incorporated (Mahut et al., 2015).

An initial empirical study within the automotive industry (detailed in chapter 4) allows us to summaries the industrial challenges according to the previously defined levels as follows:

1) & 2) The collaboration with independent business partners brings "unknowns", for example, unknowns related to the technological roadmap of the business partner that might influence the collaboratively developed solution.

2) Given that the solution to be developed involves multiples independent stakeholders including users and that the car is to intensively interact with its environment, gathering the system's requirements gets difficult

3) As service are offered along with manufactured products, the integration of products and services as well as the "alignment" of products and service lifecycles is challenging.

3) Systematic processes to develop vehicles are usual within the automotive industry. However, a systematic approach to develop services along with the products is lacking. This generates a gap between a "Systematic" and "Structured" Product (Vehicle) development and less mature development of Mobility Services (Cavalieri and Pezzotta, 2012).

1.2.2 Research gap

The challenges the automotive industry faces when participating in the development of new mobility solutions (PSSoSs) occur during the business modeling, the design and development of the solution (system architecture and service design), and the operation of the solution. Therefore, these challenges are at the center of several research areas, such as business management and organization, design engineering, systems engineering, information management, or operational research. For instance, business management research treats the collaboration of multiple stakeholders (Weiller and Neely, 2013), and also the value co-creation between service providers and customers in the context of PSSs (Bagheri et al., 2016; Kwan and Müller-Gorchs, 2011; Sabbagh et al., 2016). Design engineering research also focuses on the concept of Product Service Systems and design of its heterogeneous constituent element, namely products and services. In this domain, authors cover issues related to PSS business modeling, PSS engineering (Cavalieri and Pezzotta, 2012), product and service design processes, lifecycles (Hajimohammadi et al., 2017; Orellano et al., 2019), and integration. The issues rather related to the operation of mobility solutions as well as the interaction and interoperation of systems is the subject of interest of operation and transportation research (Bischoff and Maciejewski, 2016; Chen et al., 2016; Talebpour and Mahmassani, 2016) and (computer) systems engineering research, usually referring to Cyber-Physical Systems (Elshenawy et al., 2018). On a more conceptual level, the increasing complexity of systems is the topic of the Systems of Systems engineering research (Baldwin et al., 2011). In (Keating and Katina, 2011), the authors summarize different perspectives of the SoS engineering research into the military perspective "focused on 'interoperability' of technological command and control (individual) systems," the academic perspective aiming for more rigorous and grounded development of SoSs, and enterprise perspective taking not only independent systems into account but also independent enterprises developing these systems.

Despite this extensive research, the different research streams have been developed independently. Product Service Systems and Systems of Systems, and therefore the **servitization** and the **increasing complexity**, have rarely been studied concomitantly (Hein, Poulain, et al., 2018). The **multiplicity of stakeholders** and their relationships is lately becoming a subject of interest in both Product Service Systems research (Costa and Diegues, 2019) and Systems of Systems research (Muller, 2016). According to the author, there is a need to concomitantly and holistically address challenges related to servitization, increasing complexity, and the multiplicity of stakeholders to support the automotive industry, and in a more general sense enterprise and organization in developing new mobility solutions seen as Product-Service Systems of Systems.

1.3 Research aim

The overall objective of this research is to propose approaches able to support the PSSoS development in the context of new mobility services for a car manufacturer. These approaches aim to take into account servitization, increasing complexity, and multiple stakeholders' perspectives. However, since this research falls within the design and systems engineering domain, the proposed approaches focuses on collaborative value proposition and heterogeneous product service architecture development while keeping aspects of business management (Figure 1.1).

1.4 Research outcomes

This research aims to propose approaches to support PSSoS development and includes:

1. A **PSSoS characterization map** allowing to understand the specificities of PSSoS compared to PSS and SoS. It also shows the diversity of PSSoSs and the corresponding design challenges. This outcome participates to initiate the joint research on PSS and SoS. From an industrial perspective, this outcome gives a better understanding of the system under development as well as its overall development challenges.

The following outcomes focus on specific types of PSSoSs, namely acknowledged, use, and result oriented PSSoSs (see chapters 2 and 5).

2. A **PSSoS ontology** allowing for holistic representation of PSSoS elements and their relationships. It also supports the engineering of PSSoS. The ontology was validated through expert validation and case studies. This ontology contributes to the literature by providing a PSSoS representation model that combines PSS and SoS key concepts and takes into account PSSoS specificities. From an industrial perspective, this ontology is intended to foster the collaboration between service designers and system engineers by sharing a common understanding of a PSSoS.
3. Two aspects are of interest when **analyzing a PSSoS** (see chapter 4): **a)** the independent organization's business partnerships and involvement in the development of PSSoS, and **b)** the component systems of PSSoS functioning together to provide services and value to the customer. Therefore, this research provides two additional outcomes:
   - **3.1. A network analysis approach for PSSoS stakeholder** business partnerships and involvement in the development. This approach relies on the extensive literature on stakeholder management and organization and proposes a novel way to analyze PSSoS stakeholders considering PSSoS relevant information. From an industrial perspective, this approach helps PSSoS decision-makers picture the important PSSoS stakeholders they collaborate with from both business and development views.
   - **3.2. An analysis of functional vulnerability in SoS and as such PSSoS.** As SoS and PSSoS evolve in a highly dynamic and uncertain environment, this outcome proposes a network-based approach for characterizing functional change and failure in SoS in general and PSSoS in

particular. This approach supports the design of systems within PSSoSs and supports the decision making during PSSoS operation.

Figure 1.2 positions the thesis outcomes with regards to PSSoS research concerns.

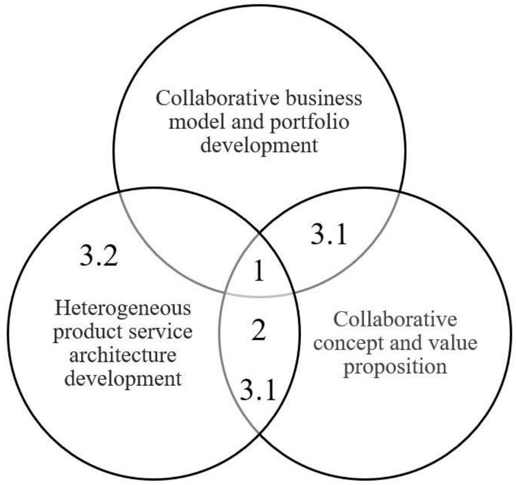

Figure 1.2: Positioning research outcomes with regards to PSSoS research concerns

An additional outcome of this research is presented as an appendix (A). In fact, the diversity of PSSs, SoSs, and therefore PSSoSs raises various questions that go beyond the scope of this thesis that focuses on specific types of PSSoSs (as previously stated). Appendix A is a review and classification of PSSs modelling approaches that aims to map modelling approaches to PSS development contexts and types.

1.5 Thesis structure

This thesis has a paper-based structure. The main thesis outcomes are presented through papers in chapters 5 to 8. Chapters 1 to 4 provide a setting for this research by introducing the context, background literature, the research methodology, and detailed industrial diagnosis. An overall discussion and conclusion of the research work and perspectives are given in chapter 9 (see Figure 1.3).

Chapter 1 introduces the research context, states the problem, presents the aim and outputs of this research work.

Chapter 2 presents the background literature and derives, more specifically, the gaps this PhD aims to address.

Chapter 3 formulates the research questions defined in accordance with the research gaps detailed in chapter 2. It also presents the adopted research methodology to answer these questions.

Chapter 4 details the industrial empirical studies undergone to answer each research question.

Chapter 5 introduces #paper1 "Towards an uncertainty framework for Product-Service Systems of Systems," presented in the International Conference on Engineering Design (ICED 2019). This paper corresponds to the first research outcome **(1)**.

Chapter 6 introduces #paper2 **"**Proposition of an ontology to support Product Service Systems of Systems Engineering" submitted to Systems Engineering Journal. This paper corresponds to the second research outcome **(2)**.

Chapter 7 introduces #paper3 "Characterizing stakeholder collaboration in Product-Service Systems of Systems," a working paper to be submitted to IEEE Transactions in Engineering Management. This paper corresponds to the outcome **(3.1.)**.

Chapter 8 introduces #paper4 "Characterizing System of Systems Change and failure via network-based metrics" presented in the DSM conference 2020. This paper corresponds to the outcome **(3.2.)**.

Chapter 9 discusses the research work and concludes giving research perspectives

Appendix A presents a working paper "A review of Product Service Systems modeling approaches using the Function-Structure-Behavior framework."

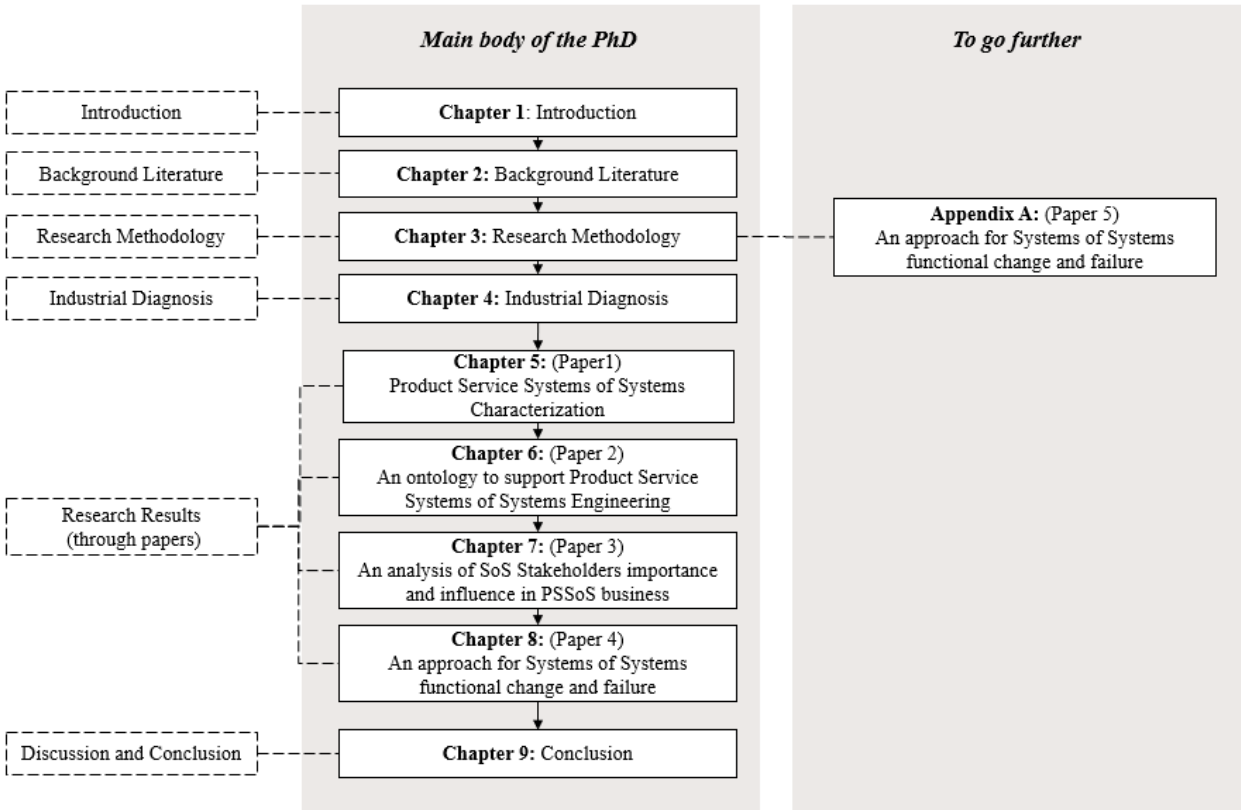

Figure 1.3: Thesis Structure

2 Background literature

This chapter presents the background literature of the present research and derives the main knowledge gaps this PhD aims to address. As mentioned in the introduction, the development of new mobility services embeds the **servitization** of the offer (Product Service Systems), an **increasing complexity** (Systems of Systems) of the systems and increasing **software and digital content** (Cyber-Physical Systems).

In the following sections, we review how these phenomena have been studied in the literature: **1)** how they have been characterized and defined, and **2)** how they have been represented and modeled to support system and service development teams. Besides, we Focus on two major characteristics of new mobility services, namely the evolutivity and uncertainty of the development and the multiplicity of stakeholders. And we review **3)** how the highly evolutive and uncertain environment of systems and the participation of multiple stakeholders have been studied and analyzed in the literature.

2.1 Servitization, increasing complexity and software content: phenomena characterization

2.1.1 Servitization

Servitization can be viewed as the process of increasing the value of manufacturing firms by offering services along with the manufactured product, and, as such, better meet customer demand and achieve a competitive advantage (Martín-Peña et al., 2017). According to authors (Baines et al., 2007; Manzini and Vezzoli, 2003), servitization is also a way to achieve better manufacturing products' sustainability. Neely et al., (2011) resume the servitization phenomenon as “(i) the shift from a world of products to a world including solutions, (ii) outputs to outcomes, (iii) transactions to relationships, (iv) suppliers to network partners, and (v) elements to eco-systems.” As such, different research perspectives have been taken on servitization (Velamuri et al., 2011): strategic, organization (Baines et al., 2017), marketing (Zhang and Banerji, 2017), design, innovation, business, sustainability, and macroeconomic perspectives. Therefore, different terms have also been used to refer to servitization: complex product system, customer solution, dematerialization, extended product, functional economy, functional product, hybrid product, hybrid solution, integrated solution, product-based service, product-related service, product service system, etc. (Velamuri et al., 2011). Given that the term Product Service System (PSS) has been largely used in

Engineering and design, business management, and information systems Boehm and Thomas, (2013), we focus in the following on PSS research.

PSSs are defined as "systems of products, services, supporting networks and infrastructure that is designed to be competitive, satisfy customers' needs and have a lower environmental impact than traditional business models" (Mont, 2002). Hence, PSSs are defined by their constituent elements. Products are defined as physical, tangible, or manufactured products. As for services, different definitions have been given (Aurich et al., 2010), and types of services have been distinguished (Bullinger et al., 2003; Haeberle et al., 2016). In this PhD, we consider that a service is, by opposition to a product, intangible, and we refer mainly to the uno-acto principle to distinguish service from a product (Meier et al., 2010). The uno-acto principle stipulates the simultaneity of production and consumption of the service. Finally, stakeholders, infrastructure, and resources are defined similarly as for a system in a more general sense. A stakeholder is *"any entity (individual or organization) with a legitimate interest in the system"*(INCOSE, 1966), e.g., suppliers, subcontractors, business partner, government, or final user. The infrastructure is used to deliver a solution to a customer to satisfy a certain need (Tran and Park, 2014). Resources is defined in the Oxford dictionaries as *"a stock or supply of money, material, staff, and other assets that can be drawn by a person or organization in order to function effectively."*

Furthermore, PSSs have been characterized as following in the literature:

- the heterogeneity of their constituent elements (Sassanelli et al., 2016; Song, 2017),
- their customer orientation (Manzini and Vezzoli, 2003),

their economic, environmental, technological, and social sustainability (Aurich et al., 2006; Maleki, Belkadi, Van der Zwaag, et al., 2017; Meier et al., 2010; Pieroni et al., 2017)

More recent studies also characterize PSSs by:

- their evolutionary nature, including the dynamic interaction within the stakeholder network (Bagheri et al., 2016; Song, 2017) and dynamic interaction between product and services throughout the lifecycle
- their organizational and technical complexity due to the high number of involved elements (Maleki, Belkadi, Van der Zwaag, et al., 2017)

Besides, focusing on the product and service elements, different PSSs classifications have been proposed. From a business perspective, Tukker, (2004) classifies PSSs in eight types based on whether the value is in the product or the service. Aurich et al., (2010) details the criteria to differentiate PSSs types, including the ownership of the product, operational and maintenance personnel, the location of the manufacturing facility, the payment method, and the delivery of raw materials and suppliers. From a design and engineering perspective, Meier et al., (2010) classify PSSs according to the engineering of products and services into service products, extended products, and industrial product-service systems. Other classifications have been proposed such as the ones proposed by (Adrodegari et al., 2015; Gaiardelli et al., 2014).

2.1.2 Increasing complexity

The increasing complexity of systems has been studied in (Baldwin et al., 2011). The authors differentiate a simple system from complicated systems, complex systems, adaptative systems, and collaborative systems of systems based on attributes of autonomy and diversity, belonging, connectivity, emergence, self-organizing, adaptability, and supporting attributes. Maier, (1996) focuses specifically on SoSs and characterizes them by the operational independence of the elements, the elements' managerial independence, evolutionary development, emergent behavior, and geographic distribution. Keating and Katina, (2011) add the interoperability, complementarity, and holism to these characteristics. Azani, (2008) has given another perspective on SoSs. The author characterizes the development of SoSs by natural development principles: self-government, emergence, conservation, natural reconfiguration, symbiosis, and modularity. More recently, Luo, (2017) studied SoS innovation and argued that the conception of a new system of systems implies expansionism, synthesis, and complementarity. We retain that SoSs are a synthesis of distributed, heterogeneous, and independent elements (component systems) and enterprises collaborating and functioning together towards a common goal (Petitdemange et al., 2018; Uday and Marais, 2015).

The literature studies SoSs from two main perspectives: **1)** SoS architecting, focusing on the complexity of the relationships between component systems (DoD, 2008), and **2)** SoS enterprise engineering and management, looking at the relationships between independent enterprises and organizations (Darabi et al., 2012; Gorod et al., 2008; Sauser et al., 2009; Sauser and Boardman, 2008). Based on both perspectives, Uday and Marais, (2015) derive other characteristics of SoSs: the heterogeneity of component systems, the uncertainty of the environment in which SoSs are developed and operated, and the multiplicity of involved stakeholders with partial control over the SoS. In the context of SoS, the heterogeneity of constituent systems refers to their diversity, variety, and geographic distribution. As for uncertainty, the authors (Uday and Marais, 2015) distinguish external and internal uncertainty. Internal uncertainty covers phasing component systems, including a new component system in the SoS, and upgrading or changing a component system. External uncertainty is related to the evolutionary nature of SoSs and the evolution of their environment (Corsello, 2008). It includes new requirements or changing stakeholder needs. Besides, according to the authors, the multiplicity of stakeholders involved in the development, management, and operation leads to “situations where some stakeholders are required to accept greater costs.”

From a rather SoS management perspective, Maier, (1996) differentiates directed, acknowledged, collaborative, and virtual SoSs. These SoS types can be distinguished based on how central the management of the system is (Tekinerdogan, 2016). For instance, directed SoS are “build and managed to fulfill a purpose.” Acknowledged SoS have “recognized objectives and a designated manager.” Military and Defense systems are usually taken as an example of directed SoS (Maier, 1996) or acknowledged SoS (Fang et al., 2018). Collaborative SoSs are “voluntarily, and the authority uses collaborative means to decides.” Maier, (1996) gives the internet as an example of collaborative SoSs. Finally, virtual SoSs have “no central authority and interactions emerge.” (Darabi et al., 2012; DoD, 2008) Both the World Wide Web and the international economies are considered to be virtual SoSs by Maier, (1996).

Concerning SoS architecting, SoS research is mostly driven by the application domain. The military and defense domain is largely interested in SoS architecting (Chen and Unewisse, 2017; DoD, 2008; Keating and Katina, 2011). Software systems development has also been using SoS principles (Nielsen et al., 2015; Zhang, 2015). More recently, intelligent transportation systems and smart cities have been considered SoSs and architected as such (Elshenawy et al., 2018; Mansouri et al., 2009).

2.1.3 Increasing software content

The advances in communication systems and computing, led by the Internet of Things and big data, transformed traditional systems and devices into smart and connected devices (Heppelmann, 2014, 2015). Heppelmann, (2014, 2015) gives different examples of such systems: smart connected mining, smart housing, smart mobility, connected and autonomous cars, and smart health. According to the author, these systems include hardware and software content (Heppelmann, 2015). Therefore, they are in both the physical world and the digital world (Cloud) (Huang et al., 2016). Heppelmann, (2014) characterizes them by their monitoring, control, optimization, and autonomy capabilities. The engineering literature usually refers to these “smart” systems as Cyber-Physical-Systems (CPS).

CPSs are defined as “open, ubiquitous systems of coordinated computing and physical elements which interactively adapt to their context, are capable of learning, dynamically and automatically reconfigure themselves and cooperate with other CPS (resulting in a compound CPS), possess an adequate man-machine interface, and fulfill stringent safety, security and private data protection regulations”(Broy et al., 2012).

Horvath, (2012) further details the features of CPSs. The authors (Broy, 2006; Broy and Schmidt, 2014; Horvath and Gerritsen, 2012) mostly focus on the challenges related to developing and implementing cyber, physical, and synergic technologies. The CPS research aims to address these challenges in systems architecting and operation (Elshenawy et al., 2018).

Finally, servitization and **PSS** research focus on the external effect of systems such as their customer orientation and sustainability (Hein, Poulain, et al., 2018). PSS research also investigates the interactions between product and service elements. More recently, PSS research looked into the increasing complexity and evolvability of PSSs (Maleki, Belkadi, Van der Zwaag, et al., 2017). In parallel, an extensive literature exists on the complexity and evolvability of systems, referred to as **SoS**s. However, while real-life systems such as mobility and transportation systems exhibit both PSS and SoS characteristics, PSSs and SoSs have rarely been studied concomitantly in the literature (Estrada and Romero, 2016a; Maleki, Belkadi, Van der Zwaag, et al., 2017; Muller, 2018). Furthermore, technology plays a crucial role in realizing PSSs (Mikusz, 2014; Scholze et al., 2016) and SoSs alike. However, **CPSs** have also been developed independently from PSSs and SoSs. Few studies bring closer CPS and SoS research (Guariniello et al., 2019; Huang et al., 2016; Zhang, 2015).

The first research gap is summarized as follows:

Research Gap 1: PSSs, SoSs, CPSs have rarely been studied concomitantly even though the servitization, increasing complexity, and increasing software content are happening at the same time in real-life examples.

This research work will focus on servitization and increasing complexity. The software and digital content is considered in studied use cases. However, case specific technological challenges are not addressed. Therefore, the following sections will review the PSS and SoS literature only.

2.2 PSS and SoS representation and modeling

This section aims to understand how PSSs and SoSs have been represented, what information is relevant for their representation, and what models have been proposed to support their design and development.

In this PhD, we define a representation or a model as “an approximation, representation, or idealization of selected aspects of the structure, behavior, operation, or other characteristics of a real-world process, concept, or system” (IEEE Standards Board, 1989, p. 12).

2.2.1 Models in PSS literature

As mentioned in paragraph (2.1.1.), PSSs have been studied from different perspectives and research streams, including business management, design engineering, and information management (Boehm and Thomas, 2013). As such, a variety of PSS models have been proposed, capturing different aspects of PSSs (Pirayesh et al., 2018)**.** One can distinguish **high-level models** and **detailed models**.

High-level models aim to give an overall perspective on PSSs. These models are mostly meta-models and ontologies that define, and group different concepts related to PSSs and their relationships. Among these concepts, we find in most ontologies and meta-models, the constituent elements of PSSs: product, service, infrastructure, resources, and stakeholder network (Hajimohammadi et al., 2017). The authors then further detail concepts related to PSS constituent elements. For instance, Medini and Boucher, (2019) define the concept of “product item”. Different PSSs ontologies define the concept of "service activity" (Bullinger et al., 2003; McKay and Kundu, 2014). Bullinger et al., (2003) differentiate resources into human resources, material resources, and immaterial resources. Annamalai et al., (2011) list different types of PSS stakeholders (e.g. receiver, end-user, capability sponsor, provider, supplier). Other defined concepts are related to the overall PSS, rather than specify one of its specific constituent elements, for example, PSS needs and requirements (Annamalai et al., 2011), system performance (Medini and Boucher, 2019), or business models (Annamalai et al., 2011; Medini and Boucher, 2019) related concepts. Concepts such as “lifecycle” and “process” are either defined for the overall system (PSS) (Annamalai et al., 2011) or specifically for products and services (Correia et al., 2017).

Detailed models focus on specific aspects of PSS. One can differentiate PSS business models, PSS stakeholders’ models, PSS scenario models, PSS lifecycle models, PSS requirement models, PSS functional models, and PSS evaluation models.

- Different *PSS business models* have been proposed. For example, Paula et al., (2016) focus on sustainability factors in PSS business models. Fernandes et al., (2018) propose a PSS value proposition based on the business model canvas (Osterwalder and Pigneur, 2010). Zine et al., (2014) concentrate on value co-creation in PSS business models.
- Other authors proposed *models for stakeholders* involved in the business and their interactions. For instance, Song et al., (2015) proposed a value-based business model between different stakeholders. Sakao et al., (2009) use flow and scope models to specifically represent the network of suppliers and customers.

- Different PSS *lifecycle and process models* have also been presented (see review in (Cavalcante and Gzara, 2018)). In the literature, PSS lifecycles are represented in two ways: linear models (Wiesner et al., 2015) or circular models (Abramovici et al., 2017). One can also distinguish waterfall models, V-models, and spiral models (Pezzotta et al., 2012). Regardless of the model, lifecycles are merely represented by a series of steps (Cavalcante and Gzara, 2018). Authors either model the PSS Lifecycle (Wiesner et al., 2015) or detail product and service elements life cycles (either overlapping or parallel).

Other models concern a specific step of the PSS lifecycle: scenery description, requirements definition, detailed design, and evaluation.

- *Scenario modeling* has been used in the PSS literature to describe what is delivered to the customer and how. One can refer to the scenario modeling approaches proposed by Morelli, (2003), Maussang et al., (2009), Sakao et al., (2009), and Geng et al., (2011).
- In the literature, *requirement models* cover different abstraction levels. Berkovich et al., (2014) propose a requirements data model with the goal, system, feature, function, and component abstraction levels. Müller et al., (2012) rather propose detection clusters for PSS requirements. Another point of view is given by Song, (2017) where requirements for products and requirements for service are distinguished.
- *Functional models* are frequently used in the PSS literature. We mainly distinguish models showing hierarchical relationships between functions (Hara, Arai and Shimomura, 2009a), input-output diagrams of functions where functions transform inputs in outputs (Kim et al., 2011), or combining both representations (Akasaka et al., 2012). The authors also identified types of functions. For instance, (Li et al., 2012) differentiate primary, axillary, and optional functions. Authors also differentiate functions allocated to service and functions allocated to products (Geng et al., 2010; Hara, Arai and Shimomura, 2009a).
- *PSS evaluation models* usually assess how a PSS reaches customer value (Geng et al., 2011; Geng and Chu, 2012; Lee et al., 2015; Mourtzis, Fotia, Gamito, et al., 2016), sustainability objectives (Mourtzis, Fotia and Vlachou, 2016), or cost and budget (Mannweiler et al., 2010; Sakao and Lindahl, 2012; Shen et al., 2017).

In summary, the literature on PSS modeling is considerable. A variety of ways to view and describe a PSS are presented with different information and relationships. However, the literature still lacks evidence on what PSS models to use in a specific industrial context, or in a broader sense for each PSS types (see paragraph 2.1.1.). Furthermore, even though models of PSS stakeholders exist, the research mainly focuses on product and service integration. In addition, the increasing complexity and independence of PSS elements, including products, services, and stakeholders are barely examined.

We summarize PSS research gaps as follows:

Research Gap 2: PSS literature lacks evidence on what PSS models to use in a specific industrial context, or for a specific PSS type.

Research Gap 3: PSS models rarely take into consideration the increasing complexity and the potential independence of PSS elements.

2.2.2 Models in SoS literature

SoS literature usually refers to SoS architecture. In the SoS context, the term "architecture" can be defined as "the fundamental organization of a system embodied in its components, their relationships to each other, and to the environment, and the principles guiding its design and evolution" (ISO/IEC 42010 standard) (Tekinerdogan, 2016). Thus, the notion of SoS or SoS architecture modeling covers a broad set of approaches. Mohsin, Janjua, Islam, Vicente, et al., (2019) present a taxonomy for SoS architecture modeling approaches. The authors distinguish **ontology-driven modeling**, **SoS architecture frameworks**, and **SoS architectural description languages (ADLs)**. Besides these modeling approach types, the SoS literature also refers to modeling **styles and patterns for SoS architecture** (Ingram et al., 2014).

Ontology-driven modeling includes semantic ontologies. Semantic ontologies have been mostly used in the software engineering domain.

An **architecture framework** organizes and structures different viewpoints on can have on the architecture of the system (Tekinerdogan, 2016). Thus, an architecture framework can be defined by a set of viewpoints. Usually, frameworks (and viewpoints) give a high-level description of a system and also embed detailed models such as lifecycle, scenario, or functional models. Different frameworks have been proposed specifically for SoSs. Generally, these frameworks are specific for a given domain, e.g., defense, or industry 4.0. Chapter 6 further reviews SoS architecture frameworks.

Defining **architecture styles and patterns** remains fuzzy (Kalawsky, Joannou, et al., 2013). According to (Ingram et al., 2014)**,** “an architectural style provides a high- level view that enables the analysis of ‘emergent system-wide properties’ while patterns are concerned much more with lower-level questions.” The authors classify SoS architecture patterns into centralized, service Oriented, publish-subscribe, pipes and filters, and blackboard architecture patterns. Kalawsky, Joannou, et al., (2013) also give examples of SoS architectural patterns. We retain from different examples that patterns mainly describe the form of the interactions among SoS component systems or enterprises. SoS architectural patterns can be used to architect and analyze SoS throughout their evolution (Kalawsky, Joannou, et al., 2013; Kalawsky, Tian, et al., 2013).

In general terms, an **architectural description language (ADLs)** is defined as the language used to describe a system and its architecture. Mohsin et al., (2019) distinguish formal and semi-formal ADLs. For example, UML and SysML profiles are commonly used semi-formal ADLs in the context of SoSs (Hause, 2010). Formal ADLs are based on a strong mathematical foundation. For example, the algebraic formalism is a formal ADL. If both semi-formal and formal ADLs are used in the context of SoSs, formal ADLs are generally used in simulating the dynamic nature and evolvability of an SoS (Al-Amin and Dagli, 2019; Guariniello and Delaurentis, 2013; Han and Delaurentis, 2013; Sanduka and Obermaisser, 2014) and evaluating the SoSs (Pape et al., 2015).

In summary, extensive literature explores how to model SoSs. The main focus of SoS models is the complexity of the relationships between independent constituent systems and enterprises. However, the “heterogeneity” or the nature of the systems themselves (e.g., products, services, infrastructure) is not necessarily a concern of SoS models. This research gap can be summarized as:

Research Gap 4: SoS models focus on the complexity of the relationships between component systems. The “heterogeneity” of component systems (products and services) is not necessarily considered.

2.3 Relevant analysis approaches

This PhD has been conducted within a car manufacturing company (see Chapter 3). Within this industrial context, some characteristics of PSSs and SoSs (section 2.1) have been identified as “critical”, namely the **uncertainty and changes** related to the dynamic nature of SoSs and their propagation among “heterogeneous” elements (products, services, infrastructure, stakeholder network), and the **multiplicity of independent stakeholder**. An initial literature review aimed to understand how these aspects have been analyzed for PSSs, SoSs, and systems in a more general sense.

2.3.1 Uncertainty and change analysis approaches

Several definitions have been given to **“uncertainty”** (Kreye, 2011; Thunnissen, 2003) and **“change”** (Colombo et al., 2016). In general, uncertainty is related to a “lack of knowledge, which may arise from not known, not definite or not reliable information ” (Kreye et al., 2018). In the same fashion, Kumar et al., (2013) and Sakao, Panshef, et al., (2009) define uncertainty as “a state of deficiency of information related to a future event.” A change can be viewed as a modification in any aspect of the system (e.g., form, material). According to Eckert et al., (2009), uncertainty leads to change. Change can also be seen as the effect of uncertainty (Colombo et al., 2016; Sakao, Panshef, et al., 2009). When a change or effect (of uncertainty) is positive, it is referred to as an opportunity, when negative, as a risk (Kumar et al., 2013; Sakao, Panshef, et al., 2009).

Both PSS literature and SoS literature identified uncertainty and change, specifically for PSS and SoS development, management, and operation (see Chapter 5). However, PSS literature and SoS literature rarely study and quantify how uncertainty and changes propagate among PSS heterogeneous elements (service, product, infrastructure, resources, and stakeholder network) (Estrada and Romero, 2016b; Wang and Durugbo, 2013) or SoS component systems (Garro and Tundis, 2015; Raman and Drsouza, 2018). In parallel, various uncertainty and change analysis and propagation methods have been proposed in system and design engineering, without necessarily addressing PSSs and SoSs specifically. For example, the Change Prediction Method (CPM) has been extensively used and referred to (Clarkson et al., 2004a; Giffin et al., 2009; Hamraz et al., 2012; Lee and Hong, 2017; Wynn et al., 2010, 2014). Other authors propose methods to design systems under uncertainty and reduce its effects (Afshari et al., 2016; Afshari and Peng, 2015; Hamel and Azarm, 2011; Keshavarzi et al., 2017). Another research stream investigates the system's (and SoSs) response to uncertainty and changes under the concepts of reliability, resilience, and robustness (Eddaoui et al., 2018; Goldbeck et al., 2019).

We resume the research gap related to the uncertainty and change concern as:

Research Gap 5: PSS literature and SoS literature lack quantitative methods for uncertainty and change analysis. Existing methods in systems and design engineering research do not necessarily address systems that are both PSSs and SoSs.

2.3.2 Stakeholders analysis approaches

With regards to the concern of **the multiplicity of independent stakeholders**, PSS literature and SoS literature also identified and classified stakeholders taking part in the development, management, and operation of PSSs (Costa and Diegues, 2019; Kimita et al., 2015) and SoSs (Axelsson et al., 2019; Hause, 2010). However, to our knowledge, no research goes beyond qualitative analysis and measures PSS or SoS stakeholders' importance. The analysis of stakeholders in a general sense has been the interest of management and organization research (Mitchell et al., 1997; Morelli et al., 1995) (see Chapter 7). However, this literature did not necessarily consider the specific characteristics of systems that are PSSs and SoSs.

Therefore, an additional research gap is identified as:

Research Gap 6: PSS literature and SoS literature lack quantitative methods for stakeholder analysis. Existing methods in management and organization research do not necessarily address systems that are PSSs and SoSs

2.4 Overview of research gaps

This section presents a visual overview of the identified research gaps through Table 2-1 and Table 2-2.

Table 2-1: Summary of the research gaps related to systems characterization and modeling

<table>
<tr><th></th><th>Systems Definition and Characterization</th><th colspan="2">Systems Modeling</th></tr>
<tr><td>PSS Research</td><td rowspan="3">Research Gap 1: PSSs, SoSs, CPSs have rarely been studied concomitantly even though the servitization, increasing complexity, and increasing software content are happening at the same time in real-life examples.</td><td>Research Gap 2: PSS literature lacks evidence on what PSS models to use in a specific industrial context, or for a specific PSS type.</td><td>Research Gap 3: PSS models rarely take into consideration the increasing complexity and the potential independence of PSS elements.</td></tr>
<tr><td>SoS Research</td><td colspan="2">Research Gap 4: SoS models focus on the complexity of the relationships between component systems. The “heterogeneity” of component systems (products and services) is not necessarily considered.</td></tr>
<tr><td>CPS Research</td><td colspan="2"></td></tr>
</table>

Table 2-2: Summary of the research gaps related to relevant analysis approaches

Uncertainty and change concern	**Research Gap 5:** PSS literature and SoS literature lack quantitative methods for uncertainty and change analysis. Existing methods in systems and design engineering research do not necessarily address systems that are both PSSs and SoSs.
Concern of the multiplicity of independent stakeholders	**Research Gap 6:** PSS literature and SoS literature lack quantitative methods for stakeholder analysis. Existing methods in management and organization research do not necessarily address systems that are PSSs and SoSs

2.5 Chapter summary

This section aims to show the links between the identified research gaps and the previous and following chapters of the thesis (Figure 2.1). Therefore, it hopes to help the reader go throughout the thesis.

This chapter presents the background literature of the thesis. It reviewed the literature based on the key concepts identified in the introduction: servitization, increasing complexity, and increasing software content. It, therefore, derived relevant research gaps. The following Chapter 3 derives the PhD research questions based on identified gaps. It also describes the research approach adopted to answer them.

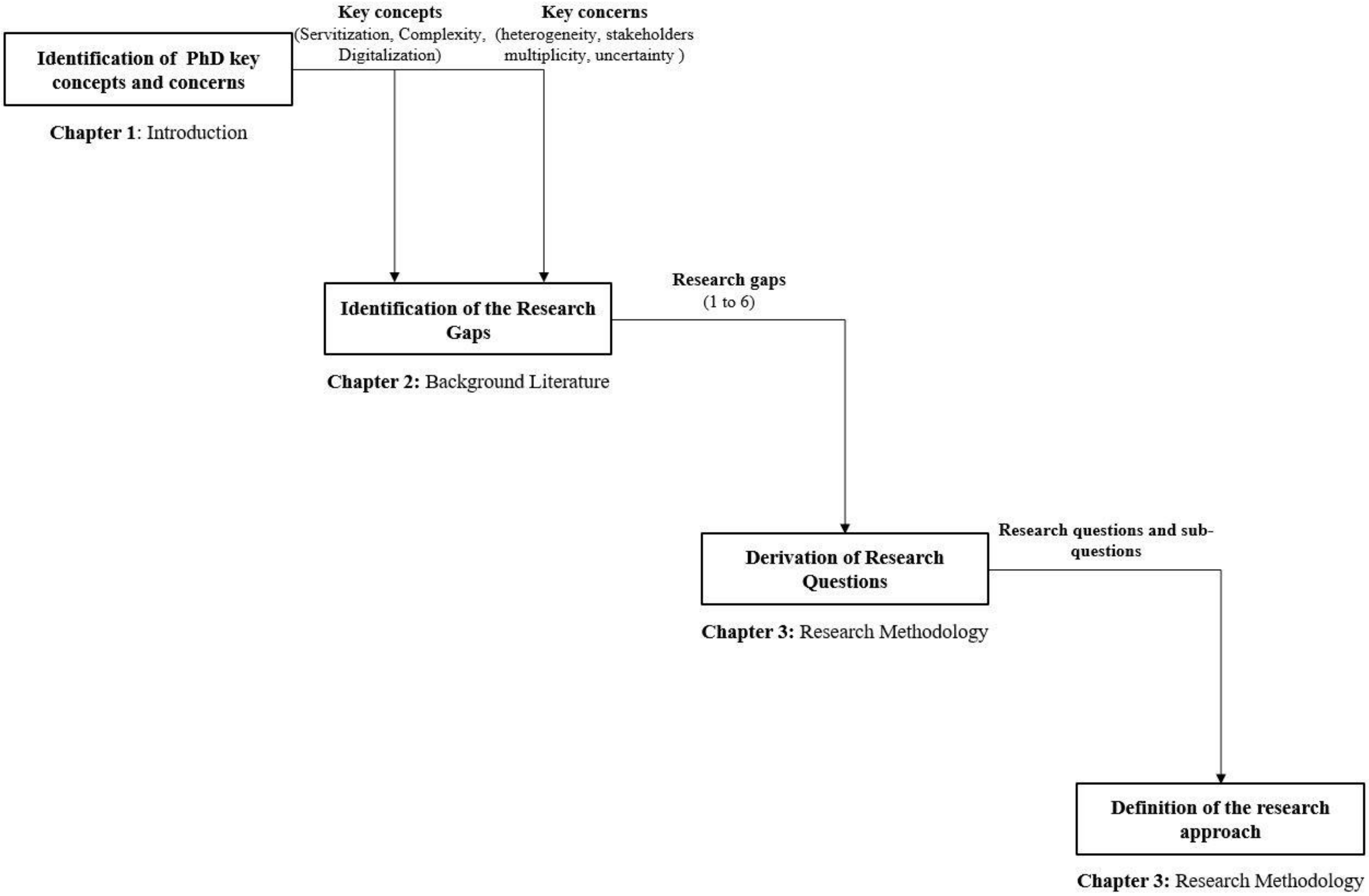

Figure 2.1: Link between chapter

3 Research methodology

This chapter describes the methodology used to address the research aim. As stated in the introduction (Chapter 1), the present research aims to propose a methodology to support PSSoS development. Since PSSoSs have rarely been studied, we relied on the PSSs, SoSs, and other relevant literature to identify the research gaps related to PSSoSs (Chapter 2). In the following sections, we first derive the research questions based on the identified research gaps. The research scope is outlined. Then, the research approach and phases are detailed.

3.1 Research questions

Following the background literature (Chapter2), we derive the research questions based on the research gaps related to **systems definition and characterization**, **representation and modeling**, and **analysis**.

As for **systems definition and characterization**, the identified gap is:

Research Gap 1: PSSs, SoSs, CPSs have rarely been studied concomitantly even though the servitization, increasing complexity, and increasing software content are happening simultaneously in real-life examples.

In the present research, we focus on systems that are PSSs and SoSs (referred to as PSSoS). The software and digital content of systems are considered for specific examples and case studies. Therefore, the first objective is to understand the characteristics of systems that are PSSs and SoSs (i.e., PSSoSs). We formulate the related research question and sub-questions as:

> **Research Question 1:** How can we characterize PSSoS and PSSoS development?
>
> - **Sub-question 1.1:** What are the characteristics of PSSoS?
> - **Sub-question 1.2:** What are the challenges for PSSoS development?

Regarding **systems representation and modeling**, two research gaps related to PSS modeling (Research Gap 2 and 3) and one related to SoS modeling (Research Gap 4) have been identified.

The **Research Gap 2 ("**PSS literature lacks evidence on what PSS models to use in a specific industrial context, or for a specific PSS type.") is rather specific for the PSS literature. A study has been conducted and presented as a complementary part in Appendix A to address this gap (see Figure 3.7).

Since our interest is in systems that are both PSSs and SoSs, we consider concomitantly Research Gap 3 and Research Gap 4**:**

Research Gap 3: PSS models rarely consider the increasing complexity and the potential independence of PSS elements.

Research Gap 4: SoS models focus on the complexity of the relationships between component systems. The "heterogeneity" of component systems (products and services) is not necessarily considered.

These gaps show the complementarity of PSS and SoS models. We express the second research question and its sub-questions as:

Research Question 2: How can we model PSSoS?

- **Sub-question 2.1:** What information is needed to describe a PSSoS?
- **Sub-question 2.2:** How to organize PSSoS descriptive information?

Two aspects were interesting to **analyze** when developing PSSoS**:** the uncertainty of the PSSoS environment and stakeholders' multiplicity. Two research gaps have been identified with regards to these two aspects, respectively:

Research Gap 5: PSS literature and SoS literature lack quantitative methods for uncertainty and change analysis. Existing methods in systems and design engineering research do not necessarily address systems that are both PSSs and SoSs.

Research Gap 6: PSS literature and SoS literature lack quantitative methods for stakeholder analysis. Existing methods in management and organization research do not necessarily address systems that are PSSs and SoSs

This research work aims to address these gaps partly by answering the following question and sub-questions:

Research Question 3: How can we assist PSSoS development and support PSSoS decision-makers?

- **Sub-question 3.1:** How can we characterize and quantify the importance of stakeholders in PSSoS development and operation?
- **Sub-question 3.2:** How to characterize the exposure and vulnerability of PSSoS functions to PSSoS Uncertainties?

3.2 Research scope

The background Literature Chapter 2 showed that PSSs and SoSs, and hence, PSSoSs, could be studied from different perspectives and research domains. This PhD falls within the **systems and design engineering domains** and aims to contribute to the research in these domains by answering the previously defined research questions.

Within the systems and design engineering domains, the present research will focus on the **collaborative value proposition among PSSoS stakeholders** and **the architecture of the system** (Introduction Figure 1.1). This PhD work does not include a PSSoS business model or a method for PSSoS portfolio development (Hein, Chazal, et al., 2018). However, it takes into account **PSSoS business aspects**.

Furthermore, this research work is conducted within the automotive industry and considers transportation and mobility PSSoS examples. As these examples are collaborative or acknowledged, use-, or result-oriented PSSoS (see Chapters 2 and 5), we consider this research relevant for these types of PSSoSs (Chapters 6, 7, and 8).

Besides, due to the novelty of the industrial projects, this research does not focus on lifecycles and processes but rather on the representation of PSSoS and analysis of key aspects identified both in the literature and in the industrial context.

Given the data available within the industrial context, this research focuses on high levels descriptions and analysis of PSSoSs. Different industrial examples have also been studied. However, this manuscript will mainly present the Plug and Charge example (see Chapter 4).

3.3 Research approach

The research approach determines how the research work is designed and planned to address the research aim, define and answer the research questions. The research approach depends on the **research paradigm** that expresses the researcher's philosophical point of view, the **research methodologies** that relate to that paradigm, and the **methods and tools** to put the research methodology into practice (Creswell, 2009; Piccolo, 2019).

Research paradigm

Research paradigms or philosophies differ mainly according to how they define knowledge (Ferris, 2009). For example, Ferris, (2009) describes a taxonomy of philosophies (288) derived from Varro's criteria. In a simplified image, we can consider that research paradigms cover a large panel going from a deterministic view of the world (e.g., positivism and post-positivism paradigms) to a less deterministic view of the world (e.g., Constructivism). In a deterministic view of the world, knowledge is rather obtained in a deductive way. Deductive research starts with the theory, tests it through examining hypothesis, leading to its confirmation, rejection, or the modification of the hypothesis. From a less deterministic view of the world, knowledge is obtained inductively, i.e., examining real-world situations. In comparison to deductive research, inductive research does not start by the theory but builds it up based on these examinations (Saunders et al., 2009). In general, deductive research is associated with quantitative research, while inductive research is associated with qualitative research. However, in social sciences and design and engineering research, mixed approaches (qualitative and quantitative) are gaining ground (Creswell, 2009).

Since this research work is conducted within an industrial context and aims to support PSSoS development teams, inductive research is appropriate (Eckert et al., 2003). Besides, given the complexity of the problem we aim to address (Chapter 1), we combine qualitative and quantitative research.

Research methodology

Different research methodologies have been identified as relevant for the present research.

This PhD has been conducted within Renault (car manufacturer), and the PhD student was part of a Renault team (see Chapter 4). The final objective of this research is to support teams in the development of PSSoSs practically. This objective includes technical aspects of the engineering design and systems engineering domains and social and organizational aspects. For this reason, action research is relevant (Järvinen, 2007; Travassos, 2009). Action research can be defined as:

"A participatory, democratic process concerned with developing practical knowing in the pursuit of worthwhile human purposes, grounded in a participatory worldview which we believe is emerging at this historical moment. It seeks to bring together action and reflection, theory and practice, in participation with others, in the pursuit of practical solutions to issues of pressing concern to people, and more generally the flourishing of individual persons and their communities." (Reason and Bradbury, 2001)

We retain that action research combines theory and practice (Brydon-Miller et al., 2015). It is concerned about developing knowledge for practical application and the improvement of the practice. As such, it benefits both the researcher and practitioners (Ferris, 2009).

Susman and Evered, (1978) describe the action research process as cyclical and comprised of five main phases (1. Diagnosing, 2. Action planning, 3. Action Taking, 4. Evaluating and 5. Specifying Learning) (see Figure 3.1). This process is achieved in collaboration between the researcher and the client system. The client system is the context in which we identify the problem. In our case, the client-system is Renault, and more specifically, teams involved in the development of PSSoSs.

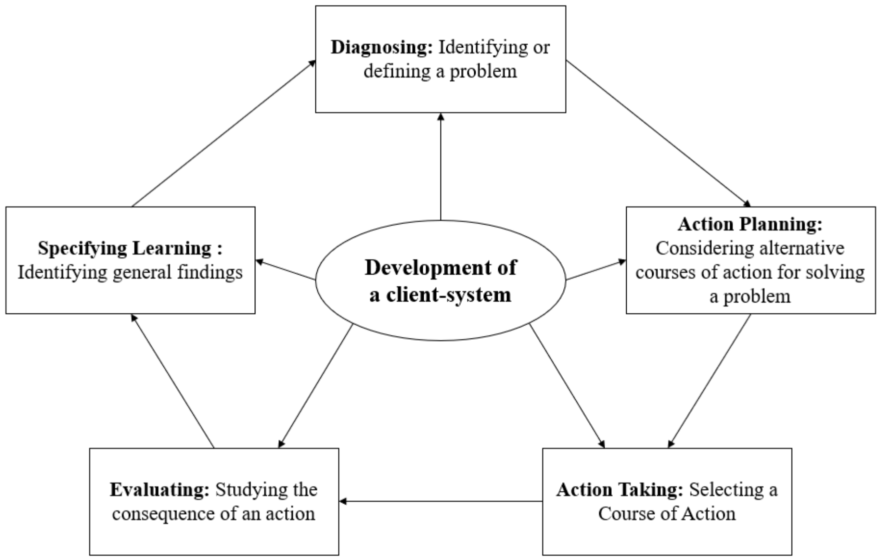

Figure 3.1: The cyclical process of action research (Susman and Evered, 1978)

In the present research, practical applicability is essential. Therefore, applied research methodologies can also be relevant. We represent in Figure 3.2 Jørgensen's Model (Michaelis, 2013; Raja, 2019), a research process for applied research. The research process starts with a scientific knowledge gap or an industrial problem (problem base) (or both). It is then a combination of analysis and synthesis of both the scientific state of the art and the industrial context. It results in new scientific insights with a knowledge transfer to the industry through practical results.

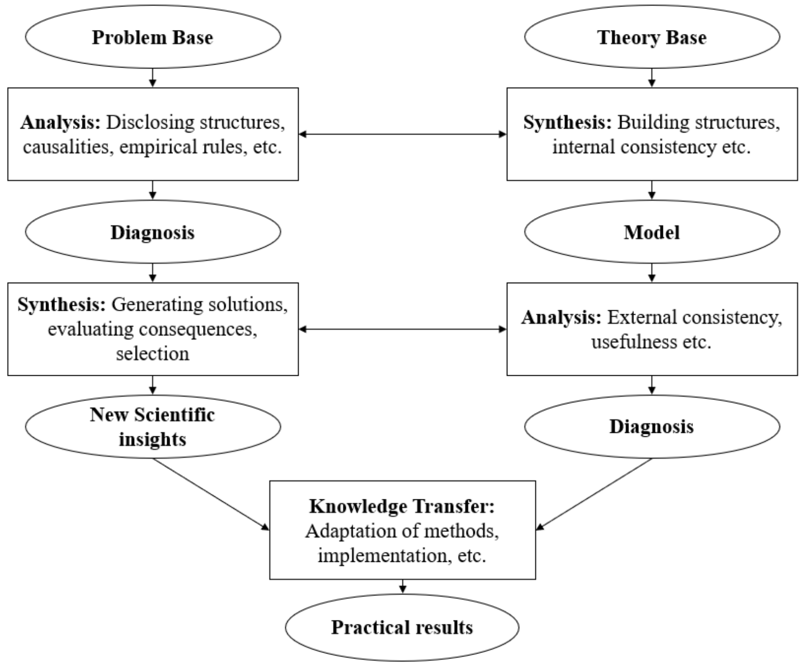

Figure 3.2: Work paradigms for research and development activities according to Jorgensen, translated from Danish by (Michaelis, 2013) , and used by (Raja, 2019)

In design research, Eckert et al., (2003) propose the eight fold model. The model is a logical circle, or a spiral process comprised of eight steps (Figure 3.3):

1. Empirical studies of design behavior, which is the observation of design activities within the industrial context,
2. Evaluation of empirical studies, which is an assessment and validation of the empirical research,
3. Development of a theory, which is an understanding of the practice,
4. The evaluation of the theory,
5. Development of tools and procedures to help and support practitioners in their design activities,
6. Evaluation of tools and procedures in collaboration with design team members and users,
7. Introduction of tools and procedures within the industrial context on a serious case
8. Evaluation of dissemination, which is the evaluation of the tool after its introduction within the industrial context.

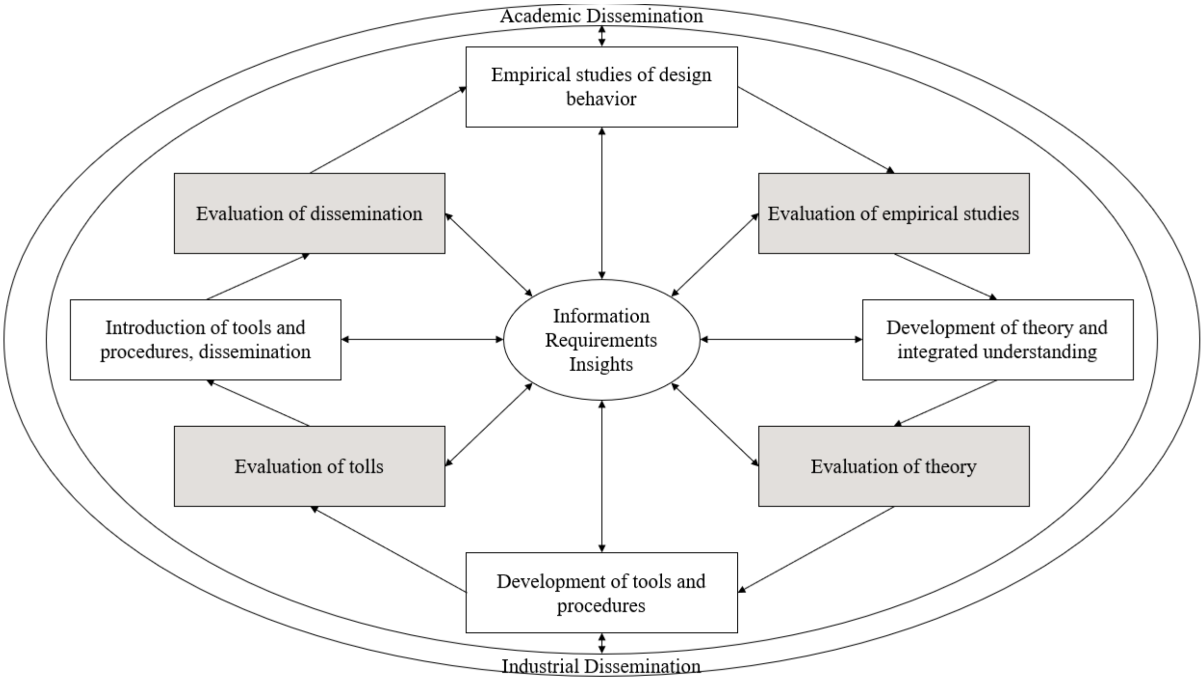

Figure 3.3: The eight fold model of design research (Eckert et al., 2003)

The presented eight fold model is agenda-driven and meant primarily for big research teams (Eckert et al., 2003). Another methodology, the Design Research Methodology (DRM) (Blessing L.T.M. and Chakrabarti, 2009), has been widely used in engineering design, especially by PhD projects and isolated projects. The DRM defines prior success criteria. An empirical study and theory building are included in the DRM first stems: Descriptive Study I. Tool building and method development take place in the Prescriptive study. Finally, the evaluation of the methods and tools and the dissemination in the industry form the prescriptive study II. Figure 3.4 presents the DRM steps.

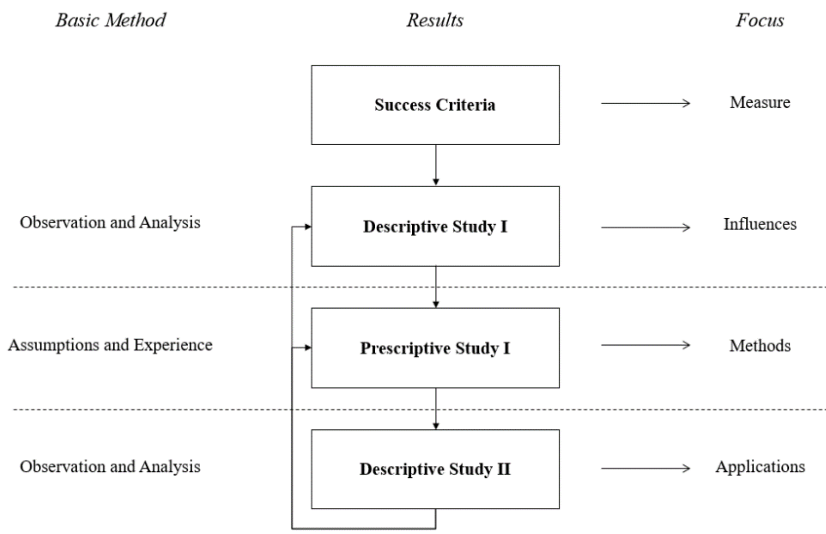

Figure 3.4: The DRM Framework (Blessing L.T.M. and Chakrabarti, 2002)

The action research, Jorgensen's model, the eight-fold model, and the DRM framework are appropriate for the present research. The author built a specific research methodology inspired by these methodologies an adapted for the industrial context of the PhD. The research methodology is represented in Figure 3.5 and described in the following Section 3.4.

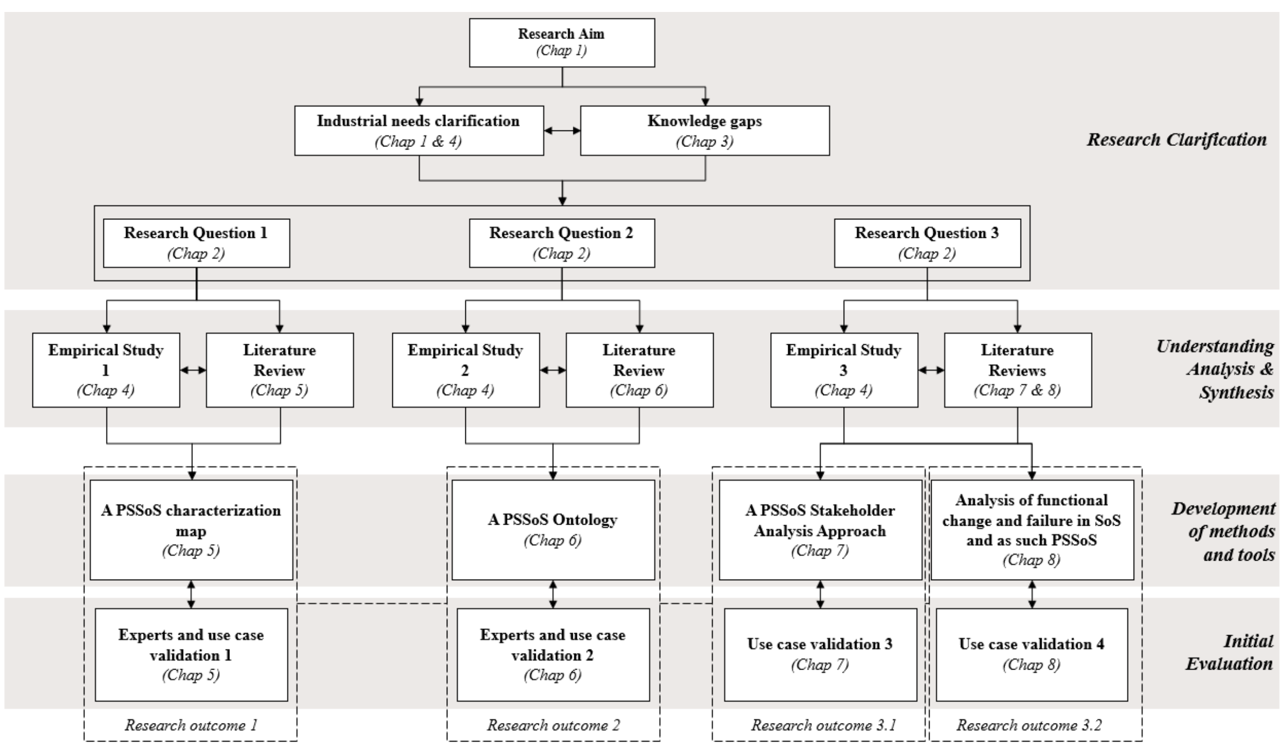

Figure 3.5: Overall research methodology

3.4 Research phases and methods

In this section, we further describe the research phases of the adopted methodology (Figure 3.5) as well as the adopted research methods.

The research methodology comprises four main phases: 1. **research clarification**, 2. **understanding (analysis and synthesis)**, 3. **development of methods and tools**, and 4. **initial evaluation**.

1. **Research clarification:**

Based on the research aim, we conduct an initial empirical study within the industry (Clarification of industrial needs Chapter 4) to further clarify the industrial needs. Concomitantly, an initial literature review (Chapter 2) is done to determine the research gaps. Based on both the initial empirical study and the initial literature review, we derive the research questions. For better readability, we structured Chapter 2 regarding the main subjects of the research questions (characterizing, modeling, and analyzing PSSoS) even though the research questions have been defined after the research gaps.

2. **Understanding (analysis and synthesis)**

For each research question, a refined literature review and a refined empirical study are conducted to better understand the issues and gaps to address. Refined literature reviews are presented in each paper (Chapters 5 to 8). Since the empirical studies have not been detailed in the published and submitted papers, we detail all the empirical studies in Chapter 4.

3. **Development of methods and tools**

This research resulted in four primary outcomes (see Chapter 1: Introduction) or contributions answering each research question and addressing the research gaps in the specific industrial context: a characterization map (Chapter 5), an ontology (Chapter 6), and two analysis methods (Chapters 7 and 8).

4. **Initial evaluation**

Initial evaluations of the outcomes/ contributions have been done through expert and case study validation.

In general terms, each contribution validation process comprises of three main stages.

We identify **relevant experts** through empirical studies and an analysis of the organization and its organigram. In the context of this work, we distinguish two types of experts; domain experts, such as experts in systems engineering or systems modeling, and project experts being those who work on specific case studies, a mobility service, for example. Experts can be involved in the early-stage development of the contribution by collaboratively (PhD student and experts) defining the contribution's expected quality criteria. Once the contribution is developed, the PhD student gathers expert feedbacks during **semi-structured interviews**. Semi-structured interviews proceed in three phases: a presentation of the contribution conceptually, a discussion of its quality, and finally, the identification of change requirement and potential case studies (information).

Following the semi-structured interviews and if relevant, the PhD student **implemented** the case studies and presented them to project experts or implemented the case studies in collaboration with project teams during workshops.

Figure 3.6 is an overall representation of the contribution’s evaluation process.

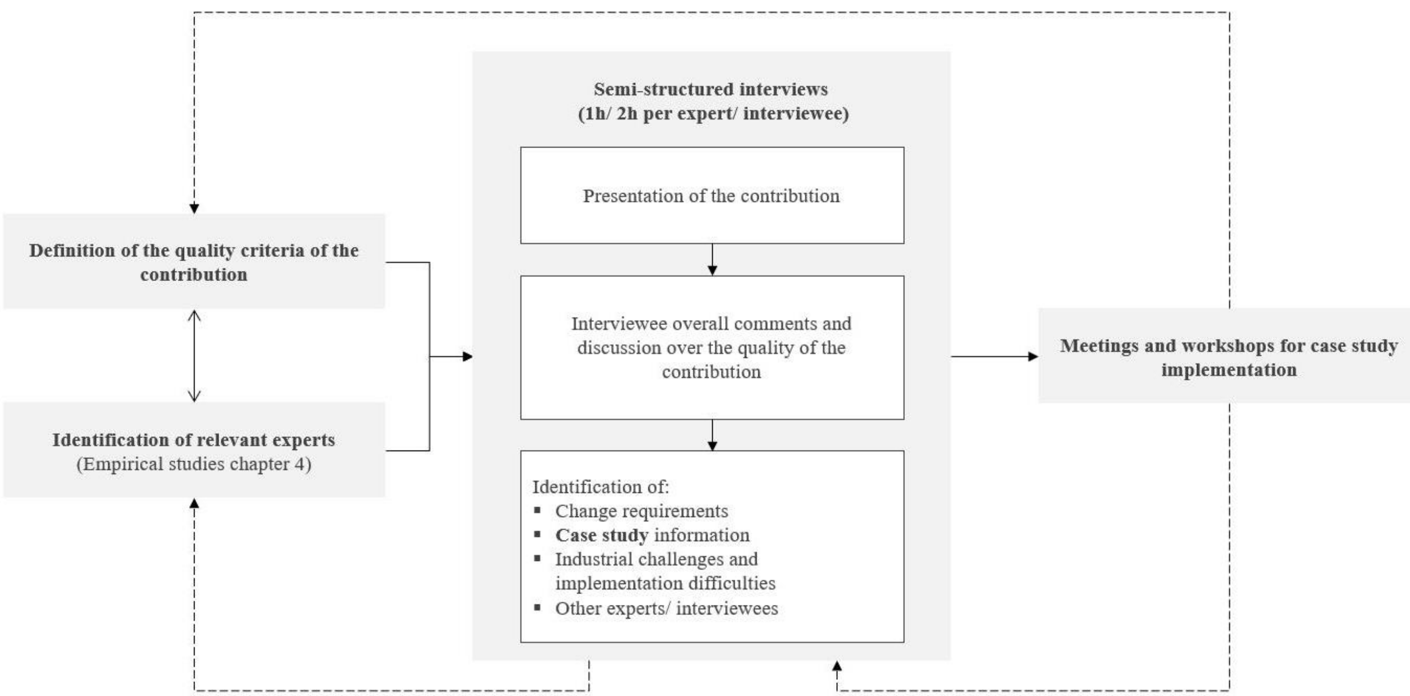

Figure 3.6: Overall contribution's evaluation process

Research methods

This research relied on qualitative and quantitative research methods. Table 3-1 lists the qualitative research methods used mainly for empirical studies.

Table 3-1: Qualitative Research Methods

Research Phase	Empirical study	Objective	Focus	Methods
Research Clarification	**Industrial needs clarification** *(Chap 1 &4)*	Clarifying the needs of the industry with regards to PSSoS development	Organization	- Direct Observations (e.g., meetings))
			Overall processes	- Documents Analysis (processes)
			Main difficulties in developing PSSoS	- Semi-structured interviews
Understanding (Analysis and Synthesis)	**Empirical Study 1** *(Chap 4)*	Characterizing PSSoS and their development	PSSoS examples and their development	- Exploratory case studies
				- Participation to workshops (related to the development of specific PSSoSs)
				- Non structured interviews
				- Documents analysis (Service Design and Systems Engineering documents)
	Empirical study 2 *(Chap 4)*	Determining how PSSoS are modeled and which tools are used (Model Based Systems Engineering)	Model Based Systems Engineering Tools	-Documents analysis
				- Models and Tools analysis
				-Training on tools and models
				- Tools usage
	Empirical Study 3 *(Chap 4)*	Defining relevant analysis for the industry	PSSoS decision maker interests	-Interactive presentation of the results

Qualitative methods and results are presented in Chapter 4.

As for the quantitative methods, case studies data has been retried from different models and tools (databases). The data analysis has been done through matrix-based approaches and network-based approaches. Table 3-2 details what quantitative methods have been used and when.

Table 3-2: Quantitative research methods

Research Phase		**Quantitative method**		
		Data retrieval	Data Analysis	
			Matrix-based approaches	Network-based Approaches
Development of methods and tools	PSSoS ontology building (Chap 6)	X	X	
	A PSSoS stakeholder analysis approach *(Chap 7)*		X	X
	Analysis of change and failure in SoS, and as such PSSoS *(Chap 8)*		X	X
Initial Evaluation	Experts and use case validation 2 *(Chap 6)*	X		
	Use case validation 3 *(Chap 7)*	X	X	X
	Use case validation 4 *(Chap 8)*	X	X	X

3.5 Chapter summary

For better readability, we propose to schematically represent the links between this chapter and the former and the following chapters in Figure 3.7.

This chapter derives the research questions from the research gaps identified in Chapter 2 and builds a methodology to answer these questions. The following Chapter 4 describes the empirical studies conducted to answer each research question. Chapters 5 to 8 present the PhD's outcomes/ contributions (answers to the research questions).

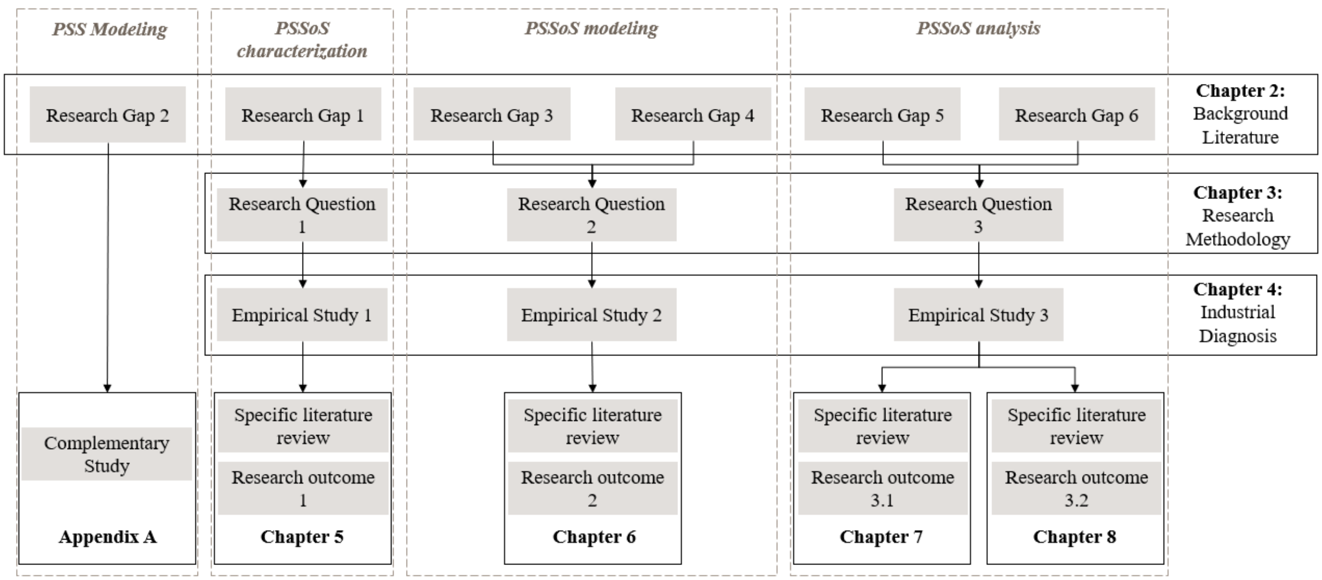

Figure 3.7: Link between chapters

4 Industrial diagnosis

This PhD has been conducted within Renault. The PhD student was part of a unit within the company's research and innovation department, working on developing future car connectivity and car autonomy, new mobility services, and businesses. This unit comprised teams working on: i) future mobility solutions and businesses such as shared mobility, ii) car connectivity and its interaction with its environment, and iii) autonomous driving technologies. Within this unit, domain experts (e.g., Systems of Systems expert, Artificial Intelligence expert) support different teams in their activities. The Systems of Systems expert supervised this PhD.

In a general sense, the research and innovation department works on rather distant future mobility services such as services involving autonomous vehicles. Less distant future mobility services such as services related to electric vehicles and historical services such as maintenance, car and battery leasing are developed or under development within other company departments. For this reason, this PhD has been conducted with tight interactions with other departments.

To facilitate the reading of this manuscript and keep the industrial confidentiality, we make an artificial and simplified representation of the organization of the other departments and consider: 1) "**system engineering departments**" where vehicles are developed and 2) "**service development departments**" where service business concepts are defined. Within each, we consider **hardware** and **software** development units. Software components include vehicle **on-board** software and **off-board** software. We include within the "service development departments", the unit working on **business development**. Figure 4.1 is a simplified representation of the organization within which the PhD took place. Figure 4.1 also gives examples of what is developed (PSS) and where/ by whom (departments). The author insists on the fact that the organization representation (Figure 4.1) is not a real and accurate representation of the organization, but a logical decomposition to help the reader understand the empirical studies.

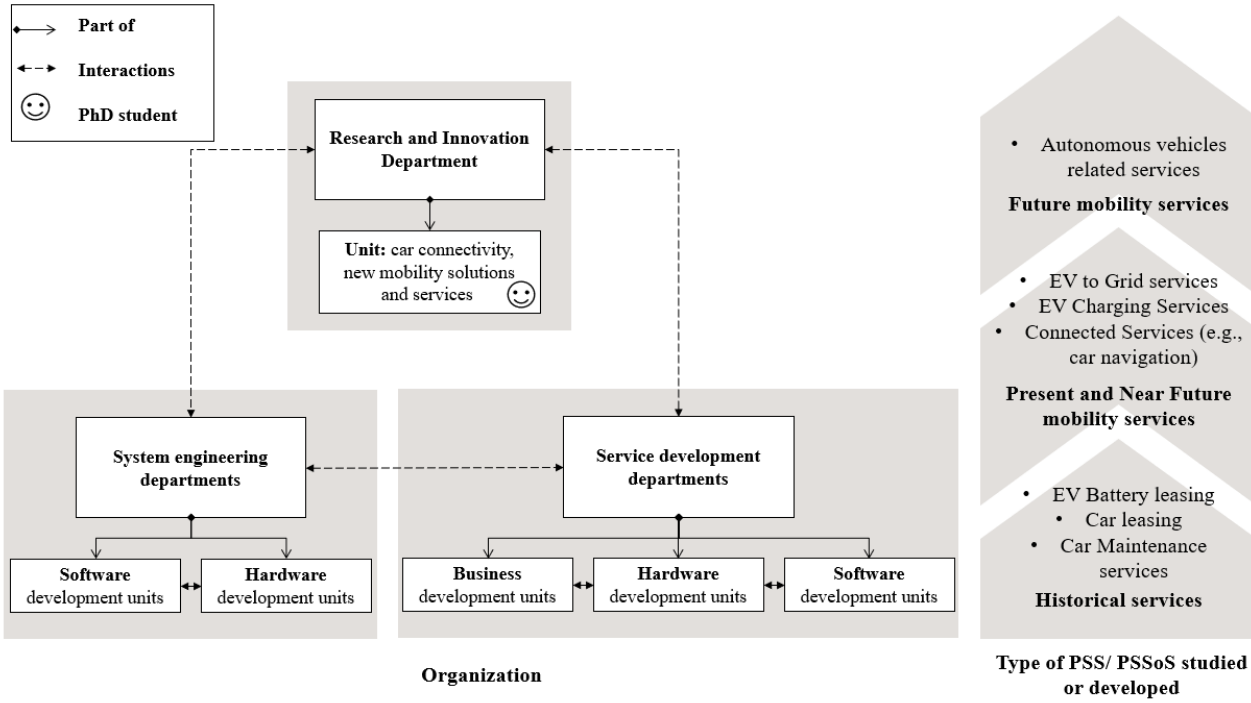

Figure 4.1: An artificial and simplified representation of the organization

In the following sections 4.1., 4.2., 4.3., and 4.4., different empirical studies are described. The empirical studies focus on difficulties in developing increasingly complex PSSs (i.e., PSSoSs) with increased interaction with the final customer and increased collaboration with other stakeholders (see examples Figure 4.1). The initial empirical study (4.1.) is part of the first research phase “Research Clarification”. It contributed to define the research questions presented in Chapter 3. Based on the initial empirical study, three empirical studies are done to more specifically answer each research questions. These empirical studies (sections 4.2., 4.3., and 4.4.) are part of the second research phase (“understanding (analysis and synthesis)”). The empirical studies 1,2, and 3 were conducted sequentially and used for the contributions 1, 2, 3.1, and 3.2 as described in Figure 4.2.

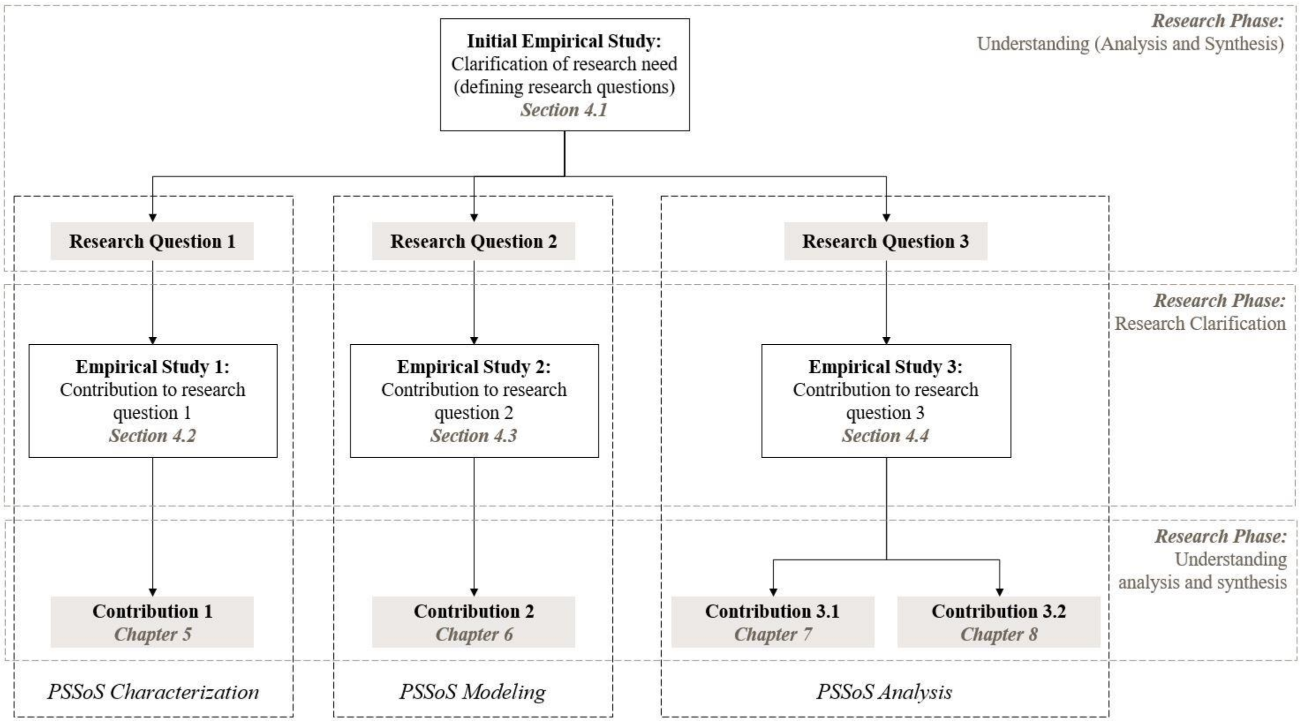

Figure 4.2: Summary of empirical studies

4.1 Initial Empirical study: Industrial needs clarification

4.1.1 Empirical study objective

The objectives of the initial empirical study are: **i)** to be aware of the organization in which the PhD takes place (Figure 4.1), **ii)** comprehend how the company develops PSS and PSSoSs (organization and process-wise), and **iii)** to understand the difficulties in the development of PSSs and future PSSoSs. As a reminder, the research falls within the engineering design and systems engineering domains. Therefore, the focus is mainly on the difficulties pertaining to these domains.

4.1.2 Empirical study methods

To achieve the defined objectives, we relied on **direct observations**, **document analysis**, and **semi-structured interviews**.

PSSs and PSSoSs comprise different elements: Product, Service, resources, infrastructure (whether these elements are under the control of the company or the control of a business partner), and stakeholders in a broad sense (SoSs). Hence, the objects under consideration for direct observations, documents analysis, or semi-structured interviews are **1)** PSS/ PSSoS elements, **2)** to the specific artifact developed (whether it is a specific service, vehicle, vehicle subsystem, or an overall solution, e.g., car navigation solution), and **3)** the organization (Figure 4.1).

Direct observations:

Direct observations have been mainly done through participation in meetings within Renault. In general, these meetings had the objective to discuss an identified difficulty in developing PSSs and PSSoSs. These meetings did not focus on one specific example (e.g., the plug and charge service) but instead considered conceptual PSSs/ PSSoSs elements and sub-elements. For example, the interactions between system (car) design and service design, or the issues in the development of on-board and off-board software.

For each meeting, the PhD student took notes during the discussion, a report was written including a list of identified difficulties, and finally, feedback is given to (at least one) meeting attendee to confirm or correct the student's comprehension of these difficulties (see Figure 4.3).

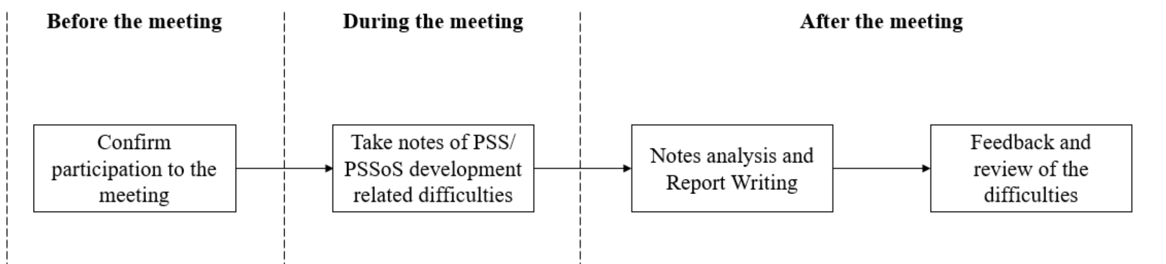

Figure 4.3: PSS/ PSSoS development difficulties identification through direct observations

Table 4-1 sums up the main meetings to which the PhD student participated.

In addition to the observations made within Renault, the PhD student participated in regular meetings of the technical committee (CT 3S-AI) of the INCOSE French Chapter (AFIS). Within this committee, issues related to PSS and SoS architecting are discussed. Different areas are represented, e.g., automotive, aerospace, energy. Therefore, the PhD student could distinguish specific and non-specific issues to the automotive industry.

Document analysis:

In complement to direct observations, a study of different documents has been conducted. In Table 4-2, we detail the type of documents considered. For each document, we analyzed the considered type of information on PSSoSs and how it is organized. For example, product functions and structure and how they are related. We also examined the link between the information contained in different documents. The student took advantage of his presence within the company to informally consult the engineers who write or use the analyzed document.

Table 4-1: Direct observations sum up

Subject of the discussion		**Organization (meeting attendees)**			**Meeting duration**
PSS/ PSSoS elements	**Specific example or artifact**	**Number of attendees**	**Departmental attachment**	**Function**	
Product and Service interaction	-	2	Research and innovation department	Systems engineering expertise	1h30
Software and data for services	-	5	Research and innovation department Systems Engineering departments (Software) Systems Engineering departments (Hardware)	Systems engineering expertise Electrical and electronics expertise Vehicle Data expertise	1h30
Products (vehicle and vehicle sub-systems) and related software	-	5	Research and innovation department Systems Engineering departments (Software) Systems Engineering departments (Hardware)	Systems engineering expertise Software engineering expertise	1h30
Future mobility services	-	3	Research and innovation department Service development department	Team leading Service Project management	1h

Table 4-2: Analyzed documents

Document type	**Content on**		**Organization (Written and used by)**
	PSS/ PSSoS elements	**Specific example or artifact**	
Vehicle Architecture: sub-systems and actors	Product, hardware and Software	-	- Systems Engineering departments
Vehicle development processes	Product, hardware and Software	-	- Systems Engineering departments
Mobility services strategy	Service (hardware and software)	-	- Service development department
Mobility services Roadmap	Service (hardware and software)	-	- Service development department
Mobility services platform description	Service (hardware and software)	-	- Service development department
Mobility services technical requirements	Interaction: Product and Service	-	- Research and innovation department - Service development department - Systems Engineering departments

Interviews:

Since both direct observations and documents gave an overall perspective on the development of PSS and PSSoS (see Tables 4-1 and 4-2), the PhD student conducted semi-structured interviews (Summers and Eckert, 2013) to understand more concretely how specific project examples and artifacts were developed and what challenges were faced.

Figure 4.4 presents the overall interviewing process. Before the interviews, the PhD student identified interviewees through an analysis of the organization, an exploration of the organization chart and by recommendation. The potential interviewees were then contacted by email. Table 4-3 lists the interviewees. In the meantime, an interviewing protocol has been developed (see Table 4-4). Because mobility services are continually evolving with increased customer participation, software content, the interviews were structured in relation to past and present development and their difficulty as well as the future development and difficulties perceived by the interviewee. A coding has also been predefined, including “artifact” (what has been, is or will be developed), “process” (how it is developed), “tools” (which tools are used to assess the development of a product, service, hardware, or software). The codes “behaviors and interactions” tag the information pertaining to the organization and knowledge sharing. “Best practices & learnings”, “difficulties”, and “keys” are rather the return of experience of each interviewee. During the interviews, the discussion was transcribed in writing (interviewee preference). After the interviews, a report and analysis are sent to the interviewee and discussed if needed. The coding of the interviews allowed to synthetize and classify the difficulties pertaining to PSSoS development.

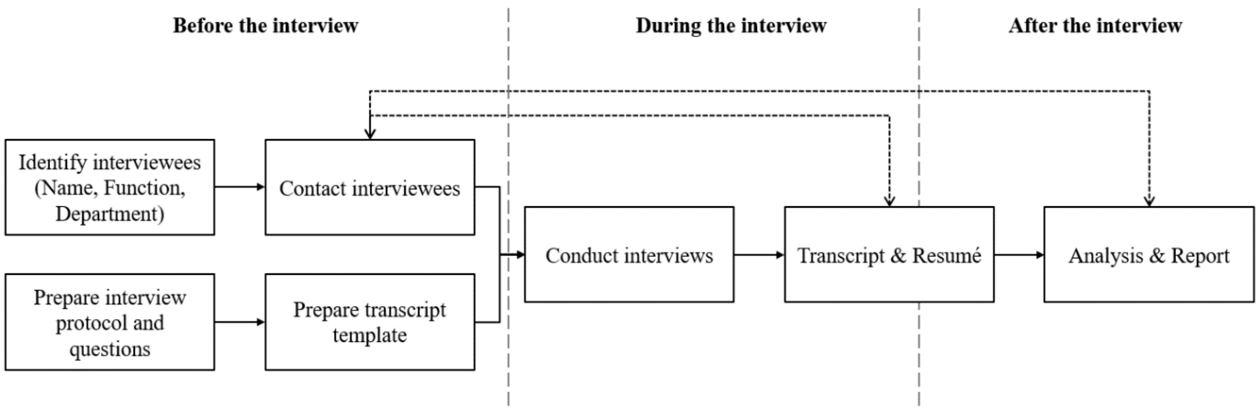

Figure 4.4: Interviewing process

Table 4-3: Description of interviewees

	Department	**Function**	**Interviewee works or worked on …**					
			Product		**Service**			**Product/ Service Integrations**
			Hardware	**Software**	**Business**	**Hardware**	**Software**	
Interviewee 1	Systems Engineering departments	- Expert in connectivity function architecture	X	X				
Interviewee 2	Systems Engineering departments	- Project manager connected platform	X	X		X	X	X
Interviewee 3	Service development department	- Service product owner			X			
Interviewee 4	Research and innovation department	-Head of new mobility businesses and services - Former project manager for navigation services		X	X	X	X	
Interviewee 5	Research and innovation department	- Heat of new mobility services unit - Former connected car and services cross system architect	X	X		X	X	X

Table 4-4: Th interviewing protocol

<table>
<tr><th colspan="4">Interview protocol</th><th>Timetable</th></tr>
<tr><td>Step 1: Introduction</td><td colspan="3">PhD subject presentation (Focus on interviewer)</td><td rowspan="4">5 min</td></tr>
<tr><td rowspan="3">Future</td><td>Overall PhD subject presentation</td><td colspan="2">Product Service Systems of Systems Development</td></tr>
<tr><td>Explain why the interviewee is being interviewed</td><td colspan="2">In relationship with PSSoS elements and their interaction Product, service, infrastructure, resources, stakeholders (hardware or software)</td></tr>
<tr><td>Explain why it is important for the PhD</td><td colspan="2">Practical Applicability of the research work</td></tr>
<tr><td>Step 2: Warm up</td><td colspan="3">Board Discussion (Focus on interviewee)</td><td rowspan="2">10 min</td></tr>
<tr><td>Past and present</td><td>Roles within Renault?</td><td colspan="2">What is the current and former functions of the interviewee within Renault</td></tr>
<tr><td rowspan="2">Step 3: Main body of the interview</td><td colspan="3">Detailed Discussion (Focus on Interviewee)</td><td rowspan="10">20min</td></tr>
<tr><td>Coding</td><td colspan="2">Question</td></tr>
<tr><td rowspan="8">Past and present</td><td rowspan="3">Artifact</td><td colspan="2">Which project did you participate in?
What was developed?</td></tr>
<tr><td colspan="2">What would be the link with the development of PSSs/ PSSoSs: service and/or product/ hardware/ software?</td></tr>
<tr><td colspan="2">Is it specific to a type of service or a type of product?</td></tr>
<tr><td>Process</td><td colspan="2">How is it developed? Processes (Activities, Duration, lifecycle, variants...)</td></tr>
<tr><td rowspan="2">Tools</td><td colspan="2">What methods and tools do you use in this process (By phase/ Activity)?</td></tr>
<tr><td colspan="2">What do you see as the advantages and disadvantages of these methods and tools?
Are you satisfied with them?</td></tr>
<tr><td>Behaviors and interactions</td><td>Internal (Team)</td><td>Who do you work with and what are their functions in the team?
How are these exchanges made (in relation to the phases of the process and the</td></tr>
</table>

<table>
<tr><th colspan="4">Interview protocol</th><th>Timetable</th></tr>
<tr><td rowspan="4"></td><td rowspan="2"></td><td></td><td>means used (meetings/emails ...))?</td><td rowspan="4"></td></tr>
<tr><td>External (Other teams)</td><td>How do you interact with other teams? What do you exchange?</td></tr>
<tr><td rowspan="2">Best practices & Learnings</td><td colspan="2">Do you keep track of information about the process, tools, methods...?</td></tr>
<tr><td colspan="2">What are the challenges you face?
How do you measure success or failure in relation to these challenges?
Do you take previous projects (successes, failures and difficulties) into consideration in new developments?</td></tr>
<tr><td>Step 4: Main body of the interview</td><td colspan="3">Discussion and Conclusions (Join Interviewer and Interviewee interests)</td><td rowspan="3">20 min</td></tr>
<tr><td rowspan="2">Present and Future</td><td>Difficulties</td><td colspan="2">What are some of the difficulties Renault faces today in jointly developing products and services? Or rather, what are the difficulties that Renault has today to develop the mobility of the future (connected vehicle, autonomous, robot cab, etc.).</td></tr>
<tr><td>Keys</td><td colspan="2">In view of these difficulties, what should Renault do?
What are the aspects and points that must absolutely be insured? (ex: software development, etc.)</td></tr>
<tr><td>Step 5: Cool-off & Closure</td><td colspan="3">Get comments on the interview itself and PhD subject</td><td rowspan="4">5 min</td></tr>
<tr><td rowspan="3"></td><td rowspan="3">Comments on interview</td><td colspan="2">Is there an important point I haven't mentioned?</td></tr>
<tr><td colspan="2">What interest would the thesis have with regard to our interview?</td></tr>
<tr><td colspan="2">Acknowledgements, transcript and analysis</td></tr>
<tr><td colspan="4"></td><td>1 h</td></tr>
</table>

4.1.3 Empirical study results

The initial empirical study led to two main results: the identification of the industrial difficulties related to PSSs and PSSoSs development and, therefore, the clarification of the industrial needs, and an overall description of PSSs/ PSSoSs development architecture (Figure 4.5).

Since the development of vehicles (products) is at the core of the company's competencies, product development is structured and systematic. The development processes are well defined. On the other hand, the development of new mobility services is relatively new. Strategic roadmaps define new mobility services, and services are described through their ecosystem and customer journeys. If these steps are essential in-service development, a significant difficulty remains in managing service development in terms of business and system architecture. More specifically, how to assess (a priori) that the vehicle can support future services? And how to evaluate the evolution of the vehicle's capabilities over time?

This gap between systematic and mature product development and a more recent and (therefore) less mature service development has already been pointed out in the broader context of manufacturing companies (Cavalieri and Pezzotta, 2012).

Teams within the system engineering departments bridge the gap between product and service development from both an organizational perspective and a system perspective by developing a connected vehicle platform (Figure 4.5). However, difficulties are still perceived regarding the development of PSSs and future PSSoSs. In the following, we summarize these difficulties/ needs as:

- The absence of a common ontology between service and product development, including hardware and software components;
- The diversity of services (going from navigation services to electric vehicles related services) supported by the vehicle raises an additional system complexity;
- The identification of PSSs or PSSoSs configurations is difficult, raising the question of how to define product and service configurations and reconfigurations concomitantly;
- The collaboration with external business partners to develop PSSoSs is new compared to the development of PSSs. Therefore, there is a need to characterize the collaboration and co-creation environment;
- Services tend to have a shorter lifecycle and tend to evolve during their usage. The question being how to ensure a priori that the vehicle can support the service and its evolution during the use phase, and concomitantly design products and services (PSSs);

- Service elements require continuous development. For instance, eventual service software updates should be done without the car going back to the garage.

Figure 4.5 summarizes the identified industrial needs. In Figure 4.5, we also show the traceability between industrial needs and defined research questions (Chapter 3). The industrial need related to the modeling and definition of PSSoS lifecycles and processes is not addressed during this PhD due to time constraints and the size and complexity of the company in which this PhD was conducted.

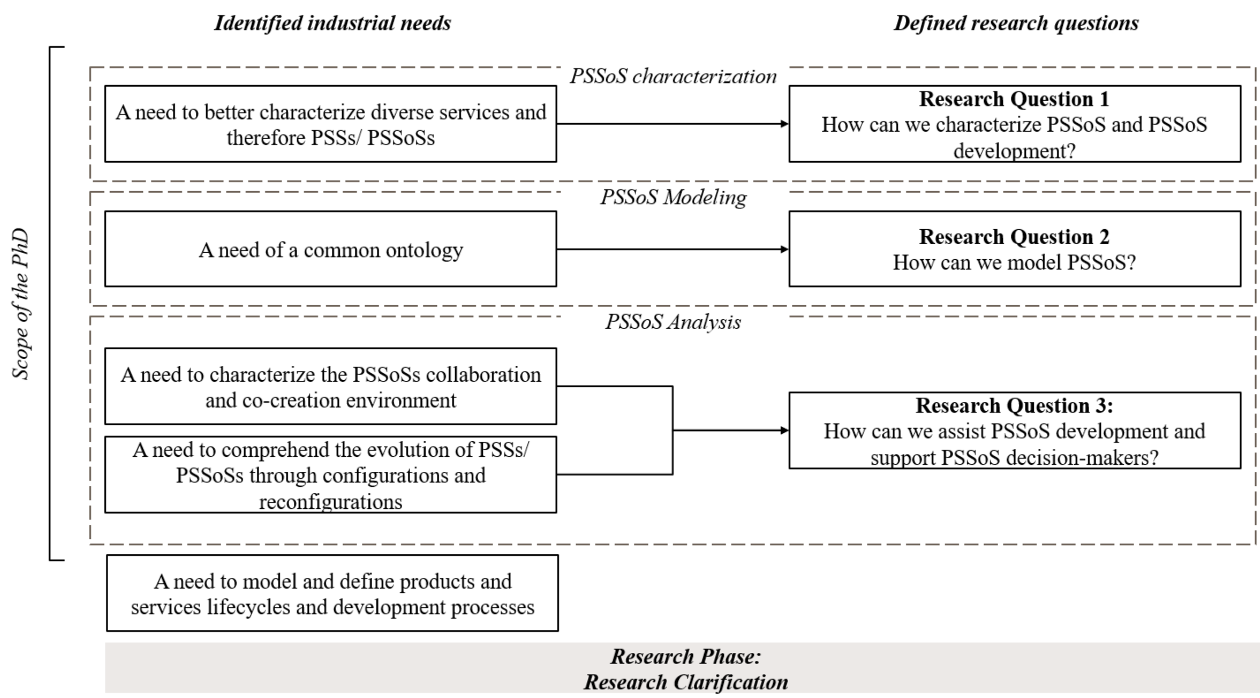

Figure 4.5: Clarification of industrial needs

In Figure 4.6, we represent how PSSs are development (AS IS). This representation results from the PhD student's comprehension following the empirical study. In no way does it represent in an exhaustive and exact manner what is really occurring in the company.

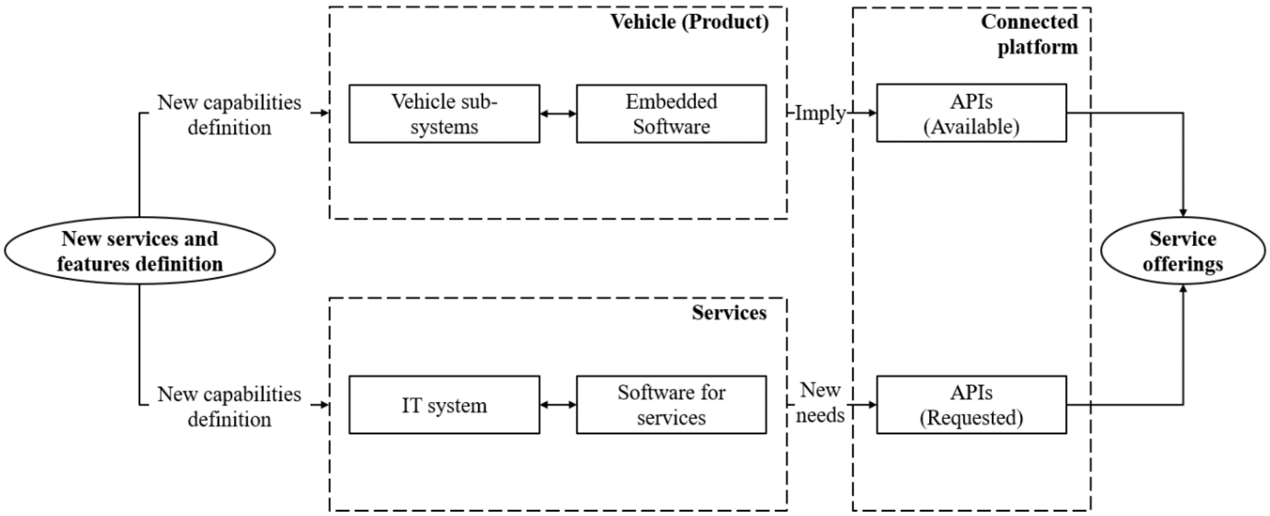

Figure 4.6: PSS development AS IS

4.2 Empirical study 1: Characterizing PSSs and PSSoSs

This empirical study complements the initial one (4.1.) and aims at further characterizing PSSs, and especially the specificities of PSSoSs developed or to be developed within Renault. In this manner, it aims to contribute to the first research question: how can we characterize PSSoSs and PSSoSs development?

For this purpose, we relied on the analysis **exploratory case studies**, e.g., examples of PSSs and PSSoSs, and participated in **workshops** (2 days) aiming to bridge the gap between product and service development and addressing the gaps described in 4.1. on concrete examples.

As for **exploratory case studies**, we mainly relied on service documents describing the service customer journey (i.e., provider/ customer activities and interactions in delivering the service -value)) and the service ecosystem, including different value chain stakeholders. In Table 4-5, we summarize the exploratory case studies.

Each **workshop** grouped system engineers, system architects, and service designers working on each case study in Table 4-5. During a 2 hours discussion, the attendees discussed how to develop the specific PSS or PSSoS and address its development issues. The PhD student participated as an observer in 4 of these discussions.

Table 4-5: Exploratory case studies

Exploratory case study	**PSS**	**PSSoS (independence of constituent systems and enterprises)**
Navigation Services	X	X
Stolen Vehicle Tracking	X	
Remote Parking Solutions	X	
Car sharing solutions	X	X
Electric Vehicle Charging Solutions (Plug & Charge)		X
Electric Vehicle to Electric Vehicle Solutions (V2)	X	X
Electric Vehicle to grid solutions (eV2G)		X
Electric Vehicle to Home Solutions		X

As a result, the PhD student could identify generic PSSs and PSSoSs types (Maier, 1996; Tukker, 2004) developed within Renault (see Chapter 5). Furthermore, the development of PSSs and PSSoSs within the company has been identified as subject to several unknowns (or uncertainties) and difficulties (refined compared to difficulties identified in the initial empirical study, see Figure 4.7):

- Collaboration context « Unknowns, » e.g., business partner behavior and systems evolutions;
- Requirements gathering or collection among stakeholders and for heterogeneous elements (products and services, for example);
- Uncontrolled increase of system complexity and heterogeneity: Not only a mechanical or electrical system but also connectivity and multimedia systems with an intensive software content;
- Difficulties in Product and Service integration that comes late in the actual development process;
- Products and services lifecycle offsets leading to the threat of obsolescence;
- The paradox between designing, at the same time, increasingly secure and closed systems (a new generation of automotive hackers) and open systems to be able to operate services (e.g., make remote updates);
- Diversity management difficulty: Product, Service, Infrastructure and resources, standards and regulations, stakeholders network diversity;

- Unknowns related to corporate behavior regarding risk (brought by new service development);
- Organizational skills and competences related issues
- Difficulties of the automotive Industry distinctive features: Certifications (Vibration Stress Levels, Temperature Range, Electromagnetic compatibility), Safety Cost, CO2 costs.

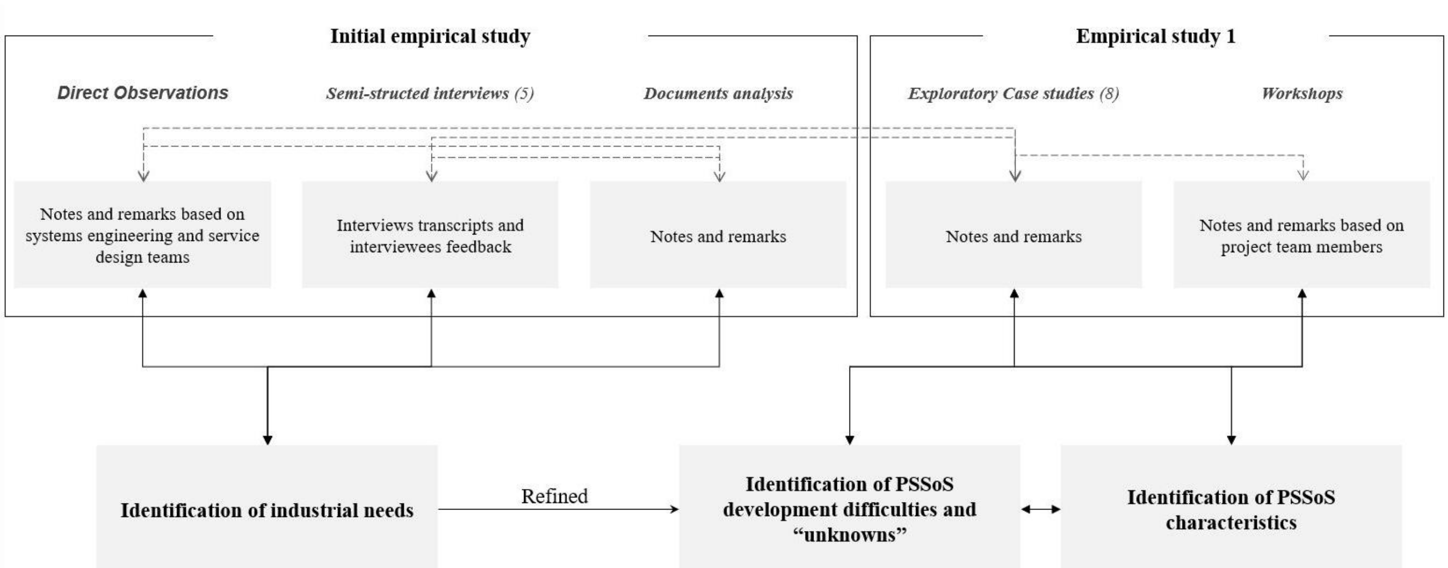

Figure 4.7: Identification of PSSoS development difficulties

The identification of PSSoSs development unknowns and related difficulties contributed to the definition of PSSoSs specific uncertainties in Chapter 5.

4.3 Empirical study 2: Methods, and tools in designing and developing PSSoS

In order to address the second research question, an empirical study is conducted. It aims to understand how the elements of PSSs and PSSoSs are modeled and represented, i.e., understanding the concepts defined and used and their relationships.

To this end, we studied models and tools used for systems engineering (Model-Based Systems Engineering (MBSE)) and models and tools used for service design. We were interested in the content of the models and tools, how they are used, and by whom. The PhD student also participated in training on MBSE tools proposed by the company (35 hours). Therefore, an overall idea of how models and tools are prescribed and how they are concretely used.

In Figure 4.8, we give an overall representation of existing models, including concepts and relationships. For instance, four distinct models exist with different levels of maturity. The **SoS model** describes the contractual relationships between stakeholders and is under development within the research department. The **service modeling** is done through documents describing the customer and how the service should be delivered (e.g., customer journeys descriptions) at the service department. The **vehicle modeling** and the **modeling of its subsystems** are done within Model Based Systems Engineering Tools (Engineering departments) and are detailed and mature within the company. We note that the representations given in Figure 4.8are simplified and do not give a detailed description of the models. Since different models are developed within different departments and are at different maturity levels, the models and tools themselves are not necessarily connected or interfaced. This interface or the transfer of information among different models is done by individuals within the organization. The links between different models are done through documents or meetings. We represent in Figure 4.9 these links specifying the transmitted information and its direction.

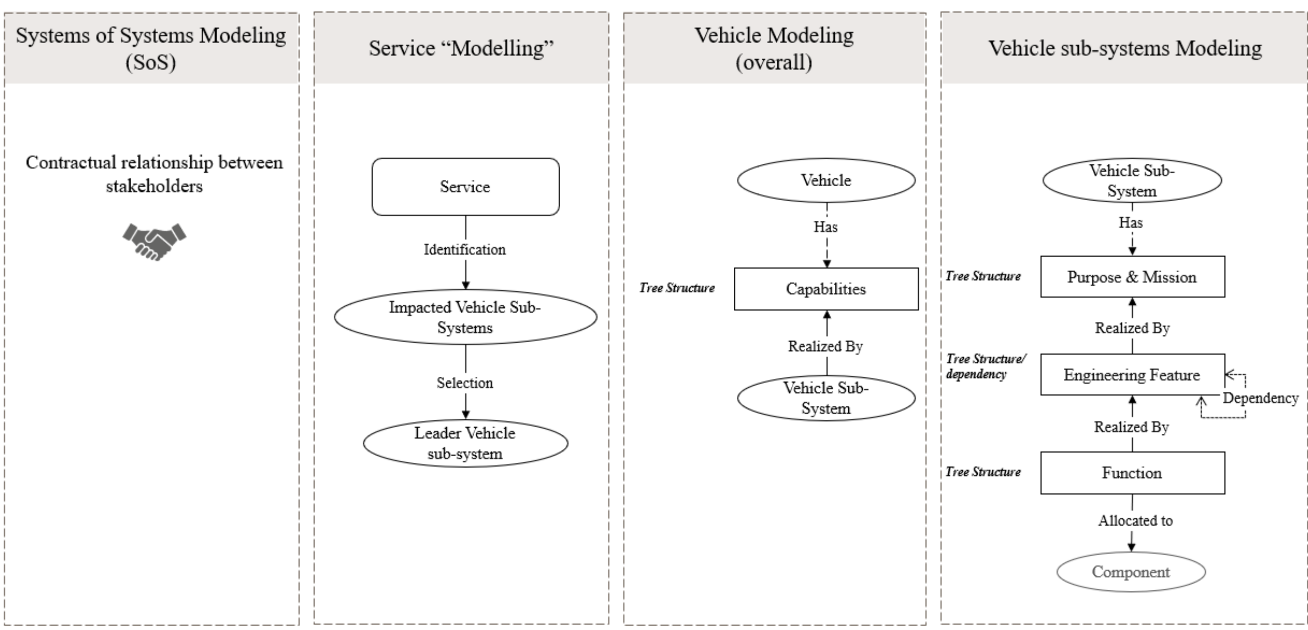

Figure 4.8: Simplified representations of existing models (PSSoS elements modeling)

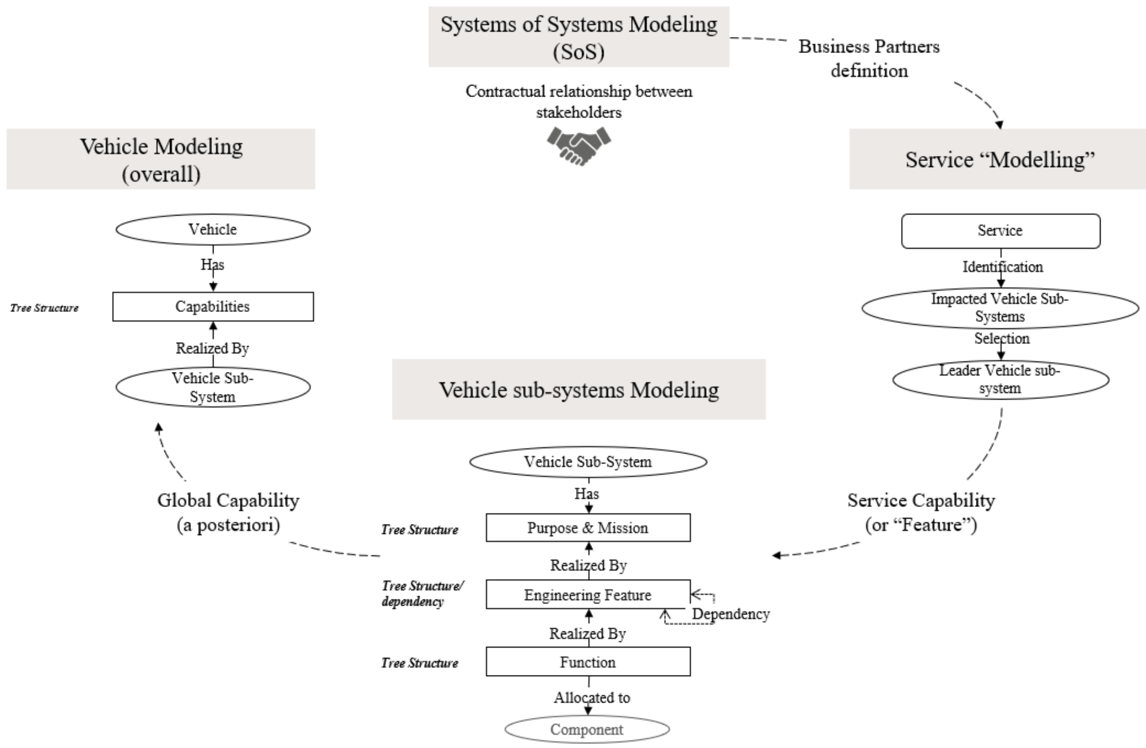

Figure 4.9: Links between models (through organization)

4.4 Empirical study 3: Observation of project teams

To better understand the needed PSSoSs analysis approaches (Research Question 3), we relied on industrial examples description and representation (using the PSSoS ontology, Contribution 2, detailed in Chapter 6).Table 4-6 details the sources of information pertaining to industrial examples and how the information is used to instantiate the PSSoS ontology and its view. The Plug and Charge example information allowed the project team to describe the case exhaustively. Therefore, the Plug and Charge is the descriptive case study detailed in this manuscript.

Several discussions with the project team (Plug and Charge development team) (detailed in the process Figure 4.10) allowed us to specify needed PSSoSs analysis approaches (Chapters 7 and 8). The process in Figure 4.10 also allowed for validating the PSSoS ontology (Contribution 2, Chapter 6). Similar but less rich discussions with project teams working on other industrial examples (Table 4-6) allowed to confirm the interest of potential PSSoS analysis approaches.

Table 4-6: Industrial examples and available information

Industrial examples		1	2	3	4	5
		Plug & Charge Service	***On Board Navigation service***	***Stolen Vehicle Tracking***	***Smart Route Planner***	***Car sharing service***
Sources of information	**Service Design documents**	X	X	X		
	Vehicle Design document	X				
	Sub-System architecture document	X	(X)			
	Other documents (Service presentation)				X	X
Available information (Ontology views)	**Stakeholder view**	X	X	X		(X)
	Service View	X	X	X	X	X
	System View	X	(X)		(X)	(X)
	Operational view	(X)				

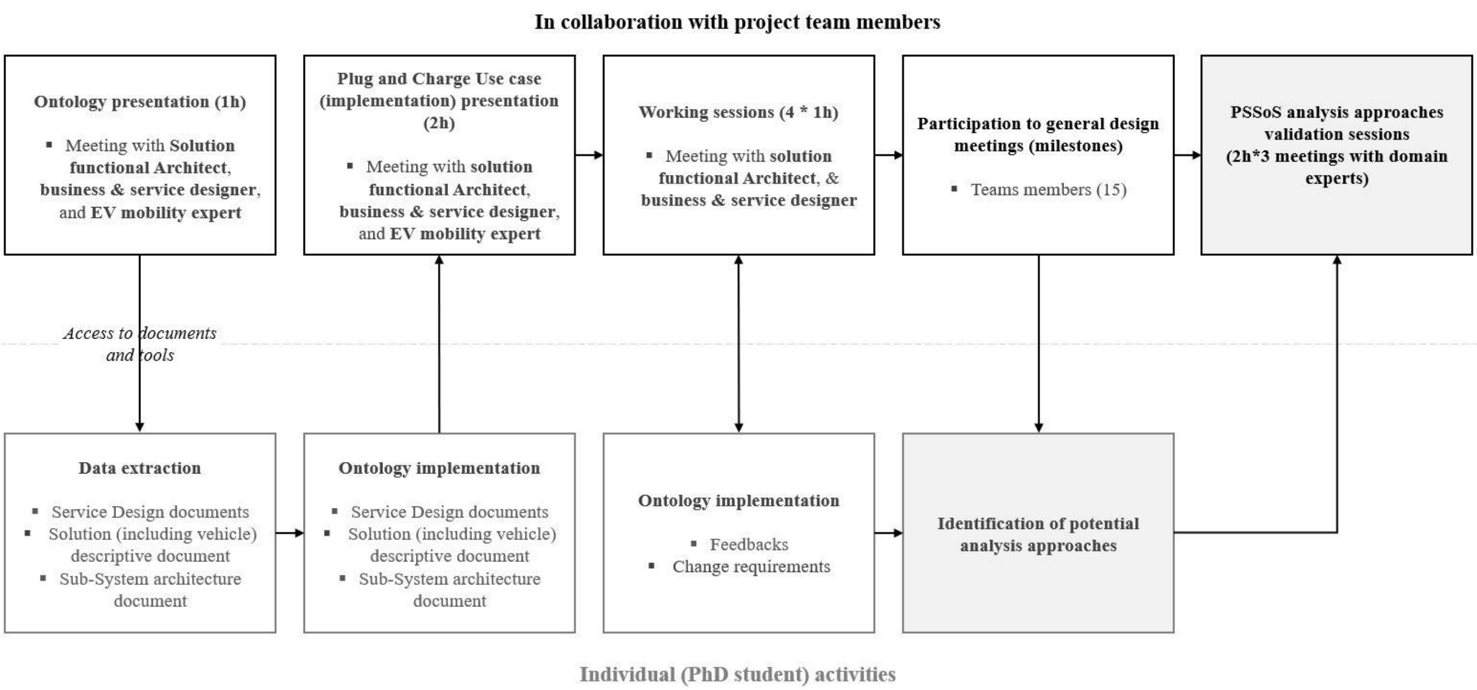

Figure 4.10: Identification of potential PSSoS analysis approaches

4.5 Chapter summary

In this chapter, we describe the empirical studies conducted during this PhD. An initial empirical study allowed for the clarification of the research needs and, as such, helped to define research questions. Empirical studies 1 to 3 aims to contribute to each research question (1 to 3).

In Figure 4.11, we represent the links between this chapter and the former and the following chapters.

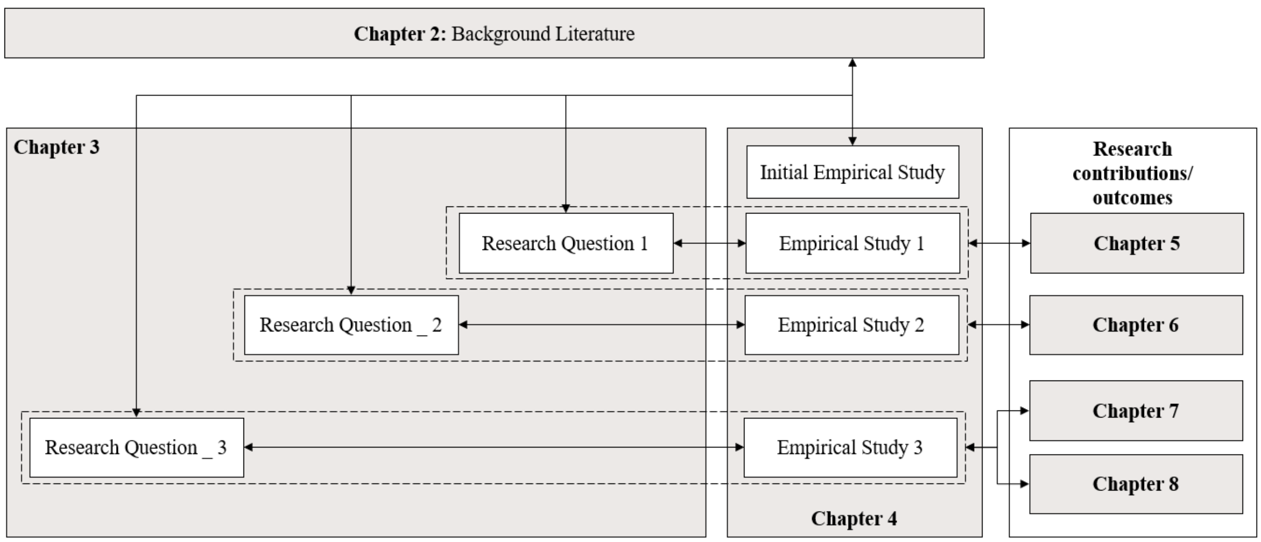

Figure 4.11: Links between chapters

5 Product Service Systems of Systems characterization

Sarra Fakhfakh, Andreas Makoto Hein, Marija Jankovic, Yann Chazal

This paper has been published under the reference:

Fakhfakh, S., Hein, A. M., Jankovic, M., & Chazal, Y. (2019, July). Towards an uncertainty framework for Product Service Systems of Systems. In *Proceedings of the Design Society: International Conference on Engineering Design* (Vol. 1, No. 1, pp. 3121-3130). Cambridge University Press.

Abstract: *Product Service Systems (PSS) are increasingly complex and collaborative. For instance, manufacturing companies, service providers, and other companies collaborate and jointly develop and operate a PSS (ex: smart grid), where its constituent elements are managed and operated independently. Managerial independence and operational independence are commonly considered key characteristics of a System of Systems (SoS). Hence, a collaborative PSS exhibits System of Systems (SoSs) characteristics. These systems have previously been introduced as Product Service Systems of Systems (PSSoSs). In this chapter, we propose to identify relevant uncertainties in the PSSoS design process. For this purpose, we go beyond the PSSoS concept definition and propose a comprehensive framework for PSS and PSSoS characterization. Moreover, based on both a literature review and an industrial diagnosis, we identify PSSoSs-specific design uncertainties.*

5.1 Introduction

Different domains propose a variety of definitions for Product Service Systems (PSS) (Haase et al., 2017; Park et al., 2012; Tukker, 2015). In engineering design, a Product Service System (PSS) is commonly defined by its constituent elements: Products, Services, Supporting networks and Infrastructure (Mont, 2002). A collaborative PSS is a bundle of interoperable systems developed and managed by different actors each one aiming at more competitiveness and sustainability (Mont, 2002). Collaborative PSS features can be seen as similar to Systems of Systems (SoSs) features (Estrada and Romero, 2016a; Hein, Poulain, et al., 2018). Hence, based on Maier's (1996) definition of a SoS, Hein et al (2018) introduce the concept of a Product Service System of Systems (PSSoSs) defined as “a set of products, services, infrastructures, and networks where its constituent elements exhibit operational and managerial independence”.

PSSoSs are already being developed and deployed by industry. For instance, a large automotive company, an energy provider and an infrastructure manager collaborate and jointly develop and operate PSSs (EV2G) (Chazal, 2018). These PSSs involve different and heterogeneous systems jointly capable of fulfilling customer needs, each of them operated and managed by independent companies. More generally, in the context of PSSoS, each actor can develop, manage and/or operate product(s), service(s), PSS(s) and/or infrastructure(s). Actors can also share the development, management and/or operation of Product(s), Service(s), PSS(s) and/or infrastructure(s) (Hein, Poulain, et al., 2018).

The multitude of possible Product Service combinations and allocation of roles among actors increases PSSoS complexity compared to "classic" PSS. Thus, PSSoS introduce the new challenge of defining the collaborative value proposition (Hein, Chazal, et al., 2018). Design for interoperability between the PSSoS' constituent elements is another challenge. In the following, we present an example for a design challenge related to interoperability in PSSoS. While a service provider develops intangible services able to interoperate with tangible products throughout their lifecycle, the responsibility of a company in the manufacturing industry for its product extends to its use phase and disposal and covers its whole lifecycle. Moreover, product lifecycles are usually longer than services lifecycles. The fact that service lifecycle is more rapidly evolving introduces additional difficulties and uncertainties in the PSSoS development.

In this chapter, we propose to identify relevant uncertainties in the PSSoS design process. For this purpose, we propose a comprehensive framework allowing for PSS and PSSoS characterization, from which these uncertainties can be derived. The aim is to identify uncertainties in order to support overall PSSoS development. The structure of the chapter is as following. In section 5.5.2, we consider the literature pertaining to both PSS and SoS as few research addresses the PSSoS concept. Moreover, we also address different PSSs and SoSs specific uncertainty definitions and modelling. In Section 5.5.3, we describe the adopted research approach. Section 5.5.4 details the proposed characterization of PSS and PSSoS. In section 5.5.5, identification of PSSoS uncertainties is discussed with regard to existing literature as well as identified industrial needs. We finally conclude by providing future research avenues in section 5.5.6.

5.2 Literature review

PSS and SoS have been traditionally discussed separately in literature. Hence, we propose to discuss both PSS and SoS characteristics in order to identify PSSoS characteristics. Moreover, uncertainties related to PSS and SoS development might be different with regard to their different characteristics. In this section, we propose to discuss different types of uncertainties pertaining to PSSoS characteristics.

5.2.1 PSS and SoS characterizations

The PSS typology presented in (Tukker, 2004) is one of the most used in the literature. In this typology, a PSS is defined as a business model. A distinction is made between product-oriented PSSs, use-oriented PSSs, and result-oriented PSSs. The differentiating criteria between these three PSS types are mainly the ownership of the product and the payment method (Aurich et al., 2010). Tukker’s typology gives a business perspective on PSSs but lacks insight on engineering difficulties related to PSSs development. Meier et al. (Meier et al., 2010) suggest a systems engineering oriented typology for PSSs. The authors distinguish “Service Products”, “Extended Products” and “Industrial Product Service Systems”. The differentiation between the three types of PSSs is based upon the engineering development methods (Independent product and service engineering, Machine/ Product oriented engineering and simultaneous service and systems' engineering respectively). Both typologies describe the decreasing product-centricity of the PSS or as one can define it's increasing heterogeneity. Product-oriented PSS, use-oriented PSS, and result-oriented PSS could be equivalent to "Service Products", "Extended products", and "Industrial Product Service Systems" respectively.

Most of the literature underlines these three PSS characteristics: customer orientation (Manzini and Vezzoli, 2003), sustainability (Pieroni et al., 2017), and heterogeneity (Meier et al., 2010; Sassanelli et al., 2016; Song and Sakao, 2017). Heterogeneity features can further be refined and related to products and services bundles (Song and Sakao, 2017), the diversity in service types (Sassanelli et al., 2016) and the variety of stakeholders expectations (Meier et al., 2010).

Other characteristics are more specifically relevant for user-oriented PSSs and result-oriented PSSs. In use-oriented and result-oriented PSSs, there is a continuous delivery of a service that needs to be supported through the entire life cycle. As customer needs evolve, (Sakao, Panshef, et al., 2009; Song, 2017) there is a need to be able to dynamically adapt PSS to satisfy these evolutions. This is linked to the notion of evolvability in the literature (Maleki, Belkadi and Bernard, 2017).

As for the SoS characteristics, several research underlined the following characteristics: independence (managerial & operational) of their elements, their evolutionary nature, emergent behaviors, geographic distribution, interoperability, complementarity and holism (Keating and Katina, 2011; Maier, 1996). Baldwin et al (2011), focuses on the taxonomy with regard to increasing complexity. Authors distinguish between a simple system, a complicated system, a complex system, an adaptative system, a System of Systems, a collaborative System of Systems and, a complex adaptative system. The taxonomy is based upon 7 characteristics or attributes: Autonomy, Connectivity, Belonging, Emergence, Diversity, Self-organization, and Adaptability (Sauser et al., 2009).

5.2.2 PSS and SoS related uncertainties

One can identify several research streams that identify and tackle the notion of development related uncertainties: engineering design, PSS literature, Innovation management and System of Systems literature. In this chapter, we consider uncertainty as «a potential deficiency in any phase or activity of the process, which can be characterized as not definite, not known or not reliable» (Kreye, 2011).

In the design engineering literature, one of the most used classification in product design is the one proposed by De Weck et al. (2007) suggesting a classification of sources of uncertainties for early design. The classification includes product, use, corporate, market, and political and cultural contexts as sources of uncertainty.

In the PSS literature, several research proposes PSS related uncertainties (Hernandez et al., 2018; Herzog et al., 2014; Kumar et al., 2013, p. 91,96).

In (Hernandez et al., 2018), the PSS specific uncertainty classification covers Environmental , Organizational, Relational, Technical and Resource uncertainty. This classification is interesting with regard to PSSSoS as authors propose under Technical uncertainty type: uncertainties related to hard/software combination, service definition, forecasting timing and scale of service, Systemic integration (Service + Product). As for Relational uncertainty, it covers uncertainties related to customer and collaboration partners. Reim et al (2014) in particular address behavioral uncertainties related to PSSs. The increased service content of a PSS leads to more value co-creation with the customer but also increases the risks of customers' opportunistic behavior. Herzog et al (2014) classify PSS uncertainties according to three main classes constraints/Requirements, system context, and development processes. This classification is relevant for PSSoSs development as it covers the whole PSS lifecycle and integrates the PSS evolvability through changing customers' needs. The uncertainty classification presented in (Kumar et al., 2013) appears to be the most comprehensive and includes: Market uncertainty, Company uncertainty, Environment uncertainty, Uncertainty of product functioning, Product function uncertainty, Uncertainty of innovative services, PSS integration uncertainty, Supplier coordination uncertainty, communication uncertainty and Uncertainty with remanufacturing. These uncertainties apply to PSSoSs development. More specifically, Product function uncertainty points out the risk of changing product's function over time through upgrades. Obsolescence appears as a cause for this uncertainty. Uncertainty of innovative services leads to technology changes. PSS integration uncertainty highlights the complexity and difficulty of adjustment when the degree of (Product and Service) integration is high. PSSs can also be seen as an "innovation strategy shifting the business focus from designing (and selling) physical products only, to designing (and selling) a system of products and services which are jointly capable of fulfilling specific client demands'" (Manzini and Vezzoli, 2003). Looking at uncertainty in the innovation management can then be relevant for PSSoS development.

O'Connor and Rice (2013) suggest 4 categories of uncertainty, Market, Organizational and Resource uncertainties. Market uncertainties include features of customer/ Product interactions. Organizational uncertainty underlines the fundamental conflict between the mainstream organization the unit engaged into radical innovation. Resource uncertainty points out the competency gap in innovation projects. These uncertainties are also interesting with regard to PSSoS development as manufacturing industry address new markets by offering services apart from their core business.

O'Connor and Rice (2013) also add latency and criticality classes to uncertainty. "Latency refers to the degree to which the uncertainty can be perceived or anticipated". Criticality is the "the degree to which resolution of the uncertainty must occur immediately or the project's survival will be at risk".

In the SoS literature review, uncertainty is considered from a SoS enterprise engineering perspective. The uncertainties are mainly business partnership organization and partners role allocation (Carlock and Fenton, 2001).

Previously discussed literature underlines the need to identify PSSoS specific uncertainties as they are not addressed by current literature to our knowledge. Therefore, we propose to address this gap, firstly by identifying relevant PSSoS characteristics that are afterward used as a basis for uncertainty identification.

5.3 Research methodology

The aim of this chapter is to identify relevant uncertainties in the PSSoSs design process. The adopted approach Figure 5.1 is inspired by both the Design Research Methodology and the Action Research Method (Blessing L.T.M. and Chakrabarti, 2009; Brydon-Miller et al., 2015; Ferris, 2009; Järvinen, 2007). A literature survey has been conducted to characterize increasingly complex PSSs, including PSSoSs. Design uncertainties related to different PSSs types are assessed. Concomitantly, the research has been conducted within a large automotive industry. The field study is based upon data gathered from documents, observations, and interviews. This descriptive study allows to identify PSSs and PSSoSs programs' features and pertaining design uncertainties. The assessment of theoretical research along with the investigation of the field permits to build a PSSs and PSSoSs characterization map and a to identify related design uncertainties. The theoretical output aims at responding to the automotive industry needs and in a larger context, the manufacturing industry needs.

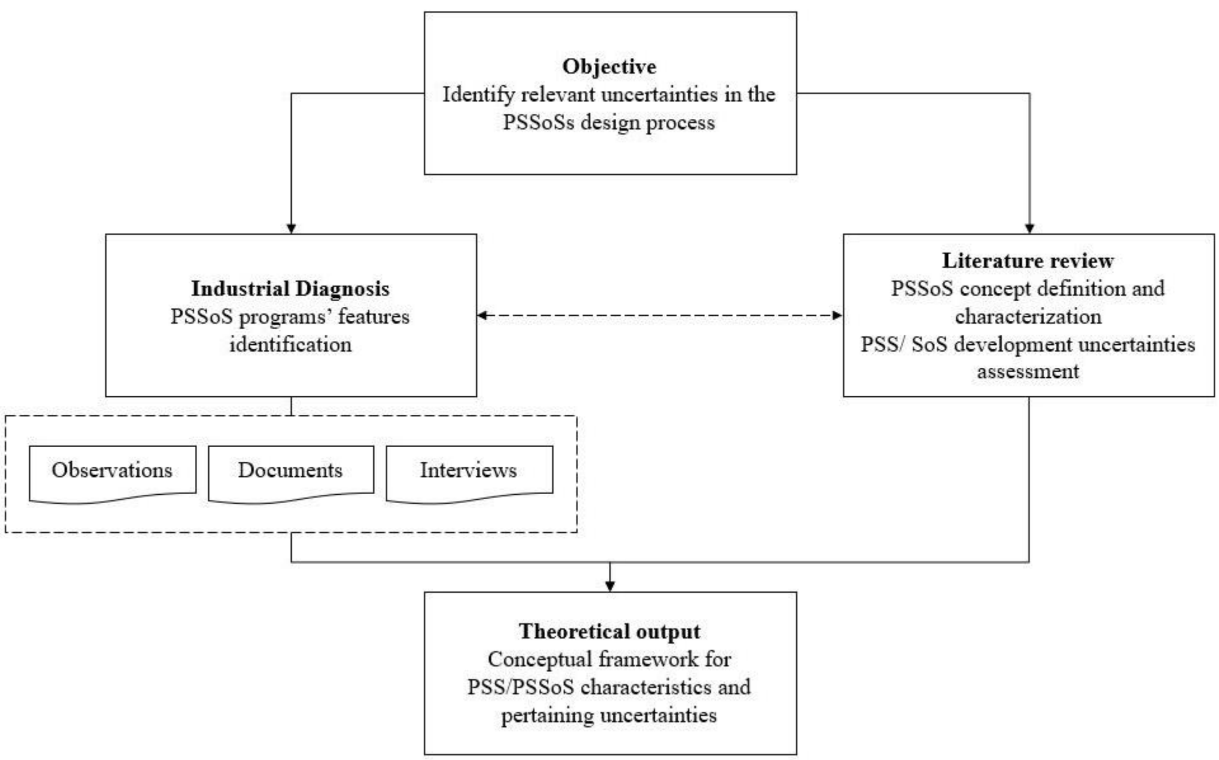

Figure 5.1: Research approach

5.4 Proposition of a PSS/ PSSoS characterization

Previously discussed literature underlines different aspects of PSS and SoS. In the following, we go beyond the PSSoS definition in (Hein, Poulain, et al., 2018) by mapping PSS-types to a system taxonomy by (Baldwin et al., 2011), including SoS.

In order to characterize PSSoSs, we base ourselves on the possible evolution of the PSS systems (product oriented, use-oriented, result-oriented) (Tukker, 2004; Wang, Ming, Li, et al., 2011) and the characterization of types of systems (Baldwin et al., 2011; Baldwin and Sauser, 2009). The proposed PSSoS characterization map is two dimensional: PSS taxonomy dimension and system taxonomy dimension (Figure 5.2).

The PSS dimension describes how product-centric a PSS is or it's increasing heterogeneity. Along the Y-axis, the product centricity of PSSs decreases. PSSs characteristics add up moving from Product Oriented PSSs to Result-Oriented PSSs (Tukker, 2004).

While product-oriented PSSs (maintenance, reuse, etc.) are customer oriented and sustainable, they only represent few features of heterogeneity. In use-oriented PSS, services, and usages diversify. The ownership of the product moves from the customer to the PSS providers which intensify the dynamic system/ customer interactions. The evolvability applies to Result oriented PSSs. In fact, the absence of a predefined product frees the PSS up to evolve throughout its lifecycle, according to customers' needs and stakeholder network configuration.

Using the systems taxonomy proposed in (Baldwin et al., 2011), we distinguish between PSSs and PSSoSs through the system dimension.

The system dimension describes the increase of systems complexity moving from simple systems to Systems of systems. Systems are characterized by their autonomy, connectivity, emergence, belonging, diversity and self-organization defined in (Baldwin et al., 2011).

According to this characterization authors distinguish between a simple system (Autonomy), a complicated system (Autonomy, Connectivity), a complex system (Autonomy, Connectivity, Belonging, Emergence), a system of system (Autonomy, Connectivity, Belonging, Emergence, Diversity) and a collaborative system (Autonomy, Connectivity, Belonging, Emergence, Diversity, Self-organization).

In (Baldwin et al., 2011), authors also introduce Adaptative systems and Complex Adaptative systems. Both systems share the adaptation characteristic. Adaption describes the ability of a system to "modify itself for the sake of its goals". The adaptive system also "has an awareness of itself in its environment and updates its behavior based on this information". As no examples of human-made adaptative systems are given in (Baldwin et al., 2011), we consider adaptability out of the scope of this chapter. The used characteristics help distinguish between simple systems and systems of systems.

In the literature, PSSs are usually studied as simple to complex systems. PSSs are little studied as SoSs or Collaborative SoSs. Yet, studied industrial examples show PSSoSs features.

In Figure 5.2, examples of mobility PSSs or PSSoSs developed by an automotive company (Renault) (except for Bike sharing) are presented (Chazal, 2018; Williams, 2007). Features of the mobility PSSs represented by black stars (Figure 5.2) have already been addressed in the Engineering Design and Systems Engineering literature (Herrmann et al., 2010; Pezzotta et al., 2011; Sakao, Panshef, et al., 2009; Shimomura et al., 2009; Zhang and Banerji, 2017). However, collaboration and evolutivity features of "On-demand Robot Vehicle", "Electric Vehicle to Grid (EV2G)" and "Battery as a Service" (Red Stars Figure 5.2) are rarely covered in the Engineering Design literature but rather in the Transportation Research Field (Bischoff and Maciejewski, 2016; Chen et al., 2016).

Figure 5.2 allows us to go beyond the uncertainties mentioned in the PSS literature, which mainly pertain to simple to complex systems. At this point, we can systematically identify PSSoS-related uncertainties that are not treated explicitly in the literature. The results are presented in the following section 5.5.5.

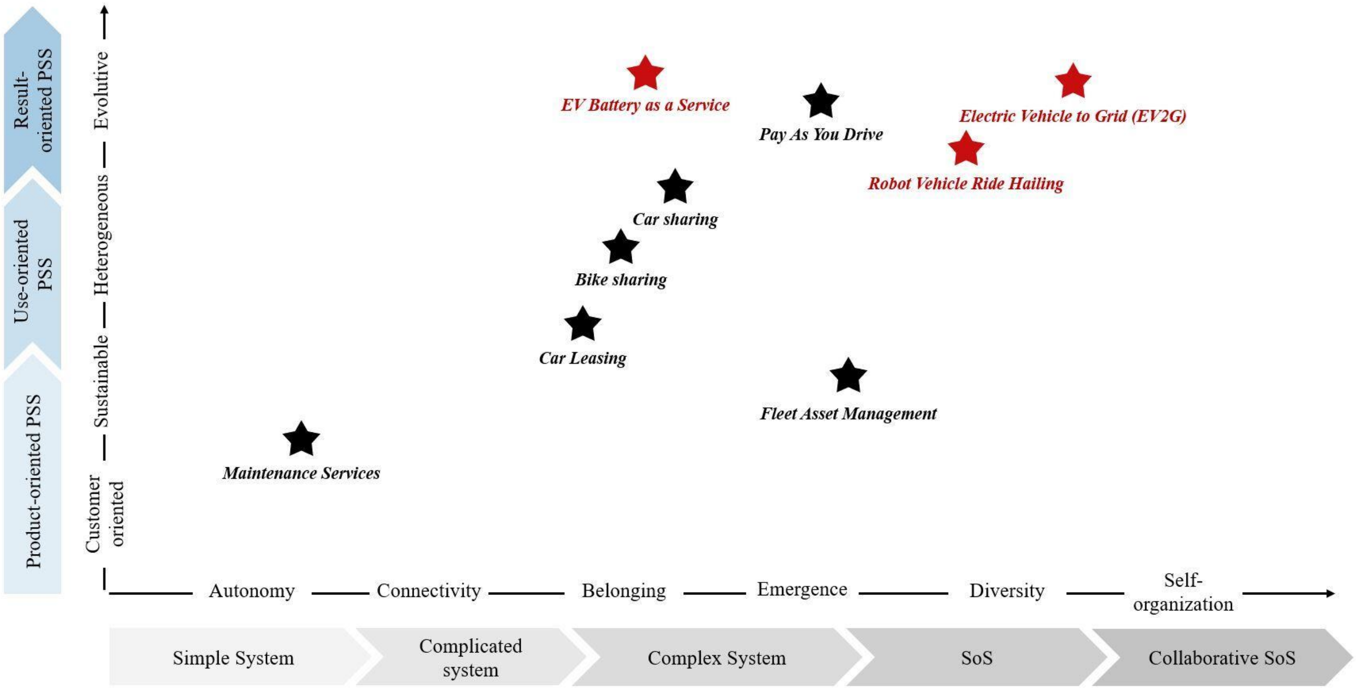

Figure 5.2: PSSs/ PSSoSs characterization map - Examples of mobility PSSs/ PSSoSs

5.5 Identification of PSSoS uncertainties

PSSoSs specific uncertainties could be deduced from both PSS literature and SoS literature (5.5.2.2). However, identified uncertainties do not cover exhaustively PSSoSs specific characteristics (Section 5.5.4).

Based on the proposed PSSoS characterization section 5.3 and through an industrial diagnosis within an automotive company, we extend identified PSSs/ PSSoSs uncertainties and attempt to map PSSoSs characteristics and PSSoSs specific uncertainties.

The industrial diagnosis has been conducted as part of the new mobility solutions and services development team and in close contact to systems engineering experts in a large automotive company. Existing and future PSSoSs development programs have been assessed. Structured and semi-structured interviews have been conducted with both systems engineering experts and project managers to comprehend PSSoSs development difficulties.

Just like any other system, PSSoS development takes place under market uncertainties, environmental (political and cultural) uncertainties, company or corporate uncertainties and, product uncertainties (Kumar et al., 2013; De Weck et al., 2007).

Besides these uncertainties, the following uncertainties both from the literature and from the industrial context have been identified and seem to be specific PSSoSs uncertainties:

- Heterogeneous and independent systems interface uncertainties:

The heterogeneity of PSSs constituent elements is studied in the literature (Hernandez et al., 2018). However, the autonomy and independence (managerial and operational) of each system within a PSSoS are not considered. As heterogeneous systems are independent, systems interfaces are harder to design, manage and control by different stakeholders.

- Heterogeneous systems interoperability related uncertainties:

Heterogeneous systems integrations are extensively studied in the PSS literature (Geum and Park, 2011). However, in a PSSoS context, integrations and interoperability are even more challenging as they involve stakeholders' collaborations.

- Lifecycle offsets uncertainties:

Products and services lifecycles and development strategies are different (Cavalieri and Pezzotta, 2012). In the PSS literature, authors tend to suggest integrated PSS lifecycles models or more precisely integrated PSS development processes (Aurich et al., 2006; Hänsch et al., 2016; Hepperle et al., 2010; Kim et al., 2011; Shimomura et al., 2009; Wang, Ming, Li, et al., 2011). However, as Products and services in a PSSoS context could be independent systems, their lifecycles remain independent. Thus, lifecycle offsets are PSSoSs-specific uncertainties.

- Uncertainty of innovative services/ products:

"Innovation often leads to technology changes, and, consequently, can be a source of uncertainties." (Kumar et al., 2013). Innovative services uncertainties lead to innovative products uncertainties as Products and Services are interoperable. This poses challenges for the manufacturing industry because their products need to keep pace with innovative services.

- Obsolescence uncertainties:

Within a PSSoS, products and services are interoperable, yet independent. Lifecycle offsets or fast evolutions of service technologies compared to product development could compromise products and services interoperability leading to systems' obsolescence.

- Usage uncertainties:

PSS development is seen as a mass customization strategy (Song and Sakao, 2017). Authors develop a PSS design framework able to support a variety of customers' needs and usages. However, in a PSSoS context, usages are not only diverse but also time dependent. Customers' needs, and perception of the service offer evolve and change throughout the PSSoS lifecycle.

- Collaboration uncertainties:

In a PSSoS context, systems contributions and stakeholders' roles allocation are not necessarily defined a priori. Systems/ actors could integrate and exit the PSSoS throughout its Lifecycle. Thus, in a PSSoS context, systems capabilities might need enhancement and changes to ensure interoperability and PSSoS functioning. This requires the right technical training, knowledge, and skills (Carlock and Fenton, 2001), a stakeholder/ company might lack. These issues are usually studied in the SoS Enterprise Engineering (SoSEE) or the SoS management literature (Carlock and Fenton, 2001; Sauser et al., 2009; Sauser and Boardman, 2008). Hence, Competency Gaps (O'Connor and Rice, 2013) are an additional PSSoS-specific uncertainty.

Uncertainties find their roots in either PSS characteristics or SoS characteristics (Figure 5.3). PSS Customer orientation, sustainability, heterogeneity, complexity, and evolutivity account for Heterogeneous and independent systems interface uncertainties, Heterogeneous systems interoperability related uncertainties, Lifecycle offsets uncertainties, Uncertainty of innovative services/ products, Obsolescence uncertainties and Usage uncertainties (Blue Rectangles Figure 5.3). However, the autonomy of each system and the diversity within a SoS make these uncertainties even more critical. Diversity and Self-organization explain the Collaboration uncertainties (Grey Rectangle Figure 5.3). Yet, competency gaps, for example, are particularly challenging as systems exhibit features of heterogeneity.

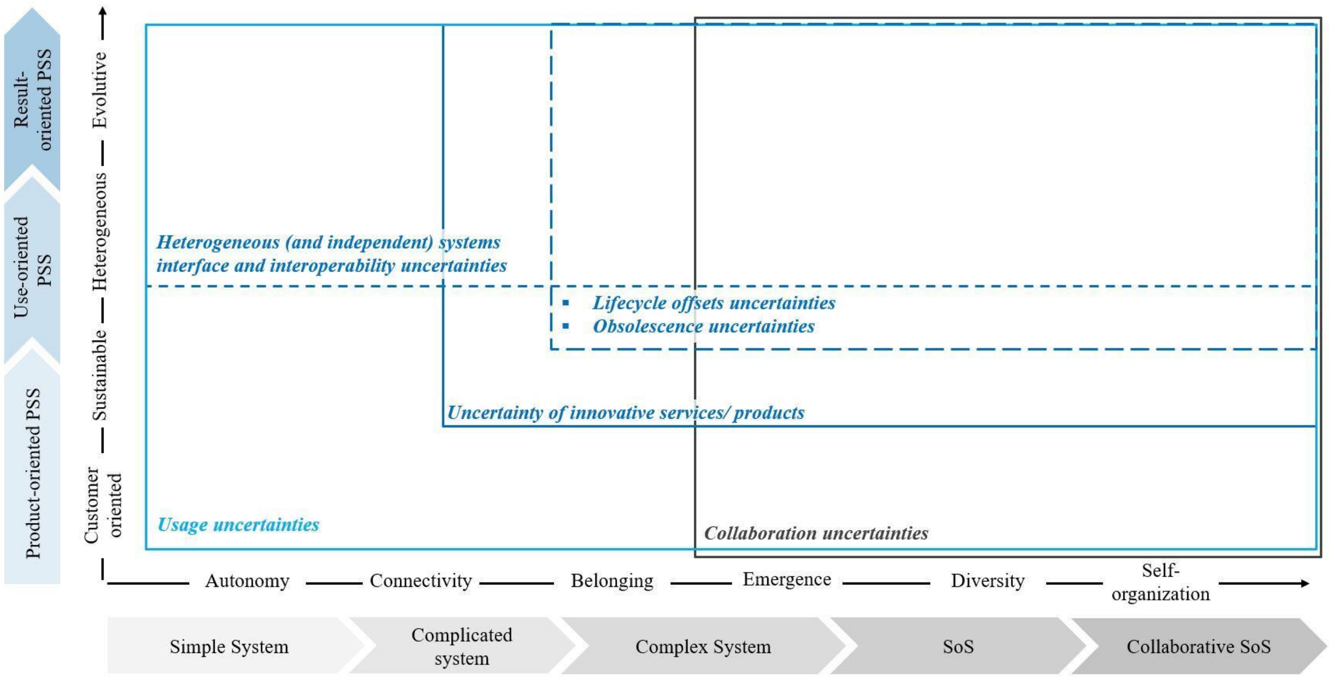

Figure 5.3: Mapping PSSs/ PSSoSs characteristics and PSSs/ PSSoSs specific uncertainties

The uncertainties described above, represent development challenges we need to specifically pay attention to, especially in the context of PSSoS and for the automotive industry. A generalization and a validation of PSSoSs-specific uncertainties are yet to be made. A PSSoS uncertainty model is needed. PSSoS uncertainty propagation methods are also to be developed. These models and methods should allow for the development of PSSoS uncertainty management strategies in design.

5.6 Conclusion

Product Service Systems (PSS) and Systems of Systems (SoS) are rarely linked in the literature. We call systems that exhibit both, PSS and SoS characteristics, Product Service System of Systems (PSSoS). For instance, the automotive industry develops increasingly complex PSSs (such as EV2G) that could be seen as PSSoSs. However, PSSoSs characterization and PSSoSs development difficulties need further discussion.

In this chapter, by assessing PSS and system types, including SoS in the existing literature, we proposed a PSSoS characterization map. PSSoS features of heterogeneity, evolutivity, and complexity on one hand, managerial and operational independence of PSSoS constituent systems, on the other hand, raised uncertainty related issues for PSSoS development. The PSS and SoS literature mention some PSSoS-specific uncertainties such as customers changing needs, Products and Services lifecycles offsets and obsolescence issues. Besides, some PSSoS specific uncertainties could be identified through automotive industry examples analysis. However, an exhaustive study of PSSoS-specific uncertainties is still required.

For future work, a PSSoS-specific uncertainty model is needed. PSSoS uncertainties propagation methods could also be developed. Uncertainty models and propagation methods could help assess uncertainty management strategies in design.

6 An ontology to support Product Service Systems of Systems engineering

Sarra Fakhfakh, Marija Jankovic, Andreas, Makoto Hein, Yann Chazal

This paper has been submitted to Systems Engineering

Abstract: *The venue of new technologies such as autonomous vehicles implies the design not only of the product but also of services related to it. These systems are known as Product Service Systems (PSS). Moreover, they are not only PSS but also System of Systems (SoS). Up till now, the research has been addressing the design of PSS and SoS separately. The PSS literature focuses mainly on the product servitization and the increasing heterogeneity of PSS elements. On the other hand, the SoS literature focuses on the relationships between SoS constituent systems and their management. These both research domains propose systems modeling approaches and systems architectural patterns independently according to PSSs and SoS development contexts. In order to address this gap and support PSSoS design and development, there is a need to identify necessary data, the PSSoS ontology. The proposed ontology is developed with the Unified Modeling Language (UML) and is structured in four views: the stakeholder view, the service view, the systems view, and the operational view. The proposed model has been validated by nine industrial experts as well as five industrial projects; and is illustrated in the case of Plug&Charge within one of the major automotive French constructors.*

6.1 Introduction

In recent years, services that are supported by complex systems are becoming more and more present, e.g., Vehicle to Grid (V2G) services, connected mobility services, or autonomous vehicles. These systems are considered to be Product Service Systems of Systems (PSSoS). Product Service Systems (PSS) are defined as “systems of products, services, supporting networks and infrastructure that is designed to be: competitive, satisfy customer needs and have a lower environmental impact than traditional business models” (Mont, 2002). SoSs are “a class of systems which are built from components which are large scale systems in their own right”(Maier, 1996). PSSoS represent a combination of these two types of systems exhibiting similar characteristics but also having their specific challenges. Like PSSs, PSSoSs are heterogeneous, and customer-oriented (Fakhfakh et al., 2019). PSSoSs are as complex as SoSs and show diversity and emergence characteristics (Baldwin et al., 2011). Thus, in the context of a PSSoS, independent stakeholders collaborate to provide a service. Each stakeholder contributes to the PSSoS by developing or operating a PSSoS (independent) constituent system (products, services, or infrastructures) (Hein, Poulain, et al., 2018). PSSoS tend to evolve as customer needs evolve, constituent systems change, and stakeholder roles allocation rearranges. For example, an automotive company, an energy provider, and an infrastructure operator can collaborate and jointly develop and operate Electric Vehicles (EV) charging services (Chazal, 2018). PSSoSs characteristics render their design, development, and operation challenging (Fakhfakh et al., 2019). The interfaces between the independent constituent systems as well as the possible related interoperability need to be identified and managed. Moreover, the lifecycles of independent systems can be different (Garnier et al., 2012), yielding in possible obsolescence management challenges. In particular, integrating innovative products or services can highlight and increase obsolescence management issues. The current state of the art underlines the lack of adequate support as well as a methodology to support the design team in the PSSoS development process.

Up till now, PSSs and SoSs have been studied separately in the literature. The focus in PSS design is, in particular, towards the value creation process and the design of the value for the customer (Hein, Poulain, et al., 2018). With regard to the value creation, there is a differentiation of product-oriented, use-oriented, and results-oriented PSSs based on whether the value is determined by the service or the product content (Tukker, 2004). On the other hand, the SoS research focuses particularly on the management of the interfaces between independent constituent systems (Hein, Poulain, et al., 2018). In particular, SoSs are classified as directed, acknowledged, collaborative, and virtual with regard to the type of interactions and their management. For both PSS and SoSs, related research studies have been proposing approaches and methodologies to support their development with regard to their specificities. However, to our knowledge, adequate support, and methodology for the development of PSSoS is still lacking.

This chapter aims at addressing this gap by proposing an ontology for PSSoSs in order to identify all necessary information for the design, integrating PSSoS specificities. We propose the following structure of the chapter. Section 6.2. reviews PSS and SoS modeling approaches and related ontologies or architectural patterns. In section 6.3, the research methodology used to support this ontology definition and validation is presented. The PSSoS meta-model is presented in section 6.4. In section 6.5, an industrial case study of Electric Vehicle charging service used for the ontology validation is given and discussed. In the end, the discussion and conclusions are given.

6.2 Literature review

PSS and SoS fields are considered to be two separate research domains. With regard to the previously discussed challenges, the first section 6.2.1 of the literature review is addressing PSS models and necessary data representations. Section 6.2.2 addresses models and data representation in the SoS field. In each section a critical analysis with regard to the potential support for the PSSoS is discussed. The overall analysis is given at the end of this section.

6.2.1 PSS modeling approaches

A PSS is defined as "a system of products, services, supporting networks and infrastructure that is designed to be: competitive, satisfy customer needs and have a lower environmental impact than traditional business models" (Mont, 2002). Initial interest for the PSS development was in the potential to support sustainable development (Baines et al., 2007). As such, different research streams studied PSSs (e.g. information systems, business management and design and engineering) (Boehm and Thomas, 2013), and various PSSs representation models have been proposed (Kim, 2020) (e.g. high level synthesis models and detailed models).

As for PSSs detailed descriptions, in general there are two major detailed models: 1) ones that address functional and physical modelling; and 2) business modelling addressing customer and value proposition modelling. Hara et al. (Hara, Arai and Shimomura, 2009b) consider service to be defined as agents and related software, while product are considered to be hardware and software components. Authors propose to use extended blueprint for PSS modelling; underlining that services are represented through activity and activity function modelling, and product are described in terms of functional modelling and product behavior. The combination of product functions and service functions realize overall PSS functions and provides value to the customer. Hajimohammadi et al., (2017) propose an ontology on product and service portfolio definition integrating PSS Life cycle management. Authors propose to model services through service functionality and different resources such as human, software, and material resources; and product are represented by functions, behaviors and physical products. Kim et al., (2011) propose to consider PSS function modelling (the modelling proposed is IDEF0) on the overall level, that is further refined and allocated onto product and service elements separately. Service elements are described by the service provider/receiver, activities, and associated product elements. Product is not considered here in detail. Service Function and Attribute Analysis (SFAA) is proposed by Song and Sakao, (2016) representing PSS closely to the modelling proposed by Kim et al. PSS functions are represented on the overall level, services and products are considered separately, while product contribute to the realization of one or more services. Some PSS are defined are Industrial Product-Service Systems (IPS2) (Welp et al., 2008). In this research, Welp et al. propose to consider IPS2 objects and processes. IPS2 objects include human resources, devices, and physical structures, while IPS2 processes include activities and software elements (e.g., algorithms). In this research one can consider that IPS2 object and IPS2 processes replace service and product elements. Function are modelled on the overall IPS2 level as well as its behavior. An ontology has been proposed by Kim et al. to represent PSS and PSS value (Kim et al., 2009). The PSS and its constituent elements (products and services) are described through their structure, function, and behavior. In addition, the proposed ontology includes a representation of the PSS value including value category, parameters, realization, and actors perceiving it.

Regarding higher-level descriptions, Correia et al., (2017) propose an ontology to support collaborative PSS development. The proposed ontology is based on the Basic Formal Ontology (BFO). It includes the concepts of PSS, product and service and describes their lifecycles. The authors also include in the ontology a representation of the stakeholder network including PSS suppliers, PSS providers, PSS vendors, PSS customers, consumers, etc. Maleki et al., (2018) propose a PSS conceptual model based on systems engineering, and differentiate the system of interest and the enabling systems. The system of interest includes the product (e.g., mechanic, electric, and cybernetic) and the service (e.g., service processing, software, and embedded systems). The enabling systems include physical, digital infrastructure, and organizational capacity. The authors also represent the PSS lifecycle and PSS business model. Annamalai et al., (2011) propose a comprehensive ontology for PSSs, built upon the PSS root concepts: need/ requirement, product-service, stakeholder, PSS design, PSS outcome, support system, PSS lifecycle, and the PSS business model. A PSS meta-model has been proposed as a support the PSS engineering (Medini and Boucher, 2019). The proposed PSS meta-model includes seven views: requirement view, PSS structure modeling views (product, service, activity, and organization views), and dynamic modeling views (demand, offer, scenario, and performance views). Kim, (2020) intend for the comparison and classification of PSSs and propose another comprehensive PSS representation framework. The representation framework comprises of eight spaces: product, customer, value, actor, service, business model, interaction context, and time-spaces.

In summary, one can distinguish detailed and higher-level PSS descriptions. Detailed PSS modeling approaches mostly describe PSSs through product and service elements. Product elements are represented by their physical structure, their functions, or behaviors. Activities, functions, and agents represent service elements. According to these modeling approaches, combinations of service and product elements achieve the PSS functionality and provide value to the customer. Higher-level PSS descriptions do not necessarily detail product and service elements. They instead give an overall perspective on PSSs, including representations of PSS stakeholders, PSS Business models, PSS lifecycles, including product and service lifecycles, along with PSS in use representations. Table 6-1 summarizes PSS main concepts.

Table 6-1: Main PSS concepts, definitions, and modeling

PSS concepts	Definition and modeling	References
Product	- Defined as hardware (physical) and its related software	Hara et al. 2009 (Hara, Arai and Shimomura, 2009b) (similar definitions and modeling in Hajimohammadi et al. 2017 (Hajimohammadi et al., 2017) Kim et al. 2011 (Kim et al., 2011))
	- Modeled as physical structure, functions, and behaviors	
Service	- Defined as agents (or human resources) and related software	
	- Modeled through functions and activities	
PSS enabling systems	- Includes infrastructure, organizational capacity, and physical resources	Maleki et al. 2018 (Maleki et al., 2018)
PSS stakeholders	-Includes customers, suppliers, vendors, providers	Correia et al. 2017 (Correia et al., 2017) (also represented in Kim et al. 2020 (Kim, 2020), Hara et al. 2009 (Hara, Arai and Shimomura, 2009b), etc.)

PSS concepts	Definition and modeling	References
PSS Value	- Product functions and service functions realize overall PSS functions and provides value to the customer	Hara et al. 2009 (Hara, Arai and Shimomura, 2009b) (also considered in Kim et al. 2011 (Kim et al., 2011), Song et al. 2016 (Song and Sakao, 2016))
	- represented by its value category, parameters, realization, and actors perceiving it	Kim et al. 2009 (Kim et al., 2009)
	- Dynamically represented through demand, offer, and scenario	Medini and Boucher 2019 (Medini and Boucher, 2019) (Kim et al. 2020 (Kim, 2020) consider the interaction context)
PSS Business Model	- Differentiating how the value is provided to the customer and mainly differentiating product-, use-, and result- oriented PSS business models	Kim et al. 2020 (Kim, 2020)
PSS lifecycle	- Describe the PSS lifecycles as well as product and service lifecycles including PSS use phase	Annamalai et al. 2011 (Annamalai et al., 2011) (also represented in Maleki et al. 2018 (Maleki et al., 2018), Correia et al. 2017 (Correia et al., 2017))

6.2.2 SoS modeling approaches

SoSs are systems "which are built from components which are large scale systems in their own right" (Maier, 1996). SoSs are characterized by the operational and managerial independence of the component systems (CSs), the evolutionary development, the emergent behavior, the geographical distribution (Maier, 1996), the interoperability and the complementarity of component systems, and holism (Keating and Katina, 2011). Another point of view is proposed by Luo, (2017) insisting upon the expansionism, synthesis, and complementarity of SoS constituent systems.

Overall, one can see that the SoS characterization in general focuses on the interactions and relationships between its constituent systems and their management rather than characterizing the constituent systems themselves (Gomes et al., 2015; Kinder et al., 2012). In the SoS literature, the major challenges focus on SoS management and SoS architecture design (integrating challenges related to SoS representations and modelling). In the work of. Mohsin, Janjua, Islam and Valdemar Vicente Graciano, (2019), the authors address the taxonomy of SoS architecture modeling approaches and distinguish: 1) SoS-architectural description languages (ADLs), 2) SoS architecture frameworks, and 3) ontology-driven modeling.

As for **SoS-ADLs**, the authors distinguish formal ADLs and semi-formal ADLs. For instance, the Systems Modeling Language (SysML) is a semi-formal ADL widely used in architecting SoS (Dahmann et al., 2017; Lane and Bohn, 2013). Lane and Bohn, (2013), point out that SysML is indeed not designed to "dynamically execute models to identify and evaluate SoS emergent behaviors or performance". Alternatively , Lane and Bohn, (2013) and Ge et al., (2014) use colored Petri net (CPN) and Petri nets (PN) as executable formalisms to model executable SoS architectures. Han and Delaurentis, (2013) focus on the constituent system interdependencies modelling and propose a Bayesian network approach. In the same direction, Agarwal et al., (2014) propose an agent modelling for representing component system interactions.

SoS **architecture frameworks** represent best practices and standards in terms of modelling and designing SoSs. Several SoS architecture frameworks exist. The US Department of Defense Architecture Framework (DoDAF) and the UK Ministry of Defense Architecture Framework (MoDAF) are widely used, especially in the defense and aerospace domains. However, DoDAF and MoDAF have also been extended and used in other domains (modeling the French emergency system in (Petitdemange et al., 2018) and modeling production industries in (Mahmood and Montagna, 2012)). In order to model SoS, a Unified Modeling Language (UML) profile has been developed for DoDAF and MoDAF (UPDM) (Hause, 2010). The UPMD is comprised of different views (Hause, 2010; Petitdemange et al., 2018):

- All-Views (AV) gathering global information and elements for the architecture,
- Acquisition/Project Views (AcV/PV) describing project details and their dependencies,
- Service-orientated Views (SOV) where a service is "a unit of work through which a particular Resource provides a useful result to a consuming Resource" (Hause, 2010),
- Strategic/Capability Views (StV/CV) describing the enterprise capabilities and their relationships,
- System/Services Views (SV/SvcV) specifying the constituent systems, and

- Technical/Standards Views (TV/StdV) containing “rules and standards underpinning the implementation of the system.”

However, system architecture frameworks tend to be adapted for a specific industrial domain. Additional development of the DoDAF framework was also proposed in particular addressing production industries, SoS Architecture Framework (SoSAF) by Mahmood and Montagna, (2012) . The proposed framework comprises of a Manufacturing Viewpoint (MV), Quality Viewpoint (QV), a Technical Maintenance Viewpoint (TV), and a Production Planning & Scheduling Viewpoint (PV). Each viewpoint is described through three different perspectives: operational, system and service, and technology perspectives. Chaabane et al., (2019) propose to adapt the framework proposed by ISO 42010 for the software industry. For this purpose, the authors replace the concept of “system of interest” by the concept of “constituent system” and adding the concept of “system of system” on which component systems (CSs) participate. The I4.0 SoS architecture (Axelsson et al., 2019) was proposed also based upon ISO42010 standard, in addition to the Reference Architecture Model for Industry 4.0 (RAMI4.0). The I4.0 architecture framework is comprised of a hierarchical view (describing the relations between the CS and the SoS), the asset integration view (representing the integration of different CSs), the communication view (showing the information transfers between CS), the information view (addressing the stability, flexibility, and functionality of the SoS), and the composition view (specifying the internal structure of a CS).

As for the **ontology modelling**, to our knowledge a few addresses the SoS development. Zhang et al., (2012) rely on an ontology modeling approach to propose a service-oriented method for analyzing of SoS dynamic requirements. The authors present a three-layer framework based on multi-ontologies: a meta-ontology, a domain ontology, and an application ontology. The meta-ontology comprises of the essential SoS concepts, relations, and rules, and includes the concept of capability, desired effect, service, service interface, service description, activity, performer, person, organization, skill, system, location, rule, condition, information, and material.

In summary, most SoS architecture modeling approaches represent SoSs by their components systems, regardless of the industrial domain. The common goal of the components systems or the overall SoS functionality is usually described. SoS architecture models detail how components systems function together towards a common goal by representing the relations between component systems in design (design dependencies) and during SoS operation (interactions). Some SoS architecture models also include a representation of the rules guiding the relations between component systems. As SoSs also involve independent enterprises, the enterprises, their roles in the SoS as well as their relationships are often represented in SoS architecture models. Table 6-2 summarizes SoS main concepts.

Table 6-2: SoS concepts, definitions, and related perspectives

SoS main concepts	***Definition and Related perspectives***	***References***
SoS	- Overall perspective: gathering global information and elements for the architecture	Petitdemange et al. 2018 (Petitdemange et al., 2018), Hause 2010 (Hause, 2010)
	- Project perspective: a SoS can be seen as a project especially in the defense and aerospace domain	Petitdemange et al. 2018 (Hause, 2010)
	- Functionality and quality perspective: describing the overall functionality of the SoS and its quality attributes such as flexibility, stability, etc.	Axelsson et al 2019 (Axelsson et al., 2019), Mahmood et al. 2012 (Mahmood and Montagna, 2012)
Component System	- Defined as a large Scale and independent systems constituting the SoS	Maier 1996 (Maier, 1996), Chabaane et al. 2019 (Chaabane et al., 2019)
	- Architecture perspective: specifying each component system	Petitdemange et al. 2018 (Petitdemange et al., 2018), Hause 2010 (Hause, 2010), Axelsson et al 2019 (Axelsson et al., 2019)
	- Relationships perspective : describing the relationships between constituent systems (e.g., hierarchy)	Axelsson et al 2019 (Axelsson et al., 2019)
	- Integration perspective: including the integration of component systems	Axelsson et al 2019 (Axelsson et al., 2019), Zhang et al. 2012 (Zhang et al., 2012)
	- Communication perspective : describing the information transfers among component systems	Axelsson et al 2019 (Axelsson et al., 2019), Zhang et al. 2012 (Zhang et al., 2012)

SoS main concepts	***Definition and Related perspectives***	***References***
Enterprise	- Defined as enterprises and organizations developing, managing or operation a constituent system	Maier 1996 (Maier, 1996), Zhang et al. (Zhang et al., 2012)
	- Capability perspective: describing the capabilities of each enterprise	Petitdemange et al. 2018 (Petitdemange et al., 2018), Hause 2010 (Hause, 2010) , Zhang et al. 2012 (Zhang et al., 2012)
	- Dependencies perspective: describing the relationships between enterprises	Petitdemange et al. 2018 (Petitdemange et al., 2018), Hause 2010 (Hause, 2010)
Rules and Standards	- “Rules and standards underpinning the implementation of the system.”	Petitdemange et al. 2018 (Petitdemange et al., 2018), Hause 2010 (Hause, 2010), Zhang et al. 2012 (Zhang et al., 2012)

With regard to previously defined PSS and SoS research domains, one can see that:

- PSS detailed descriptions focus on the functional and structural modeling of products and services and their interactions. As the service is considered to be what delivers value to the client (Hara, Arai and Shimomura, 2009b; Song and Sakao, 2016), the authors also consider the value proposition and the interactions between the customer and the PSS provider.
- PSS high-level descriptions represent not only products and services, but also the infrastructure and the stakeholder network. Moreover, high-level PSS descriptions provide a representation of PSS, product, and service lifecycle, and a view on the PSS business process and model, and the PSS performance indicators.
- SoS modeling approaches focus in general on the complexity of the relationships and the interactions between organizations, projects, and component systems during the SoS design and operation.

Hence, the PSS modeling approaches in the current research do not consider the complexity of the relationships between independent systems. On the other hand, the SoS modeling approaches tend not to focus on the nature of each component system (product, service, or infrastructure) and the value proposition and business perspectives. Hence, as the PSSoS design and development need all these, we propose an ontology specifically for PSSoS that aims at supporting their design and operation.

6.3 The ontology construction method

Different methodologies have been proposed for developing conceptual models (ontologies and meta-models) in the domain of engineering and design. Annamalai et al., (2011) review and summarize these methodologies (Eris et al., 1999; Grüninger et al., 1995; Noy and McGuinness, 2001; Pinto and Martins, 2004; Uschold and King, 1995). According to the review, most methodologies start by defining the purpose and scope of the ontology (Eris et al., 1999; Grüninger et al., 1995; Noy and McGuinness, 2001; Pinto and Martins, 2004; Uschold and King, 1995). Moreover, most methodologies also pursue by studying existing conceptual models (through extensive literature reviews) and implementing and testing the existing models on particular applications in order to refine and enrich them (Ahmed et al., 2007). Finally, the final stages of ontology building are the evaluation, validation, and maintenance of the ontology (Eris et al., 1999; Uschold and King, 1995). Uschold and King, (1995) and Eris et al., (1999) underline the importance of the definition of the quality criteria for the ontology. The importance of empirical analysis and domain knowledge acquisition has also been highlighted (Ahmed et al., 2007; Annamalai et al., 2011). Grüninger et al., (1995) insist on the iterative process of building ontologies.

With regard to these ontology definition methodologies, we propose the following research approach for PSSoS ontology development and validation (Figure 6.1).

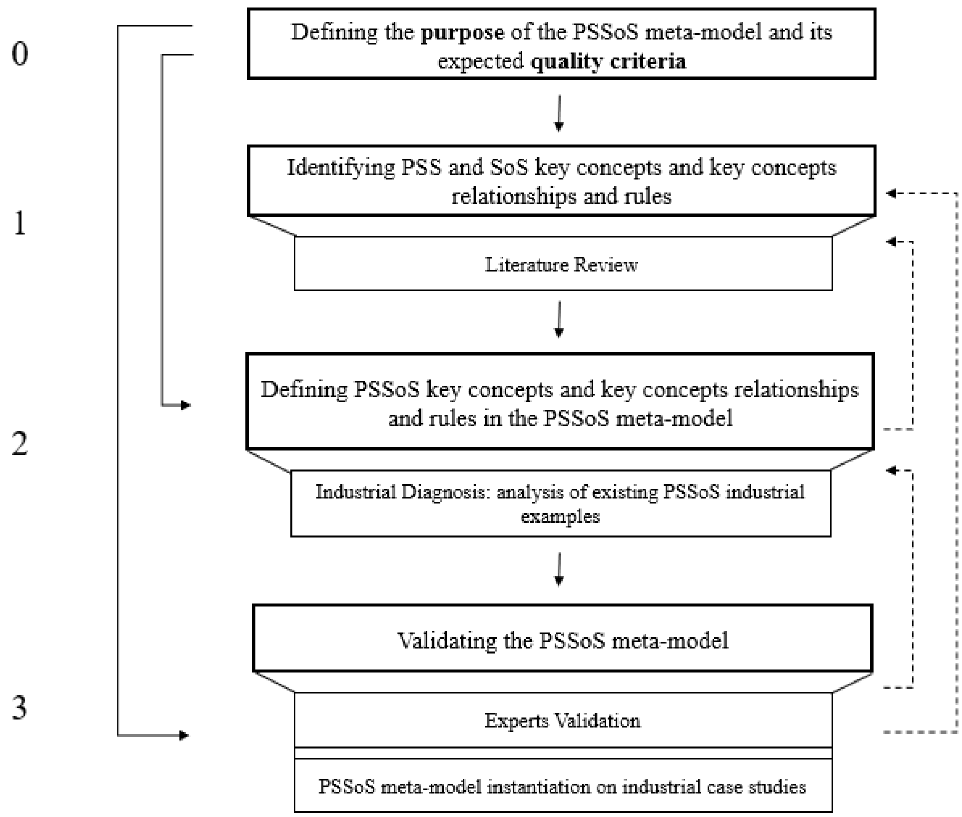

Figure 6.1: The Ontology construction steps

6.3.1 Defining the purpose of the ontology and its quality criteria

We aim to develop a PSSoS ontology able to represent key concepts and integrate all necessary information concerning PSSoS characteristics (Fakhfakh et al., 2019; Hein, Poulain, et al., 2018). The overall objective is to support PSSoS design and operation, in particular in the automotive industry. The automotive industry collaborates with other industries or service providers to offer different PSSoSs such as connected mobility services, V2G services, or future autonomous vehicle services, and hence diversifies its sources of value and remains competitive. Thus, the PSSoS ontology must be capable of representing these examples of PSSoSs as well as different types of PSSoSs (Fakhfakh et al., 2019) to be useful for the industry. Moreover, SoSs are systems that underline a considerable challenge of evolvability management, needing as well to define and represent these aspects of these systems. We also underline the need for clear definitions, comprehensiveness, and easiness for implementation as additional criteria that have been considered for ontology development. Hence, in this work we propose the following criteria for PSSoS ontology:

- The PSSoS ontology must be **complete**
- The PSSoS ontology must be **consistent** with the concepts used in industry
- The PSSoS ontology must be **simple**, **understandable,** and **easy to implement** in industry
- The PSSoS ontology must be **able to represent industrial PSSoS examples**
- The PSSoS ontology must be **extendable**

6.3.2 Identifying PSS and SoS key concepts and key concepts relationships

The objective of this step is to identify PSS and SoS key concepts and to define their relationships. For this purpose, an extensive literature review on PSS and SoS has been conducted to identify, analyze, and compare relevant PSS and SoS modeling approaches (literature review section 6.2).

6.3.3 Defining PSSoS key concepts, relationships, and rules

The objective of this step is to elicit PSSoS key concepts and their relationships. Industrial examples have been analyzed and discussed on top of the PSS and SoS key concepts identified in step (1).Considering industrial examples have been recommended in ontology development methodologies (Ahmed et al., 2007; Annamalai et al., 2011; Correia et al., 2017; Medini and Boucher, 2019). They are all the more important for the present research work, as very few research exists on PSSoSs and focuses on their characterization (Fakhfakh et al., 2019; Hein, Poulain, et al., 2018). Hence, taking into account PSS and SoS key concepts, PSSoSs characteristics, and PSSoSs industrial examples ensures that the defined PSSoSs key concepts are relevant in the context of the automotive industry. More specifically, in the context of this chapter, V2G related services, connected mobility services, and future autonomous vehicles related services were analyzed. We retrieved case studies data through documents and interviews with expert engineers and managers.

6.3.4 Validating the PSSoS ontology

As required by most ontology development methodologies (Annamalai et al., 2011), we validated the proposed PSSoS ontology through expert validation and a real case deployment.

The first phase is a validation of the ontology by modeling experts and domain experts. Table 6-3 details the number of interviewees, their roles, and the industrial sectors in which they are involved. Semi-structured interview(s) (1h-2h) have been conducted. The interviews were organized in two stages: (1) a presentation of the PSSoS ontology and (2) a discussion of the quality of the PSSoS ontology according to the criteria defined in paragraph 6.3.2; i.e., the ontology must be complete, consistent, simple, understandable, easy to implement, capable of representing industrial PSSoS examples, extendable and easy to integrate into a PSSoS or a constituent system design methodology.

Table 6-3: Interviewed experts

Role	Systems Engineering Expert	4
	Model based systems engineering expert	2
	Systems Architect	1
	Project manager	1
	Business manager	1
Industrial Sector	Automotive industry	7
	Other industrial sectors	2

The second phase of the validation is the deployment of the PSSoS ontology on a concrete industrial project. Several industrial PSSoS cases have been identified such as V2G services, connected vehicle services (e.g., onboard navigation, route planner), and car-sharing services. Workshops with project team members have been used to deploy the ontology on the example of Plug&Charge which will serve as an instantiation example in this chapter.

6.4 A PSSoS ontology

In industry, most of the tools for systems modeling are based upon UML or SysML. Hence, in order to be consistent with existing models, we have developed a Unified Modeling Language (UML) profile to represent PSSoS key concepts and their relationships. As discussed in the literature review, the PSS literature showed the importance of the service and the value provided to the customer. The SoS literature review highlighted the complexity of the relationships between organizations and between component systems in design and operation. The proposed PSSoS ontology aims to capture these dimensions and consists of four views: (1) service view, (2) operational view, (3) stakeholder view, and (4) system view. Figure 6.2 shows the PSSoS ontology views and related key concepts.

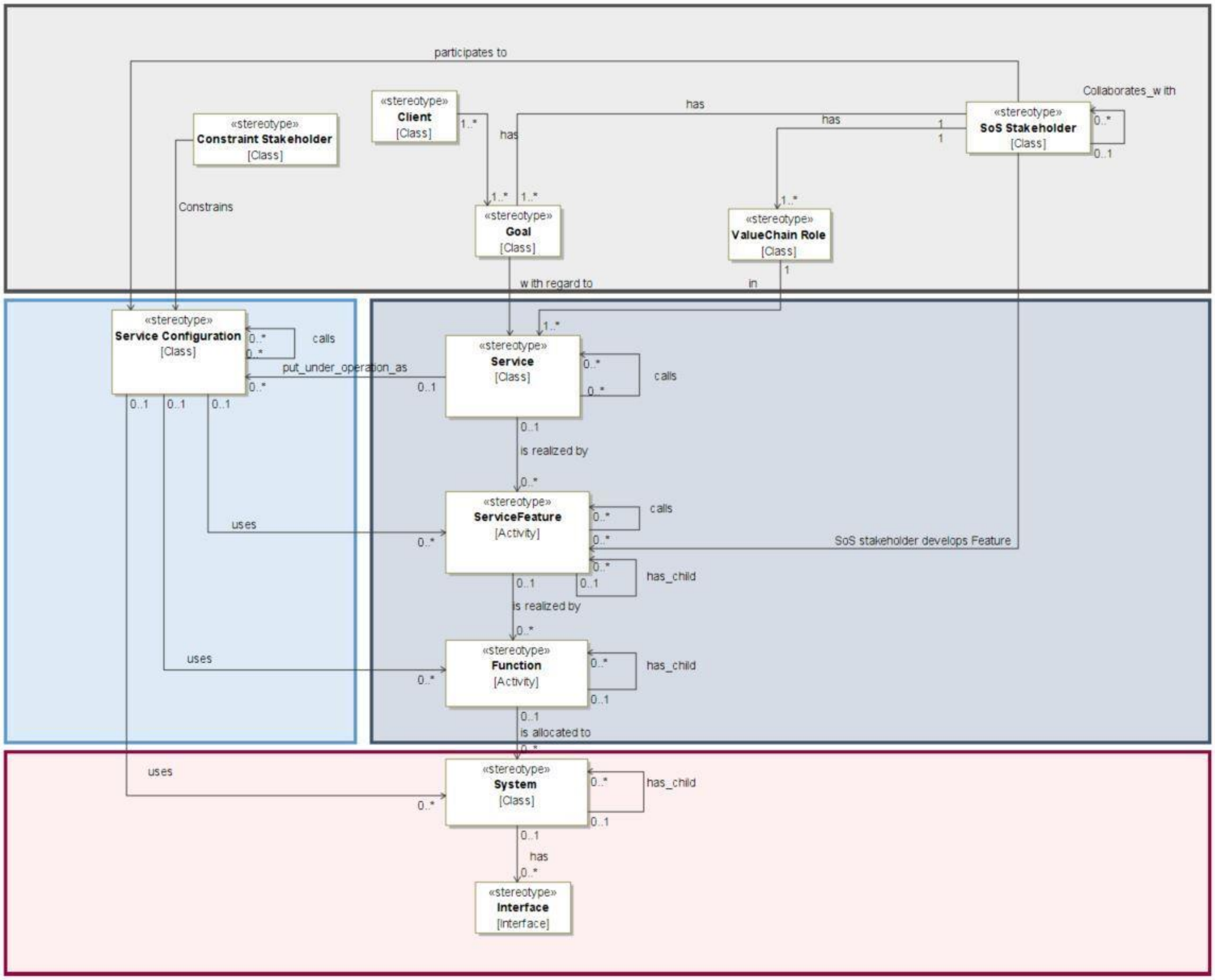

Figure 6.2: The PSSoS ontology

6.4.1 Service view

The service view is intended to allow the representation of the value proposed to the client and how it is achieved. Thus, we aim to represent the information related to the customer journey and to identify activities that permit the achievement of the service. For this purpose, the service view is comprised of the concepts: **"service"**, **"service feature"**, and **"service function"**.

The service is a constituent element of a PSS and one of its key concepts. However, different definitions have been given to the notion of service (Fakhfakh, Hein, Kokkolaras, et al., 2020). In the context of the PSSoS ontology, a **"service"** is defined as what is sold to the customer and what provides him value and achieves his/ her goals (Yang et al., 2010). For example, car-sharing, EV battery leasing, or onboard navigation are services that are sold to the customer and that provide him/ her value. We define a many to many relationship *"calls"* between services. For instance, car-sharing services might rely on or use (*"calls"*) onboard navigation services. Hence, the services are represented as a network.

Furthermore, a service is realized by a set of **"service features".** "Service features" are in general defined as types of performance required for the receiver's goal to be accomplished satisfactory (Hussain et al., 2012). Here we define "Service features" as the capabilities needed to provide the "service" and perceived by the customer and are represented as activities in UML. As such, "service features" allow to represent customer journeys (see section 6.5). Moreover, the PSSoS ontology includes two types of relationships between "service features". A "service feature" might be decomposed in sub-features (*"has_child"*) and might also rely on or use another "service feature" (*"calls"*). Hence, the PSSoS ontology allows for representing service features as a tree (using the relationship *"has_child"*) or as a network (using the relationship *"calls"*).

A "service feature" is realized by **"functions"**. "Functions" (an instance of the UML meta-class "activity"**)** is considered in its general definition as activity transforming input flows into output flows. Thus, "functions" enable to represent functional flows (not necessarily perceived by the customer). The relationship (*"has_child"*) between "functions" allows for building functional trees.

6.4.2 Stakeholder view

In the context of PSSoS (Hein, Poulain, et al., 2018), actors (or organizations (Chaabane et al., 2019; Medini and Boucher, 2019)) collaborate to develop, manage and operate CSs. The purpose of the stakeholder view is to capture and characterize the relationships between these actors, their participation in the development and operation of PSSoSs, and their expectations with regards to the PSSoS development.

In the context of the PSSoS ontology, **"stakeholders"** are defined as those who have a direct stake in the PSSoS project (Feng, 2013). In this view, four types of "stakeholders" are identified: **"clients"** (or customers), **"SoS stakeholders"**, and **"constraint stakeholders"**, and "**internal stakeholders**". The

“clients” or customers are those who benefit from the final service (Costa and Diegues, 2019). **“SoS stakeholders”** are independent actors or enterprises, who collaborate, develop, and operate together the SoS and the constituent systems. **“Constraint stakeholders”** include, among others, law, and policy actors (Hause, 2010; Petitdemange et al., 2018). Finally, **“internal stakeholders”** are actors internal to an enterprise or an “SoS stakeholder” (e.g., suppliers and engineers) (Correia et al., 2017).

In order to represent the collaboration networks of “SoS stakeholders” (independent organizations), we define the *"collaboration"* relationship between “SoS stakeholders”. As for representing the participation of “SoS stakeholders” in the development of a PSSoS, the concept of **“Value Chain Role”** and the relationship *“SoS_stakeholder_develops_feature”* is proposed. The “value chain role” expresses the position in the value chain the “SoS stakeholder” or organization has in the delivery of a service (Weiller and Neely, 2013). For example, OEM and service provider are value chain roles. The relationship “SoS_stakeholder_develops_feature” links SoS stakeholder to the “service feature” (or capability) he/ she develops.

Finally, both “clients” and “SoS stakeholders” have expectations or goals with regards to the service. Thus, the concept of **“Goals”** are defined in terms of quality goals (attributes) and strategic goals (specifically for the SoS stakeholders) (Schenkl et al., 2014).

6.4.3 System view

The objective of the system view is to describe the PSSoS component systems, their relationships, and interactions yielding the emerging behavior of the SoS (Maier, 1996). In a general sense, these concepts are considered as standard in the SoS domain. Hence, this view is constituted of **“Systems”** and **“Interfaces”**.

Since PSS include heterogeneous systems, we propose to include in the definition of a **“system”**: 1) the products (hardware and software), 2) the infrastructure, and 3) the humans and agents (Fakhfakh et al., 2019; Hein, Poulain, et al., 2018). **“Interfaces”** define the functional and structural interfaces between heterogeneous “systems”.

“Functions” are allocated to these component systems (products, infrastructures, and agents). The relationship *“allocated to”* permit to allocate the “functions” defined in the service view to “systems”. Specifically, for products and infrastructures, the ontology allows for a lower modeling granularity through the definition of sub-systems and components. The relationship *"has_child"* allows defining sub-systems and components of a constituent system.

6.4.4 Operational View

SoSs tend to evolve throughout their lifecycle (Luo, 2017; Maier, 1996). PSSoS evolve, for example, according to the involved stakeholders, or the involved component systems. Moreover, a service can be deployed in different operational contexts (e.g. different countries with different laws and policies). Hence, depending on the operational context, a service can rely on the participation of different stakeholders and different component systems. It also requires a set of service features and functions. In this respect, the objective of the operational view is to capture PSSoS evolutions and their operational diversity.

We propose to model the evolution of PSSoS through modeling **"service configurations"** similarly to (Petitdemange et al., 2018).The relationship *"put_under_operation_as"* links a service to service configurations and permits to represent diverse ways in which the "service" is put under operation. A "service configuration" can *"call"* another one, hence trying to integrate the composability of "services" and "service configurations". As such, "service configurations" are also represented as a network.

The relationship "participates to" is defined in order to represent the SoS stakeholders involved in a given "service configuration". It links SoS stakeholders to a service configuration. The relationship "*uses*" defines sets of "service features", "functions", and "systems" involved in the realization of a "service configuration". Therefore, in the service view, available "service features", "functions", and "systems" for the realization of a "service" are defined, while from in operational view, the "service features", "functions", and "systems" used explicitly in a given operational context can be further characterized.

6.5 Case study: Plug and Charge

In order to illustrate and validate the proposed PSSoS ontology, an industrial project has been used. The Plug&Charge service is part of EVs charging services and V2G related services. The service allows the customer to automatically start charging his/her vehicle (i.e., without manual authentication) (Clarity and Hubject, 2019). The service implies that plugging the EV to the charging station allows the identification of the EV and that unplugging the EV stops the charging and generates the payment.

6.5.1 Service view

In order to represent necessary services, the project has identified the main service features required for the realization of the service such as identification, plugging/ unplugging, charging, and payment (Figure 6.3). The relationship between these features is further refined through "call" relationship. For instance, the service feature "payment" "*calls"* "access_to_customer_data".

Additionally, for example, the service feature "identification" is realized by the functions "manage certificate", "communicate with the customer", "communicate with electric infrastructure", and "supervise Plug&Charge session" (Figure 6.3). Furthermore (see Figure 6.4) an activity diagram can be used to represent customer journey through different service features (In order to charge an EV, a customer needs to plug his/her vehicle to the charging station. The identification of the customer is done concomitantly. Once the EV is charged, the unplugging generates the payment)

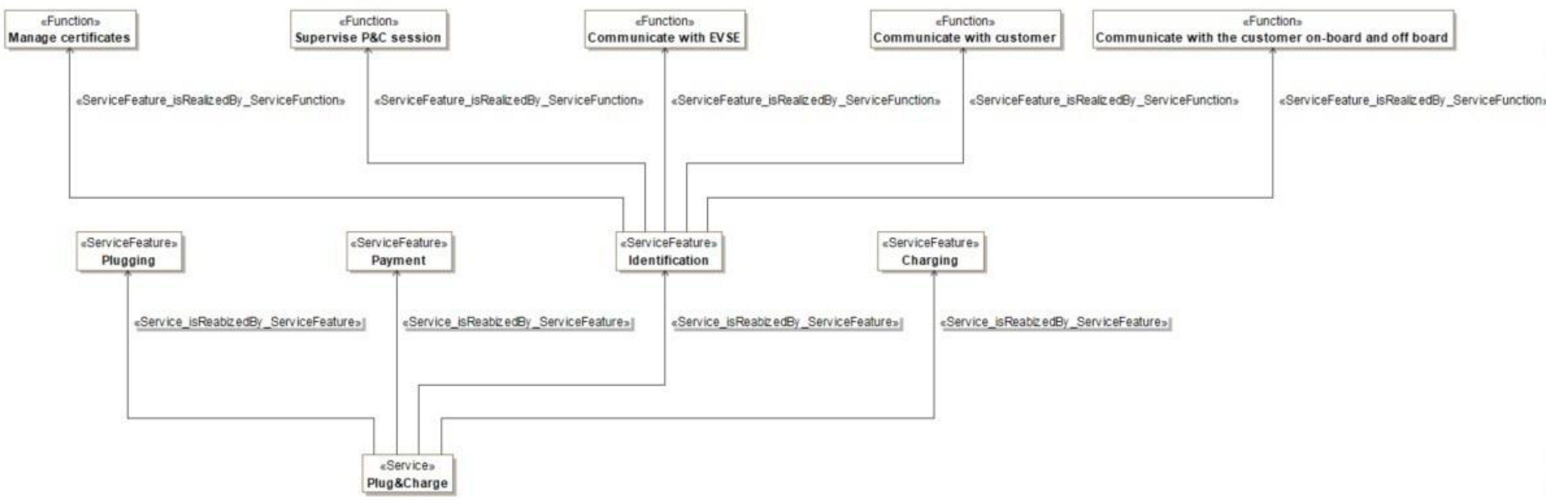

Figure 6.3: Plug and Charge Service Features and Functions

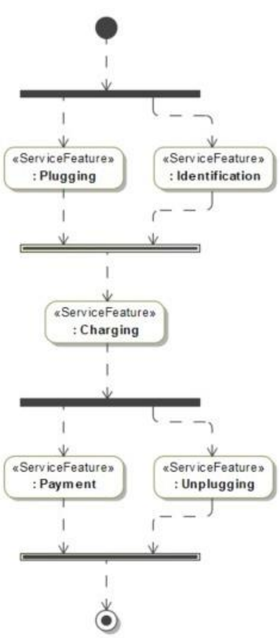

Figure 6.4: A simplified representation of Plug and Charge customer journey (using service features)

6.5.2 Stakeholders view

Plug and Charge requires, among others, the collaboration of an OEM, a mobility operator, a charging station owner, and a charging station operator. Different enterprises or SoS stakeholders can have these value chain roles. In this example a car manufacturer is “OEM1”. The “OEM1” can also play the role of a mobility operator in this service. Another configuration is that the “OEM1” can collaborate with the SoS stakeholders “Mobility operator 1” and “Mobility operator 2”. Some other SoS stakeholders are “Charging station owner and operator 1” and “Charging station owner and operator 2” as charging station owners and operators. Figure 6.5 gives an excerpt of the value chain roles in the Plug&Charge service and the potential SoS stakeholders participating in Plug&Charge service configurations.

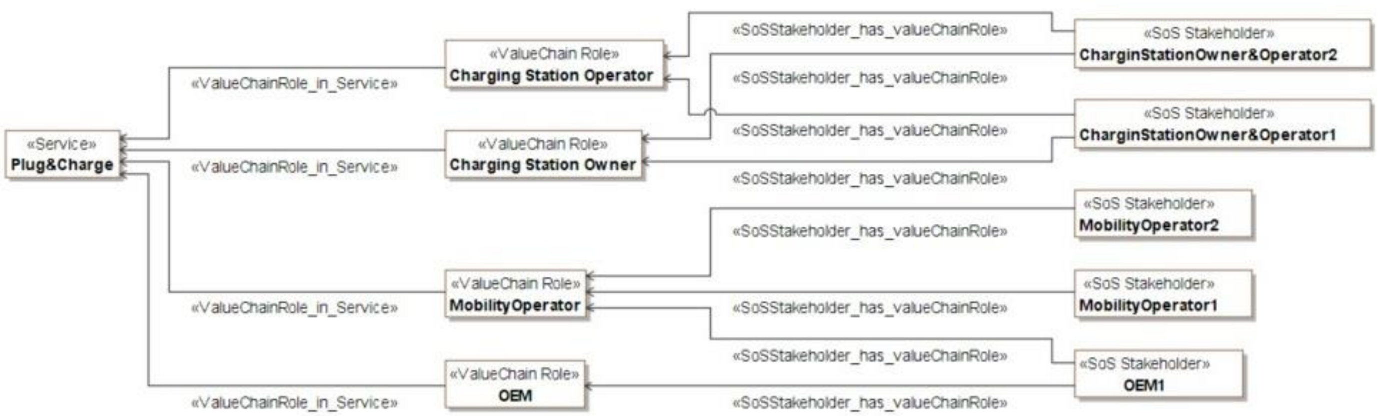

Figure 6.5: Plug&Charge _ Stakeholder view _ Value chain roles and SoS stakeholders

In this view it is possible to integrate also the different standardization bodies that should be considered in the PSSoS design and operations. In this case, the ISO 15118 enables the integration of the EV into smart grids. It sets, among other things, the specifications of the communication between EVs and the charging equipment. Hence, the ISO15118 can be defined as a constraint stakeholder.

In this view it is possible to defined different goals for each SoS stakeholder. They are not represented here but it is possible to integrate that clients might expect a full charge within X minutes or an SoS stakeholder might expect the service to generate additional revenues.

6.5.3 Operational view

In the context of the Plug&Charge service, the project team members have defined different service configurations through different participating SoS stakeholders definition. For example, “OEM1” and

"Charging station owner and operator 1" collaborate and participate in the realization of "service configuration 1". In this case, "OEM1" is an OEM and a mobility operator. In another context (e.g., another country), "OEM1" collaborates with "Charging station owner and operator 2" and "Mobility operator 1" to provide "service configuration 2". Hence, "OEM1" does not play the role of mobility operator in "service configuration 2".

ISO15118 constrains both "service configuration 1" and "service configuration 2". However, service configurations can be further refined on different levels (such as functions, components, etc.) even though for this early PSSoS design project team members considered the definition of service configuration through stakeholder differentiation sufficient.

Figure 6.6 shows the SoS stakeholder collaborations in the realization of the Plug&Charge service.

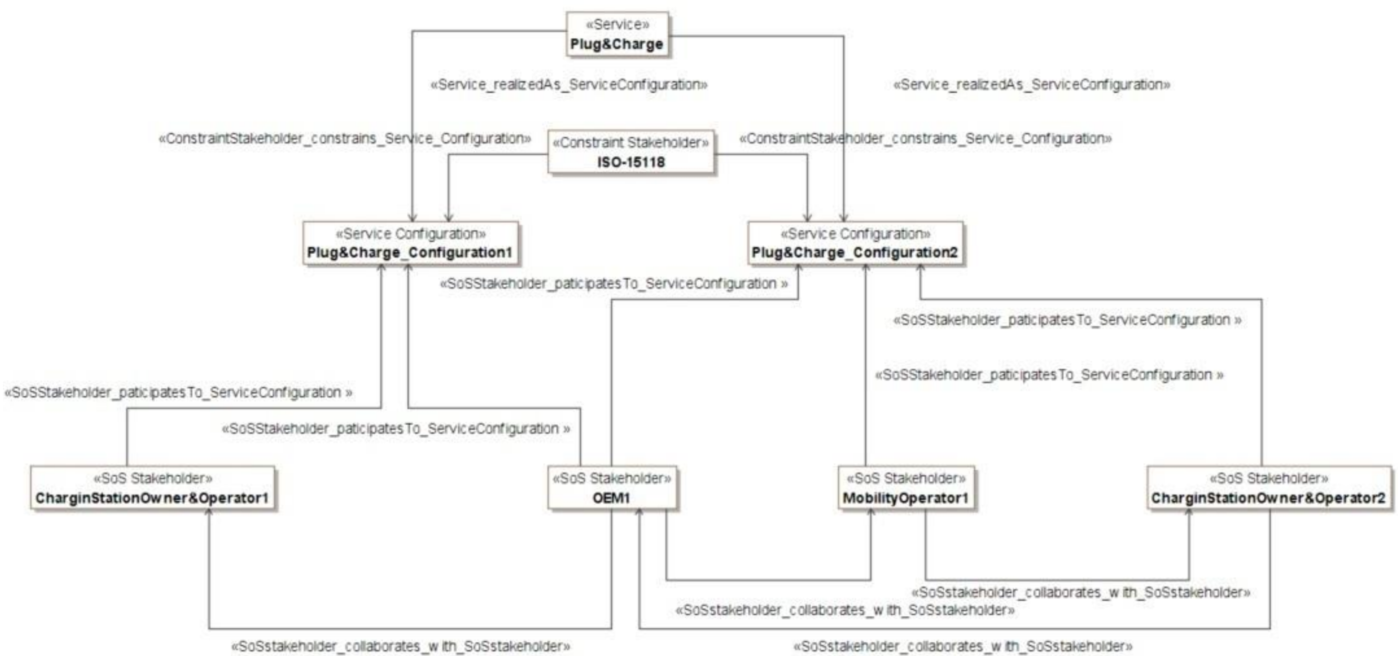

Figure 6.6: Plug&Charge Operational view _ representation of SoS stakeholder collaborations

6.5.4 System view

The systems view can be seen as a standard representation of a system. In this case, different systems are involved in the realization of the Plug& Charge service e.g., EVs, charging stations, off board servers, and off board interfaces. These systems realize service functions. For example, the function "communicate with customers" can be allocated to an offboard interface. "Communicate with the electric infrastructure" can be allocated to the EV and its subsystems.

6.6 Discussion

This chapter presents a PSSoS ontology comprised of four views: (1) service view, (2) stakeholder view, (3) operational view, and (4) systems view. This ontology has been presented to different domain experts, instantiated, and deployed on several case studies to validate the usefulness for the automotive industry and the ability to represent industrial project development data.

A total of nine experts have been interviewed to validate the proposed ontology. Most experts worked in the automotive industry, and a few had former experience in other domains. Among these experts, five were experts in systems engineering or model-based systems engineering. The four other interviewees were involved in the development of EV ad connected mobility services either as business managers, project managers, or systems architect. The interviews were 1h to 2h duration, semi-structured, and comprised of a presentation of the PSSoS ontology followed by a discussion related to the ontology quality with regard to the criteria defined in paragraph 6.3.1. Moreover, the ontology was presented and discussed in 5 group meetings with total of 20 engineers having different roles in system engineering.

As for the case studies, five have been considered (e.g., V2G services, onboard navigation, route planner and car-sharing services) and studied through available service description and design document, in addition to the participation to workshops.

The foremost benefit of the PSSoS ontology, as highlighted by domain experts, is its ability to give a holistic perspective on the PSSoS, including PSS and SoS characteristics, while remaining simple and consistent with lower granularity models in industry (e.g., vehicle models). Using the PSSoS ontology allowed both system designers and service designers to draw and share a bigger picture of the global PSSoS developments. In this respect, using the PSSoS ontology contributed to fostering the collaboration and knowledge sharing among engineering and non-engineering disciplines. However, several deployment challenges still need to be addressed. For instance, the ontology usage requires an understanding of Model-Based Systems Engineering (MBSE) and therefore is less accessible to non-engineering disciplines. Hence, the additional training is needed. In this sense, the development of an easy-to-use collaboration platform is considered to be an important objective. An additional effort should also be made to ensure the complete consistency between this model and existing system related models (system design and configuration design) as well as their continuity. Furthermore, the PSSoS ontology needs to be extended, including process and lifecycle perspectives, to capture the dynamic nature and evolvability of PSSoS. Finally, the present research work has been conducted within the automotive industry and considers examples of mobility PSSoS, such as V2G related services, connected mobility services, and future autonomous vehicles related services. These PSSoSs are mostly use-oriented or result-oriented PSS; and acknowledged or collaborative SoS. Therefore, to test its genericity, we need to implement the proposed PSSoS ontology in other domains and industries.

6.7 Conclusion

The mobility of the future includes not only new technologies such as the autonomous vehicles but also several related services, e.g., autonomous vehicles related services and EV2G services. These new systems represent a great challenge because they involve both a servitization and collaborations with other industries and organizations. These systems entitled PSSoSs are defined as “sets of products, services, infrastructures, and networks where its constituent elements exhibit operational and managerial independence” (Hein, Poulain, et al., 2018). However, the current literature considers PSS and SoS separately. In order to address this gap, a PSSoS ontology was proposed aiming at representing PSSoS necessary information and integrating key PSSoS characteristics. The proposed PSSoS ontology is constituted of four views: (1) service view, (2) stakeholder view, (3) operational view, and (4) system view. For each view, the included concepts and detailed their relationships and rules are defined and illustrated. The ontology was validated by nine experts and tested on five case studies in the automotive industry. The validation process allowed us to assess the quality criteria of the ontology, namely its ability to be understandable, its completeness, its consistency, its simplicity, its extendibility, its easiness to be implemented in industry, and its ability to represent industrial examples. In this chapter, the example of the Plug and Charge service was used to illustrate the instantiation and potential use of the PSSoS ontology.

However, since this research work focuses on the automotive industry, there is a need to consider expert feedback and case studies from other domains to discuss its genericity. Furthermore, the dynamic evolution and the emergent behavior are essential characteristics of SoSs; hence the PSSoSs. Modeling service configurations supports the possible evolution of the PSSoSs. However, this current modelling may be insufficient for modeling and simulating its dynamic evolution and emergent behavior. For this purpose, future work will focus on the potential use of formal ADLs (e.g., graphs) to represent key concepts of PSSoSs and their relationships

7 A PSSoS Stakeholder analysis approach

Sarra Fakhfakh, Marija Jankovic, Andreas Makoto Hein, Yann Chazal

This paper is a working paper to be submitted to IEEE Transactions on Engineering Management

Abstract: *Developing new mobility services such as electric vehicles and autonomous vehicles services requires not only the interaction and interoperation of independent systems such as electric vehicles, electric infrastructure, or off-board servers, but also the collaboration of independent business partners, namely car manufacturers, energy providers, and service providers, developing, managing and operating these systems. Such services show both Product Service Systems and Systems of Systems characteristics and, as such, can be defined as Product-Service Systems of Systems. While extensive literature exists on developing and managing PSS product and service elements and SoS constituent systems, little research explicitly focuses on PSSoS stakeholders. In particular, the analysis of PSSoS stakeholder business partnerships and involvement in PSSoS development. PSSoS development is seen as the development, operation, and management of constituent systems. This paper contributes to addressing this gap and proposes an approach to qualify and quantify stakeholder participation in the PSSoS business partnership and PSSoS development. The proposed approach focuses on PSSoS business partners that develop, manage, or operate a constituent system and enables the representation of stakeholder collaboration through a network reflecting their business partnerships and importance and a network reflecting their development dependencies and importance. Moreover, the proposed approach relies on a network topology metric to characterize PSSoS stakeholder influence in PSSoS business partnerships and PSSoS development. An electric vehicle charging service is used to illustrate this approach's use and shows its industrial implications.*

7.1 Introduction

Electric and autonomous vehicle related services are gaining importance in the development of new mobility. Such services require not only the interoperation of independent systems (e.g., electric vehicles (EV) and electric infrastructure), but also the collaboration of independent business partners such as car manufacturers, energy providers, or service providers developing, managing, or operating these systems. These services are considered to be Product Service Systems of Systems (PSSoSs) defined as “sets of products, services, infrastructures, and networks where its constituent elements exhibit operational and managerial independence” (Hein, Poulain, et al., 2018). PSSoSs are both Product Service Systems (PSS) (Mont, 2002) and Systems of Systems (SoS) (Maier, 1996). Given that PSSs and SoSs have rarely been studied concomitantly in the literature, we rely on the PSS literature and SoS literature to address PSSoS questions.

An extensive literature exists on PSS design and development focusing on product and service elements (Vasantha et al., 2012), and PSS business modeling and value proposition (Reim et al., 2015). A large body of knowledge also explores SoS architecture (Ingram et al., 2014; Mohsin, Janjua, Islam and Valdemar Vicente Graciano, 2019) and SoS management (Sauser and Boardman, 2008). More recently, the PSS literature and the SoS literature have become more and more interested in identifying and characterizing the stakeholders taking part in PSS or SoS development. As for the PSS literature, Kimita et al., (2015) and Costa & Diegues, (2019) identify the stakeholders involved in PSS development, mainly providers and customers. Another stream (Liu et al., 2018; Pezzotta et al., 2018; Yin et al., 2020) is taking the business perspective. Its focus is on business development and the notion of value co-creation amongst different PSS stakeholders. Additional studies (Mougaard et al., 2012; Orellano et al., 2019; Yoonyee and Sang, 2017) propose collaborative value network models describing the business partnerships and the relationships between PSS stakeholders in PSS development and operation.

Regarding the SoS literature, most SoS frameworks (Axelsson et al., 2019; Hause, 2010) include a representation of SoS stakeholders defined as independent enterprises and organizations managing and operating SoS component systems (Maier, 1996). The SoS literature describes strategic relationships (Hause, 2010) between SoS stakeholders and their relationships in the development and operation of the SoS constituent systems (Fang et al., 2018; Uday and Marais, 2015).

Hence, the PSS literature and the SoS literature identify PSS and SoS stakeholders, characterize their relationships from a business partnership perspective, or describe their relationships in the development and operation of the PSS or SoS through product, service, or component system interaction and interoperation.

However, to our knowledge, no research goes beyond qualitative analysis and measures the importance and influence of PSS or SoS stakeholders. On the other hand, quantitative methods to characterize stakeholders more generally have been proposed by specialists in project management and organization (Mitchell et al., 1997). However, these methods, since adopted by many other fields (Mok et al., 2014; Oppong et al., 2017; Reed et al., 2009), have not been developed for PSS, SoS, or PSSoS stakeholders.

This chapter aims to address this gap in the context of PSSoSs and specifically focuses on independent enterprises that collaborate, develop, and operate the PSSoS constituent systems. This research proposes a novel approach to qualify and quantify the importance and influence of PSSoS stakeholders in the business partnership and development. This approach is comprised of three steps. The first step aims to identify and model PSSoS stakeholders (Fakhfakh, Hein, Chazal, et al., 2020) and their relationships with the system, proposing the PSSoS network. The second step aims at analyzing their importance, therefore consisting of the construction of two SoS stakeholder networks: a network reflecting the importance of SoS stakeholders in the business partnerships and a network reflecting the importance of SoS stakeholders in the PSSoS development. The third step proposes using a network topology measure to quantify the influence of PSSoS stakeholders from both perspectives, business partnerships, and PSSoS development.

We propose the following structure of the chapter. Section 7.2 reviews existing stakeholder analysis approaches and assesses their potential of use in the context of PSSoSs. In section 7.3, we describe the underlying PSSoS model. We also detail the analysis of PSSoS stakeholder importance and influence. In section 7.4, we discuss an EV charging service industrial case study and its implications. Finally, a discussion and conclusion are given in sections 7.5 and 7.6.

7.2 Literature review

This research aims to propose an approach for the quantitative analysis of PSSoS stakeholders in the context of business partnerships and development. PSSoS stakeholders are independent business partners, collaborating in the development, management, and operation of PSSoS constituent systems.

As PSSoS stakeholders are, by definition, similarly involved in the management, operation, and development of PSSoS component systems, two main literature domains are of interest: 1) management literature and 2) design engineering literature.

Furthermore, stakeholder analysis approaches generally aim to i) identifying stakeholders, ii) differentiating and categorizing them, or iii) investigating their relationships (Reed et al., 2009). Since the identification of PSS and SoS stakeholders, and their qualitative characterization have already been addressed in the literature (see the introduction), we focus in this chapter on quantitative methods categorizing and differentiating stakeholders and investigating their relationships.

In general terms, stakeholders are defined as "groups that have a stake in the activities that make up the business," including customers, suppliers, employees, financiers, communities, managers (Parnar et al., 2010). Based on this definition, stakeholder analysis has been historically the focus of management and organization research with stakeholder theory as its foundation (Mitchell et al., 1997). Since then, several stakeholder analysis methods have been proposed. Several contexts have also been specifically addressed, e.g., business management (Bourne and Walker, 2005), policy analysis (Berardo, 2014; Varvasovszky, 2000), environmental management (Reed et al., 2009), or construction projects management (Mok et al., 2014; Oppong et al., 2017). Aragonés-Beltrán et al., (2017) propose a method to analyze stakeholder influence from a product manager's perspective. The authors considered both internal stakeholders, including engineers and managers, and external stakeholders, including contractors and suppliers. They defined the influence of a stakeholder based on four clusters of criteria: knowledge, social skills, assets, and external factors such as the public image. The authors modeled the dependencies among stakeholders, the dependencies among influence criteria, and between stakeholders and influence criteria. They also relied on the Analytic Network Process Model to compute each stakeholder's influence index.

In particular, the literature focusing on construction projects, large-scale engineering projects, and software projects is interesting as these projects show similar characteristics to PSSoSs, namely the complexity, the participation of various organizations, and the potential geographic distribution (Keating and Katina, 2011; Maier, 1996). In the context of *construction project management*, other interpretations of stakeholder influence have been given. Zedan & Miller, (2018) reinterpret the influence attributes: power, proximity, and interest proposed by Bourne and Walker (2005) to the context of construction project management, and more specifically to assess the influence of stakeholders (internal and external) on the energy efficiency of housing. The power attribute includes authority, knowledge, and connectivity. Connectivity is defined based on the communication network between stakeholders during the design and construction stages. Proximity indicates the degree of involvement in decision making. As for interest, it is defined with regard to the objective that is, in this case, energy efficiency. For example, "the level of priority of energy efficiency compared to other aspects" or "the willingness to spend time, money, effort, etc. to achieve energy efficiency". Based on these attributes, the influence of stakeholders in the energy efficiency of housing is calculated as the sum of the power, proximity, and interest multiplied by the time factor indicating the overall time that a stakeholder is involved in the project. Another perspective on influence in construction projects has been proposed by R. J. Yang & Zou, (2014). Considering specifically green construction projects, the authors highlight the importance of studying stakeholders and the risks associated with them.

They focus on risks associated with stakeholders and use risk network topological measures (e.g., node (risk) eigenvector centrality). In the same fashion, Dadpour et al., (2019) underline the importance of stakeholder concerns and their impact on planning and executing construction projects. The authors propose a network of stakeholder concerns and use network metrics to characterize the power and influence of stakeholder concerns.

Considering *large-scale engineering systems*, we highlight the work around the PhD thesis of Feng (Feng, 2013) concerning stakeholder value network modelling (Feng et al., 2010; Fu et al., 2011). In this research, the authors propose a qualitative/quantitative approach to characterize stakeholder power and influence taking into consideration direct and indirect relationships between stakeholders. They propose to identify the stakeholders and consider their roles, objectives, and needs. Based on this stakeholder characterization, the "stakeholder value network" is proposed where nodes are stakeholders and edges are quantified value flows reflecting specific needs of stakeholders and their perceived utility to recipient stakeholders. Finally, the authors define the Weighted Stakeholder Occurrence (WSO) and the Weighted Value Flow Occurrence (WVFO) to measure the importance of a stakeholder. The "stakeholder value network" has also been used and adapted to specific contexts such as space exploration (Cameron et al., 2011) or industrial symbiosis (Hein et al., 2017).

In the context of *large-scale software projects*, several authors have also taken an interest in prioritizing stakeholders and investigating their relationships. Ballejos & Montagna, (2011) argue that software project management is "integrally affected by stakeholders' perspectives and their participation," especially when it involves different organizations. Therefore, they propose an approach for quantifying the interest and influence of stakeholders in the project. The interest characterizes the needs of a stakeholder with regard to the project and its objectives. The authors propose different expressions to capture this interest: either a weighted sum of the stakeholders' interests in various project objectives or the most significant interest in a specific project objective. The influence depends on the role (e.g., decision-maker, developer, or sponsor) and power of the stakeholder, including positional power, personal power, and political power. Lim et al., (2010) propose another method named "StakeNet" to identify and prioritize stakeholders based on their influence on the software project. The proposed method comprises six steps. The first three steps consist of finding stakeholders based on the identification of roles. The fourth step consists of identifying the stakeholder's stake (how the stakeholder influences the project) and the recommendation of each stakeholder, which is the identification of other roles, stakeholders, and stakes. A network of stakeholders represented by nodes that are stakeholders and edges that are recommendations is then constructed in the fifth step. Step six prioritizes stakeholders based on topological network measures. This method was further discussed in the case of systems of systems in (Lim and Ncube, 2013).

To resume, most stakeholder analysis approaches in the management research domain consider skills (Aragonés-Beltrán et al., 2017), interests, concerns (Dadpour et al., 2019), or needs (Feng et al., 2010) as important attributes characterizing stakeholders. In most cases, different network topological measures are used to quantify the importance of a stakeholder (or a node). The difficulty lies in the fact that these measures do not give concrete insights in the manner of participation of different stakeholders in the development and operation in general. Another research current addresses this question in a more precise manner, focusing in particular on system design and development.

Luo, Baldwin, Whitney, & Magee, (2012) recognize that most products are manufactured by firms collectively designing and producing the systems. These firms are linked through transactions. In this context, the authors proposed an analysis of transaction networks. More specifically, they characterize the hierarchy of the transaction network "defined as the degree to which transactions flow in one direction, from "upstream" to "downstream". In this research, the authors do not focus on the analysis of each stakeholder but on the characterization of hierarchy in transaction networks. Son & Cho, (2017) focus on collaborative R&D activities in the pharmaceutical industry. They considered pharmaceutical companies and enterprises, research institutes and universities, and hospitals and public bodies. The relationships between stakeholders represent their mutual engagement in projects. The authors relied on node network metrics to characterize the centrality of each organization in the collaboration network.

Another area of the literature considers stakeholders that are directly involved in product development. For instance, Morelli, Eppinger, & Gulati, (1995) already analyzed technical communication within a product development organization seen as a way to improve product development activities. The authors differentiated coordination, knowledge, and inspiration types of communication. Based on interviews, the authors could report the communications (or interactions) in a predicted-communication matrix. The predicted-communication matrix was then compared to an actual communication matrix build throughout the project via questionnaires. Later, Sosa, Eppinger, Pich, McKendrick, & Stout, (2000) empirically investigated the factors that influence communication, drivers, and barriers, especially for distributed product development. Batallas & Yassine, (2006), propose to use communication matrices and node network measures (degree centrality, closeness centrality, betweenness centrality, and brokerage measures) to identify information leaders and to distinguish internal coordinators, external coordinators, representatives, gatekeepers, and liaisons. Bashir, (2019) also uses network centrality measures to analyze the information flows among product development teams. Based on these measures, the author classifies product development teams in four other categories autonomous, receivers, transmitters, and transceivers. Parraguez, Steven, & Maier, (2015) rely on a dynamic cross-domain network approach to characterize the information flows in engineering design. In their approach, they consider not only the network of people communications, but also the network of activities and their information flows, along with the network people-activities, and that throughout the engineering design stages (as a temporal dynamic). In this work, cross-domain network measures (information centrality (or influence), information centralization, and information clustering) are used to characterize the importance and influence of an activity rather than a stakeholder. Similarly, Wu, Rosen, Panchal, & Schaefer, (2016) analyzed the communication and collaboration mechanisms in social product development using multi-domain networks at actor and system levels, including customer needs, functional requirements, design parameters, and process variables. One can see that the majority of this research current has been focusing on communication and information flows. However, there is also research that addresses other attributes to characterize teams in view of better organization. For example, Chen & Lin, (2014) propose a model for team member rating based on multifunctional knowledge, teamwork capability, and working relationship ratings. This rating model aims at assessing the formation of multifunctional teams in concurrent engineering.

To resume, the approaches considering stakeholder definitions related to project and engineering either

- Consider firms participating in the design, development, or manufacturing of the product (Luo et al., 2012; Son and Cho, 2017) and characterize their partnerships and engagements in the project, or
- Focus on product development teams and characterize their communication and collaboration via design activities and throughout the design process (Bashir, 2019; Batallas and Yassine, 2006; Morelli et al., 1995; Parraguez et al., 2015).

In summary, in the management domain, stakeholder analysis approaches gave various interpretations of the importance and influence of a stakeholder. Approaches in the design engineering domain addressed two aspects: stakeholder partnerships, such as transactions, and development implications, e.g., activities of the design team and their communication. However, both domains did not specifically address PSSoS stakeholders. In section 7.3, we address this gap by identifying information pertaining to PSSoS business partnerships and development and giving relevant interpretations of PSSoS stakeholder importance and influence in these contexts.

7.3 Analyzing PSSoS stakeholder importance and influence in business partnerships and development

In this section, we aim to quantify the importance and the influence of each PSSoS stakeholder in business partnerships and development in light of the literature review and the characteristics of PSSoSs (Fakhfakh et al., 2019; Fakhfakh, Hein, Chazal, et al., 2020; Hein, Poulain, et al., 2018). The literature review showed that quantitative stakeholder analysis approaches give various interpretations of the importance or influence of stakeholders depending upon the definition of a stakeholder (broad or narrow), the type of information (communication between stakeholders, needs, skills, or capabilities), and the objective (e.g., energy efficiency). Hence, we propose a high-level PSSoS ontology (Fakhfakh, Jankovic, et al., 2020) to capture relevant information describing PSSoS stakeholder business partnerships and their implication in PSSoS development. This information is afterward used as a basis for the importance and influence evaluation of PSSoS stakeholders. Since networks have been extensively used and proven effective for modeling and analyzing stakeholders, we propose a network approach to analyze PSSoS stakeholders.

In our approach, we propose to define a multidimensional network describing the collaboration of PSSoS stakeholders, and their relation to key concepts related to business partnerships and development based upon the PSSoS ontology. In order to analyse stakeholder collaborations, this multidimensional network is transformed into two unidimensional networks:

- A PSSoS stakeholder network reflecting the business partnerships and the business importance of each PSSoS stakeholder,
- A PSSoS stakeholder network reflecting dependencies and the importance in the development process for each PSSoS stakeholder.

Finally, a network node metric measures the business and development "influence" of each PSSoS stakeholder.

Hence, the proposed approach consists of 3 steps (detailed further in this chapter):

1. Building a multidimensional network based on the PSSoS ontology,
2. Constructing two PSSoS stakeholder unidimensional networks showing PSSoS stakeholder importance in business partnerships and development,
3. Using a network metric to measure the influence of PSSoS stakeholders in business partnerships and development.

7.3.1 A PSSoS multidimensional network

The PSSoS ontology (Fakhfakh, Jankovic, et al., 2020) represents PSSoS key concepts and their relationships. It consists of four views: (1) service view, (2) operational view, (3) stakeholder view, and (4) system view. The ontology gives a more extensive definition with regard to the PSSoS development. As we focus on PSSoS stakeholder analyses, we propose to detail only one part of the ontology used for network building (Figure 7.1). In the following, we will define relevant concepts and relationships, based on which we build a multidimensional network.

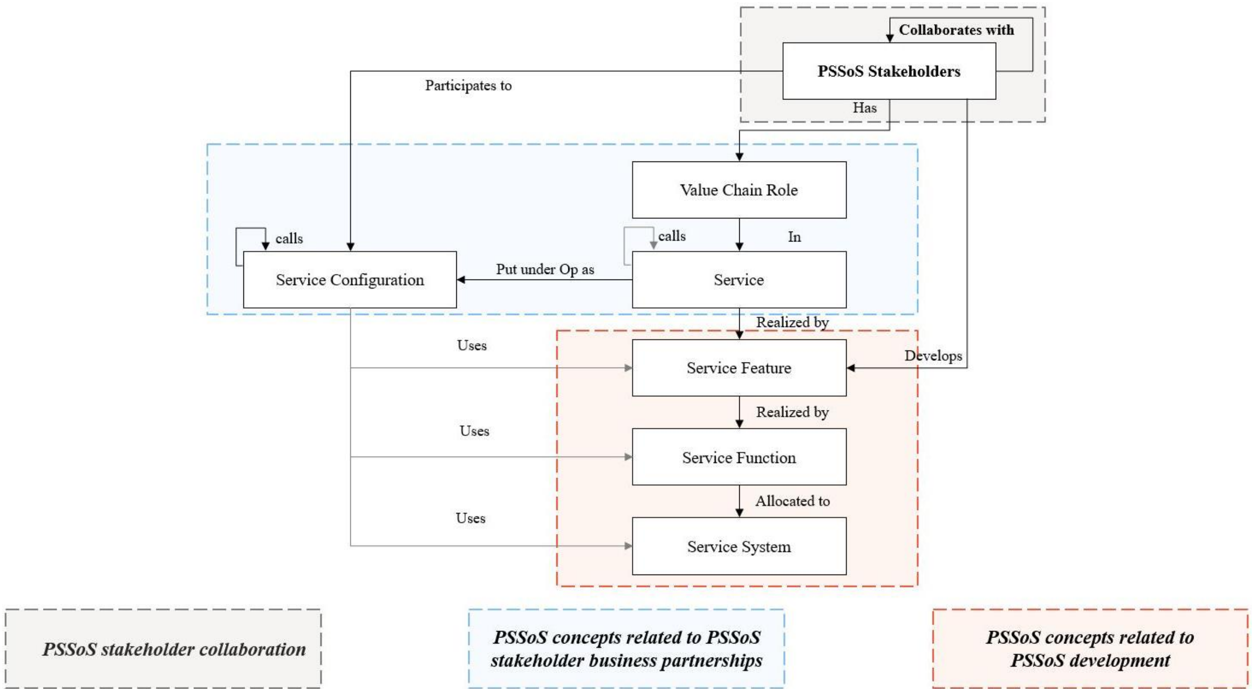

Figure 7.1: An extract from the PSSoS Ontology

PSSoS stakeholder collaboration

PSSoS stakeholder collaboration level is represented by the "grey" level in the ontology. The aim is to represent collaboration and collaborative links between PSSoS stakeholders in a business sense as value creation for a client. In the ontology, "client," "constraint stakeholder," and "PSSoS stakeholders" are defined. In this research, we focus explicitly on the collaboration between the PSSoS stakeholders. Here, we propose to define them as "independent actors or enterprises, who collaborate, develop, and operate the PSSoS and the constituent systems". PSSoS stakeholders are connected through relations "collaborate with" (Figure 7.1). This information can be represented as an undirected (edges are not directed) unidimensional (one type of node and one type of relationship) network (Figure 7.2).

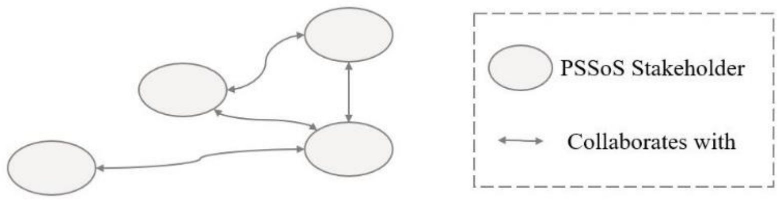

Figure 7.2: Network of PSSoS stakeholder collaborations

PSSoS concepts related to PSSoS stakeholder business partnerships

In the ontology, the information related to the business side and the businesses developed, such as value creation, is defined in the "blue" level. This information relates to "Service," "Value Chain Role," and "Service configuration," and aims at representing how different stakeholders collaborate to provide value. The concept "service" is defined here as "what is sold to customers and what provides them value and achieves their goals". Each PSSoS stakeholder has a "value chain role," expressing their position in the value chain or the service delivery. "Service configuration" expresses how a service is put into operation in a specific context (e.g., Plug&Charge service in city A and city B). One PSSoS stakeholder can "participate" concretely in the delivery of one or many service configurations. Besides, services can be composed of several services; and one service can "call" another service that is already existing or to be developed. As service configuration concerns operational deployment, the same relationship "call" can be used between services configurations. This information can be used to identify the number of service configuration to which a PSSoS stakeholder is actively participating and their role in the business development. This information can be represented as a multidimensional network (multiple node types and multiple relationships) pertaining to PSSoS business development (Figure 7.3).

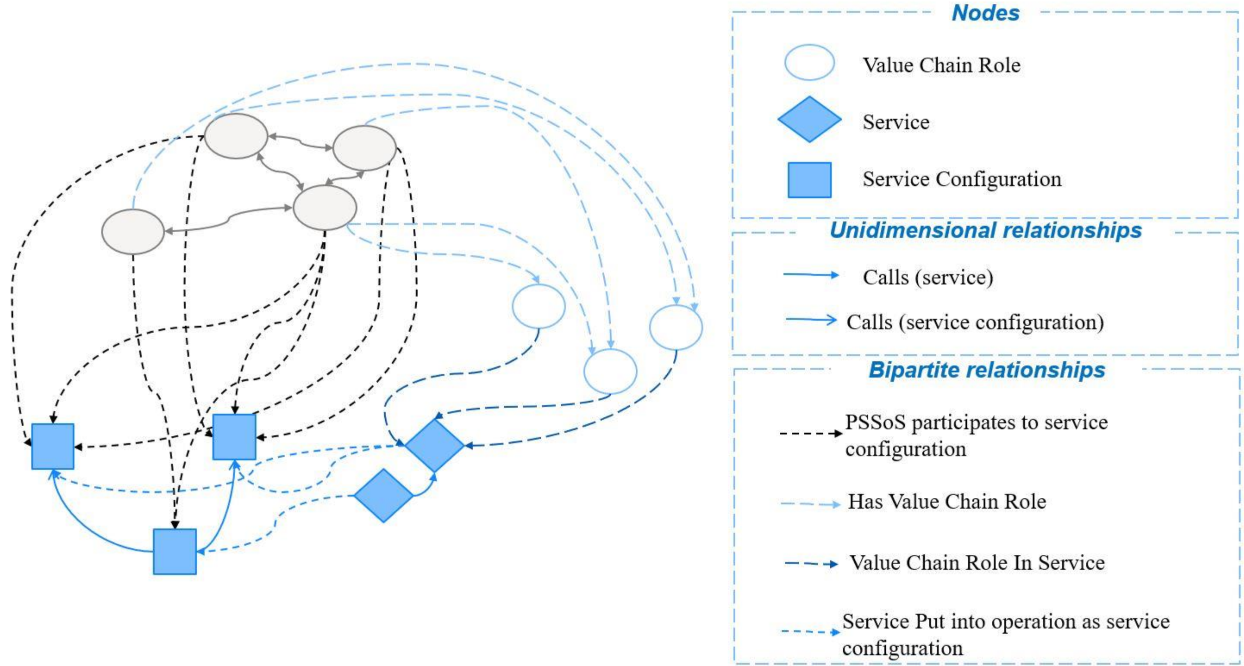

Figure 7.3: PSSoS concepts related to PSSoS stakeholder business partnerships

PSSoS concepts related to PSSoS development

The part of the ontology represented in the "orange" level aims at further specifying the object of the collaboration and information pertaining to the development of PSSoSs. Hence, the data regarding the "Service feature," "Service function," and "system" are detailed. "Service features" are defined as "the capabilities needed to provide the "service" and perceived by the customer and are represented as activities". "Service features" and their relationships can be used to represent what is commonly known in the development as the customer journey. A customer journey is considered as a sequence of "service features" and how they are linked together. In the development process, for each object developed, "functions" are defined in order to model what the object is doing or should do. Hence, each "Service feature" is accomplished by "functions. "Functions" are here defined as activities transforming input flows into output flows and are used to represent functional flows. Finally, a "system," representing concretely what is developed (the electric vehicle, electric infrastructure, or offboard servers), is allocated to each "function". As in previous examples, a multidimensional network of PSSoS development can be used to represent this information (Figure 7.4).

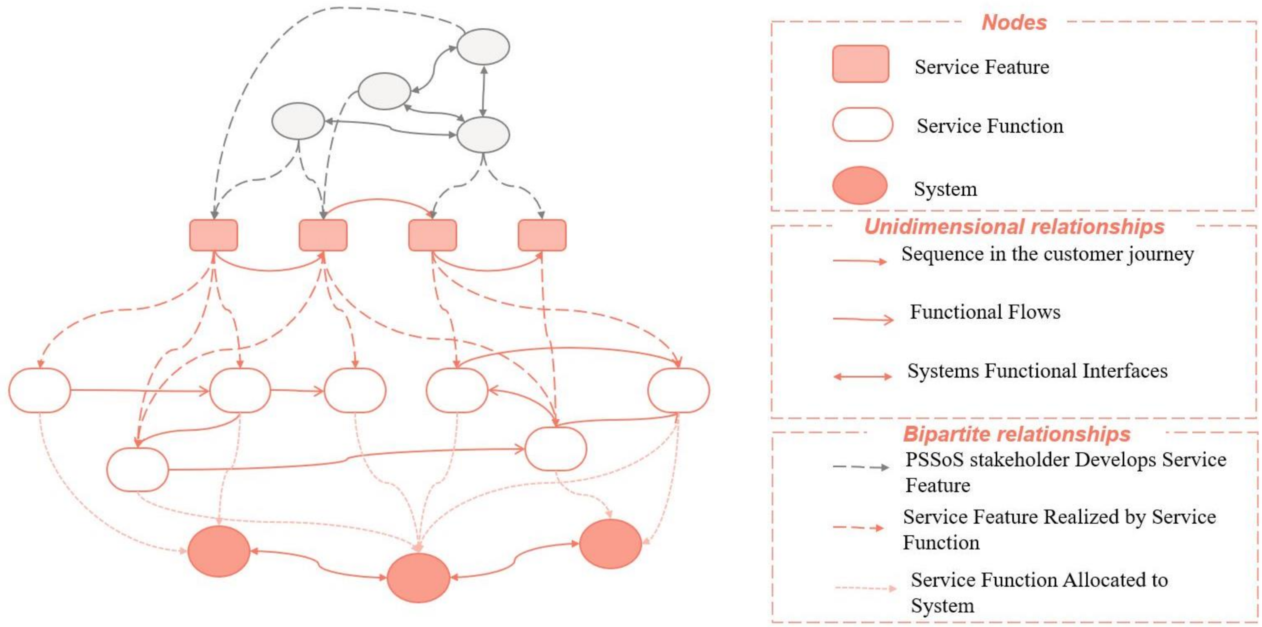

Figure 7.4: PSSoS concepts related to PSSoS development

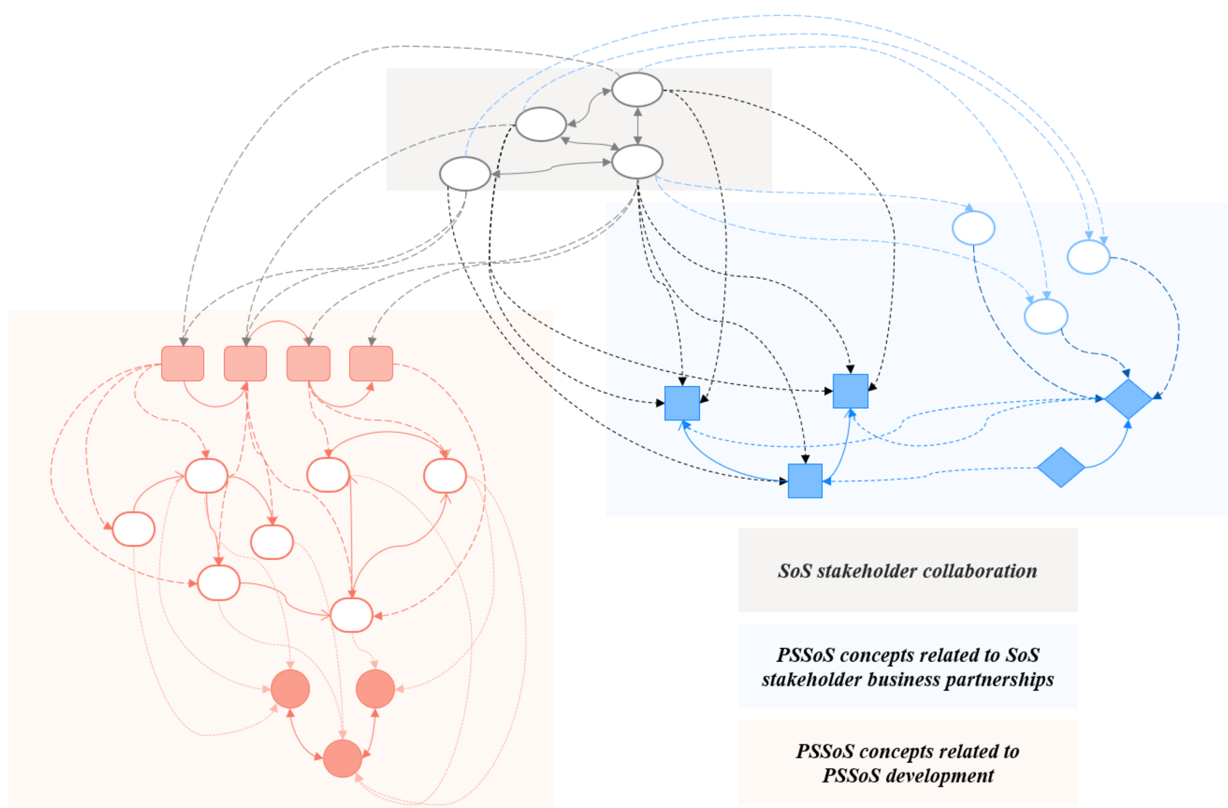

Figure 7.5: A schematic representation of the PSSoS multidimensional network

For clarity reasons, we have represented the information as several networks. However, an overall multidimensional network representing the PSSoS business partnership and development can be seen in Figure 7.5.

Previous research highlighted the difficulty of measuring topological measures on a multidimensional network raises an interpretation issue (Parraguez-Ruiz, 2015). One of the possibilities in managing these interpretation issues is to reduce dimensionality (hence transforming multidimensional network into uni- or bi-dimensional networks) (Parraguez-Ruiz, 2015). In this research we propose to develop two unidimensional networks addressing PSSoS business partnership and development.

7.3.2 From a multidimensional network to two unidimensional networks reflecting PSSoS stakeholder importance in business partnerships and development

In paragraph 7.3.2.1 and 7.3.2.2, two unidimensional networks are developed, i.e., networks that involve only one type of node and one type of edge. The first focuses on the PSSoS stakeholder business partnership and the second on PSSoS stakeholder involvement in the development. Similarly to the work of (Parraguez-Ruiz, 2015), we get from the multidimensional network (Figure 7.5), involving multiple node and edge types to the unidimensional networks by aggregating the information contained in nodes and edges, and therefore reducing the dimensionality. Because aggregation inevitably involves a loss of information, we do not consider in this chapter the direction of the network's edges. All edges will be regarded as undirected. In paragraphs 7.3.2.1 and 7.3.2.2, we explain step by step how the unidimensional networks are constructed.

7.3.2.1 PSSoS stakeholder business partnership network

This section explains a step by step process of transforming the multidimensional network to unidimensional network related to PSSoS business partnership (blue level). We propose a two steps process: **1)** the characterization of each PSSoS stakeholder, and **2)** the characterization of a collaboration between two PSSoS stakeholders.

Step 1: Characterizing a PSSoS stakeholder

This research aims to understand which and how a PSSoS stakeholder participates in service configurations. To do so, we propose to consider/put Value Chain Roles as attributes in the PSSoS Stakeholder network (Figure 7.6). In the ontology, PSSoS stakeholders are not related directly to the services, as this is a conceptual definition. However, a "service" is operationally deployed and concretely defined through "service configurations". To understand PSSoS stakeholder involvement, we consider services as attributes of the service configuration network (Figure 7.6). Here, a service can be seen as a "type" of a service configuration. For example, both service configurations "Navigation service city A" and "Navigation service city B" are "typed" "Navigation Service". This allows us to reduce the dimensionality of the initial network (represented in Figure 7.3) that contains information related to the PSSoS stakeholders participating in different service configurations. Here, we propose two analysis:

- the number of service configurations a PSSoS stakeholder participates in, noted $|\mathrm{SC_i}|$, where $\mathrm{SC_i}$ is the set of service configurations the PSSoS stakeholder i participates in and,
- how these service configurations are linked together through the relationship "calls." As a reminder, the relationship "calls" indicates that a service configuration relies upon / uses another service configuration. For instance, some charging vehicle service configurations rely on or use navigation service configurations. To capture this, we consider the network on service configurations the PSSoS stakeholder participates in and measure its density ($\mathrm{density(SC_i)}$ (eq. 1)) (indicating the extent to which configurations rely upon or use each other).

$$\mathrm{density(SC_i)} = \frac{2 \times \mathrm{E_{calls}^{SC_i}}}{|\mathrm{SC_i}| \times (|\mathrm{SC_i}| - 1)} \quad \textbf{(1)}$$

Where $\mathrm{E_{calls}^{SC_i}}$ is the sum of the edges representing the relationship "calls" among the service configurations in $\mathrm{SC_i}$.

The number of service configurations and their density inform on the PSSoS stakeholder's importance in the business partnerships. Figure 7.6 sums up how PSSoS stakeholders are characterized.

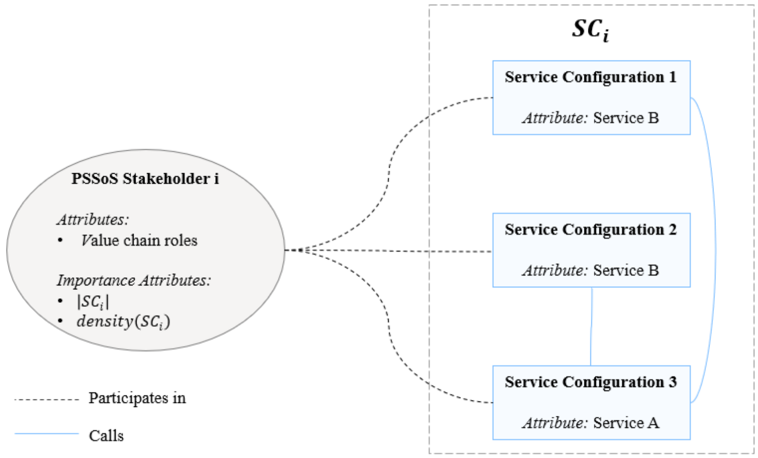

Figure 7.6: Characterizing a PSSoS stakeholder

Step 2: Characterizing PSSoS stakeholder collaborations

To characterize the collaboration between two PSSoS stakeholders, we consider the service configurations they both participate in. Similarly to the characterization of a PSSoS stakeholder, we measure the number, and the density of the service configurations both PSSoS stakeholders participate in, denoted $|SC_i \cap SC_j|$ and $density(SC_i \cap SC_j)$, (eq. 2) respectively, with i and j the indices of the two collaborating PSSoS stakeholders.

$$\mathrm{density}(\mathrm{SC_i} \cap \mathrm{SC_j}) = \frac{2 \times \mathrm{E}_{\mathrm{calls}}^{\mathrm{SC_i \cap SC_j}}}{|\mathrm{SC_i} \cap \mathrm{SC_j}| \times (|\mathrm{SC_i} \cap \mathrm{SC_j}| - 1)} \qquad \mathbf{(2)}$$

Figure 7.7 shows how PSSoS stakeholder collaborations are characterized.

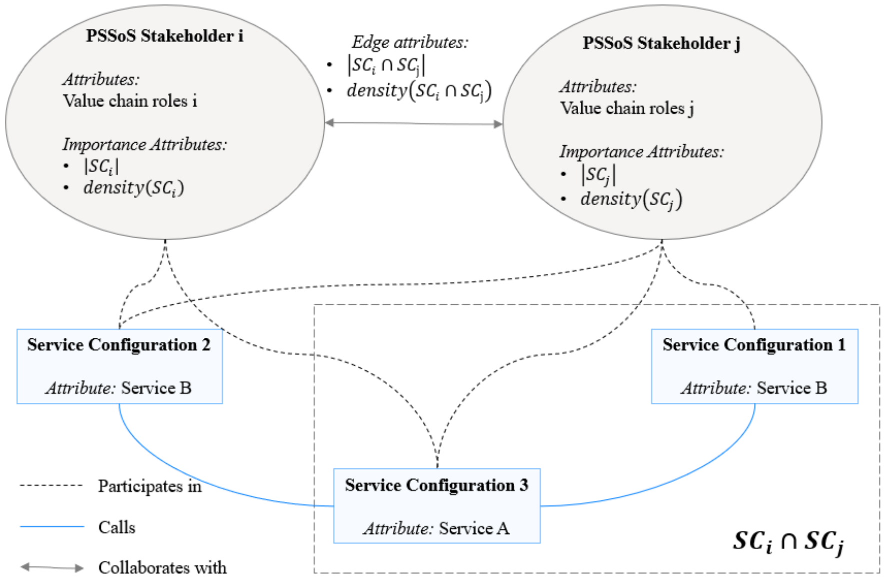

Figure 7.7: Characterizing PSSoS stakeholder business partnerships

Since the number and density measures are complementary because the first pertains to the size and the second the coupling between service configurations (Ameri et al., 2008), we give a weight (W_{i-j}^{BP}, ($eq.$ 3)) to the collaboration relationships between PSSoS stakeholders i and j.

$$W_{i-j}^{BP} = \left|\mathrm{SC_i} \cap \mathrm{SC_j}\right| + \frac{\mathrm{density}\left(\mathrm{SC_i} \cap \mathrm{SC_j}\right)}{\mathrm{density}\left(\mathrm{SC_i} \cup \mathrm{SC_j}\right)} \qquad \textbf{(3)}$$

Therefore, we specify the PSSoS stakeholder collaboration network using information (value chain roles, services, and service configurations) relevant for PSSoS business partnerships. Figure 7.8 describes the constituent elements of the resulting PSSoS weighted unidimensional network: the PSSoS stakeholder business partnership network.

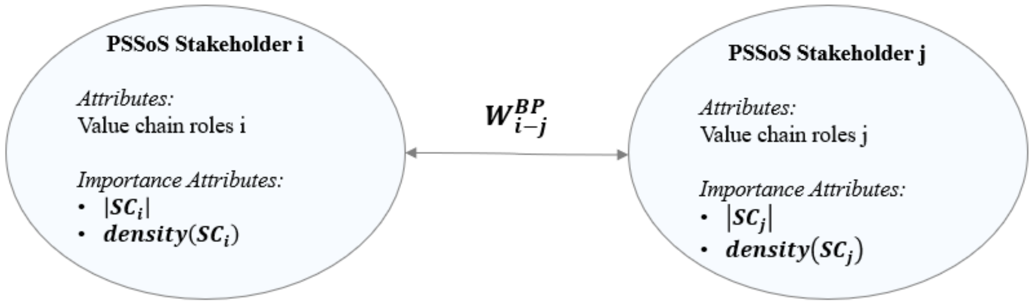

Figure 7.8:The PSSoS stakeholder business partnership network (elements)

7.3.2.2 The network of PSSoS stakeholder involvement in the development

In line with section 3.2.1., we describe a step-by-step process to transform the multidimensional network to a unidimensional network related to the involvement of PSSoS stakeholders in the development (orange level). In this case, we propose a two steps process: step **1)** characterizes service features and their relationships, and step **2)** characterizes PSSoS stakeholders and their relationships in the development.

The proposed process is structured in accordance with the activities of the design teams. As a matter of fact, service and system design teams usually start by defining the service (value to the customer), the potential collaboration between PSSoS stakeholders to achieve it, and service configurations. They proceed by describing the customer journey (through service features) and then detail functions and functional flows to realize service features. Finally, functions are allocated to systems. Hence, each step further details the development of the concept defined in the previous one. For instance, functions and functional flows detail how service features are developed. Therefore, once all the steps are completed, we characterize each network by the more detailed one. So, systems characterize the functional network. The characterized functional network characterizes the feature network. Finally, the characterized feature network characterizes the involvement and interdependencies between PSSoS stakeholders in the development.

In the following, we detail the characterization of the service feature network (step **1**) that will be used to characterize the PSSoS stakeholder network (step **2**).

Step 1: Service feature network characterization

This step aims to reduce the dimensionality of the multidimensional network in the "orange" level (Figure 7.4). For this purpose, we propose first to characterize the network of service features based on the information pertaining to their realization contained in the service function and system networks (Figure 7.4).

In our context, the available information only allows us to define the functional interfaces between systems. For this reason, we start by simply setting systems as attributes of functions. Then, we propose to characterize service features and their interactions based upon the functional network (built upon functional flows).

Two measures are used to characterize the development complexity of a service feature:

- the number of functions realizing it (service feature scope), noted $|F_i|$, with $\boldsymbol{i}$ the service feature identifier, and
- the density of their interactions $(\text{density}(F_i), \text{eq. } 4)$

$$\text{density}(F_i) = \frac{2 \times E^{F_i}_{\text{functional flows}}}{|F_i| \times (|F_i| - 1)} \tag{4}$$

Where $E^{F_i}_{\text{functional flows}}$ is the sum of the edges representing the functional flows between the functions in F_i.

As for service feature relationships (expressing a sequence in the customer journey), we analyse them through a size and two coupling complexity measures:

- the number of functions realizing both service features (size) denoted $|F_i \cup F_j|$, with i and j the service feature Ids, and
- the functional overlap defined as the number of functions participation in the realizations of both features denoted $|F_i \cap F_j|$ (coupling)
- the functional interaction index (noted FII_{i-j}) defined as the ratio of functional interactions linking the feature scopes and the functional interactions within service features scopes (coupling). The functional interaction index is null if there are no functional interactions among all the functions or between F_i and F_j**.** In case, the only interactions occur between F_i and F_j and not within F_i and F_j, the FII_{i-j} is equal to 1.

  The functional interaction index is measured as follows:

$$FII_{i-j} = \begin{cases} \dfrac{E^{F_i \cup F_j}_{\text{functional flows}} - E^{F_i}_{\text{functional flows}} - E^{F_j}_{\text{functional flows}}}{E^{F_i}_{\text{functional flows}} + E^{F_j}_{\text{functional flows}}}, & if \left(E^{F_i}_{\text{functional flows}} + E^{F_j}_{\text{functional flows}} \right) \neq 0 \\ 1, \quad if \left(E^{F_i}_{\text{functional flows}} + E^{F_j}_{\text{functional flows}} \right) = 0 \text{ and } \left(E^{F_i \cup F_j}_{\text{functional flows}} \right) \neq 0 \\ 0, \quad if \left(E^{F_i}_{\text{functional flows}} + E^{F_j}_{\text{functional flows}} \right) = 0 \text{ and } \left(E^{F_i \cup F_j}_{\text{functional flows}} \right) = 0 \end{cases} \tag{5}$$

Figure 7.9 shows how the service feature network is characterized.

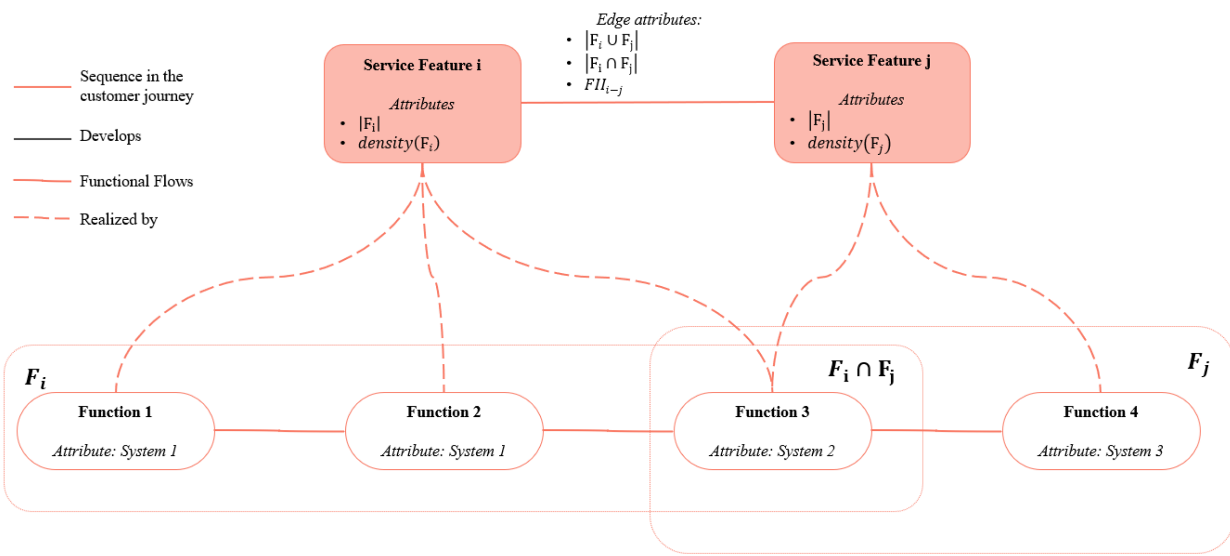

Figure 7.9: Characterizing the Service Feature Network

We weight the interaction between two service features i and j based on the size and coupling measures of the functions realizing the service features as follows:

$$W^{SF}_{i-j} = FII_{i-j} + \frac{|F_i \cap F_j|}{|F_i \cup F_j|} \tag{6}$$

Step 1 results in the definition of a weighted service features network described in Figure 7.10.

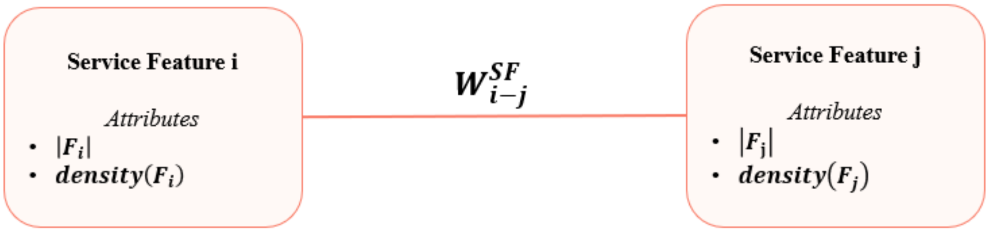

Figure 7.10: Weighted service feature network (elements)

Step 2: PSSoS stakeholder network characterization

The objective of this research is to characterize the involvement and interdependencies between PSSoS stakeholders in the development. In this step, we characterize the PSSoS stakeholder network in the development based on the Service Features characterization done in step 1.

In the context of PSSoS development, we relate the importance of PSSoS stakeholders to the development difficulty of the service features they develop. Therefore, a PSSoS stakeholder is characterized by:

- The number of service features they develop, $|SF_i|$, with i the PSSoS stakeholder identifier
- The maximum number of functions realizing these service features noted $max(F)_i$, which indicates their development complexity (eq. 7).

$$max(F)_i = \max_{j \in |SF_i|} (|F_j|) \quad \textbf{(7)}$$

- The maximum (functional interaction) density of these service features (Figure 7.8), which is another indication of their complexity (eq. 8)

$$max(density)_i = \max_{j \in |SF_i|} (\text{density}(F_j)) \quad \textbf{(8)}$$

- Since the service feature network is weighted according to step 1 (Figure 7.10), we adapt the notion of network density to the weighted network of service features the PSSoS stakeholder develops. Equation 9 shows how the weighted density is measured with E^{SF_i} the number of edges within SF_i . If the PSSoS stakeholder develops only one service feature (one node), the denominator of equation 9 is equal to zero. In this case, the one node network is considered not dense and the weighted density is equal to zeo.

$$Weighted\ density(\mathrm{SF_i}) = \begin{cases} \dfrac{2 \times \sum_{j,k \,\in\, \mathrm{SF_i}} (W_{j-k}^{SF})}{(|\mathrm{SF_i}| + \sum_{j,k \,\in\, \mathrm{SF_i}} (W_{j-k}^{SF}) - E^{SF_i}) \times (|\mathrm{SF_i}| + \sum_{j,k \,\in\, \mathrm{SF_i}} (W_{j-k}^{SF}) - E^{SF_i} - 1)}, & if\ |\mathrm{SF_i}| \neq 1 \\ 0, \quad if\ |\mathrm{SF_i}| = 1 \end{cases} \quad \textbf{(9)}$$

Figure 7.11 summarizes the characterization of a PSSoS stakeholder in the development.

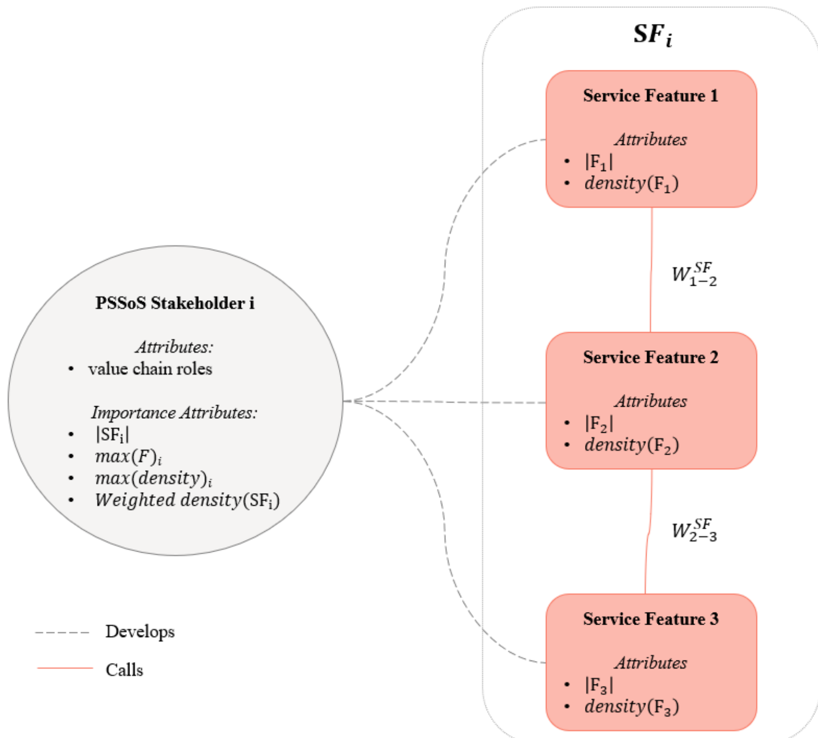

Figure 7.11: Characterization of PSSoS stakeholder in the development

With regards to PSSoS stakeholder interactions in the development, we consider the number of service features the PSSoS stakeholders develop noted $|\mathrm{SF_i} \cup \mathrm{SF_j}|$ where i and j are the PSSoS stakeholders ids, as well as the service features interaction index $SFII$ defined as:

$$SFII_{i-j} = \begin{cases} \dfrac{\sum_{k,l\in(\mathrm{SF_i}\cup\mathrm{SF_j})} W_{k-l}^{SF} - \sum_{k,l\in\mathrm{SF_i}} W_{k-l}^{SF} - \sum_{k,l\in\mathrm{SF_j}} W_{k-l}^{SF}}{\sum_{k,l\in\mathrm{SF_i}} W_{k-l}^{SF} + \sum_{k,l\in\mathrm{SF_j}} W_{k-l}^{SF}}, if \left(\sum_{k,l\in\mathrm{SF_i}} W_{k-l}^{SF} + \sum_{k,l\in\mathrm{SF_j}} W_{k-l}^{SF}\right) \neq 0 \\ 1, \quad if \left(\sum_{k,l\in\mathrm{SF_i}} W_{k-l}^{SF} + \sum_{k,l\in\mathrm{SF_j}} W_{k-l}^{SF}\right) = 0, and \left(\sum_{k,l\in(\mathrm{SF_i}\cup\mathrm{SF_j})} W_{k-l}^{SF}\right) \neq 0 \\ 0, \quad if \left(\sum_{k,l\in\mathrm{SF_i}} W_{k-l}^{SF} + \sum_{k,l\in\mathrm{SF_j}} W_{k-l}^{SF}\right) = 0 \; and \left(\sum_{k,l\in(\mathrm{SF_i}\cup\mathrm{SF_j})} W_{k-l}^{SF}\right) = 0 \end{cases} \quad \textbf{(10)}$$

Figure 7.12 sums up the characterization of PSSoS Stakeholder collaborations in the development.

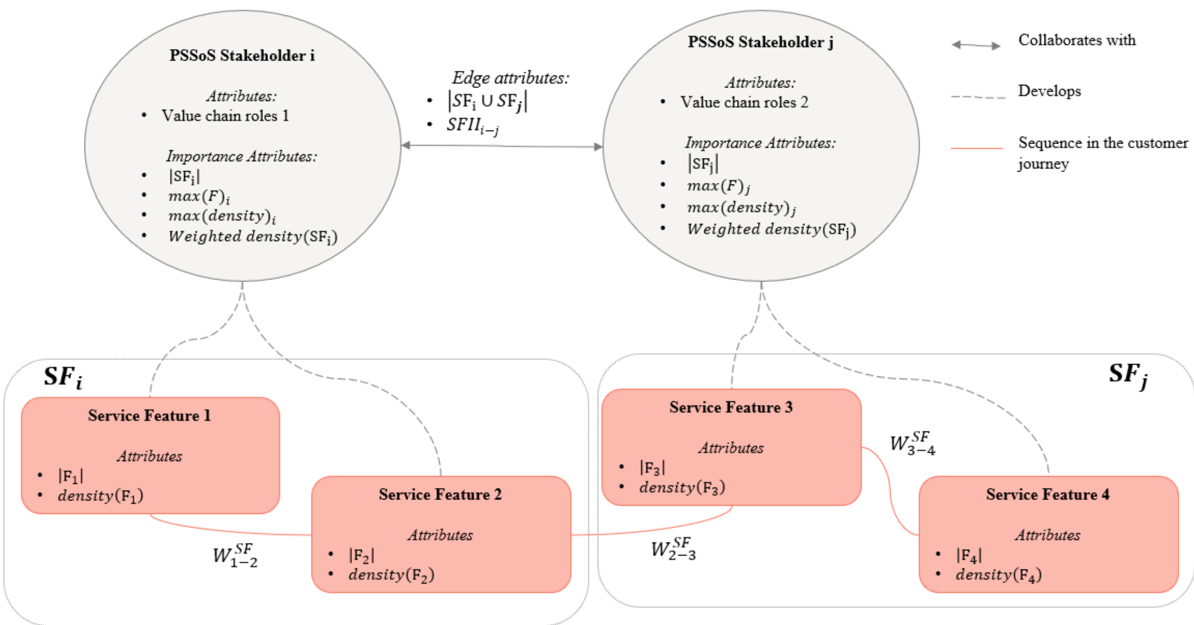

Figure 7.12: Characterizing the PSSoS stakeholder collaboration in the development

The measure of service features involved in the collaboration of two stakeholders and the Service Feature interaction index are complementary. Therefore, in a similar fashion as for the PSSoS business partnership network (bleu level), we give a weight (W_{i-j}^{Dev}, $(eq.W)$) to the collaboration relationships between PSSoS stakeholders i and **j.** |SF| is the total number of service features.

$$W_{i-j}^{Dev} = \frac{\left|SF_i \cup SF_j\right|}{|SF|} + SFII_{i-j} \quad (11)$$

Figure 7.13 describes the constituent elements of the resulting PSSoS weighted unidimensional network: the PSSoS stakeholder development network**.**

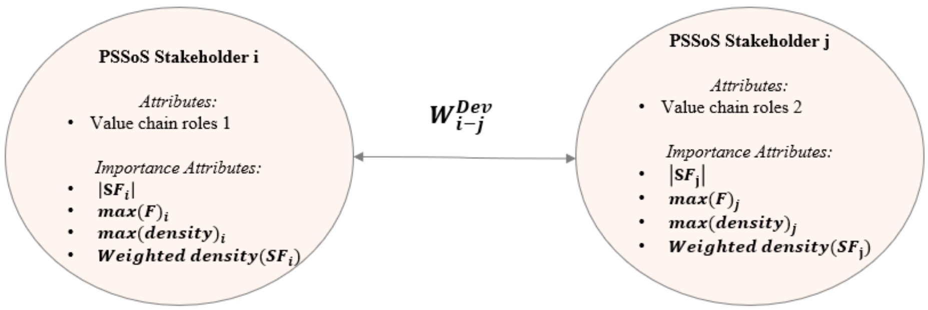

Figure 7.13: the PSSoS stakeholder development network (elements)

To summarize, in paragraphs 7.3.2.1 and 7.3.2.2., we characterized PSSoS Stakeholder importance in business partnerships and development through different measures. These measures suggest the individual importance of a PSSoS stakeholder by looking at the service configurations they participate in, and the service features they develop. However, these measures do not consider the importance of a PSSoS stakeholder regarding the interactions a PSSoS stakeholder has with other PSSoS stakeholders.

In the following section 7.3.3, we use the measures characterizing PSSoS collaborations in business partnerships (paragraph 7.3.2.1.) and development (paragraph 7.3.2.1.) to quantify the importance of a PSSoS stakeholder with regards to the interactions he/she has with other PSSoS Stakeholders. To clearly distinguish the importance of a PSSoS stakeholder with regards to his/ her interactions from the individual or local PSSoS stakeholder importance, we name it PSSoS stakeholder influence.

7.3.3 Analysis of SoS Stakeholder business partnership influence and development influence

In the literature, different network centrality measures have been used to quantify stakeholder importance or influence. To capture a PSSoS stakeholder's influence in business partnerships and development, we chose to use the eigenvector centrality in both networks: the weighted PSSoS stakeholder business partnerships network and the weighted development PSSoS stakeholder network.

In general terms, the eigenvector centrality measures how central a node in the network is in relation to how central all the other nodes are. Unlike the degree centrality, the eigenvector centrality does not only consider the node direct neighbors but rather the whole network. The eigenvector centrality can be interpreted as the influence of the node in the network. The influence of a node i, x_i can then be written as (λ being a constant):

$$A^t \boldsymbol{p} = \lambda_p \boldsymbol{p} \tag{12}$$

Matrix A is the adjacency matrix of the network. Since the networks we consider in this chapter are undirected and weighted (the PSSoS stakeholder business partnerships network and the PSSoS stakeholder development network), A is a symmetric matrix and its coordinates $a_{(i,j)}$ are the weights of the edges between nodes i and j.

With regards to the PSSoS stakeholder business partnership network, a high value of eigenvector centrality hints at the fact that PSSoS stakeholders tend to have business partnerships with PSSoS stakeholders that themselves have many business partnerships. This indicates the importance of a PSSoS stakeholder in the overall business scene, for example, the importance of a PSSoS stakeholder in the electric vehicle related services and businesses. Such a PSSoS stakeholder tends to be highly influential.

In the context of PSSoS development, SoS stakeholders (development network) with high values of eigenvector centrality are highly influential in developing the PSSoS. They develop service features and functions that are highly related to service features and functions that other influential PSSoS stakeholders develop.

7.4 Case study, results, and analysis

7.4.1 PSSoS case description

To illustrate the use of the approach presented in section 7.3, an industrial project has been considered. This study focuses on the development of EVs charging services and V2G related services. In the following, we consider one service, "the Plug and Charge service," and its related information. The "Plug & Charge service" has been chosen because of data availability, and coherence between information related to PSSoS business partnerships and development. This service allows the customer to automatically start charging his/her vehicle (i.e., without manual authentication). The service implies that plugging the EV to the charging station allows identifying the EV and that unplugging the EV stops the charging and generates the payment.

Service and system design teams identified seven potential PSSoS stakeholders collaborating to realize this service and six value chain roles. The project teams distinguished three main service configurations in which the PSSoS stakeholders participate (blue level). As for the service development (orange level), 16 service features, and 48 service functions have been defined. Fifteen systems, including the EV, the charging station, and various servers realize these functions. The relationships between different elements have been retrieved from documents and model-based systems engineering tools.

The network of the collaboration between PSSoS Stakeholders (grey level) is given in Figure 7.14, where the seven PSSoS stakeholders are identified by their IDs going from 0 to 6.

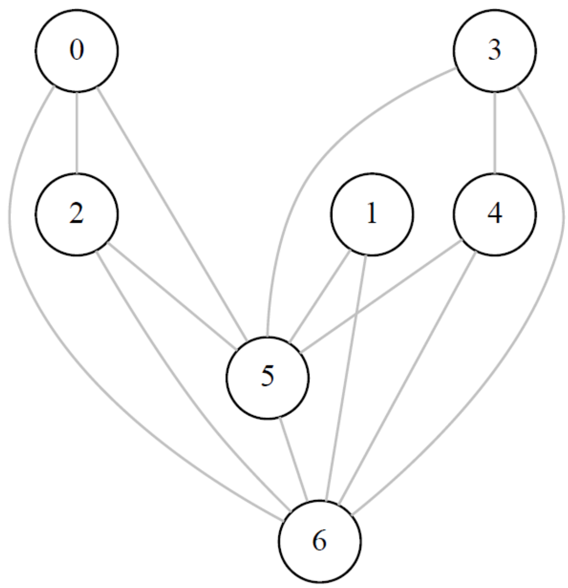

Figure 7.14: Network of the collaboration between Plug and Charge Service PSSoS Stakeholders

7.4.2 Resulting unidimensional networks

In the following paragraphs, we present the analysis of PSSoS stakeholders and their relationships in the Plug and Charge service business partnerships and development following the steps presented in 7.3.2.1 and 7.3.2.2.

7.4.2.1 Business partnership network and PSSoS stakeholder importance in business partnerships

The value chain roles are defined as attributes of PSSoS stakeholders. For instance, the PSSoS stakeholder 5 is an Original Equipment Manufacturer (OEM) that can also play an electric mobility service operator's role. PSSoS stakeholder 4 is another potential electric mobility operator. Both PSSoS stakeholders 0 and 1 are charging station owners and operators. The other PSSoS stakeholders, they mainly develop, manage, and operate different offboard servers required to realize the service.

Since we consider a single service (Plug and Charge), the three service configurations are of the same "type" (Plug and Charge Service in operation). As such, these service configurations are rather independent and do not "call" one another. Therefore, the densities of service configuration networks and sub-networks are null in this context.

Following the approach presented in 7.3.2.1, each PSSoS stakeholder (node) is characterized by the number of service configurations he/she participates in and by their density. As for collaborations between PSSoS stakeholders, they are characterized by the number of service configurations, both PSSoS stakeholders participate in and their density. We present the results in Table 7.1and Table 7.2.

Table 7-1: Measures characterizing the importance of PSSoS stakeholders in business partnerships

PSSoS Stakeholder ID	Number of Service Configurations	Density of Service Configuration
0	1	0
1	1	0
2	1	0
3	1	0
4	1	0
5	3	0
6	3	0

Table 7-2: Measures characterizing PSSoS stakeholder business partnerships

Collaboration between PSSoS Stakeholders		Number of Service Configurations	Density of Service Configuration
PSSoS Stakeholder ID	PSSoS Stakeholder ID		
0	2	1	0
0	5	1	0
0	6	1	0
1	5	1	0
1	6	1	0
2	5	1	0

Collaboration between PSSoS Stakeholders		Number of Service Configurations	Density of Service Configuration
PSSoS Stakeholder ID	PSSoS Stakeholder ID		
2	6	1	0
3	4	1	0
3	5	1	0
3	6	1	0
4	5	1	0
4	6	1	0
5	6	3	0

Figure 7.15 is a representation of the weighted PSSoS stakeholder business partnership network (see section 7.3.3). The node size represents the number of service configurations the PSSoS stakeholders participate in, their colour the service configurations density. The edge thickness represents their weights.

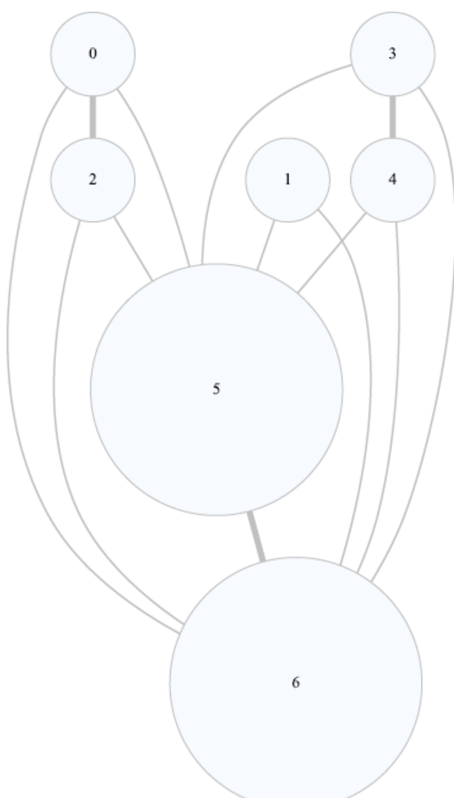

Figure 7.15:The weighted PSSoS stakeholder business partnerships network

Results show that both stakeholders 5 and 6 are important in business partnerships as they participate in all service configurations. The other PSSoS stakeholders are rather local players participating each in one specific service configurations. On a broader data set, such information gives hints on the important PSSoS stakeholder participating in the realization of EV related services in different locations, for example.

7.4.2.2 PSSoS Development relationships network and SoS stakeholder development importance

In the PSSoS development context, our approach proposes to 1) characterize the service features network, and 2) characterize the PSSoS stakeholder network.

Table 7-3 and Table 7-4 present the results of the measures characterizing Service Features and Service Feature interactions.

Table 7-3: Measures Characterizing Service Features

Service Features Ids (i , j)	Functional Interaction Index	Total number of functions	Overlap
(7, 10)	0	9	0
(7, 15)	0	5	0
(7, 16)	0	3	0
(7, 17)	1	2	0
(7, 18)	0	4	0
(7, 20)	1	3	0
(7, 21)	1	3	0
(8, 10)	0	10	0
(8, 15)	0	6	0
(8, 16)	0	4	0
(8, 17)	1	3	0
(8, 18)	0	5	0
(8, 20)	1	4	0
(8, 21)	1	4	0
(10, 9)	0.2	15	0
(10, 11)	0.5	10	0
(10, 12)	0.0	13	0
(10, 14)	0.0	9	0
(10, 19)	1.5	10	0
(10, 22)	0	12	0
(11, 9)	0	9	0
(11, 12)	0.33	7	0
(11, 14)	1	3	0

Service Features Ids (i , j)	Functional Interaction Index	Total number of functions	Overlap
(11, 15)	0	6	0
(11, 16)	0	4	0
(11, 18)	0	5	0
(11, 19)	1	4	0
(11, 20)	1	4	0
(11, 22)	1	6	0
(13, 9)	0	9	0
(13, 11)	0	4	0
(13, 12)	0	7	0
(13, 14)	1.0	3	0
(13, 15)	0	6	0
(13, 16)	0	4	0
(13, 18)	0	5	0
(13, 19)	0	4	0
(13, 20)	0	4	0
(13, 22)	0	6	0
(15, 9)	0.2	11	0
(15, 10)	0.5	12	0
(15, 12)	0.2	9	0
(15, 14)	0.5	5	0
(15, 16)	0.33	6	0
(15, 17)	0	5	0
(15, 18)	0.25	7	0
(15, 19)	0	6	0
(15, 20)	0	6	0
(15, 21)	0	6	0
(15, 22)	0	8	0
(16, 9)	0	9	0
(16, 12)	0	7	0
(16, 14)	0	3	0
(16, 18)	0	5	0
(16, 19)	0	4	0
(16, 20)	0	4	0
(16, 22)	0	6	0
(17, 9)	0	8	0
(17, 11)	1	3	0
(17, 12)	0	6	0
(17, 14)	1	2	0
(17, 19)	1	3	0
(17, 22)	1	5	0
(18, 9)	0	10	0
(18, 10)	0	11	0
(18, 12)	0	8	0
(18, 14)	0	4	0
(18, 17)	0	4	0
(18, 19)	0	5	0

Service Features Ids (i , j)	Functional Interaction Index	Total number of functions	Overlap
(18, 20)	0	5	0
(18, 21)	0	5	0
(18, 22)	0	7	0
(20, 9)	0	9	0
(20, 10)	0	10	0
(20, 12)	0	7	0
(20, 14)	1	3	0
(20, 17)	1	3	0
(20, 19)	1	4	0
(20, 21)	1	4	0
(20, 22)	1	6	0
(21, 9)	0	9	0
(21, 11)	1	4	0
(21, 12)	0	7	0
(21, 14)	1	3	0
(21, 19)	1	4	0
(21, 22)	1	6	0

Table 7-3 shows service feature ID = 3 is realized by a high number of functions (8) with a high network density (0.71). Therefore, realizing such service features is complex as it requires the development of different functions and their functional interfaces. Other service features are realized by one or a few functions that are not necessarily part of the same functional chain, e.g., IDs 1, 10, 12, 13, 14.

Table 7-4: Measures Characterizing service feature relationships

Service Features Ids (i, j)	Functional Interaction Index	Total number of functions	Overlap
(7, 10)	0	9	0
(7, 15)	0	5	0
(7, 16)	0	3	0
(7, 17)	1	2	0
(7, 18)	0	4	0
(7, 20)	1	3	0
(7, 21)	1	3	0
(8, 10)	0	10	0
(8, 15)	0	6	0
(8, 16)	0	4	0
(8, 17)	1	3	0
(8, 18)	0	5	0
(8, 20)	1	4	0

Service Features Ids (i, j)	Functional Interaction Index	Total number of functions	Overlap
(8, 21)	1	4	0
(10, 9)	0.2	15	0
(10, 11)	0.5	10	0
(10, 12)	0	13	0
(10, 14)	0	9	0
(10, 19)	1.5	10	0
(10, 22)	0	12	0
(11, 9)	0	9	0
(11, 12)	0.33	7	0
(11, 14)	1	3	0
(11, 15)	0	6	0
(11, 16)	0	4	0
(11, 18)	0	5	0
(11, 19)	1	4	0
(11, 20)	1	4	0
(11, 22)	1	6	0
(13, 9)	0	9	0
(13, 11)	0	4	0
(13, 12)	0	7	0
(13, 14)	1.0	3	0
(13, 15)	0	6	0
(13, 16)	0	4	0
(13, 18)	0	5	0
(13, 19)	0	4	0
(13, 20)	0	4	0
(13, 22)	0	6	0
(15, 7)	0	5	0
(15, 8)	0	6	0
(15, 9)	0.2	11	0
(15, 10)	0.5	12	0
(15, 11)	0.0	6	0
(15, 12)	0.2	9	0
(15, 13)	0.0	6	0
(15, 14)	0.5	5	0
(15, 16)	0.33	6	0
(15, 17)	0.0	5	0
(15, 18)	0.25	7	0
(15, 19)	0	6	0
(15, 20)	0	6	0
(15, 21)	0	6	0
(15, 22)	0	8	0
(16, 7)	0	3	0
(16, 8)	0	4	0
(16, 9)	0	9	0
(16, 11)	0	4	0

Service Features Ids (i, j)	Functional Interaction Index	Total number of functions	Overlap
(16, 12)	0	7	0
(16, 13)	0	4	0
(16, 14)	0	3	0
(16, 15)	0.33	6	0
(16, 18)	0	5	0
(16, 19)	0	4	0
(16, 20)	0	4	0
(16, 22)	0	6	0
(17, 9)	0	8	0
(17, 11)	1	3	0
(17, 12)	0	6	0
(17, 14)	1	2	0
(17, 19)	1	3	0
(17, 22)	1	5	0
(18, 7)	0	4	0
(18, 8)	0	5	0
(18, 9)	0	10	0
(18, 10)	0	11	0
(18, 11)	0	5	0
(18, 12)	0	8	0
(18, 13)	0	5	0
(18, 14)	0	4	0
(18, 15)	0.25	7	0
(18, 16)	0	5	0
(18, 17)	0	4	0
(18, 19)	0	5	0
(18, 20)	0	5	0
(18, 21)	0	5	0
(18, 22)	0	7	0
(20, 7)	1	3	0
(20, 8)	1	4	0
(20, 9)	0	9	0
(20, 10)	0	10	0
(20, 11)	1	4	0
(20, 12)	0	7	0
(20, 13)	0	4	0
(20, 14)	1	3	0
(20, 15)	0	6	0
(20, 16)	0	4	0
(20, 17)	1	3	0
(20, 18)	0	5	0
(20, 19)	1	4	0
(20, 21)	1	4	0
(20, 22)	1	6	0
(21, 9)	0	9	0

Service Features Ids (i, j)	Functional Interaction Index	Total number of functions	Overlap
(21, 11)	1	4	0
(21, 12)	0	7	0
(21, 14)	1	3	0
(21, 19)	1	4	0
(21, 22)	1	6	0

As for the interactions among service features, in the chosen example functions participate in realizing only one service features (overlap = 0). The high values of the Functional Interaction Index show that service features (3,5), (11,2), and (11,5) are sequential in the customer journey and highly interdependent functionally.

Based on the Service Feature Network characteristics, our approach defines measures to characterize the importance of PSSoS stakeholders and their relationships in the development. Results are presented in Table 7-5 and Table 7-6.

Table 7-5: Measures characterizing the importance of PSSoS stakeholders in development

PSSoS stakeholder Id	Number of service Features	Service Features weighted density	Maximum number of functions	Maximum functional density
0	2	0.0	2	1.0
1	2	0.0	2	1.0
2	11	0.17	4	1.0
3	5	0.44	8	1.0
4	2	1.0	3	0.66
5	6	0.21	7	0.3
6	1	0	2	0

According to Table 7-5 , PSSoS stakeholder 2 develops the largest number of service features. This result is expected as the PSSoS stakeholder 2 manages and operates the main offboard platform providing all information (on, e.g., vehicles, contracts) enabling the service. However, the service features realized by PSSoS stakeholder 2 are not as dense as those developed by PSSoS stakeholders 3, 4, and 5. As such, a failure in a service feature developed by PSSoS stakeholders 3, 4, and 5 potentially compromises the service's delivery. This result is coherent with empirical evidence since PSSoS stakeholders 3, 4 are service providers, and 5 is a car manufacturer. The maximum number of functions and their maximum density indicate the complexity of the features developed by a PSSoS stakeholder. In this case, the service feature developed by PSSoS stakeholder 6 is shown to be non-complex. This is explained by the fact that the service feature developed by PSSoS stakeholder 6 is used for all service configurations, and mostly because system engineers did not detail its functions.

Table 7-6: Measures characterizing PSSoS stakeholder collaboration in development

Collaboration between PSSoS Stakeholders		Service Features Interaction Index	Number of service Features
PSSoS Stakeholder ID	PSSoS Stakeholder ID		
0	2	0.11	12
0	5	0.84	8
0	6	1	3
1	5	0.84	8
1	6	1	3
2	5	0.09	13
2	6	0.23	12
3	4	1.24	7
3	5	1.81	11
3	6	0.34	6
4	5	1.71	8
4	6	3.0	3
5	6	1.20	7

Figure 7.16 is a representation of the weighted PSSoS stakeholder development network (see section 7.3.3). The node size represents the number of service features the PSSoS stakeholders develops, their colour the weighted density of the service features. The edge thickness represents their weight.

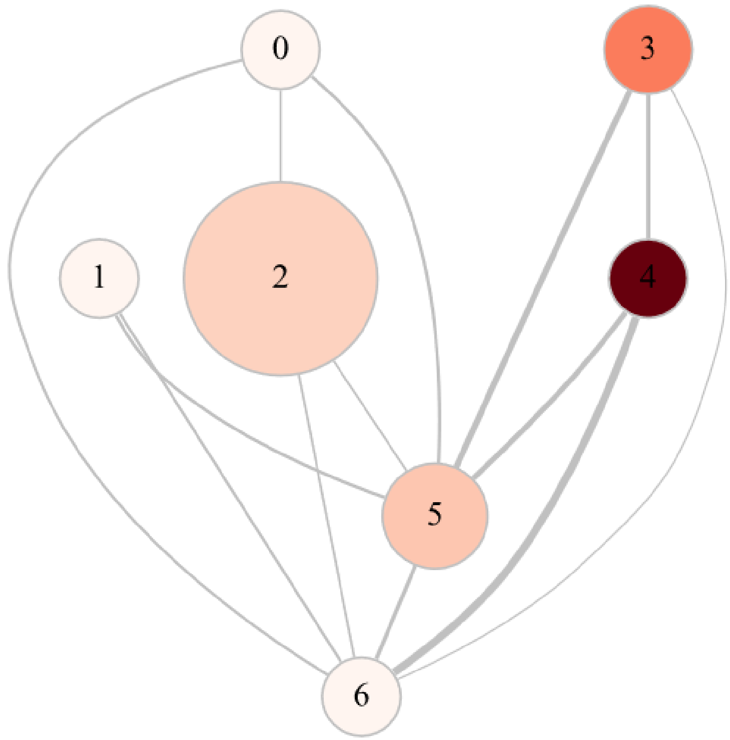

Figure 7.16: The weighted the PSSoS stakeholder development network

7.4.3 PSSoS stakeholder influence in business partnerships and development

In section 7.4.2, the importance of PSSoS stakeholders is quantified using different measures. As for the influence of these PSSoS stakeholders, we consider both weighted graphs (Figure 7.15 and Figure 7.16) and use centrality measures (taking into consideration the weights of network edges) to quantify the influence of each PSSoS stakeholder. Results are presented in Table 7-7. The influence is also measured for the unweighted PSSoS stakeholder network for the sake of comparison.

Table 7-7: PSSoS stakeholders influence in business partnerships and development

	Network of PSSoS stakeholder collaborations (Grey Level)		PSSoS stakeholder business partnership network (Blue Level)		PSSoS stakeholder development network (Orange Level)	
PSSoS Stakeholder Id	Eigenvector Centrality Measure	Rank	Eigenvector Centrality Measure	Rank	Eigenvector Centrality Measure	Rank
0	0,33	3	0,34	3	0,21	5
1	0,25	7	0,17	7	0,19	6
2	0,33	3	0,34	3	0,17	7
3	0,33	3	0,34	3	0,37	4
4	0,33	3	0,34	3	0,49	2
5	0,50	1	0,51	1	0,52	1
6	0,50	1	0,51	1	0,49	3

Table 7-7 shows that both the unweighted collaboration network and the weighted PSSoS stakeholders business partnership network (Grey and Blue levels) give similar results. This is partly due to the limited scope of the considered data. The measures do not largely differentiate PSSoS stakeholders but rather group them: PSSoS stakeholders 5 and 6 rank 1, PSSoS stakeholders 2, 3, 4, and 0 rank 3, and 1 rank 7. We notice that each group's value chain roles are similar: 5 and 6 manufacturing industry-related value chain roles, 2, 3, 4, and service providers or servers and offboard platforms operators. PSSoS stakeholder 1 is the charging station owner. As for results for the PSSoS stakeholder development network (Orange Level), the influence ranks are different. This shows that both perspectives are complementary.

7.5 Discussion

This chapter presented a PSSoS stakeholder analysis approach. This analysis aimed to quantify the importance and influence of PSSoS stakeholders in business partnerships and development. For this purpose, we represented PSSoSs, including concepts related to PSSoS business partnerships and development and their relationships as a multidimensional network. For interpretability purposes, the proposed approach reduces the dimensionality and builds two unidimensional networks of PSSoS stakeholder collaborations, reflecting the PSSoS stakeholders' importance and their collaborations in business partnerships and development. The eigenvector centrality has finally been used to measure the business partnerships and development influences of PSSoS stakeholders. The Plug and Charge Service has been used to show the usability of the proposed analysis approach.

The main advantage of the presented approach is that it is specifically designed to analyze PSSoS stakeholders. The proposed analysis approach also keeps a holistic perspective on PSSoSs, including business partnership and development perspectives. From a business partnership perspective, it allows for a PSSoS decision-maker to identify PSSoS stakeholders engaged in several service configurations and potentially important and influential collaborators. From a PSSoS development perspective, the analysis approach shows the importance of each PSSoS stakeholder in the PSSoS development seen as the functional (Service Features and Functions) complexity of the system he/she develops. This approach also permits to identify influential PSSoS stakeholders in the development seen as those highly relied upon in the functional realization of the PSSoS. Such information can help a PSSoSs decision-maker in the PSSoS design by redesigning service features and functions less dependent on what other PSSoS stakeholders develop. During the management and operation of the PSSoSs, the proposed analysis approach provides knowledge on service features and functions exposed to service features and functions developed by other PSSoS stakeholders.

The proposed approach reduces the dimensionality of a PSSoS multidimensional network and uses a set of measures to quantify the importance and influence of PSSoS stakeholders. Reducing dimensionality generates a loss of information. In some cases, a loss of information might lead to flawed decisions, which is a well-known problem in decision-making (Kujawski, 2013). Besides, different measures can be used to characterize networks. In this study, we mainly rely on how the automotive industry participates in mobility PSSoS development and its needs to define the dimensionality reduction strategy and choose and interpret measures to quantify PSSoS stakeholder importance influence. Therefore, other examples and domains should be considered and studied to confirm the proposed approach's genericity. Besides, qualitative information such as the value chain roles of PSSoS stakeholders, services typing service configurations, and systems set as attributes of functions have not been explicitly used in this chapter. In this respect, the proposed approach can be complemented by a qualitative variations analysis.

Furthermore, the results of the proposed PSSoS stakeholder analysis approach and their interpretation depend on the scope of the available data as well as the model (ontology) level of granularity (e.g., Service Features, Functions). For instance, the used example focuses on a service and its different configurations. The study could also consider multiple services and related service configurations or focus on service configurations in a given area. For such scopes, the use and interpretation of the business partnerships' results are to be slightly adapted. From a development perspective, the considered level of granularity for service features and functions impacts the results and their interpretation.

7.6 Conclusion

Electric and autonomous mobility services can be viewed as Product Service Systems of Systems (PSSoS). Such systems are both PSS and SoS. They not only require the interoperability of independent and heterogeneous systems (e.g., Electric Vehicle, Electric Infrastructure, Servers, Services) but also the collaboration of independent stakeholders. We name them PSSoS stakeholders and define them as those developing, managing, and operating the PSSoSs component systems. Even though few studies consider PSSoSs, both the PSS and SoS literature are increasingly interested in stakeholder identification and analysis. However, most proposed (PSS and SoS) stakeholder analysis approaches are rather qualitative. In the meantime, quantitative stakeholder analysis approaches have been proposed by other research domains (e.g., management and design engineering) not necessarily addressing PSSoS stakeholders specifically. In order to address this gap, we propose a PSSoS stakeholder analysis approach in this chapter. The proposed approach is comprised of three stages: Building a multidimensional network based on the PSSoS ontology, constructing two PSSoS stakeholder unidimensional networks showing PSSoS stakeholder importance in business partnerships and development, and using network metrics to measure the influence of PSSoS stakeholders in business partnerships and development. We illustrate the use of this approach through the Plug and Charge service example and discuss its advantages for a PSSoS decision maker.

However, this research focuses on the automotive industry and mobility services. The interpretability of the results of the proposed approach in other domains is to be verified. Furthermore, the results and their interpretability highly depend on the data available as well as the model granularity. Both effects are to be studied in future work.

8 An approach for Systems of Systems change and failure characterization

Sarra Fakhfakh, Andreas Makoto Hein, Marija Jankovic, Yann Chazal

This paper has been published under the reference:

Fakhfakh, S., Hein, A. M., Jankovic, M., & Chazal, Y. (2020, October). Characterizing Systems of Systems change and Failure via network-based metrics. In Proceedings of the International Dependency and Structure Modelling conference (DSM)

Abstract: *A System of System (SoS) is a synthesis of independent systems functioning together towards a common goal. They are characterized by their dynamic nature and evolvability during operation: addition, removal, and modification of component systems and functions. It is, therefore, important to characterize the tolerance of such systems to changes and failures. Most change propagation and failure analysis methods require some knowledge of failure and change probabilities, failure modes, and design parameters, which is difficult to obtain or unavailable to an SoS decision-maker, as component systems are independent in their management and operation. Consequently, this chapter uses high-level SoS functional models and network-based metrics to characterize SoSs functions and assess the functional change and failure of such systems. The proposed measures are deployed on an electric vehicle to grid-related service to show how it can aid an SoS decision-maker during the system's development and operation.*

8.1 Introduction

New mobility services such as Electric Vehicle to Grid (EV2G), connected mobility, and autonomous vehicle services are becoming more and more important and complex. Such services are supported by systems (e.g., electrical grids and electric vehicles) and are developed, managed, and operated by various stakeholders (e.g., energy providers, car manufacturers, and service providers). These systems can be considered as Systems of Systems (SoSs). SoSs are defined as "a class of systems which are built from components which are large scale systems in their own right" (Maier, 1996). SoS are characterized by the operational and managerial independence of their elements, their evolutionary development, emergent behavior, geographic distribution (Maier, 1996), as well as the interoperability, complementarity, and holism of their Component Systems (CSs) (Keating and Katina, 2011). In essence, SoSs are a synthesis of distributed, heterogeneous, and independent CSs collaborating and functioning together towards a common goal (Petitdemange et al., 2018; Uday and Marais, 2015). By nature, SoSs are evolvable, and their design is dynamic as CSs and functions are added, removed, or modified during operations and runtime (Mohsin, Janjua, Islam, Vicente, et al., 2019; Petitdemange et al., 2018). Furthermore, SoSs operate in highly uncertain environments (e.g., new requirements or changing stakeholder needs) (Uday and Marais, 2015), leading to changes and failures in CSs functioning. Therefore, it is important to characterize the tolerance of such systems to changes and failures.

Various change and failure analysis methods have been proposed in the systems engineering literature. Failure mode and effect analysis (FMEA), Fault Tree Analysis (FTA), or Risk in Early Design (RED) are widely used failure analysis methods (Walsh et al., 2018). Among others, the Change Prediction Method (CPM) (Clarkson et al., 2004b) is a significant reference for change propagation analysis (Sarica and Luo, 2019). However, these methods require some knowledge of failure likelihood, change probabilities, and design parameters. Knowledge of changes and failures (e.g., probabilities) is difficult to obtain or unavailable for an SoS decision-maker due to the dynamic and evolving nature of SoS. Moreover, the CSs' design parameters and detailed descriptions are usually unknown to an SoS decision-maker because he/ she usually develops, manages, or operates a specific CSs. Besides, the mentioned methods focus on independent failures or changes and do not necessarily consider life cycle dependencies. In addition, they are computationally costly (Sarica and Luo, 2019; Uday and Marais, 2015; Walsh et al., 2018). These limitations are significant in the context of SoS development (Sarica and Luo, 2019) as (Luo, 2015) showed that design dependency cycles between components are one of the main causes of product evolvability.

The use of network-based metrics to analyze system change and failure propagations (Haley et al., 2016; Sarica and Luo, 2019) is increasingly recognized to address the gaps of usual methods. In this chapter, we propose to use network-metrics to characterize functional SoSs change and failure. For this purpose, we build a network of SoS functions based on high-level SoS functional descriptions.

Section 2 reviews the use of network-based metrics in characterizing systems change and failure propagation. In section 3, we show how to build a functional network based on SoS functional chains and how network-based metrics can be used. We deploy these measurements on an electric vehicle-related service use case in section 4. Finally, we conclude in section 5 and provide future research perspectives.

8.2 Literature review

The previously presented methods for analyzing changes and failures are rather limited when addressing SoS development. For SoS development, we argue that a method would need to have the following characteristics:

- ***(C1)*** *No knowledge of failure likelihood, change probabilities required:* Knowledge on failure likelihood and change probabilities is difficult to obtain in the context of SoSs development as CSs, and their functions change and evolve during runtime.
- ***(C2)*** *No knowledge of design parameters required:* Since CSs are independent, design parameters are not necessarily available to an SoS decision-maker.
- ***(C3)*** *Consider cycle dependencies:* Luo, (2015) showed that intercomponent design dependency cycles in system architecture give rise to product evolvability. As such, dependency cycles concern SoSs (Sarica and Luo, 2019).
- ***(C4)*** *Low computational cost*

In the following, we review network-based change and failure analysis methods. Table 8-1 shows how the network metrics they use address partly or fully these limits (Sarica and Luo, 2019; Uday and Marais, 2015; Walsh et al., 2019), and as such, can be relevant in the context of SoSs development.

Representing complex engineering systems as a network of interconnected components, node centrality metrics such as degree centrality and eigenvector centrality are used to characterize the tendency of a node (e.g., component) to propagate changes and failures. For example, Sosa et al., (2011) propose a method to identify hubs (defined as highly connected components) using product Design Structure Matrices (DSMs) and measuring node degrees. The authors empirically show that the presence of hubs in system architectures is associated with a low number of defects in response to changes. Chai et al., (2011) considered a networked infrastructure system in the context of oil and gas industries and used degree centrality measures to identify infrastructures that are most relied upon and, as such, might cause most significant cascading failures. To consider cyclic dependency between components, Sarica & Luo, (2019) use eigenvector centricity measures to characterize the influence and susceptibility of components to change. Eigenvector calculations–based measures have also been used by (Li et al., 2018) to identify influential function modules by considering function modules as the nodes of the network.

Other studies explore network metrics to characterize the overall robustness of a system (or an SoS) to the removal or loss of a node or an edge (e.g., a CS removal or an interaction loss between two CSs). For instance, Antul et al., (2017) represents an SoS as the network of its CSs and measures the algebraic connectivity to capture "a network's vulnerability to disconnection (e.g., removal of a CSs)." In a similar fashion, the robustness coefficient has been used in the literature (Haley et al., 2016; Paparistodimou et al., 2020; Walsh et al., 2019) and characterizes the largest connected component (connected nodes) after a node removal (e.g., removal of a CS in an SoS or the loss of a function). Paparistodimou et al., (2020) use the robustness coefficient to compare naval distributed engineering system architectures options. Walsh et al., (2019) use the robustness coefficient to explore the correlation between robustness and modularity. The Average Shortest Path Length (ASPL) is another metric that has been used to characterize the robustness of a network (a system) (Walsh et al., 2019). The ASPL measures the average shortest distance between two nodes in the network. As such, the ASPL describes the relative efficiency of a flow to travel throughout a network. The ASPL has been usually used to characterize the robustness of the overall network and compare nominal architectures and failed cases (after node removal) (Haley et al., 2016). In (Walsh et al., 2018), a variation in the ASPL is used to characterize the relative vulnerability of each node locally. A "vulnerable" node is defined as a node whose removal disconnects a large portion of the network or increases the ASPL. To evaluate the vulnerability of a system parameter, the authors measure the variation of the ASPL (ΔASPL) of a behavioral network (i.e., design parameters network) after the parameter node failure. The authors express a failure by decreasing the weights of all edges associated with that node. As such, the higher the ΔASPL is, the more vulnerable the parameter node is.

Succinctly, network-based change and failure analysis methods rely on local network-metrics (network centrality metrics) characterizing the tendency of each node to propagate change or failure, or global network-metrics characterizing the robustness of the overall network to changes or failures (e.g., Robustness Coefficient) (Table 8-1). Global network-metrics (ASPL) have also been adapted to characterize the local vulnerability of nodes (Walsh et al., 2018). Local and global metrics are complementary and address different purposes. Hence, both global and local network-metrics can be useful tools for analyzing and comparing different SoS architectures giving insights to an SoS decision-maker during the system's development and evolution.

Table 8-1: Characteristics of the most used network metrics in change and failure analysis methods

Network Metrics used in change and failure propagation methods		***Measures characteristics***			
		C1	***C2***	***C3***	***C4***
Local metrics	***Degree centrality***	x	x (depending on the considered network)		x
	Eigenvector centrality	x	x (depending on the considered network)	x	x
Global metrics	***Algebraic connectivity***	x	x (depending on the considered network)	x	x
	Robustness coefficient	x	x (depending on the considered network)		x
	ASPL	x	x (depending on the considered network)		x

The various studies of the literature use networks with different views of the systems, leading to different interpretations of the network metrics. The authors mostly consider networks of interconnected components (or CSs for SoSs). The interconnection or dependency between components might model spatial, structural, material, energy, or information dependencies. A component dependency is represented by a weighted or unweighted edge, depending on the intensity or type of dependency (Sarica and Luo, 2019). More recent publications considered networks of function modules built based on functional chains (Li et al., 2018) or behavioral networks based on mathematical details of the system's governing equations Walsh et al., (2018) (in which case the design parameters are required C2 Table 8-1). Thus, considering such networks in the context of SoS is worth exploring since they have rarely been considered in the literature.

The use of network-metrics is a promising avenue to analyze changes and failures in SoS development. However, SoS changes and failure include CSs and functionalities addition, removal, or modification during runtime, which distinguishes them from monolithic systems. Therefore, the interpretability of measures and results highly depends on both the systems specificities and the network used to model them. As most SoS network-based change and failure analysis methods consider a network of the CSs, we propose an approach to build an SoS functional network and justify its use. We also propose a use and an interpretation of local network-metrics to analyze such a network.

8.3 An approach for Systems of Systems functional change and failure characterization

8.3.1 SoS functional dependency matrix and network definition

In the following, we focus on functions and their dependencies as the main object of analysis, due to their practical relevance and the availability of SoS frameworks that are based on this perspective. From a practical perspective, an SoS decision-maker usually develops, manages, and operate a specific CS, or manages the overall SoS from a high-level perspective. Hence, SoS decision-makers do not have extensive knowledge on the structure of all CSs or their design parameters. They rather have a high-level representation of how CSs function together to achieve a common goal, mission, or service during development and operation. From a theoretical perspective, Luo, (2017)puts functions and functionality at the heart of SoS innovation and design. SoS development is described as the expansion of the thinking beyond the boundaries of independent systems and how the combination of the functions of individual systems can be synthetized to create a new functionality. Different SoS frameworks include functional representations for SoS (Fakhfakh, Hein, Chazal, et al., 2020) . For instance, functional chains represent functions and their logical and execution relationships (including information and energy flows for example). For these reasons, we rely specifically on SoS functional chains to build an SoS functional network.

Based on SoS functional chains, shown on the left of Figure 8.1, we define the SoS functions dependency matrix $A = [a_{i,j}]_{i,j \in [\![1,n]\!]}$, where n is the number of considered SoS functions. An element $a_{i,j}$ of matrix A is equal to 1 if function i requires the output of function j as its input and 0 otherwise. In other words, ($a_{i,j} = 1$) if the execution of function i depends on function j. Thus, A is a squared non-symmetric matrix. The graph G corresponding to the dependency matrix A is unidimensional, directed, and unweighted, as shown in Figure 8.1. Graph G represents an SoS functional network.

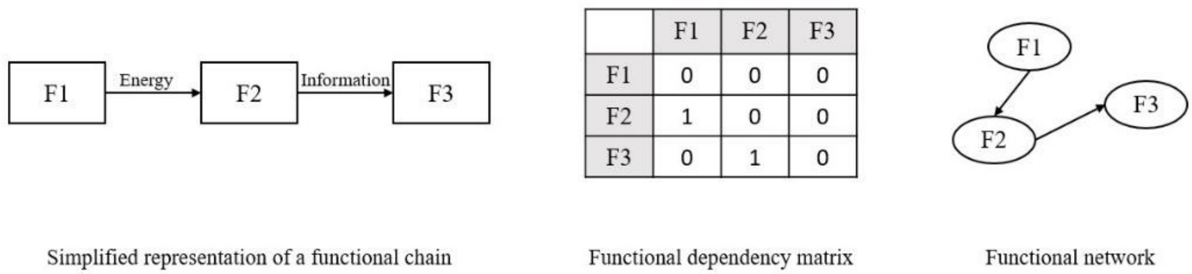

Figure 8.1: Building an SoS functional network from SoS functional chains

8.3.2 Network-based metrics to characterize SoS functional change and failure

8.3.2.1 Local centrality measures: characterizing the tendency of functions to propagate change and failure

In the following paragraphs, we detail the definitions of the local network-measures we considered for characterizing the tendency of functions to propagate change and failure and the impact a function's change or failure on the robustness of the network. We also propose an interpretation of such measures when looking at an SoS functional network.

- The ***degree centrality*** simply counts the number of edges linked to a given node. In the context of a directed network, we differentiate in-degree centrality and out-degree centrality. In-degree centrality counts the number of edges incident to the node (*nb_in_ed*) while out-degree count the number of edges linked to the node and pointing toward other nodes (*nb_out_ed*). Equations (1) and (2) give the formula for normalized in- and out-degree centrality measures. In general, in/out-degree centrality measures the importance of a node looking at its direct connections. Considering the SoS functional network, a high out-degree centrality value indicates that the function is highly relied-upon (i.e., provides inputs to many other functions) and might cause cascading changes and failures. A high in-degree centrality value reveals that a function highly relies on its neighbor functions and can be changed or can fail as soon as one of its neighbor functions undergoes a change or a failure.

$$DC_{in} = \frac{nb\_in\_ed}{n-1} \tag{1}$$

$$DC_{out} = \frac{nb\_out\_ed}{n-1} \tag{2}$$

Degree centrality considers direct links alike. Thus, it does not include the quality of the links or the cyclic dependency.

- The ***eigenvector centrality*** defines the node importance with respect to the importance of the nodes to which it is connected. The importance of node i (x_i) can then be written as (λ being a constant):

$$x_i = \frac{1}{\lambda} \sum_{j \in \Gamma(\mathrm{i})} x_j \tag{3}$$

With Γ(i) the neighborhood of node i.

The SoS functional network being directed, we differentiate node influence (i.e., function influence) and node susceptibility as suggested by (Sarica and Luo, 2019). The influence of a node is quantified by the number of edges pointing out to other nodes that are themselves influential (i.e., a function is as influential as it is highly relied-upon by functions that are themselves influential). The susceptibly of a function is proportional to the number of susceptible functions on which it relies on. Influential functions tend to propagate changes and failures in the networks, while susceptible functions are susceptible to changes and failures that are carried to them.

Replacing the importance of a node i (x_i) by its influence (p_i) and its susceptibility (q_i) in equation (3), it can be written in a matrix form as equation (4) and (5) for influence and susceptibility, respectively.

$$A^t \boldsymbol{p} = \lambda_p \boldsymbol{p} \tag{4}$$

$$A \boldsymbol{q} = \lambda_q \boldsymbol{q} \tag{5}$$

Where $\boldsymbol{p}$ and $\boldsymbol{q}$ are vectors of size n with $\boldsymbol{p}[i] = p_i$ and $\boldsymbol{q}[i] = q_i$ for $i \in [\![1, n]\!]$.

According to the Perron–Frobenius theorem, Eq. (4) and (5) have unique solutions (with non–negative indices p_i and q_i), which are the eigenvector corresponding to the largest eigenvalue λ_p and λ_q of A^t and A respectively. Both vectors $\boldsymbol{p}$ and $\boldsymbol{q}$ can be normalized as $(\frac{n}{\sum_{i \in [\![0,n]\!]} p_i} \boldsymbol{p})$ and $(\frac{n}{\sum_{i \in [\![0,n]\!]} q_i} \boldsymbol{q})$ (Sarica and Luo, 2019).

8.3.2.2 Topological dysconnectivity and ΔASPL: characterizing the impact a function's change or failure on the robustness of the network

In a network, a “vulnerable” node is such that its removal disconnects a large portion of the network or increases the ASPL (Walsh et al., 2018). Thus a “vulnerable” node is a node that diminishes the robustness of the network. In the context of SoS development, a change or a failure of a CS corresponds to the removal of a function (or multiple functions) or deterioration of functional dependencies. Such change or failure can jeopardize the overall functionality of the SoS. When a function is removed, its direct dependencies are also removed. The functional chain is consequently shredded and the overall SoS functionality may be lost. Similarly, when the functional dependencies are deteriorated, the functional chain and the overall SoS functionality may be degraded. Two options are considered to characterize the consequences of a change or a failure undergone by a specific function on the network. The first option is to consider the number of connected networks and the size of the largest connected network after its removal; The second option is to compute the ΔASPL after a deterioration of its direct functional dependencies materialize by a decrease in the weight of all edges linked to it from 1 to 0.5 (fault variable suggested by (Walsh et al., 2018)). Since, the aim is to assess the effect of the function deterioration on the overall robustness of the network, the network is considered undirected and incoming and outgoing edges are equivalent. Equation 6 reminds the ASPL formula ($d_{i,j}$being the shortest distance between node i and j).

$$ASPL = \frac{1}{n^2} \sum_{i,j \in [\![1,n]\!]} d_{i,j} \tag{6}$$

The higher the number of connected graphs generated by a function removal; the more effort can be expected to recover the overall functionality of an SoS. The more extensive the largest connected network, the more robust the network is to the function removal. Looking at the ΔASPL, higher values indicate that the function is more “vulnerable” compared to other nodes in the network. Thus, high ΔASPL indicates that a deterioration of a function’s dependencies (as a consequence of its change or failure) degrades the overall SoS functionality.

Both topological dysconnectivity and ΔASPL can be measured after the removal or deterioration of multiple functions, thus reflecting multiple changes or failures.

8.4 Network-Based metrics comparison and implications on a use case

We compute the local network-metrics introduced in section 3 on a functional network corresponding to an SoS related to Electric Vehicles (EVs). A car manufacturer, an energy provider, and eventually several service providers collaborate to offer EV charging service (Plug & Charge) in the context of Electric Vehicle to Grid (V2G) services (Chazal, 2018). Such a service is an SoS as it requires independent systems (CSs) (e.g., EV, charging stations, electricity grids, and service provision servers) to function together to provide the EV charging service. Based on the operational and functional descriptions of the service provision modeled in SysML, we counted 8 CSs performing 22 high-level functions to provide the service. We construct the functional dependency matrix and the functional network of the SoS from the available functional chains (Figure 8.1). Table 8-1 presents the values of in- and out-degree centrality and eigenvector centrality measures (influence and susceptibility score). It also gives the number of connected networks and the size of the largest connected network after the function removal and the ΔASPL after the deterioration of the function direct dependencies. In both Figure 8.2 and Table 8-2, CSs and CSs functions are identified by their Ids.

According to the results in Table 8-2, most functions have the same tendency to propagate changes and failures to their neighbors. The same tendency can be observed for functions to undergo a change or a failure when the neighbor functions change or fail (in-degree equals out-degree for functions 1,2,3,4,5,11,12,15,16,18, and 22). Function 6 highly relies on its neighbor functions and, as such, is highly susceptible to its neighbor functions changes and failures. On the contrary, function 10 presents a high out-degree centrality measure and can cause cascading changes and failures to its neighbors. Since the considered directed network Figure 8.2 does not present cycles and has low connectivity, influence and susceptibility indicators do not allow to clearly differentiate functions (function 7 being the most influential and function 6 the most susceptible).

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
1		1																				
2				1																		
3	1																					
4							1															
5			1																			
6					1					1	1								1			
7																						
8																						
9							1															
10								1												1		1
11										1												
12										1												
13												1										
14																						
15														1								
16															1							
17																			1			
18																1						
19										1								1				
20																						
21																						
22																					1	

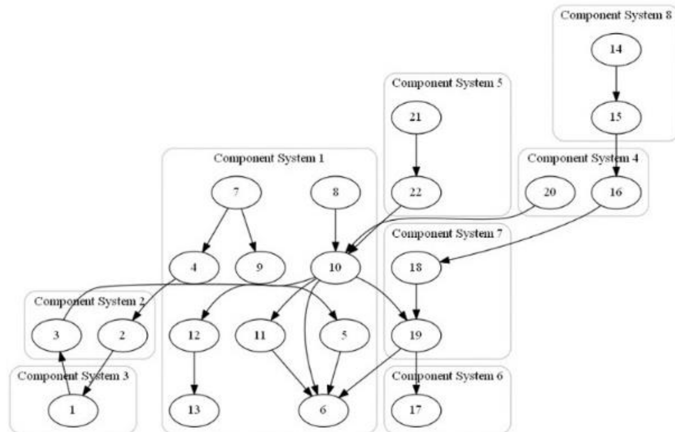

Figure 8.2. SoS functional dependency matrix and corresponding functional network

Besides, changes or failures of functions with high ΔASPL values (functions 10, 6, and 5, for example) are likely to degrade the SoS overall functionality. Functions 10 and 19 seem critical as their removal disconnects the network in 5 and 3 connected networks, respectively. Such disconnection might involve a significant effort to retrieve the overall SoS functionality. Both the removals of functions 6 and 7 disconnect the network into 2 connected networks. However, the largest connected networks caused by the removal of function 7 is larger than that caused by the removal of function 6 (20 and 14 nodes). This might indicate that the removal of function 6 has a larger impact on the overall network robustness than the removal of function 7.

Therefore, these measures allow the identification of functions critical to the propagation of change and failure or functions whose change or failure degrades the overall functionality of the SoS. During the SoS early design stages, such measures allow the SoS decision-makers to prioritize the redevelopment of critical functions or allocate them to CSs of which they control the management and operation. Furthermore, local network-metrics complemented by global-network metrics can be used to compare different SoS functional architectures and assess "what-if" scenarios. Thus, network-metrics can aid SoS decision-makers to identify which SoSs are worth getting involved in. During operation and runtime, these measures help track the critical functions as the system evolves.

Table 8-2: Network metrics measures for the considered EV related SoS functional network

Id	In-degree	Out-degree	Influence Indicator	Susceptibility Indicator	ΔASPL	Nb of disconnected networks	Size of the largest connected network
1	0,048	0,048	0	0	0,340	2	17
2	0,048	0,048	0	0	0,279	2	18
3	0,048	0,048	0	0	0,392	2	16
4	0,048	0,048	0	0	0,210	2	19
5	0,048	0,048	0	0	0,435	2	15
6	0,190	0	0	22	0,496	2	14
7	0	0,095	22	0	0,132	2	20
8	0	0,048	0	0	0,045	1	21
9	0,048	0	0	0	0,045	1	21
10	0,143	0,190	0	0	0,517	5	15
11	0,048	0,048	0	0	0,045	1	21
12	0,048	0,048	0	0	0,132	2	20
13	0,048	0	0	0	0,045	1	21
14	0	0,048	0	0	0,045	1	21
15	0,048	0,048	0	0	0,132	2	20
16	0,048	0,048	0	0	0,210	2	19
17	0,048	0	0	0	0,045	1	21
18	0,048	0,048	0	0	0,279	2	18
19	0,095	0,095	0	0	0,409	3	16
20	0	0,048	0	0	0,045	1	21
21	0	0,048	0	0	0,045	1	21
22	0,048	0,048	0	0	0,132	2	20

8.5 Conclusion and Future work

In this chapter, we use an SoS functional network and measure degree and eigenvector centrality to characterize the influence or susceptibility of a function to change and failure propagation in its direct neighborhood and the network in general. We also assess the tendency of the SoS to maintain its functionality after a function removal or a function deterioration. Through an example on an EV related SoS, we show that such measures are complementary and can aid an SoS decision-maker during the SoS development or runtime. However, further industrial applications are to be analyzed to confirm the usefulness of network-metrics. Other network-metrics, including global metrics, can be used in the analysis of SoS evolution, including changes and failures. Furthermore, theoretical work is still to be done to better understand the possible uses of graph theory in SoSs, specifically in terms of results interpretation. This is all the more important as SoSs involve not only heterogeneous and independent systems and their functionalities but also independent stakeholders. Therefore, they can be modeled as multilayer networks.

9 Conclusion

In this chapter, we summarize the research work: context, aim, and contributions. We also discuss each contribution and its limitations and summarize the implications of this PhD for research and industry. Finally, we give directions for future research.

9.1 Summary

This thesis focuses on transportation and mobility solutions related to connected automotive vehicles such as vehicle to grid or vehicle ride-hailing solutions in the context of urban mobility solutions. New transportation and mobility solutions raise the challenges of collaborative business models and portfolio development, collaborative concept and value proposition, as well as collaborative development and architecture of products and services (heterogeneous elements).

As this thesis falls within the design engineering research, it addresses concerns related to the increasing complexity and servitization phenomena by studying Product Service Systems of Systems. This PhD has also been conducted within the research department of a car manufacturer. Hence, it aims to support PSSoS development in the context of new mobility services for a car manufacturer.

For this purpose, we reviewed the literature pertaining to both servitization and increasing systems complexity and identified design engineering research gaps. Cross referencing the research gaps and industrial needs, three research questions have been defined and addressed through contributions. Table 9-1 summarizes the research gaps, industrial needs, research questions, and contributions.

This research work studies PSSoSs from three perspectives: **characterization**, **modeling**, and **analysis**.

Concerning the **characterization**, to our knowledge, the literature review showed that the concomitant study of increasing complexity and servitization had not been done. In the company, this characterization presents a real need. This is why *the first research question* is: How can we characterize PSSoS and PSSoS development? *Contribution 1* “A PSSoSs characterization framework” is presented in chapter 5 and summarized in the following section 9.2., paragraph 9.2.1.

As for PSSoSs **modeling**, PSS and SoS modeling approaches present two complementary perspectives (PSS modeling focusing on the heterogeneity of product and service elements and the value co-creation with the customer, and SoS modeling focusing on the complexity of the relationships between component systems and enterprises) that needed to be brought together. Since a PSSoS holistic ontology was lacking within the industrial context, the *second research question* is: How can we model PSSoSs? This PhD work's *second contribution* is the PSSoS ontology presented in chapter 6 and summarized in the following section 9.2., paragraph 6.2.2.Finally, PSSoSs characteristics: the uncertain environment and multiplicity of PSSoS stakeholders have been identified as relevant issues to be **analyzed** within the industrial context. However, existing analysis approaches do not specifically address PSSoSs. The *3rd research question* and *sub-questions* are: How can we assist in PSSoSs development and support PSSoS decision-makers? How can we characterize and quantify the importance of stakeholders in PSSoS development and operation? How to characterize the exposure and vulnerability of PSSoS functions to PSSoS Uncertainties? Two contributions tackle these issues: *contribution 3.1.* "A PSSoS stakeholders analysis approach" is presented in chapter 7 and *contribution 3.2.* "An SoS functional failure and change analysis approach" is presented in chapter 8. *Contributions 3.1.* and *3.2.* are summarized and discussed in the following section 9.2., paragraphs 9.2.3. and 9.2.4.

As a reminder, the **research gap 2** (PSS literature lacks evidence on what PSS models to use in a specific industrial context, or for a specific PSS type.) is addressed in the paper entitled "A review of Product Service Systems (PSS) modeling approaches using the Function-Structure-Behavior framework" and presented in appendix A. The author chose to present the paper as a complementary material because it addresses PSS modeling and not necessarily PSSoSs.

Table 9-1: Mapping research gaps, industrial needs, research questions, and contributions

	Research Gap	***Industrial Need***	***Research Question***	***Contribution***
PSSoS Characterization	**Research Gap 1:** PSSs, SoSs, CPSs have rarely been studied concomitantly even though the servitization, increasing complexity, and increasing software content are happening at the same time in real-life examples.	A need to better characterize diverse services (developed or t be developed) and therefore PSSs and PSSoSs	**Research Question 1:** How can we characterize PSSoSs and PSSoSs development? **Sub-question 1.1:** What are the characteristics of PSSoSs? **Sub-question 1.2:** What are the challenges for PSSoSs development?	**Contribution 1:** Towards an uncertainty framework for Product Service Systems of Systems

	Research Gap	***Industrial Need***	***Research Question***	***Contribution***
PSSoS Modeling	**Research Gap 3:** PSS models rarely take into consideration the increasing complexity and the potential independence of PSS elements.	A need for a common ontology	**Research Question 2:** How can we model PSSoSs? **Sub-question 2.1:** What information is needed to describe a PSSoS? **Sub-question 2.2:** How to organize PSSoS descriptive information?	**Contribution 2:** An ontology to support Product Service Systems of Systems Engineering
	Research Gap 4: SoS models focus on the complexity of the relationships between component systems. The “heterogeneity” of component systems (products and services) is not necessarily considered.			
PSSoS Analysis	**Research Gap 5:** PSS literature and SoS literature lack quantitative methods for uncertainty and change analysis. Existing methods in systems and design engineering research do not necessarily address systems that are both PSSs and SoSs.	A need to characterize PSSoS collaboration and co-creation environment	**Research Question 3:** How can we assist PSSoS development and support PSSoS decision-makers? **Sub-question 3.1:** How can we characterize and quantify the importance of stakeholders in PSSoS development and operation? **Sub-question 3.2:** How to characterize the exposure and vulnerability of PSSoS functions to PSSoS Uncertainties?	**Contribution 3.1.:** An analysis of PSSoS Stakeholders importance and influence in business partnerships and development
	Research Gap 6: PSS literature and SoS literature lack quantitative methods for stakeholder analysis. Existing methods in management and organization research do not necessarily address systems that are PSSs and SoSs	A need to comprehend the evolution of PSSs and PSSoSs		**Contribution 3.2.s:** An approach for Systems of Systems functional change and failure characterization

In the following section 9.2., we summarize the contributions, their validity, and limitations. Section 9.3. synthesizes the research and industrial implications of the present work. Finally, section 9.4. gives perspective for future research.

9.2 Discussion: Contributions and limitations

9.2.1 Contribution 1: Product Service Systems of Systems characterization

Since PSSs and SoSs have been studied separately in the literature, characterizing PSSoSs and their development was an important initial step towards supporting PSSoSs development. The literature on PSSs and SoSs provides a characterization of the systems as well as a typology. By definition, the PSS literature focuses on the servitization process, whereas the SoS literature on the increasing complexity of systems. For this reason, we proposed a two-dimensional framework enabling us to characterize and classify PSSs and PSSoSs. Transportation and mobility examples have been mapped within this framework. Furthermore, the literature on both PSSs and SoSs pointed out their uncertain environment either because of the heterogeneity of the constituent elements (e.g., products and services) or the constituent systems' independence. Based on types of uncertainty identified in the literature and an industrial diagnosis, uncertainties specific for PSSoSs have been identified. The validity of the proposed framework and the identified uncertainties has been done through expert validation in the automotive industry and other industries through participation in meetings of the French INCOSE chapter (AFIS).

The proposed framework is based on commonly used PSSs and Systems classifications, namely Tukker's typology of PSSs (Tukker, 2004) and the taxonomy of increasingly complex systems proposed by Baldwin et al., (2011). Because it is based on largely adopted classifications in different research areas, the proposed framework is also useful in business management and design engineering domains in research and industry. As discussed previously, the proposed PSSoS framework initiates the concomitant research on servitization and increasing complexity.

The proposed PSSoSs characterization framework is based on specific PSS and SoS classifications. Since other PSSs and SoSs classifications exist in the literature, other characterization frameworks can be thought of exhibiting other PSSoSs features. Concerning the PSSoS framework and uncertainties, this research is based on observations within a car manufacturer, and a number of transportation and mobility solutions have been studied. Therefore, the scope of their applicability is, for now, **limited** to transportation and mobility field. Hence, other PSSoS uncertainties specific to other fields can be identified.

9.2.2 Contribution 2: Product Service Systems of Systems ontology

PSS and SoS models have been developed separately. In the background literature, we showed that PSS models rather focused on the value co-creation and the design and architecture of heterogeneous elements, mainly products and services. These models went from business models to lifecycle and process models. On the other hand, the SoS literature provided architecture frameworks focusing on the complexity of independent component systems and enterprise relationships. Therefore, a representation of PSSoSs, combining both perspectives, was required. However, it was not clear what model to use. For example, what PSSoS elements should be represented? At what granularity? For what use?

Since the industrial diagnosis highlighted a need for a common ontology between system engineers and service designers, we chose to build a high level and holistic representation of PSSoS usable from both perspectives. Moreover, the studied case studies were collaborative use and result oriented PSSoSs. Hence, we aimed to address these types of PSSoSs. The proposed PSSoS ontology has four views: the stakeholder, service, operational, and system views. A set of criteria has been defined a priori to ensure its quality: complete, consistent, simple, understandable, easy to implement, representing industrial examples and extendable. The proposed ontology was validated according to the defined quality criteria through case studies and expert validation.

Giving a big picture of PSSoS is the prominent benefit of the proposed ontology. As such, it permits system engineers and service designers to share their knowledge on the PSSoSs. It also enables to share knowledge between service and business departments and engineering departments.

However, the proposed ontology is **limited** regarding other perspectives. It requires minimal knowledge of model-based systems engineering (MBSE) and its related tools, making it less accessible outside engineering departments, for example, in business development and service design departments. Even though the PhD student tried to ensure the coherence between the proposed ontology and other ontologies in the company, further work should be done to validate the coherence and connect different MBSE tools. From a rather organizational point of view, identifying the role capable of instantiating the proposed ontology is still to be done. From a rather academic perspective, the scope of validity of the proposed ontology beyond mobility solutions and collaborative use and result oriented PSSoSs is to be addressed.

9.2.3 Contribution 3.1.: Product Service Systems of Systems stakeholders analysis

Studying the importance and influence of independent PSSoS stakeholders has been identified as an essential concern for the automotive industry. However, existing stakeholder analysis approaches in the management and design literature did not specifically address PSSoS stakeholders. In this PhD, we contribute by proposing a PSSoS stakeholders analysis approach addressing PSSoS business partnerships and development. The proposed approach considers a PSSoS multidimensional network built upon the PSSoS ontology. In order to ensure the interpretability of data, two unidimensional PSSoS stakeholders' networks have been constructed: a PSSoS stakeholders business partnerships network and a PSSoS stakeholders development involvement network. Different metrics are then defined to quantify PSSoS stakeholder importance and influence. A case study has been used to show the usability and validity of the approach.

The proposed analysis approach addresses specifically PSSoSs and their characteristics. It also provides a PSSoS decision-maker (e.g., a car manufacturer) with key indicators on the importance and influence of the PSSoS stakeholders he/she collaborates with or will collaborate with. Such indicators are relevant both during the design and operation of PSSoSs component systems. During design, these indicators can help identify functionalities to be redesigned to limit PSSoS business and development partners' influence. During operations, such measures can be used to monitor the evolution of the component systems managed by a PSSoS stakeholder. From a practical perspective, the proposed approach does not necessarily require a broad set of descriptive data, and measures are relatively simple to compute.

However, the proposed PSSoS stakeholder analysis approach remains **limited**. The measures and their interpretation (importance and influence) were derived from a car manufacturer's needs in developing mobility and transportation solutions. As such, they represent the car manufacturer's point of view, and their usefulness for other PSSoS stakeholders (e.g., a service provider) is yet to be confirmed as projects are developed. From a technical perspective, the proposed approach is based on a network representation of PSSoS and information aggregation. The results highly depend on the initial data and its granularity. Because of the multidimensional nature of the network, there is also a need to aggregate information. The aggregation necessarily leads to information loss. This information loss needs to be carefully identified and managed through the analysis process.

9.2.4 Contribution 3.2.: An approach for Systems of Systems functional change and failure characterization

Another concern of the company is to analyze how uncertainty (materialized by changes) propagate in the context of PSSoSs and how PSSoSs elements behave with regards to uncertainty. This concern is difficult to address for mainly two reasons. First, the uncertainty in the context of PSSoSs initiates and propagates in different levels: PSSoS stakeholders collaboration, service delivery, systems functioning, or systems structure (Fakhfakh et al., 2019). In the literature, change propagation in such a multidimensional context is rarely addressed (Afshari et al., 2016; Keshavarzi et al., 2017). Second, because PSSoSs component and stakeholders are independent and because PSSoSs are evolutive, a PSSoS decision-maker (e.g., a car manufacturer) rarely has complete knowledge of the PSSoSs component systems architecture or stakeholders' intentions. Information such as change probability or likelihood is not available.

In the context of this thesis, addressing these gaps has been initiated. Chapter 8 proposes an approach to analyze the systems of systems functional change and failure characterization. This approach uses network metrics to characterize the tendency of functions to propagate change and failure and the impact of their change or failure on the SoS functional network's overall robustness. The proposed approach's usability has been shown through the use case: the plug and charge service.

The evident advantage of the proposed approach is that it only requires a description of how SoS component systems function together to provide an overall capability or service. For a PSSoS decision-maker, the proposed approach is relevant prior, during SoS design and operation. Prior to the detailed design, the proposed approach can support which SoSs are worth getting involved in. It can be used during design to redesign the system architecture (functional architecture, and functional allocation to components). As the approach is not computationally costly, it can be used to simulate "what if" scenarios. During SoS operation, it helps track the critical functions as the system evolves.

The proposed approach is **limited** because it does not consider the multidimensionality of SoSs or PSSoSs and focuses on a functional representation of such systems.

9.3 Implications

9.3.1 Implications for research

From an academic perspective, the key implications of this PhD are:

- The literature studied PSSs and SoSs separately. The PSS literature focused on the heterogeneity of product and service elements as well as the value co-creation with the customer. The SoS literature investigates the complexity of the relationships between constituent systems and their management by independent stakeholders. This research argues that both perspectives are to be studied concomitantly. Moreover, systems that are both PSSs and SoSs have specific characteristics. This research contributed to initiating the work on PSSoSs.
- This research provided several approaches allowing to characterize, model, and analyze PSSoS considering their specific characteristics. We specifically considered PSSoSs elements' heterogeneity and their independence, the multiplicity of independent stakeholders, and PSSoSs uncertain environment.
- Besides, the PSSoS characterization framework described in section 5 shows the diversity of PSSs and PSSoSs types. The complementary study presented in Appendix A contributes to demonstrating that modeling and analyzing PSSs highly depends on their types and development contexts (e.g., new mobility, administration). Even though the present research work proposes approaches to support collaborative use- and result-oriented PSSoSs development, it stresses the importance of reflecting on types and contexts of the development of PSSoSs to adapt proposed approaches.

9.3.2 Implications for industry

We summarize the implications of this research for industry (a car manufacturer specifically) as follows:

- This research can be considered a starting point for supporting PSSoSs architects in designing PSSoSs and their constituent systems. The proposed approaches allow PSSoSs architects to represent, analyze, and evaluate the characteristics of a given PSSoSs. These approaches can also be extended into a tool to structure and analyze information on PSSoSs.
- For a PSSoSs decision-maker, the proposed approaches are useful both during design and operation. During design, the ontology permits to describe simply and holistically the PSSoSs. The PSSoS stakeholder analysis approach allows for identifying important and influential collaborators in business partnerships and development. Finally, the SoS functional analysis method helps identify

vulnerable parts of the system under development. Business and development strategies can be derived from such an analysis. Through the modeling of "what-if scenarios," a PSSoS decision-maker can also keep track of the evolution of the PSSoSs during operation. Simulation and monitoring tools can be further developed based on the proposed approaches.

9.4 Directions for future research

During this PhD thesis, the research questions partly addressed the identified research gaps (Chapter 2). The answers to the research questions were oriented according to the industrial context. The development and validation of the contributions were done according to the availability of experts, project teams, data, and time. Therefore, the contributions and their validity are limited (section 3.2.) and can be further developed and extended. In the following paragraphs (9.4.1. and 9.4.2.), directions are given for future work to complement the contributions and further address the research gaps.

The present research work focused on specific types of PSSoS: collaborative, use- and result- oriented. Besides, it only considered the perspective of car manufacturers in mobility and transportation. Paragraph 9.4.3. provides perspectives on the generalization of the proposed approaches.

9.4.1 Evaluation and validation

An initial validation of the proposed approaches has been conducted, including case studies and expert validation. However, due to the novelty of the developed urban and mobility solutions, eight exploratory case studies with a limited amount of data were considered and one descriptive case study was used with a richer data but not enough to further demonstrate the interest of the proposed approaches. In future work, a larger number of case studies with more detailed information (business, value, architecture, and stakeholders) should be considered to validate the proposed approach. Furthermore, the proposed approaches should be introduced within the industrial context (on a concrete project) to evaluate their dissemination (Eckert et al., 2003).

9.4.2 Extensions towards a PSSoS design methodology

This PhD thesis proposes a set of approaches to support PSSoS development within a car manufacturer towards new mobility solutions. We believe these approaches to have the potential to be extended and tooled to constitute a PSSoS design methodology.

As for the PSSoS representation model (i.e., ontology), it is to be extended to include systems lifecycles and processes. It is also essential to integrate and interface it with other MBSE tools within the company from an industrial perspective. Besides, the proposed ontology is a static representation of PSSoS key concepts. However, PSSoSs are dynamic and evolve throughout their operation. Therefore, the proposed PSSoS ontology can be used as a basis for the development of a PSSoS behavior simulation model. To do so, one can think of using a formal modeling language for PSSoS representation, for example, networks.

Concerning the evolutionary nature of PSSoSs, this PhD also showed the importance of uncertainty in developing PSSoSs covering changes and failures. For future work, a PSSoS-specific uncertainty model and qualitative and quantitative methods for PSSoS change and failure propagation and analysis can be developed. The particularity (and novelty) of such models and methods is to consider the multidimensionality of PSSoSs, including stakeholders, services, functionalities, and component systems.

The proposed PSSoS stakeholders and PSSoS functional change and failure analysis approaches initiate the representation of PSSoSs as networks, as well as the consideration of PSSoS multidimensionality. On the one hand, we consider network theory to be a good theoretical basis for PSSoS analysis in general terms. On the other hand, the multidimensionality of networks raises interpretability issues. An interesting research avenue is, therefore, to investigate the theoretical background of multidimensional network analysis. Moreover, the study of networks clearly requires the collection of sufficient data for the analysis. A recommendation for industry is to initiate data collection related to key PSSoS concepts in a single database. This will consequently allow the combination of design research and data science approaches in the analysis of PSSoSs.

Practically, we suggest developing a platform extending and tooling different approaches usable by different stakeholders within the company, for example, service designers and systems engineers.

Furthermore, other complementary studies can address the PSSoS business and portfolio development concerns, such as collaborative PSSoS business modeling, including cost and revenue modeling.

9.4.3 Generalizability

PSSoSs are of different types. This research work focused on collaborative use and result oriented PSSoSs. The potential generalizability of the proposed approaches across other types of PSSoSs, for example, virtual result oriented PSSoSs (e.g., administrative online services), is to be studied.

Besides, the concept of PSSoSs is not restricted to mobility and transportation solutions. As PSSoS materialize the servitization, increasing complexity and software content phenomena, administration, safety, energy, economy, healthcare, education, housing, and welfare urban solutions can be treated as PSSoSs. Therefore, the generalizability of the proposed approaches to other domains constitutes another research avenue. For instance, because energy and housing solutions are usually developed similarly to transportation solutions (they involve the manufacturing or construction of a product, and therefore, involve the value chain role of the manufacturing or construction company). , these domains (energy and housing)could be considered in the near future. Administration, health care, and education urban solutions are different from mobility solutions because they involve other types of stakeholders (e.g., governments, states) and present other value chains. Therefore, a specific diagnosis of each of these domains' specificities is required before the generalization of the proposed approaches. This implies a great deal of empirical and fieldwork. Thus, we envision addressing these areas in a more distant future.

Appendix A- A review of Product Service Systems (PSS) modeling approaches using the Function-Structure-Behavior framework

S*arra Fakhfakh, Marija Jankovic, Michael Kokkolaras, Andreas Makoto Hein, Yann Chazal*

This paper is a working paper to be submitted.

Abstract: *To remain competitive, the traditional manufacturing industry develops new business strategies and diversifies its sources of value by offering services along with manufactured products. Such systems are in the literature referred to as Product-Service Systems (PSS). Because of their strategic importance for the manufacturing industry, PSSs have been the subject of interest of several research streams: business and management, Information systems, and Engineering and Design. As such, extensive literature exists on how to characterize, design, develop, and sell PSSs. However, if the literature acknowledges the diversity of PSSs development contexts and distinguishes product-oriented, result-oriented, and use-oriented PSS an explicit reference to which PSS modeling to use in which context seems to be lacking. To address this gap, the present study reviews PSS modeling approaches and proposes to classify them regarding to different PSS development contexts. In order to understand the genericity of these modelling approaches, the Function, Structure, Behavior (FBS) framework is used as a backbone to classify PSS modeling approaches.*

A.1 Introduction

The manufacturing industry develops new business strategies and diversifies its sources of value by offering services along with manufactured products. Such systems are called Product Service Systems (PSS). A PSS is a bundle of products, services, infrastructure, and supporting network (Mont, 2002). PSS value is in the use of the product rather than its ownership (Baines et al., 2007). As such, PSS offerings increase customer satisfaction and retention. PSS offerings also increase the competitiveness of manufacturing companies. Moreover, PSSs appear to have a lower environmental impact than traditional businesses (Beuren et al., 2013). Developing PSSs is can be seen as beneficial in many ways and, consequently, is of strategic importance. Several research streams have been focusing on PSS; Business Management, Information Systems and, Engineering and Design (Boehm and Thomas, 2013). An extensive literature exists on PSSs and, several consequent literature reviews have been published (Andriankaja et al., 2018; Annarelli et al., 2016; Baines et al., 2007; Becker et al., 2010; Beuren et al., 2013; Boehm and Thomas, 2013; Cavalieri and Pezzotta, 2012; Cedergren et al., 2012; Goedkoop et al., 1999; Haase et al., 2017; Lindahl et al., 2009; Mahut et al., 2015; Malik et al., 2019; Mont, 2002; Nilsson and Lindahl, 2016; Pieroni et al., 2017; Piontek and Müller, 2018; Qu et al., 2016; Reim et al., 2015; Sabbagh et al., 2016; Song, 2017; Tukker, 2004, 2015; Vasantha et al., 2012; Velamuri et al., 2011; Vezzoli et al., 2015; Wang, Ming, Li, et al., 2011). PSS literature aims at understanding the drivers for PSS development. It also focuses on characterizing such systems. Considerable research contributes to PSS development methods and methodologies. Other research investigates PSS development in industry. Moreover, the PSS literature underlines the diversity of PSSs types and development contexts. Tukker’s (Tukker, 2004) PSS topology is frequently used in the literature and distinguishes Product-oriented PSS, Use-oriented PSS and, Result-oriented PSS. Despite the considerable literature on this topic and the clear distinction between PSS types, to our knowledge there is no research specifically addressing types of the PSS modeling to be used in a given context (e.g., if a particular PSS modeling approach is more suited for use-oriented PSS or more product-oriented PSS). To address this gap, this research aims at reviewing existing PSS modeling approaches and at proposing a classification with regard to different development contexts. Different frameworks have been proposed to define and explain design methodologies and support design activities such as design thinking etc. Because of its genericity and applicability, the Function, Structure, Behavior (FBS) framework is used as a backbone for the classification of PSS modeling approaches. Three major modelling approaches have been identified in the literature and analyzed with regard to the development contexts that have been described and discussed in papers.

We propose the following structure of the paper. In section A.2, a overview of existing PSS literature reviews has been detailed and the need for a review on PSS modeling approaches is discussed and argued.

In section A.3, we detail the methodology used for PSS modeling approaches analysis. Section A.4 details the classification of PSS modelling approaches that had been identified in the literature and their positioning with regard to the FBS framework. Section A.5 presents the limitations of the proposed classification. Finally, we conclude in section 6 by providing future research avenues.

A.2 Existing literature surveys on PSS

PSS has been the object of different research streams (Boehm and Thomas, 2013; Velamuri et al., 2011) and there has been a constant growing interest in characterizing, modeling and supporting PSS development. Considerable literature exists on this topic as well as several consequent literature reviews (Andriankaja et al., 2018; Annarelli et al., 2016; Baines et al., 2007; Becker et al., 2010; Beuren et al., 2013; Boehm and Thomas, 2013; Cavalieri and Pezzotta, 2012; Cedergren et al., 2012; Goedkoop et al., 1999; Haase et al., 2017; Lindahl et al., 2009; Mahut et al., 2015; Malik et al., 2019; Mont, 2002; Nilsson and Lindahl, 2016; Pieroni et al., 2017; Piontek and Müller, 2018; Qu et al., 2016; Reim et al., 2015; Sabbagh et al., 2016; Song, 2017; Tukker, 2004, 2015; Vasantha et al., 2012; Velamuri et al., 2011; Vezzoli et al., 2015; Wang, Ming, Li, et al., 2011). Although there is a considerable literature on this topic, to our knowledge there is no research specifically addressing PSS models and modelling approaches to be used for a given development context (e.g. if one model is more used for a use-oriented PSS or more product-oriented PSS). The aim of this research is to identify PSS model classes with regard to existing literature and analyze what model is more relevant to which PSS development context. The overarching objective is to propose adequate support for PSS design so that design teams can identify what model can be used for a given context.

Many literature reviews exist related to PSSs. Our initial research focuses on those literature reviews and attempts to identify if there is a specific literature review pertaining to the question of adapting PSS models to different the PSS types. We propose to classify these literature reviews in several categories:

- Literature reviews focusing on PSS definitions and characterizations aiming to answer the question *What is a PSS?*
- Literature reviews focusing on PSS development drivers aiming to contribute to the question of *Why designing PSSs?*
- Literature reviews focusing on PSS development methods contributing to the knowledge of *How to design PSSs?*
- Literature reviews focusing on PSS development in the industry aiming at answering the question of How are PSSs developed in the industry?

In order to give an overview of existing literature reviews and underline why there is a need for yet another study in the PSS modeling in design, in following sections (A.2.1, A.2.2, A.2.3, A.2.4) we propose to give an overview of these studies and key findings underlined by them.

A.2.1 Literature reviews on PSS definitions and characterizations

Baines et al. (Baines et al., 2007) reviewed the PSS literature between 1995 and 2006, and focused on PSS origins and definitions. Authors emphasize that the concept of PSS originated in the northern Europe in the late 1990s. The main contributors were academics from environment and social sciences and published mainly in the Journal of Cleaner Production. The authors underline that the concept of PSS is a special case of servitization where the value is in the utilization rather than the ownership. The integration of products and services provides value in use to the customer. Baines at al. (Baines et al., 2007) conclude that the first PSS definition given by Goedkoop et al. (Goedkoop et al., 1999) is broadly adopted in the literature: *"product(s) and service(s) combined in a system to deliver required user functionality in a way that reduces the impact on the environment"*. The literature before 2006 also provides a shared PSS categorization (Tukker, 2004). This PSS categorization, proposed by Tukker, distinguishes product-oriented PSS, use-oriented PSS, and result-oriented PSS by whether the value is determined by the product or the service component.

In (Tukker, 2015), authors argue that the literature after 2006 did not change the essence PSS definition and characterization, but refined it (Cedergren et al., 2012; Gaiardelli et al., 2014; Lay et al., 2009; Van Ostaeyen et al., 2013; Park et al., 2012; Waidelich et al., 2019). According to Haase et al. (Haase et al., 2017), the most referenced PSS definition by 2015 is the definition provided by Mont (Mont, 2002): *"A system of products, services, supporting networks and infrastructure that is designed to be: competitive, satisfy customer needs and have a lower environmental impact than traditional business models"*. A PSS is then defined by its constituent elements and potential benefits. Beuren et al. (Beuren et al., 2013) further detailed PSS key elements as: (i) the product; (ii) the service, in which an activity is performed without the need for a tangible good or the need for the system; and (iii) the combination of products, services, and their relationships. In Haase et al. (Haase et al., 2017), authors identified among PSS characteristics: customers' needs satisfaction and value creation, environmental impact reduction, and competitiveness. These characteristics are classified by Beuren et al. (Beuren et al., 2013) as PSS customer benefits, PSS provider benefits, PSS environment, and society benefits respectively.

PSS benefits show how combining products and services is of strategic importance (Velamuri et al., 2011). Velamuri et al. (Velamuri et al., 2011) explain the increase of the literature and terms used to describe the phenomenon of combining products and services to its strategic importance. Authors classified research areas studying PSSs, covering an extensive literature related to PSS and other related concepts: strategic view, organization view, marketing view, design view, innovation view, business level view, sustainability aspects, and macroeconomic perspective. Analyzing the number of publications per category between 1995 and 2010, the authors showed that most publications were within the PSS business level research category by 2010.

A.2.2 Literature reviews on the benefits of PSSs

Some PSS literature reviews focus on their benefits, and more specifically, sustainability and competitiveness. In 2004, Tukker (Tukker, 2004) defines sustainability as fulfilling needs with minimal material use and emissions. PSS sustainability "depends on whether a PSS is less material intensive, and whether actors in the chain feel incentives to lower material intensity even more" (Tukker, 2004). Based on the former definition, Tukker (Tukker, 2004) suggests a mechanism to characterize the sustainability of different types of PSSs. As a conclusion, the author claims that PSS development will not automatically result in an environmental–economic win-win situation. Later in 2015, Vezzoli et al. (Vezzoli et al., 2015) discuss sustainable PSS implementation and diffusion barriers, and classify them into:

1. Barriers for companies and service providers such as un-adapted corporate mindset and organization or lack of sustainable PSS methods and tools,
2. Barriers for customers. For example, sustainable PSS contradict the well-established norm of ownership,
3. Context-related barriers: for instance, sustainable PSS might not compete with industrialized products as their environmental and social costs are not included in their market prices.

Authors also give clues on the research that might overcome these barriers:

1. Sustainable PSS design of user acceptance and satisfaction,
2. Sustainable PSS design of industrial partnerships and stakeholder interactions,
3. Sustainable PSS design and socio-technical change,
4. Sustainable PSS and policy approaches.

In (Pieroni et al., 2017), eight relevant PSS design process models are analyzed and assessed with respect to supporting the design of sustainable PSS. The study concludes that a minority of the analyzed process models suggest activities or methods/tools supporting sustainable PSS design. In addition, the authors identified a gap between what practitioners expect from a PSS design process model and what the majority of the existing PSS design process models offer in terms of sustainability-related activities, methods and, tools.

The literature underlines that the overall objective of sustainability remains important, however that it is difficult to reach. As gaining competitiveness seems even more important (Velamuri et al., 2011), authors are interested in PSS strategy, PSS business modeling and PSS value creation. Becker et al. (Becker et al., 2010) describe value bundles as comprising "marketable services and physical goods and can be offered as individual value propositions for customers. If a value proposition is accepted by customers, value bundles are delivered in a service process that needs to be integrated into the customers' business processes and therefore requires customer input". Value bundles are also able to create outcomes for customers superior to the summed-up outcomes of their components (Becker et al., 2010). Authors also assess the business potential of value bundles as they achieve differentiation from competitors, increase customer satisfaction, and improve customer retention. Moreover, Reim et al. (Reim et al., 2015) conduct a systematic literature review on PSS business models. Authors differentiate 3 types of PSS Business Models (BM): Product-Oriented BM, Use-oriented BM, and Result oriented BM. In (Reim et al., 2015), PSS BMs are compared in terms of value creation, value delivery, and value capture.

A.2.3 Literature reviews on PSS design and development methods

Since the late 90s, PSS design and development have also been a central subject in the PSS research.

(Baines et al., 2007), the authors already concluded that *"successful PSS needs to be designed at the systemic level from the client perspective and requires early involvement with the customer and changes in the organizational structures of the provider"*. The authors made the following conclusions regarding available PSS design methods and tools by 2004:

- *"They are typically a subtle development of more conventional processes",*
- *"There is a lack of evidence for the completeness of the set of tools and methods proposed",*
- *"They lack a critical and in-depth evaluation of their performance in practice".*

More recent PSS reviews seem to share the same conclusions.

According to Tukker (Tukker, 2015), the literature before 2006 agreed on the three main stages of PSS development namely: Analysis, Idea Generation, and Implementation. PSS design process also appeared to be iterative rather than linear. However, after 2006, some translate the traditional process of product design into a process of technical service design while others use service engineering for PSS development (Tukker, 2015). Becker et al. reached the same conclusion by classifying PSS reference models into: goods manufacturing reference models and service sector reference models (Becker et al., 2010). Authors criticized the low number of integration of services and physical goods in reference models.

In (Cavalieri and Pezzotta, 2012), the authors present a state of the art on Service Engineering and PSS engineering. These authors classify reviewed papers into: 1) papers providing a theoretical perspective on PSS (methods, frameworks, and methodologies), 2) papers providing a detailed definition or description of the main elements characterizing a PSS (entities, lifecycle, and actors), and 3) papers providing detailed PSS process models. They concluded that there is a need for a multi-disciplinary view integrating different perspectives of different PSS elements. In (Vasantha et al., 2012), the authors reached a similar conclusion stating that business models and multidisciplinary approaches are overlooked in the literature.

Specifically, the authors measure the relative maturity of various issues considered in PSS domain namely: context specification, positioning & importance of stakeholders, design stages, development cycle, lifecycle considerations, and representation rigor. By doing so, they conclude that the first two aspects (context specification and positioning & importance of stakeholders) need to be strengthened; especially co-design and co-creation among stakeholders. This research also underlines that lifecycle thinking needs to be further developed. Wang at al also insist on the need for a more frequent and intense collaboration among stakeholders as part of PSS lifecycle management (Wang, Ming, Li, et al., 2011).

In their literature review, Qu et al. focus on PSS design, evaluation and operation methodologies between 2000 and 2015 (Qu et al., 2016). They underline that:

- PSS Design methodologies focus on the customer perspective, modeling techniques, visualization methods, modularity methods, TRIZ and systems dynamics,
- PSS Evaluation methodologies focus on customer value, sustainability, or investigate tradeoffs between perspectives,
- PSS Operation methodologies focus on PSS business models, policy perspective, technology perspective, knowledge management Barrier analysis and Fault monitoring perspective

In their paper, authors also conclude that attention should be given to modularity and system dynamics. It is interesting to notice that the authors pointed out the need for quantitative studies.

In (Andriankaja et al., 2018), on the other hand the authors focus on identification of the integrative potential and the applicability as key challenges for PSS design (Andriankaja et al., 2018). The integrative potential describes how a design method covers the whole PSS design stages and how a design method ensures the development and integration of key PSS elements (Product, Service and Value network). The applicability of a design method describes how it can capture the contextual specificities of any particular PSS and how easily a method could be implemented in an industrial context. With regard to the integrative potential of design methods, the authors conclude (1) that there is a need to further develop a conceptual foundation for PSS design, and (2) that there is a need to develop integration requirements not only covering product and service but also the value network. From an applicability perspective, the need for a better diffusion of academic results through a higher level of standardization and normalization is pointed out (Andriankaja et al., 2018). The authors in (Cavalieri and Pezzotta, 2012; Vasantha et al., 2012) also raise the importance of knowledge transfer between academic research and industrial practitioners. Tran and Park, (2016) propose a set of scoring criteria to help designers and practitioners compare and select an appropriate methodology for a certain PSS.

A considerable focus in PSS design methodologies has been given to requirement management. Several research (Nilsson and Lindahl, 2016; Song, 2017) focus their literature reviews on this topic. Nilsson and Lindahl, (2016) identified customers as main stakeholders involved in the requirements derivation. Song, (2017) also underlined the difficulty of forecasting customer behavioral characteristics and user preferences. Piontek and Müller, (2018) emphasize the importance of integrating users' behavior needs not only in the requirements management but also throughout the PSS design process.

A.2.4 Literature reviews on PSS applications in industry

There is also an extensive body of literature reviews focusing on PSS applications in industry.

The most known are Xerox, Canon and Oce leaders in pay per copy lease and take-back programs. Baines et al., (2007) in their literature review noticed that the literature up to 2006 gave a multitude of examples of PSSs. This research study (Baines et al., 2007) emphasizes the economic success of such examples and their environmental and social impact. Lindahl et al., (2009) detail industrial PSS examples in Sweden, Japan, Italy, and Germany. They underline that customer satisfaction and cost decrease remain the main drivers for PSS adoption. The authors also highlight that sustainability does not seem to be the interest of the studied companies. Another conclusion of this study relates to the type of PSSs developed in the industry. The most developed PSS in the industry correspond to the maintenance and repair of physical products. Consumption goods and time energy consumption come up far behind. Hence, in most reported cases, PSS development was focalized and organized as Product Development. Moreover, most products used for PSS are standard products seldom adapted for PSS. Biege et al., (2011) further discuss the motives and challenges of product adaptation for PSS. The survey in capital goods companies presented in Adrodegari et al., (2015) also shows that companies mostly offer product-oriented PSS.

In particular, Mahut et al., (2015) focus on PSS development in the automotive industry. In the automotive industry, most PSSs also appeared to be product-oriented whether they include pre-sales, sales or, after-sales services. However, authors noticed that in use service are to be even more important for a car manufacturer with the connected car features and services such as assisted driving, embedded communication services, dematerialized keys of a car, personalization, etc. These trends underline the shift in the automotive industry from product-oriented PSS development to use- and result-oriented PSS development (Mahut et al., 2015).

Several studies focused (Matschewsky et al., 2018; Meier et al., 2010, 2011) on identifying challenges industrial companies and OEMs (Original Equipment Manufacturer) face in developing PSSs and more specifically product-oriented PSSs (also referred to as Industrial Product Service Systems IPS2 (Meier et al., 2010, 2011)). Meier et al., (2010) list the challenges for an OEM in developing PSS: 1) Stakeholders identification, 2) Create proper business models, 3) Identify chances and risks, 4) develop and deliver IPS2 processes, 5) set up IPS2 oriented organization, 6) qualify the staff (empowerment), 7) industrialize and automate his IPS2 processes and, 8) adapt his product understanding and business culture. Furthermore, Matschewsky et al., (2018) study the challenges faced by two industrial companies undergoing the transition to designing and providing PSS and summarize them as: 1) persisting product-centered mindset, 2) separating product and service design, 3) alignment with changing companies' incentive structures and, 4) prevalence of product-focused information and costing structures. The authors also identify PSS methods as a guiding light for the integration of product-service design and as one among other solutions to the challenges of servitization.

A.2.5 Discussion on the difficulty of identifying PSS development methodology with regard to different PSS types

Previously discussed literature shows an extensive work related to PSS definition as well as the identification of PSS benefits (Mont, 2002). If sustainability was the driver for developing the PSS concept (Baines et al., 2007), customer satisfaction and increased competitiveness are now considered to be the main drivers for PSS development from an industrial perspective (Lindahl et al., 2009; Velamuri et al., 2011). However, whatever the driver, the industry needs an adapted PSS development methodology with regard to different contexts (Meier et al., 2010).

With regard to this point, many authors criticized the lack of knowledge transfer from research to the industry (Andriankaja et al., 2018; Cavalieri and Pezzotta, 2012; Vasantha et al., 2012). Andriankaja et al., (2018) specifically discussed the applicability of PSS design methods. Here, the applicability of a design method is measured with regard to the capacity to capture the contextual specificities of any PSS and easiness of method implementation in an industrial context (Andriankaja et al., 2018). Capturing contextual specificities of a PSS has also been understood as the ability to apply to any type of PSS (Andriankaja et al., 2018). Authors in their research focus on different context considerations that one PSS design method needs to take into account.

Current literature points out that available PSS development methodologies are either product like development methodologies, service like development methodologies, or integrative design methodologies (Andriankaja et al., 2018; Becker et al., 2010; Cavalieri and Pezzotta, 2012; Vasantha et al., 2012). For instance, Mahut et al., (2015) pointed out the evolution of developed PSS in the automotive industry. The automotive industry spans from product-oriented PSS development (maintenance, reuse, etc.) to use and result-oriented PSS (connected car features, and services such as assisted driving, embedded communication services, dematerialized car keys, etc.) (Mahut et al., 2015). However, it is not clear if different types of PSS require different and adapted PSS development processes and methodologies. Moreover, even though some literature review underlines the assessment of the applicability of existing PSS design methods (Andriankaja et al., 2018), to our knowledge no literature addresses the difference among PSS design methods according to the considered “kind” or type of PSS.

Hence one can see that in-depth analysis of the literature on PSS is not allowing for an understanding of how a PSS design model integrates PSS type specificity; whether it is in the description of PSS elements, their interactions, their development processes, or lifecycle. Therefore, in this paper, we propose to address this gap and investigate different PSS models and design methods.

A.3 Review methodology

A.3.1 Literature review methodology and criteria definition

This research aims at conducting a systematic literature review in order to propose the classification of existing PSS model types with regard to different PSS development contexts. The study includes papers on PSS design and development from 2003 to 2019. As such, it includes papers describing PSS itself PSS development process and, PSS lifecycle. Papers that do not explicitly consider PSS but other concepts such as servitization or concepts of selling bundles of products and services are also included in this research.

A structured keywords search has been conducted. The review combined keywords referring to the object of interest (PSS), and keywords referring to modeling approaches and design methods. Terms such as "Product Service System" (PSS), "Product services", "Industrial Product Service Systems" (IPS2), "Integrated Service Product" (IPS), "functional products", "total care product", and "product related services" are used, and refer to product and service bundles. "Conceptual design", "Design process", "Design method", "Design methodology", "Modularization", "Configuration", "Service design", "Service Engineering", "PSS representation", "PSS modeling", "PSS architecture", and "PSS development" are the terms used to cover the literature on PSS modeling approaches, PSS design, and development methods.

We searched for combinations of the identified terms in paper title, keywords, and/or abstract. In this review, articles from different research streams are included (Information Systems, Business Management, and Engineering and Design (Boehm and Thomas, 2013)) with a specific focus on articles in the design and engineering domains. Major databases were used to search for relevant articles such as Web of Science, Scopus, and Springer Link (Table A-1).

Table A-1: Main search combinations

Combination keywords	**Databases**		
	Web of Science	**Scopus**	**Springer Link**
(Product Service System OR PSS OR Product services OR Industrial Product Service Systems OR Integrated Service Product OR functional products OR total care product OR product related services) AND (Conceptual design OR Design process OR Design method OR Design methodology OR Modularization OR Configuration OR Service design OR Service Engineering, OR PSS representation OR PSS modeling OR PSS architecture OR PSS development)	Papers: 169 Conference: 285	Papers: 347 Conference: 515	Papers: 99 Conference: 390

With regard to the extension of the existing literature we have identified two inclusive criteria:

Selection Criterion 1: The first criterion is linked to the definition of a PSS. The PSS definition used in the article is that of Mont (Mont, 2002), as it is the most used in the literature (Haase et al., 2017). Therefore, a PSS is defined by its constituent elements; Product, Service, Supporting Network and Infrastructure.

Selection Criterion 2: The second criterion is referring to the PSS types included in the systematic review. We propose to use the PSS typology given by Tukker (Tukker, 2004). The author distinguishes product-oriented PSS, use-oriented PSS, and result-oriented PSS. Although this typology emanates from business management research, it is broadly accepted in the literature (Tukker, 2015; Tukker and Tischner, 2006). To differentiate PSS types, we base ourselves on the differentiation criteria given in (Aurich et al., 2010):

- Ownership of the product (in this case of the manufacturing facility),
- Operational personnel, maintenance personnel,
- Location of the manufacturing facility, payment method,
- Delivery of raw materials and supplies (Lay, 2003).

Finally, in order to support the rigorous exploration of the literature and the identification of PSS models with regard to different PSS contexts, several categories of related information have been systematically captured:

- the context or type of the PSS model described in the research;
- The modeling approach is used in order to model and design the PSS
- elements and/or data are modeled,
- how these elements and related and what types of relationships are considered, and
- the context of the case study.

A.3.2 Proposition of the use of FBS framework to classify PSS modeling approaches

In order to define and explain design methodologies as well as to support design activities, several frameworks have been proposed (e.g. Design thinking (Brown, 2008), Function Structure Behavior (FBS) framework (Gero and Kannengiesser, 2004), Axiomatic Design (Suh, 2001), etc.). Because of its genericity and applicability, we propose to use the FBS framework to classify PSS modeling approaches. If the initial scope of the FBS framework is representing design objects in the field of design research (Cascini et al., 2011; Gero and Kannengiesser, 2007), several research underlines its capacity to represent a large scope such as processes, tasks, and lifecycles beyond the field of design research (Cascini et al., 2010, 2011; Gero and Kannengiesser, 2007; Labrousse and Bernard, 2008; Stalker, 2002). The FBS framework is *"formed by three classes of variables describing different aspects of a design object"* or a system (Gero and Kannengiesser, 2004). These variables are Function (F), Behavior (B), and Structure (S). (Dorst and Vermaas, 2005) review different definitions of (F), (B), and (S). In essence, we retain that the function (F) expresses what the system does/should do, the behavior (B) describes how the system behaves, and the structure (S) describes what the system is. Moreover, according to the FBS framework, a design process is seen as a sequence of steps linking (F), (B), and (S) (Cascini et al., 2010; Dorst and Vermaas, 2005) (see Figure A.1). The first step (the formulation step) transforms functions into artifact behaviors expected to perform the functions. The second step (the synthesis step) transforms the behavior into the structure intended to exhibit them. The third step is the analysis of the actual behavior of the structure. The fourth step (the evaluation step) is a comparison between the actual and expected behaviors. Finally, the evaluation step leads either to the documentation of the design description (step 5) if the evaluation is satisfactory or to a return to earlier steps expressed as the reformulations 1, 2, and 3 steps (see Table A-2).

Table A-2: The eight steps of the FBS model (from (Dorst and Vermaas, 2005))

Step 1: formulation Step	F → Be	transformation of the posited functions into behaviours that are expected to enable these functions.
Step 2: synthesis Step	Be → S	transformation of these expected behaviours into a structure that is intended to exhibit these behaviours.
Step 3: analysis	S → Bs	derivation of the actual behaviours of the structure.
Step 4: evaluation	Bs ←→ Be	comparison of the actual and expected behaviours.
Step 5: documentation	S → D	production of the design description.
Step 6: reformulation 1	S → S’	choice of a new structure.
Step 7: reformulation 2	S → Be’	choice of new expected behaviours.
Step 8: reformulation 3	S → F’	choice of new functions.

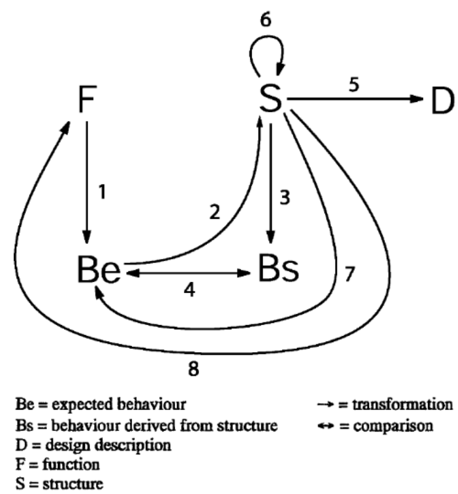

Figure A.1: The FBS framework according to (Gero and Kannengiesser, 2004)

We argue that PSS can be seen through the prism of the FBS framework. Whether a PSS is described from an information systems, business management, or design and engineering perspectives (Boehm and Thomas, 2013), there are at least notions of what the PSS is (S), how the PSS behaves (B), and / or what it does (F). Also, contributions from conceptual PSS models, PSS development processes to PSS lifecycle models can be studied using the FBS framework.

Table A-3 provides the final list of selected publications.

A.4 A classification of PSS models used in PSS development methodology

This paper aims to identify what are the design methodologies proposed for different PSS types and what PSS elements are modeled and considered in concrete studies. Hence, in all papers, we have tried to systematically identify elements pertaining to the FBS framework as defined in section A.3.2.

As for **Function,** several concurrent elements have been discussed and modeled in the literature. The Design Engineering and Systems Engineering literature describes PSS *functions* (Estrada and Romero, 2016a; Maleki, Belkadi and Bernard, 2017; Mannweiler and Aurich, 2012; Mourtzis, Fotia, Gamito, et al., 2016; Neves-silva et al., 2016; Sakao and Shimomura, 2007; Welp et al., 2008; Zhu et al., 2011), PSS engineering characteristics (Geng et al., 2010, 2011), PSS capabilities (Hussain et al., 2012), or PSS jobs and desired outcomes (Lim et al., 2012). The business, management, and innovation literature refers to value propositions (Morelli, 2003), customer needs (Li et al., 2012; Long et al., 2013, 2016), requirements (Kölsch et al., 2017) or utility (Li et al., 2016) to express what a PSS is for . The authors either describe the PSS functions (F) globally (Welp et al., 2008), (Estrada and Romero, 2016b), (Abramovici et al., 2017), or consider product functions and service functions separately (Andriankaja et al., 2018), (Li et al., 2016), (Li et al., 2012). In the service engineering literature, service is considered as carrying the function and the product aspect is considered only as a resource used to satisfy the PSS function (Curiazzi et al., 2016; Pezzotta et al., 2014, 2015, 2016).

As for **Structure**, PSS is considered to be constituted of Product and Service. The literature is quite unanimous regarding the definition of a product. However, the definition of the service is not uniform. A product is tangible (Li et al., 2016; Maleki, Belkadi and Bernard, 2017), physical (Annamalai et al., 2011; Geng et al., 2010, 2011; Li et al., 2012; Mannweiler and Aurich, 2012; Sakao and Shimomura, 2007; Wang, Ming, Li, et al., 2011), manufactured, produced (Mourtzis, Fotia, Gamito, et al., 2016; Neves-silva et al., 2016) or, technical (Kölsch et al., 2017). It is the hardware and its related software (Hara, Arai and Shimomura, 2009a; Hara, Arai, Shimomura, et al., 2009). A product can also be divided into subassemblies, parts, or components (Estrada and Romero, 2016a). As opposed to a product, a service is defined as non-physical or intangible (Akasaka et al., 2012),(Fargnoli et al., 2018; Haber et al., 2018),(Hajimohammadi et al., 2017). However, the distinction between product and service in the literature is not straightforward. Morelli et al. (Morelli, 2003) suggest differentiating products and services based on the simultaneousness of production and consumption, and the ownership transfer. Products are produced and consumed at different times while services are produced at the same time they are being provided and used. Considering the second criterion, the ownership of products is transferred when the product is sold, while the ownership of services is not generally transferred. According to authors in (Hara, Arai and Shimomura, 2009a; Hara, Arai, Shimomura, et al., 2009), service activities are realized by humanware and related software. More generally, in the studied PSS literature, service components are considered to be human resources, actors, or agents (Sakao and Shimomura, 2007), their relationships (Geng et al., 2010, 2011), their technical skills, activities between actors (Akasaka et al., 2012; Andriankaja et al., 2018; Annamalai et al., 2011; Bullinger et al., 2003; Hussain et al., 2012; Idrissi et al., 2017; Kim et al., 2011; Kimita et al., 2018; Komoto and Tomiyama, 2008; Lim et al., 2012; Mourtzis, Fotia, Gamito, et al., 2016; Neves-silva et al., 2016; Zhu et al., 2011), and/or processes (Doualle et al., 2016; Estrada and Romero, 2016a; Kölsch et al., 2017; Li et al., 2012).

PSS behavior is rarely described compared to its functions and its structure (Table A-3). Authors either define systems behavior in a general sense without specifically detailing PSS behavior (Annamalai et al., 2011; Maleki, Belkadi and Bernard, 2017; Welp et al., 2008) or describe specifically the product behavior and the service activities. In the studied PSS literature, most authors focus on the expected behavior of the PSS rather than the actual PSS behavior. As for the expected behavior, the authors in (Hara, Arai and Shimomura, 2009a; Hara, Arai, Shimomura, et al., 2009) include how hardware and its related software achieve tasks (product behavior) and how human ware and its related services perform service activities (service "behavior"). With respect to the actual PSS behavior, Kimita et al., (2018) describe it as failure modes. Zhu et al. (Zhu et al., 2011) consider the behavior through the definition of PSS performances such as time, cost, and quality measurement.

For the considered literature, we have gathered data on PSS elements modeled and different relationships that have been modeled and considered in different research. We distinguish overall and detailed PSS descriptions. The overall PSS descriptions describe the PSS as a whole and do not detail the functions and/or behaviors of the elements that make up a PSS, namely products and services. Whereas, the detailed PSS descriptions cover the functions, behaviors, and/or components of products and services. Detailed PSS descriptions are divided into three types of PSS modeling approaches: structure-oriented, behavior-oriented, and service-oriented PSS modeling approaches. Thus, the four types of PSS models that emerge from the literature are as following (see Figure A.2):

- **Overall PSS descriptions:** These approaches describe the PSS as a whole, do not detail the function, behavior, or structure of PSS constituent elements e., products and services.
- **Detailed PSS descriptions:** These approaches describe PSS at the product and service level. These approaches can themselves be subdivided into:
  - **Structure-oriented PSS modeling approaches:** These approaches focus on relationship modelling between PSS function to PSS structure including products and services,
  - **Behavior-oriented PSS modeling approaches:** These approaches explore relationships between PSS function to PSS behavior including products and services,
  - **Service-oriented PSS modeling approaches:** These approaches focus on service modeling and design. The product is a service special resource.

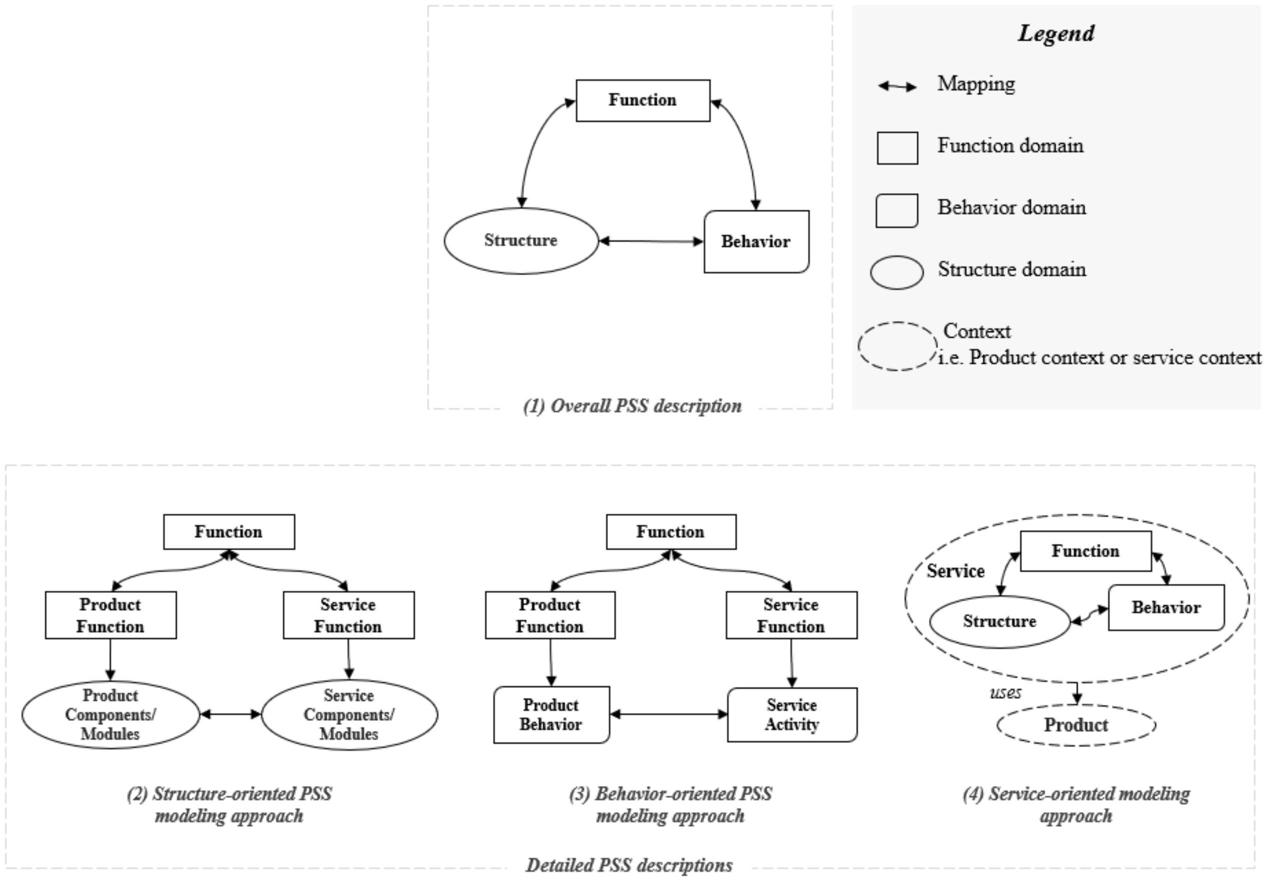

Figure A.2: A typology for PSS modeling approaches

For each PSS model described in the following sections, we have highlighted three pieces of information: 1) Elements that are modeled in the Function, Structure, and Behavior domain; 2) Relationships that have been represented and considered in a given research study, 3) Application domain that have been illustrated and exemplified in a paper.

A.4.1 Overall PSS description approaches

These approaches give an overall perspective on PSSs. First, authors define PSS functions. They then describe the structure (product and service components) that concretizes PSS functions. Finally, the authors observe how the structure should or does achieve PSS functions (expected and actual PSS behavior) and measure global performance indicators or parameters (see Figure A.2). These approaches have mainly been used in the context of product-oriented PSS and to a lesser extent, in the context of use-oriented PSS. In the following, we detail how the literature refers to the elements in Function, Behavior, and Structure.

The literature commonly refers to **PSS functions** (Estrada and Romero, 2016a; Li et al., 2016; Maleki, Belkadi and Bernard, 2017; Welp et al., 2008). They also refer to the system function through variables such as features, functionalities (Mourtzis, Fotia, Gamito, et al., 2016; Neves-silva et al., 2016), capabilities, and sub-capabilities (Hussain et al., 2012). From a business management and innovation perspective, the value proposition encompasses what is to be delivered to the customer, and as such the system function (Colledani et al., 2016). Kölsch et al., (2017) adopt a design thinking approach and describe the purpose of the PSS through the persona's needs and service ideas.

Regardless of the used terminology, the purpose of a PSS is realized by its **structure** i.e. its constituent elements or components. The components of the PSS are traditionally separated into products and services (Annamalai et al., 2011; Colledani et al., 2016; Li et al., 2016; Maleki, Belkadi and Bernard, 2017). However, other classifications of PSS components are available in the literature. In (Welp et al., 2008), Industrial Product Service Systems (IPS2) objects and processes form the structure of a PSS. According to this classification, service and product could be represented in the IPS2 objects layer or the IPS2 process layer indifferently. For example, service actors and service activities are included within IPS2 objects and IPS2 processes respectively. Maleki et al., (2017) use Systems Engineering as a conceptual foundation for PSS development. Thus the authors rather distinguish the system of Interest (SOI) as the hardware, software, or services implementing the PSS function and the Enabling System (ES) as organization and information supporting the SOI achieving the function. If authors describe the structure of the PSS and detail its constituent components, authors do not distinguish product functions from service functions (Annamalai et al., 2011; Colledani et al., 2016; Li et al., 2016; Maleki, Belkadi and Bernard, 2017), or functions realized by IPS2 objects and functions realized by PSS processes (Welp et al., 2008).

The **PSS behavior** is usually the description of how the PSS achieves its purpose continuously (Annamalai et al., 2011). According to Welp et al., (2008), IPS2 behavior is the combination of IPS2 objects and IPS2 processes throughout the IPS2 lifecycle, including the delivery and use phase. Estrada and Romero, (2016b) distinguish the PSS functional result and the PSS function performance. The PSS functional result is defined as the expected output of the PSS. The functional performance captures how many functional results are being delivered and how well. Hence, we can compare PSS functional result to PSS expected behavior, and the PSS functional performance to the PSS actual behavior. Other authors propose generic parameters (Hussain et al., 2012) or performance indicators (Mourtzis, Fotia, Gamito, et al., 2016; Neves-silva et al., 2016) to measure the PSS behavior or how well the PSS purpose or function is achieved. For example, Hussain et al., (2012) use cost, responsiveness, availability, functionality, etc. as generic parameters to measure how the PSS achieves its capabilities. Li et al., (2016) refer to PSS flexibility and service availability as PSS quality parameters, and time to set up and response rate of logistics as PSS characteristics. Performance indicators enable evaluation of the PSS (Li et al., 2016) and possibly generation of the functions of future PSSs (Hussain et al., 2012; Mourtzis, Fotia, Gamito, et al., 2016; Neves-silva et al., 2016).

To illustrate this type of PSS modeling approaches, we consider the work of Li et al., 2016). The authors propose an evaluation method for PSS business models. They consider the correlations of different dimensions of the PSS value and PSS business models using the Quality Function Deployment (QFD) technique. Here we detail the two first steps of the proposed evaluation method. The first step consists of an analysis of customers and a definition of the desired quality (expected behavior) of a PSS. The second step "Design value proposition" consists of identifying PSS characteristics (PSS functions), defining the correlation of PSS quality indicators and PSS characteristics, identifying PSS components (PSS Structure); and defining the correlation matrix between PSS characteristics and PSS components. The authors do not map PSS quality indicators to PSS components (see Figure A.3). The case study detailed in this research concerns a solution of electronics and home application with a dozen of services for real estate companies.

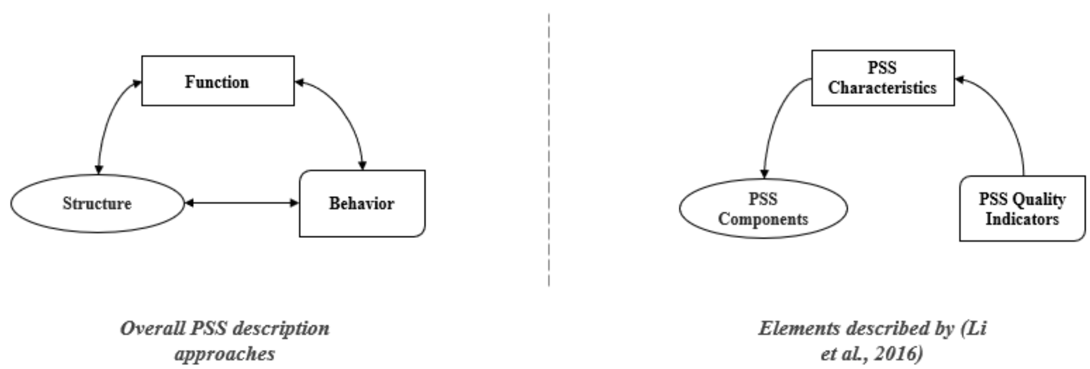

Figure A.3: An illustration of the 2 first steps of the PSS business model evaluation method proposed by (Li et al., 2016)

As for **the applicability domain** of these PSS modeling approaches,examples and case studies have been analysed. We note that the authors mainly consider product-oriented PSS and to a lesser extent, use-oriented PSS. Product maintenance and diagnosis services are redundant in the literature (Colledani et al., 2016; Hussain et al., 2012; Kölsch et al., 2017; Maleki, Belkadi and Bernard, 2017). Customization solution such as product design and re-design are the examples given in (Colledani et al., 2016).

A.4.2 Structure-oriented PSS modeling approaches

These approaches detail the PSS architecture up to its constituent elements level (products and services). Authors often start by defining the purpose of the PSS or its functions. PSS functions are then subdivided into functions realized by the product and functions realized by the service. The interaction between product components (or modules) and service components (or modules) is what realizes PSS functions (see Figure A.2). These PSS modeling approaches are applied in the contexts of product-oriented, use-oriented, and result-oriented PSSs. In the following, we detail how authors refer to the elements in Function, Behavior, and Structure spaces.

Maxwell et al., (2006) express “what the PSS is for” using the terms **function** or functionality. In (Sakao, Shimomura, et al., 2009; Sakao and Shimomura, 2007), a PSS function is also defined as the realization method to provide the value in the service product engineering. From the perspective of Andriankaja et al., (2018) and Idrissi et al., (2017a), PSS functions are the link between the customers' needs and designed solutions. In addition to defining the functions of the overall PSS, authors conduct a PSS functional decomposition. The proposed functional decompositions result in the allocation of functions to the product realizing it or the service realizing it (Mannweiler and Aurich, 2012; Maxwell et al., 2006; Sakao, Shimomura, et al., 2009; Sakao and Shimomura, 2007). While some authors simply allocate a function to a product, a service and/or a PSS (Wang, Ming, Wu, et al., 2011),(Maxwell et al., 2006), others differentiate what the product is for and what the service is for. The authors in (Geng et al., 2010, 2011) refer to product engineering characteristics and service engineering characteristics. Kim et al., (2011) refer to functions and activities when describing what the product is for and what the service is for respectively.

The structure realizing the product function appears straightforward. The product is defined as concrete (Morelli, 2003), material (Maxwell et al., 2006) or physical (Geng et al., 2010, 2011). As such, assemblies and sub-assemblies form its structure. The service structure definition is less evident. The service is defined as intangible (Morelli, 2003), or non-physical (Geng et al., 2010, 2011). Service structure can be defined as activities and agents realizing them (Andriankaja et al., 2018; Idrissi et al., 2017; Sakao, Shimomura, et al., 2009; Sakao and Shimomura, 2007). Service structure can also be modeled by service providers, service receivers and their relationships (Geng et al., 2010, 2011; Kim et al., 2011). Service scenarios are, according to (Wang, Ming, Wu, et al., 2011), what realize service functional modules. In (Li et al., 2012), services processes in their interactions with physical modules realize service functions.

These approaches rarely describe **the behavior** of the PSS or its constituent elements (products and services). For example, Zhang et al., (2017) considered business performance indicators (cost, value energy efficiency factors, etc.) to evaluate products, services, or IPS2s.

To **illustrate** this type of PSS modeling approaches, we consider the work of (Sakao, Shimomura, et al., 2009). The authors propose a design-object model and a prototype called Service Explorer (service CAD system) to support Product/Service Engineering (PSE). The model represents key concepts such as value, cost, functions. We consider the service CAD system modules that correspond to different design steps in the PSE process. Authors define the following modules: (a) Analyzing customers, followed by (b) designing Value (**Function space**), subdivided into (c) designing functions of products (**Function space**) and (d) designing functions of service activities (**Function space**). The functions of products and the functions of services activities are then allocated to structures of products and service activities (**Structure space**). We illustrate the proposed service CAD system modules (PSE design process steps) pertaining to the function space and structure space in Figure A.4. The authors relied on the Pay-per-wash service to demonstrate the use of the proposed service CAD system.

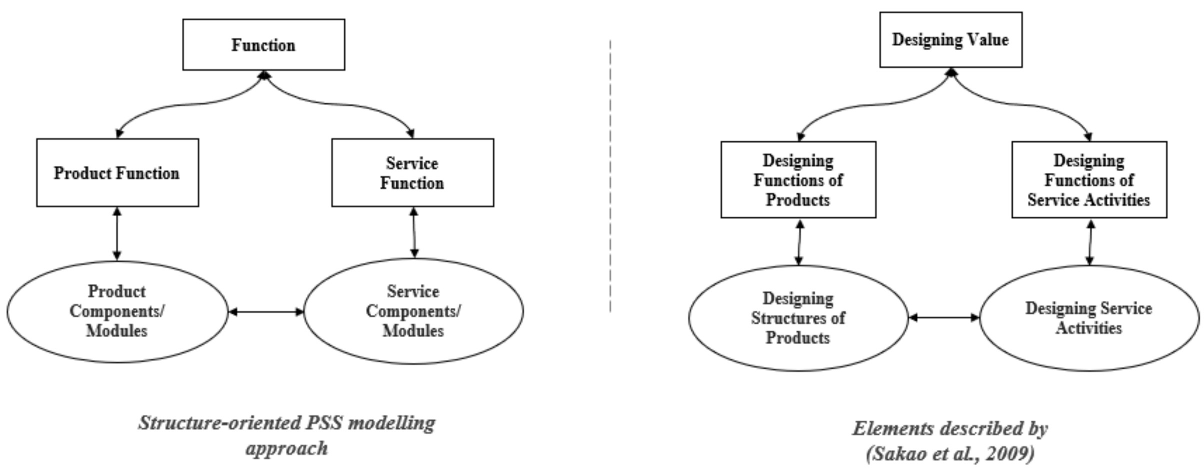

Figure A.4: An illustration of the modules of the service CAD system proposed by (Sakao, Shimomura, et al., 2009)

Looking at **the applicability domain** of proposed methods, one can note that most case studies are product-oriented PSS (Geng et al., 2010, 2011). Very few examples are use-oriented PSSs and result-oriented PSSs. Morelli, (2003) treat the example of support services for nomadic workers and telecommuters. The example of the collection of wood waste and production of soil improver is given in (Maxwell et al., 2006). In (Andriankaja et al., 2018; Idrissi et al., 2017), authors study the case of Robot', an offer of autonomous industrial cleaning service.

A.4.3 Behavior-oriented PSS modeling approaches

These modeling approaches describe the PSS architecture up to its constituent elements level (products and services). The authors start by defining the purpose of the PSS or its functions. PSS functions are then subdivided into functions realized by the product and functions realized by the service. The authors then detail how the product function is achieved (Product behavior) and how the service function is achieved (Service "behavior"). These modeling approaches have been mostly used in the contexts of use-oriented and result-oriented PSSs. In the following, we detail how authors refer to the elements in Function, Behavior, and Structure spaces.

The PSS function is what the system is for (Hara, Arai and Shimomura, 2009a; Hara, Arai, Shimomura, et al., 2009) and it fulfills customers' needs (Maussang et al., 2008, 2009). In (Lim et al., 2012), the PSS function is described using the theory of jobs and desired outcomes. These modeling approaches also decompose PSS functions and distinguish product and service functions (Hara, Arai and Shimomura, 2009a; Hara, Arai, Shimomura, et al., 2009).

As for the Structure space, a product is defined as tangible (Geum and Park, 2011) or physical (Maussang et al., 2008, 2009) while a Service is immaterial (Fargnoli et al., 2018; Haber et al., 2018) or intangible (Geum and Park, 2011). According to (Hara, Arai and Shimomura, 2009a; Hara, Arai, Shimomura, et al., 2009), a product is a hardware and its related software, and a Service is a human ware and its related software. More specifically, authors include in the service human ware, agents, their skills, their labor (Maussang et al., 2008, 2009), and their activities (Kimita et al., 2018; Lim et al., 2012). These PSS modeling approaches do not further detail the structure of products and services.

Product behavior and service "behavior" describe how product and service functions are achieved (Hara, Arai and Shimomura, 2009a; Hara, Arai, Shimomura, et al., 2009). In (Hara, Arai and Shimomura, 2009a; Hara, Arai, Shimomura, et al., 2009), product behaviors are *"tasks performed by hardware and its related software"*. Service activities (or "behaviors") are *"tasks performed by human ware and its related software"*. Authors in (Fargnoli et al., 2018; Haber et al., 2018) refer to product behavior and service "behavior" as product characteristics and service characteristics (describing the product and service components) respectively. In (Geum and Park, 2011; Hara, Arai and Shimomura, 2009a; Hara, Arai, Shimomura, et al., 2009), the authors describe the expected PSS behavior in adapted service blueprints. Lim et al. (Lim et al., 2012) suggest a PSS Board allowing for a PSS process visualization including the service delivery phase. Kimita et al., 2018) use the Failure Mode and Effect Analysis (FMEA) to assess the actual behavior of the PSS. In the context of a PSS, authors (Kimita et al., 2018) define a failure mode as *"the way in which a component's behaviour or an actor's activity could fail to perform its desired function"*.

To illustrate this type of PSS modeling approaches, we consider the work of (Hara, Arai and Shimomura, 2009b). The authors propose a service modeling method and a corresponding service CAD system for service innovation. In the proposed service modeling method, authors consider the service as an artifact that can be represented by functions (Function space). They also extend service blueprints and include product behavior (Behavior space). We illustrate the proposed service modeling method in Figure A.5. The use case used in this research is an elevator-operating service.

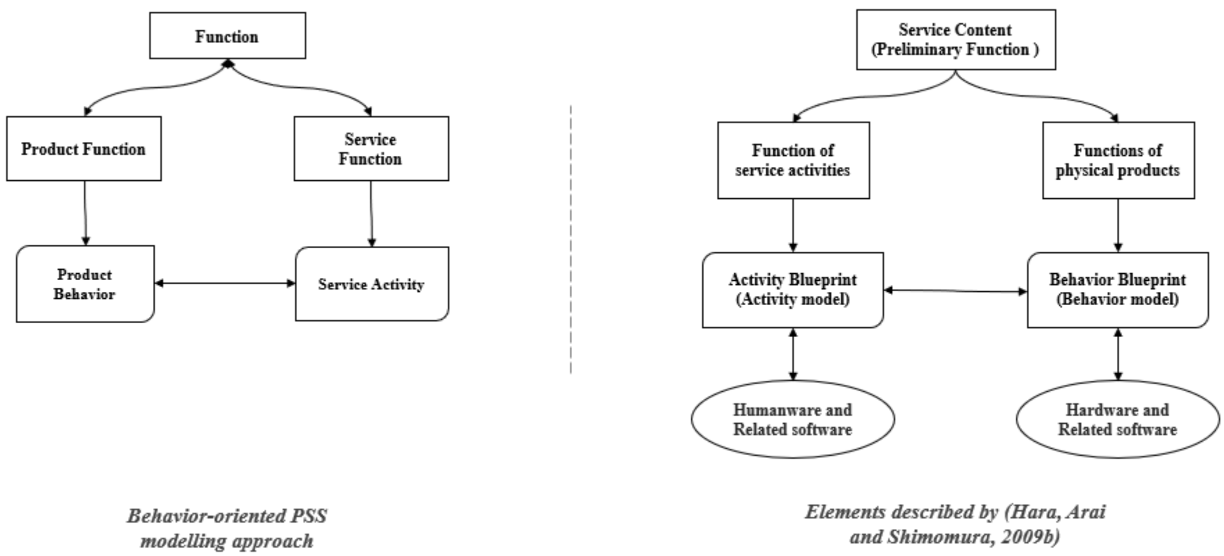

Figure A.5: An illustration of the service modeling method proposed in (Hara, Arai and Shimomura, 2009b)

Looking at the **applicability domain**, one can notice that use-oriented PSSs and result-oriented PSSs are prominent. In (Maussang et al., 2008, 2009), the authors consider the Vélo'v example: a renting bike system installed in Lyon, France. The Mayo line is another transportation service given as an example in (Hara, Arai and Shimomura, 2009b, 2009a). Car Sharing is a case study in various publications. However, Lim et al., (2012) show in their study that product-oriented PSS are more prevalent than other types (123 cases among 181).

A.4.4. Service-oriented modeling approaches

These PSS modeling approaches focus on service modeling. Firstly, authors define the service function. Service function is realized by service activities. Service activities rely on resources e.g. the product. Finally, service processes describe how service activities achieve the service function. These modeling approaches have been mostly used in the contexts of product-oriented and use-oriented PSS. In the following, we detail how authors refer to the elements in Function, Behavior, and Structure spaces.

The service according to Bullinger et al., 2003) satisfies the customer segment needs. According to authors in (Alonso-rasgado et al., 2004; Alonso-Rasgado and Thompson, 2006), the service ensures that the function is provided to the customer. We retain that the **PSS function** achieves customer's needs (Akasaka et al., 2012). Moreover, the function appears to be held by the service. Wang et al., (2014) go further and define a function module as a single service. In (Wang et al., 2014), the service and the function appear to be equivalent.

Following these modeling approaches, service activities form **the structure** of the service. In (Song, Wu, et al., 2015; Song and Sakao, 2016), a service activity is defined as a service component. According to (Bullinger et al., 2003; Wang et al., 2014) a service system relies on service activities to ensure that the function (or the service) is provided to a customer. (Alonso-rasgado et al., 2004; Alonso-Rasgado and Thompson, 2006) rather speak of service actions. Service activities are realized by resources (Curiazzi et al., 2016; Pezzotta et al., 2014, 2015, 2016). Resources may be material, human, or software resources (Hajimohammadi et al., 2017). The product appears to be a special resource (Curiazzi et al., 2016; Pezzotta et al., 2014, 2015, 2016). (Song, Wu, et al., 2015; Song and Sakao, 2016) in their research include the product in the service technical attributes. The same idea can be found in (Hajimohammadi et al., 2017). Authors state that a service is processed by a service parameter, which is linked to an entity; an entity that ca be a product function, a product behavior or just a product. Hence, in these modeling approaches, the product, its function, or its behavior are considered as a special resource the service relies on to achieve the PSS function.

According to these PSS modeling approaches, **the PSS behavior** is described through the description of service processes. Service processes are composed of service activities and include the resources they use (Akasaka et al., 2012; Bullinger et al., 2003). Akasaka et al., (2012) suggest a service process modeling approach. A service process model consists of an interrelated service activity blueprint and product behavior blueprint. Hence, service processes can be considered as a description of the expected behavior of the service or the PSS. Moreover, the authors consider service performance indicators. These indicators could be considered as a means to assess the service or the PSS actual behavior.

To **illustrate** this type of PSS modeling approaches, we consider the work of (Wang et al., 2014). Authors propose an ontology-based product-service configuration approach. The proposed approach is based on a layered model for PSS modular architecture. The model includes in its two upper layers Service Businesses

(**Function space**) and Functions modules (**Function space**). A service business is defined as *"a service package for certain demand"* and is composed of *"a set of service functions"*. A function module *"is a single service which could be bought and delivered independently"*. Function modules are connected through function ports and service flows. Service flows are represented in the service flow layer, are composed of service activities, and form Service processes. Service processes describe how the PSS is delivered (**Behavior space**). The final layer of the proposed model is composed of service elements (**Structure space**) that can be service steps or any kind of service resource (i.e. a product) (see Figure A.6). The authors used air-material services from an aviation company as a case study to illustrate the use of the approach they propose.

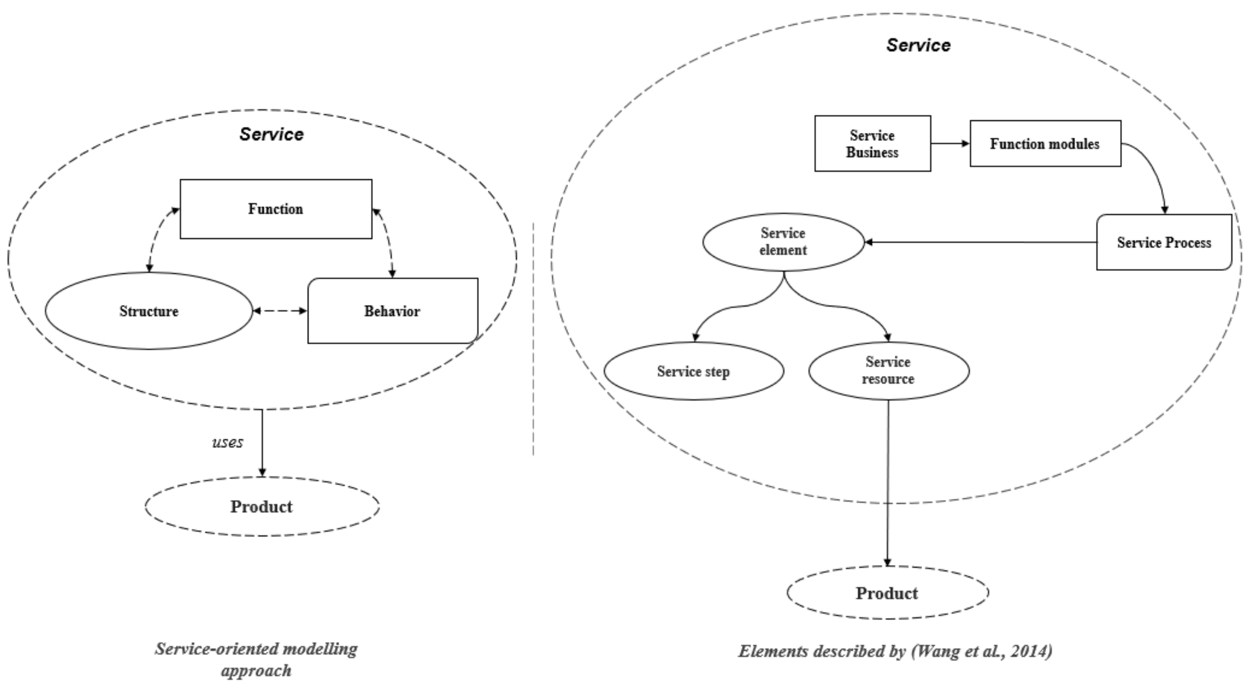

Figure A.6: An illustration of the layered model for PSS modular architecture proposed by (Wang et al., 2014)

Looking at **the applicability domain** of these PSS modeling approaches, product-oriented PSS and use-oriented PSS are the most studied PSSs examples. Authors in (Alonso-rasgado et al., 2004; Alonso-Rasgado and Thompson, 2006; Curiazzi et al., 2016; Song, Wu, et al., 2015; Song and Sakao, 2016; Zhu et al., 2011) give examples of product support and maintenance services in the context manufacturing industries. Sharing and leasing services are given as examples in both (Wang et al., 2014) (Sharing and Leasing aviation services) and (Hajimohammadi et al., 2017) (Bike System). Result-oriented PSSs are the subject of interest in Yang et al. (Yang et al., 2010).

A.5. Discussion

This research study considers different PSS contributions (PSS conceptual models, PSS design process, PSS lifecycle models, and PSS development methods) describing what the PSS is (structure dimension), what a PSS is for (function dimension), and/or how the PSS behaves. We propose a classification for PSS modeling approaches, and we attempt to map types of PSS modeling approaches to various PSS development contexts (product-oriented, use-oriented, or result-oriented PSS).

The proposed classification of PSS modeling approaches has some limitations. This classification does not claim to be exhaustive as it considered a set of PSS contributions (Table A-3). Thus, it may evolve by considering other contributions. A type of PSS modeling approach may emerge from the combination of two others, for example, a combination of structure-oriented and behavior-oriented approaches. Other types of PSS modeling approaches may also be added to the proposed classification.

Moreover, the correctness of the proposed classification highly depends on the rigorous identification of a models' elements and terms pertaining to the function space, behavior space, and structure space. For instance, the terms function, functionality, capability, characteristics, etc. refer to what the system does. As for the structure space, even though the literature acknowledges products, services, infrastructure, and supporting networks as the constituent elements of the PSS, most PSS modeling approaches only consider products and services (see Table A-3). Furthermore, different definitions were adopted to define what a product is and what a service is. The behavior space is the least considered dimension in the literature (see Table A-3). Functional performance indicators and quality indicators (-ilities) are usually what is in most cases represented in the behavior space. Another difficulty pertains to understanding how FBS elements are related and linked in different PSS modeling approaches as they are not consistently detailed in different research articles.

Another limitation of our work is that it does not allow to conclude with certainty which modeling approach to use in which development context. As the literature does not systematically discuss the application domain of the presented contributions (PSS models, ontologies, development processes, etc.), we based ourselves on the case studies and examples considered in the selected papers to map PSS modeling approaches to PSS development contexts. As such, the results of this research only show trends of the use of certain PSS modeling approaches in certain PSS development contexts. For example, mostly use-oriented and result-oriented PSSs have been used to illustrate behavior-oriented PSS modeling approaches.

In addition, the identified types of PSS modeling approaches do not necessarily cover increasingly complex PSSs. In fact, most of the proposed models focus mainly on the description of products and services. The infrastructure and the actors' network are also PSS constituent elements rarely considered and, in our opinion, should be integrated into PSS models and development methods. This has been discussed in the literature previously. Vasantha et al., (2012) highlighted the need to consider the positioning and importance of stakeholders especially in the context of the co-design and co-creation of PSSs. Others (Estrada and Romero, 2016a; Hein, Poulain, et al., 2018) also underline that these collaborative PSSs are increasingly complex and show features of Systems of Systems (SoS). Based on PSSs definition (Mont, 2002) and SoSs definition (Maier, 1996), Hein et al., (2018) define a Product Service System of Systems as "a set of products, services, infrastructures, and networks where its constituent elements exhibit operational and managerial independence". Looking at the automotive industry specifically, there is a noticeable shift towards use- and result-oriented PSSoSs (e.g. Electric vehicle to Grid services (EV2G) or robot vehicle ride-hailing, etc. (Fakhfakh et al., 2019; Mahut et al., 2015). If one considers the previous PSS models and their applicability domains, there is an additional effort needed to understand what PSS underlying model can and should be used in developing such PSSoS systems. In particular, because the literature in the SoS domain is underlying different SoS types that need a specific development methodology (directed, acknowledged, collaborative, and virtual (Maier, 1996)) and development models (such as system architecture patterns (Ingram et al., 2014)). Hence the need to bridge the gap between the existing PSS and SoS literature seems necessary to address these new types of developments.

A.6. Conclusion

This research aims to understand what PSS model should be used in what type of development context. This literature survey highlights that there is no explicit study referring to which PSS modeling to use in which context. Hence, a considerable body of knowledge has been analyzed in order to identify models that have been proposed and detailed in different research studies and analyze the correlation with the context of the case study used to detail the proposed PSS model. To be able to identify models, we propose to use the FBS framework due to its genericity in describing the development process and activities. Four major types of PSS models have been found in literature: 1) overall PSS descriptions, 2) structure-oriented PSS modeling approaches, 3) behavior-oriented PSS modeling approaches, and 4) service-oriented PSS modeling approaches. Moreover, additional analysis has been performed to understand if there is a correlation between an identified PSS model and a specific application domain (development context). No clear patterns have emerged from the literature. However, some trends have been identified and discussed in the paper.

Looking at the automotive industry specifically, there is a noticeable shift towards use- and result-oriented PSSoSs (e.g. Electric vehicle to Grid services (EV2G) or robot vehicle ride-hailing, etc. (Fakhfakh et al., 2019; Mahut et al., 2015). Our interest in understanding PSS model types comes from current challenges in expanding the development to these PSSoS. In order to adequately support the design team, there is a need to understand what PSS model to be used and integrated regarding the additional difficulty that is SoS types and SoS model patterns

Table A-3: Selected papers

Reference	Reference Title	PSS elements definition (✓explicitly defined, (✓) an be deduced, × not defined)				FBS variables description (✓ explicitly described, (✓) addressed, × not described) **For** (PSS, Product P, or Service S)		
		Product	**Service**	**Network**	**Infrastructure**	**Function**	**Structure**	**Behavior**
(Welp et al., 2008)	"Modeling Approach for the Integrated Development of Industrial Product-Service Systems"	(✓)	(✓)	×	×	✓ (PSS)	✓ (PSS)	✓ (PSS)
(Annamalai et al., 2011)	"An ontology for product service systems"	✓	✓	✓	✓	(✓) (PSS)	✓ (PSS)	(✓) (PSS)
(Hussain et al., 2012)	"A framework to inform PSS Conceptual Design by using system-in-use data"	(✓)	(✓)	×	×	(✓) (PSS)	(✓) (PSS)	✓ (PSS)
(Estrada and Romero, 2016b)	"Towards a Cost Engineering Method for Product-Service Systems Based on a System Cost Uncertainty Analysis"	✓	✓	(✓)	×	✓ (PSS)	(✓) (P, S)	(✓) (PSS)
(Li et al., 2016)	"A QFD-Based Evaluation Method for Business Models of Product Service Systems"	✓	✓	✓	×	✓ (P, S)	×	(✓) (PSS)
(Colledani et al., 2016)	"Technology-based product-services for supporting frugal innovation"	✓	✓	(✓)	(✓)	×	✓ (PSS)	(✓) (PSS)
(Mourtzis, Fotia, Gamito, et al., 2016; Neves-silva et al., 2016)	"PSS Design Considering Feedback from the Entire Product-Service Lifecycle and Social Media" "Supporting context sensitive lean product service engineering"	✓	✓	(✓)	×	✓ (PSS)	×	×

Reference	**Reference Title**	**PSS elements definition** **(**✓explicitly defined, (✓) an be deduced, × not defined**)**				**FBS variables description** **(**✓ explicitly described, (✓) addressed, × not described**)** **For** (PSS, Product P, or Service S)		
		Product	**Service**	**Network**	**Infrastructure**	**Function**	**Structure**	**Behavior**
(Maleki, Belkadi and Bernard, 2017)	"Systems Engineering as a Foundation for PSS Development Project: Motivations and Perspectives"	✓	✓	✓	✓	✓ (PSS)	✓ (PSS)	✓ (PSS)
(Kölsch et al., 2017)	"A Novel Concept for the Development of Availability-Oriented Business Models"	✓	✓	×	×	(✓)	×	(✓)
(Morelli, 2003)	"Product-service systems, a perspective shift for designers: A case study - The design of a telecentre"	✓	✓	×	(✓)	(✓) (PSS)	(✓) (P, S)	×
(Maxwell et al., 2006)	"Functional and systems aspects of the sustainable product and service development approach for industry"	✓	(✓)	×	×	(✓) (PSS)	(✓) (P, S)	×
(Sakao, Shimomura, et al., 2009; Sakao and Shimomura, 2007)	"Service Engineering : a novel engineering discipline for producers to increase value combining service and product" "Modeling design objects in CAD system for Service/Product Engineering"	✓	✓	(✓)	×	(✓) (PSS)	✓ (P, S)	×
(Geng et al., 2010, 2011)	"An integrated approach for rating engineering characteristics' final importance in product-service system development" "A systematic decision-making approach for the optimal product – service system planning"	✓	✓	×	×	✓ (PSS, P, S)	✓ (P, S)	×
(Wang, Ming, Li, et al., 2011)(Wang, Ming, Wu, et al., 2011)	"Modular Development of Product Service Systems" "Status review and research strategies on product-service system"	✓	✓	(✓)	×	✓ (PSS, P, S)	✓ (P, S)	×

Reference	**Reference Title**	**PSS elements definition** **(**✓explicitly defined, (✓) an be deduced, × not defined**)**				**FBS variables description** **(**✓ explicitly described, (✓) addressed, × not described**)** **For** (PSS, Product P, or Service S)		
		Product	**Service**	**Network**	**Infrastructure**	**Function**	**Structure**	**Behavior**
(Kim et al., 2011)	"Representing product-service systems with product and service elements"	✓	✓	✓	×	✓ (PSS)	✓ (P, S)	×
(Li et al., 2012)	"Module partition process model and method of integrated service product"	✓	✓	×	×	✓ (PSS, P, S)	✓ (P, S)	×
(Mannweiler and Aurich, 2012)	"Modularization of Products and Services for Configuring Product-Service Systems"	✓	✓	×	×	✓ (PSS, P, S)	✓ (PSS, P, S)	×
(Long et al., 2013, 2016)	"Product service system configuration based on support vector machine considering customer perception" "An approach to rule extraction for product service system configuration that considers customer perception"	✓	✓	×	×	✓ (PSS)	✓ (P, S)	×
(Doualle et al., 2016)	"Design of Sustainable Product-service Systems (PSS): Towards an Incremental Stepwise Assessment Method"	✓	✓	✓	×	✓ (PSS)	✓ (P, S)	×
(Zhang et al., 2017)	"A systematic decision-making method for evaluating design alternatives of product service system based on variable precision rough set"	✓	(✓)	×	×	✓ (PSS, P, S)	✓ (P, S)	×
(Abramovici et al., 2017)	"Knowledge-Based Lifecycle Management Approach for Product Service Systems (PSS)"	✓	(✓)	×	×	✓ (PSS)	✓ (P, S)	×
(Andriankaja et al., 2018)	"A method to design integrated product-service systems based on the extended functional analysis approach"	✓	✓	✓	×	✓ (PSS, P, S)	✓ (P, S)	×

Reference	Reference Title	PSS elements definition (✓explicitly defined, (✓) an be deduced, × not defined)				FBS variables description (✓ explicitly described, (✓) addressed, × not described) For (PSS, Product P, or Service S)		
		Product	Service	Network	Infrastructure	Function	Structure	Behavior
(Maussang et al., 2008, 2009)	"Evaluation of Product-Service Systems During Early Design Phase" "Product-service system design methodology: from the PSS architecture design to the products specifications"	✓	✓	×	×	✓ (PSS)	(✓) (P, S)	(✓) (S)
(Hara, Arai and Shimomura, 2009a; Hara, Arai, Shimomura, et al., 2009)	"A Method to Analyze PSS from the Viewpoints of Function , Service Activity , and Product Behavior" "Service CAD system to integrate product and human activity for total value"	✓	✓	×	×	✓ (PSS, P, S)	✓ (S)	✓ (P, S)
(Geum and Park, 2011)	"Designing the sustainable product-service integration: A product-service blueprint approach"	✓	✓	(✓)	(✓)	✓ (PSS)	(✓) (P, S)	✓ (P, S)
(Lim et al., 2012)	"PSS Board: A structured tool for product-service system process visualization"	✓	✓	✓	✓	(✓) (PSS)	(✓) (P, S)	✓ (P, S)
(Fargnoli et al., 2018; Haber et al., 2018)	"PSS modularisation: a customer-driven integrated approach PSS modularisation: a customer-driven integrated approach" "Integrating QFD for product-service systems with the Kano model and fuzzy AHP Integrating QFD for product-service systems with the Kano model and fuzzy AHP"	✓	✓	×	×	(✓) (PSS)	✓ (P, S)	(✓) (P, S)
(Bullinger et al., 2003)	"Service engineering - Methodical development of new service products"	✓	✓	×	×	(✓) (S)	✓ (P, S)	✓ (S)

Reference	Reference Title	PSS elements definition (✓explicitly defined, (✓) an be deduced, × not defined)				FBS variables description (✓ explicitly described, (✓) addressed, × not described) For (PSS, Product P, or Service S)		
		Product	**Service**	**Network**	**Infrastructure**	**Function**	**Structure**	**Behavior**
(Alonso-rasgado et al., 2004; Alonso-Rasgado and Thompson, 2006)	"A rapid design process for total care product creation" "The design of functional (total care) products"	✓	✓	×	(✓)	✓ (PSS, S)	✓ (P, S)	✓ (S)
(Komoto and Tomiyama, 2008)	"Integration of a service CAD and a life cycle simulator"	✓	✓	(✓)	(✓)	(✓) (S)	(✓) (P, S)	✓ (S)
(Yang et al., 2010)	"A New Conceptual Life Cycle Model for Result-Oriented Product-Service System Development"	✓	✓	×	×	✓ (PSS)	(✓) (P)	(✓) (S)
(Zhu et al., 2011)	"Implementing an industrial product-service system for CNC machine tool"	✓	✓	×	×	✓ (PSS, P)	✓ (P)	(✓) (S)
(De Coster, 2011)	"A collaborative approach to forecasting product – service systems (PSS)"	✓	✓	(✓)	(✓)	(✓) (PSS)	(✓) (S)	✓ (S)
(Akasaka et al., 2012)	"Development of a knowledge-based design support system for Product-Service Systems"	✓	✓	×	×	✓ (S)	(✓) (P, S)	✓ (P, S)
(Wang et al., 2014)	"Research on industrial product – service configuration driven by value demands based on ontology modeling"	(✓)	✓	(✓)	×	✓ (S)	✓ (P, S)	✓ (S)
(Curiazzi et al., 2016; Pezzotta et al., 2014, 2015, 2016)	"Process standardization to support service process assessment and re- engineering"	(✓)	✓	(✓)	(✓)	✓ (PSS, S)	✓ (P)	✓ (S)

Reference	Reference Title	PSS elements definition (✓explicitly defined, (✓) an be deduced, × not defined)				FBS variables description (✓ explicitly described, (✓) addressed, × not described) For (PSS, Product P, or Service S)		
		Product	Service	Network	Infrastructure	Function	Structure	Behavior
	"Balancing product-service provider's performance and customer's value: The SErvice Engineering Methodology (SEEM)" "A Service Engineering framework to design and assess an integrated product-service" "Towards a methodology to engineer industrial product-service system – Evidence from power and automation industry"							
(Song, Wu, et al., 2015; Song and Sakao, 2016)	"Service conflict identification and resolution for design of product-service offerings" "Modularizing product extension services: An approach based on modified service blueprint and fuzzy graph"	✓	✓	(✓)	×	✓ (PSS, P, S)	✓ (P, S)	×
(Hajimohammadi et al., 2017)	"Ontology for the PSS Lifecycle Management"	✓	✓	×	(✓)	✓ (PSS, S)	✓ (PSS)	✓ (PSS, P)

Bibliography

Abramovici, M., Aidi, Y. and Dang, H. (2017), “Knowledge-Based Lifecycle Management Approach for Product Service Systems (PSS)”.

Adrodegari, F., Alghisi, A., Ardolino, M. and Saccani, N. (2015), “From ownership to service-oriented business models: A survey in capital goods companies and a PSS typology”, *Procedia CIRP*, Vol. 30, Elsevier B.V., pp. 245–250.

Afshari, H. and Peng, Q. (2015), “Using Big Data to Minimize Uncertainty Effects in Adaptable Product Design”, *Volume 4: 20th Design for Manufacturing and the Life Cycle Conference; 9th International Conference on Micro- and Nanosystems*, available at:https://doi.org/10.1115/DETC2015-46475.

Afshari, H., Peng, Q. and Gu, P. (2016), “Reducing effects of design uncertainties on product sustainability”, *Cogent Engineering*, available at:https://doi.org/10.1080/23311916.2016.1231388.

Agarwal, S., Pape, L.E., Kilicay-Ergin, N. and Dagli, C.H. (2014), “Multi-Agent Based Architecture for Acknoledged System of Systems”, *Systems Engineering Research*, Vol. 28, pp. 1–10.

Ahmed, S., Kim, S. and Wallace, K.M. (2007), “A methodology for creating ontologies for engineering design”, *Journal of Computing and Information Science in Engineering*, Vol. 7 No. 2, pp. 132–140.

Akasaka, F., Nemoto, Y., Kimita, K. and Shimomura, Y. (2012), “Development of a knowledge-based design support system for Product-Service Systems”, *Computers in Industry*, Elsevier B.V., Vol. 63 No. 4, pp. 309–318.

Al-Amin, M. and Dagli, C.H. (2019), “A Tool for Architecting Socio-Technical Problems : SoS Explorer”, *International Symposium on Systems Engineering (ISSE), IEEE*, pp. 1–7.

Alonso-Rasgado, T. and Thompson, G. (2006), “A rapid design process for total care product creation”, *Journal of Engineering Design*, Vol. 17 No. 6, pp. 509–531.

Alonso-rasgado, T., Thompson, G. and Elfström, B. (2004), “The design of functional (total care) products”, *Journal of Engineering Design*, Vol. 15 No. 6, pp. 515–540.

Ameri, F., Summers, J.D., Mocko, G.M. and Porter, M. (2008), “Engineering design complexity: An investigation of methods and measures”, *Research in Engineering Design*, Vol. 19 No. 2–3, pp. 161–179.

Andriankaja, H., Boucher, X. and Medini, K. (2018), “A method to design integrated product-service systems based on the extended functional analysis approach”, *CIRP Journal of Manufacturing Science and Technology*, available at:https://doi.org/10.1016/j.cirpj.2018.02.001.

Annamalai, G., Hussain, R., Cakkol, M., Roy, R., Evans, S. and Tiwari, A. (2011), “An Ontology for Product-Service Systems”, *Functional Thinking for Value Creation*, Springer., Berlin, Heidelberg, pp. 231–236.

Annarelli, A., Battistella, C. and Nonino, F. (2016), “Product service system: A conceptual framework from a systematic review", *Journal of Cleaner Production*, Elsevier Ltd, Vol. 139, pp. 1011–1032.

Antul, L., Ricks, S., Mann, L., Cho, K., Cotter, M., Jacobs, R.B., Markina-khusid, A., et al. (2017), "Toward Scaling Model-Based Engineering for Systems of Systems", *2018 IEEE Aerospace Conference*, IEEE, pp. 1–9.

Aragonés-Beltrán, P., García-Melón, M. and Montesinos-Valera, J. (2017), "How to assess stakeholders' influence in project management? A proposal based on the Analytic Network Process", *International Journal of Project Management*, Elsevier Ltd, APM and IPMA, Vol. 35 No. 3, pp. 451–462.

Aurich, J.C., Fuchs, C. and Wagenknecht, C. (2006), "Life cycle oriented design of technical Product-Service Systems", *Journal of Cleaner Production*, Vol. 14 No. 17, pp. 1480–1494.

Aurich, J.C., Mannweiler, C. and Schweitzer, E. (2010), "How to design and offer services successfully", *CIRP Journal of Manufacturing Science and Technology*, CIRP, Vol. 2 No. 3, pp. 136–143.

Axelsson, J., Fröberg, J. and Eriksson, P. (2019), "Architecting systems-of-systems and their constituents : A case study applying Industry 4 . 0 in the construction domain", *Systems Engineering*, Vol. 22 No. 6, pp. 455–470.

Azani, C.H. (2008), "System of systems architecting via natural development principles", *2008 IEEE International Conference on System of Systems Engineering, SoSE 2008*, available at:https://doi.org/10.1109/SYSOSE.2008.4724137.

Bagheri, S., Kusters, R.J., Trienekens, J.J.M. and Zandt, H.V.N. Van Der. (2016), "Classification framework of knowledge transfer issues across value networks", *Procedia CIRP*, The Author(s), Vol. 47, pp. 382–387.

Baines, T., Ziaee Bigdeli, A., Bustinza, O.F., Shi, V.G., Baldwin, J. and Ridgway, K. (2017), "Servitization: revisiting the state-of-the-art and research priorities", *International Journal of Operations and Production Management*, available at:https://doi.org/10.1108/IJOPM-06-2015-0312.

Baines, T.S., Lightfoot, H.W., Evans, S., Neely, A., Greenough, R., Peppard, J., Roy, R., et al. (2007), "State-of-the-art in product-service systems", *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, Vol. 221 No. 10, pp. 1543–1552.

Baldwin, W.C., Felder, W.N. and Sauser, B.J. (2011), "Taxonomy of increasingly complex systems", *International Journal of Industrial and Systems Engineering*, available at:https://doi.org/10.1504/IJISE.2011.043140.

Baldwin, W.C. and Sauser, B. (2009), "Modeling the Characteristics of System of Systems", *IEEE International Conference on System of Systems Engineering (SoSE)*, pp. 1–6.

Ballejos, L.C. and Montagna, J.M. (2011), "Modeling stakeholders for information systems design processes", *Requirements Engineering*, Vol. 16 No. 4, pp. 281–296.

Bashir, H. (2019), "A New Approach for Classifying Cross-functional Teams in Product Development Projects", *International Conference on Industrial Engineering and Operations Management*, pp. 903–909.

Batallas, D.A. and Yassine, A.A. (2006), "Information Leaders in Product Development Organizational Networks : Social Network Analysis of the Design Structure Matrix", *IEEE Transactions on Engineering Management*, No. April, available at:https://doi.org/10.1109/TEM.2006.883706.

Becker, J., Beverungen, D. and Knackstedt, R. (2010), "The challenge of conceptual modeling for product– service systems: status-quo and perspectives for reference models and modeling languages", *Inf Syst E-Bus Manage*, pp. 33–66.

Berardo, R. (2014), "Bridging and Bonding Capital in Two-Mode Collaboration Networks Bridging and Bonding Capital in Two-Mode", *Policy Studies Organization*, No. May 2014, available at:https://doi.org/10.1111/psj.12056.

Berkovich, M., Marco, J., Hoffmann, A. and Krcmar, H. (2014), "A requirements data model for product service systems", *Requirements Engineering*, Vol. 19 No. 2, pp. 161–186.

Beuren, F.H., Gitirana, M., Ferreira, G. and Miguel, P.A.C. (2013), "Product-service systems : a literature review on integrated products and services", *Journal of Cleaner Production*, Elsevier Ltd, Vol. 47, pp. 222–231.

Biege, S., Schröter, M. and Weissenberger-eibl, M. (2011), "Product Adaptation for Industrial Product-Service Systems – Characteristics, Motives and Challenges", *Functional Thinking for Value Creation*, available at:https://doi.org/10.1007/978-3-642-19689-8.

Biff, S., Gerhard, D. and Lüder, A. (Eds.). (2017), *Multi-Disciplinary Engineering for Cyber-Physical Production Systems Data Models and Software Solutions for Handling Complex Engineering Projects*, Springer, available at:https://doi.org/10.1007/978-3-319-56345-9.

Bischoff, J. and Maciejewski, M. (2016), "Autonomous Taxicabs in Berlin - A Spatiotemporal Analysis of Service Performance", *Transportation Research Procedia*, The Author(s), Vol. 19 No. June, pp. 176–186.

Blessing L.T.M. and Chakrabarti, A. (2009), "DRM: A Design Research Methodology", *Springer London*, pp. 13–42.

Boardman, J. and Sauser, B. (2006), "System of Systems - the meaning of of", *IEEE/SMC International Conference on System of Systems Engineering*, available at:https://doi.org/10.1109/SYSOSE.2006.1652284.

Boehm, M. and Thomas, O. (2013), "Looking beyond the rim of one's teacup: A multidisciplinary literature review of Product-Service Systems in Information Systems, Business Management, and Engineering & Design", *Journal of Cleaner Production*, Elsevier Ltd, Vol. 51, pp. 245–250.

Bondavalli, A., Bouchenak, S. and Kopetz, H. (2016), *CYBER-PHYSICAL SYSTEMS OF SYSTEMS Foundations, a Conceptual Model and Some Derivations: The AMADEOS Legacy*.

Boukhris, A., Fritzsche, A. and Möslein, K. (2017), "Co-creation in the Early Stage of Product-service System Development", *Procedia CIRP*, The Author(s), Vol. 63, pp. 27–32.

Bourne, L. and Walker, D.H.T. (2005), "Visualising and mapping stakeholder influence", *Management Decision*, Vol. 43 No. 5, pp. 649–660.

Brown, T. (2008), "Design Thinking", *Harvard Business Review*.

Broy, M. (2006), “The ‘grand challenge’ in informatics: Engineering software-intensive systems”, *IEEE Computer Society*, IEEE, Vol. 39 No. 10, pp. 72–80.

Broy, M. (2012), “Cyber-Physical Systemps: Imminent Challenges”, *Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, Vol. 7539 No. August 2015, pp. 71–80.

Broy, M., Cengarle, M.V. and Geisberger, E. (2012), “Cyber-Physical-Systems: Imminent Challenges”, *Monterey Workshop*, Springer, Berlin, Heidelberg, pp. 1–28.

Broy, M. and Schmidt, A. (2014), “Challenges in Engineering Cuber-Physical Systems”, *IEEE Computer Society*, IEEE, pp. 70–72.

Brydon-Miller, M., Greenwood, D. and Maguire, P. (2015), “Why action research?”, *Action Research*, Vol. 1 No. 1, pp. 1–21.

Bullinger, H.J., Fähnrich, K.P. and Meiren, T. (2003), “Service engineering - Methodical development of new service products”, *International Journal of Production Economics*, Vol. 85 No. 3, pp. 275–287.

Cameron, B.G., Seher, T. and Crawley, E.F. (2011), “Goals for space exploration based on stakeholder value network considerations”, *Acta Astronautica*, Elsevier, Vol. 68 No. 11–12, pp. 2088–2097.

Carlock, P.G. and Fenton, R.E. (2001), “System of Systems (SoS) Enterprise Systems Engineering for Information-Intensive Organizations”, *Systems Engineering*, Vol. 4 No. 4, pp. 242–261.

Cascini, G., Fantoni, G. and Montagna, F. (2010), “Reflections on the Fbs Model : Proposal for an Extension To Needs and Requirements modeling”, *International Design Conference - Design 2010*, pp. 651–660.

Cascini, G., Del Frate, L., Fantoni, G. and Montagna, F. (2011), “Beyond the Design Perspective of Gero’s FBS Framework”, *Design Computing and Cognition ’10*, pp. 77–96.

Cavalcante, J. and Gzara, L. (2018), “Product-Service Systems lifecycle models: Literature review and new proposition”, *Procedia CIRP*, Elsevier B.V., Vol. 73, pp. 32–38.

Cavalieri, S. and Pezzotta, G. (2012), “Product – Service Systems Engineering : State of the art and research challenges”, *Computers in Industry*, Elsevier B.V., Vol. 63 No. 4, pp. 278–288.

Cedergren, S.I., Elfving, S.W., Eriksson, J. and Parida, V. (2012), “Analysis of the Industrial Product-Service Systems (IPS2) Literature : A Systematic Review”, *2012 IEEE International Conference on Management of Innovation & Technology (ICMIT)*, IEEE, pp. 733–740.

Chaabane, M., Bouassida Rodriguez, I., Colomo-Palacios, R., Gaaloul, W. and Jmaiel, M. (2019), “A modeling approach for Systems-of-Systems by adapting ISO_IEC_IEEE 42010 Standard evaluated by Goal-Question-Metric”, *Science of Computer Programming*.

Chai, C.L., Liu, X., Zhang, W.J. and Baber, Z. (2011), “Application of social network theory to prioritizing Oil & Gas industries protection in a networked critical infrastructure system”, *Journal of Loss Prevention in the Process Industries*, Elsevier Ltd, Vol. 24 No. 5, pp. 688–694.

Chazal, Y. (2018), “Service Systems, System od Systems, Cyber Physical Systems: Lessons leearned from Electric Vehicles to achieve new Mobility Challenges”, *IEEE SOSE*, available at:

http://sosengineering.org/2018/wp-content/uploads/2014/07/Y.Chazal.pdf.

Chen, P. and Unewisse, M. (2017), "SoS thinking : an approach to conceptualising and understanding military systems-of-systems", *International Journal Systems of Systems Engineering*, Vol. 8 No. 1, pp. 74–101.

Chen, S.G. and Lin, L. (2014), "Modeling Team Member Characteristics for the Formation of a Multifunctional Team in Concurrent Engineering", No. June 2004, available at:https://doi.org/10.1109/TEM.2004.826011.

Chen, T.D., Kockelman, K.M. and Hanna, J.P. (2016), "Operations of a shared, autonomous, electric vehicle fleet: Implications of vehicle & charging infrastructure decisions", *Transportation Research Part A: Policy and Practice*, Elsevier Ltd, Vol. 94, pp. 243–254.

Clarity and Hubject. (2019), *Secure and User-Friendly EV Charging. A Comparison of Autocharge With ISO 15118's Plug & Charge*.

Clarkson, P.J., Simons, C. and Eckert, C. (2004a), "Predicting Change Propagation in Complex Design", *Journal of Mechanical Design*, available at:https://doi.org/10.1115/1.1765117.

Clarkson, P.J., Simons, C. and Eckert, C. (2004b), "Predicting change propagation in complex design", *Journal of Mechanical Design, Transactions of the ASME*, Vol. 126 No. 5, pp. 788–797.

Colledani, M., Silipo, L., Yemane, A., Lanza, G., Bürgin, J., Hochdörffer, J., Georgoulias, K., et al. (2016), "Technology-based product-services for supporting frugal innovation", *Procedia CIRP*, Elsevier B.V., Vol. 47, pp. 126–131.

Colombo, E.F., Cascini, G. and De Weck, O.L. (2016), "Classification of Change-Related Ilities Based on a Literature Review of Engineering Changes", *Journal of Integrated Design and Process Science*, available at:https://doi.org/10.3233/jid-2016-0019.

Correia, A., Stokic, D., Siafaka, R. and Scholze, S. (2017), "Ontology for colaborative development of product service systems based on basic formal ontology", *2017 International Conference on Engineering, Technology and Innovation: Engineering, Technology and Innovation (ICE/ITMC)*, pp. 1173–1180.

Corsello, M.A. (2008), "System-of-Systems Architectural Considerations for Complex Environments and Evolving Requirements", *IEEE Systems Journal*, Vol. 2 No. October, pp. 312–320.

Costa, S. and Diegues, L. (2019), "Who are the stakeholders mentioned in cases of Product-Service System (PSS) design?", *International Conference on Engineering Design*, pp. 5–8.

De Coster, R. (2011), "A collaborative approach to forecasting product – service systems (PSS)", *The International Journal of Advanced Manufacturing Technology*, Vol. 52 No. 9–12, pp. 1251–1260.

Creswell, J.W. (2009), *Research Design Qualitative, Quantitative, and Mixed Methods Approaches*, Third Edit., SAGE Publications.

Curiazzi, R., Rondini, A., Pirola, F., Ouertani, M. and Pezzotta, G. (2016), "Process standardization to support service process assessment and re- engineering", *Procedia CIRP*, Elsevier B.V., Vol. 47, pp. 347–352.

Dadpour, M., Shakeri, E. and Nazari, A. (2019), "Analysis of Stakeholder Concerns at Different Times of Construction Projects Using Social Network Analysis", *International Journal of Civil Engineering*, Springer International Publishing, No. August, available at:https://doi.org/10.1007/s40999-019-00450-1.

Dahmann, J., Markina-Khusid, A., Doren, A., Wheeler, T., Cotter, M. and Kelley, M. (2017), "SysML executable systems of system architecture definition: A working example", *11th Annual IEEE International Systems Conference, SysCon 2017 - Proceedings*, IEEE, pp. 1–6.

Darabi, H.R., Gorod, A. and Mansouri, M. (2012), "Governance mechanism pillars for systems of systems", *Proceedings - 2012 7th International Conference on System of Systems Engineering, SoSE 2012*, IEEE, No. 1, pp. 374–379.

DoD. (2008), *Systems Engineering Guide for Systems of Systems*, *Technology*, Vol. 36, available at:https://doi.org/10.1109/EMR.2008.4778760.

Dorst, K. and Vermaas, P.E. (2005), "John Gero's Function-Behaviour-Structure model of designing: a critical analysis", *Research in Engineering Design*, Vol. 16 No. 1–2, pp. 17–26.

Doualle, B., Medini, K., Boucher, X., Brissaud, D. and Laforest, V. (2016), "Design of Sustainable Product-service Systems (PSS): Towards an Incremental Stepwise Assessment Method", *Procedia CIRP*, available at:https://doi.org/10.1016/j.procir.2016.04.074.

Eckert, C., De Weck, O., Keller, R. and Clarkson, P.J. (2009), "Engineering change: drivers, sources and approaches in industry", *ICED*, Stanford, pp. 4–47.

Eckert, C.M., Clarkson, P.J. and Stacey, M.K. (2003), "The spiral of applied research : A methodological view on integrated design research", *International Conference on Engineerign Design, ICED*.

Eddaoui, I., Itmi, M., Hami, A. El, Hmina, N. and Mazri, T. (2018), "A deterministic approach for systems-of-systems resilience quantification", *International Journal of Critical Infrastructures*, Vol. 14 No. 1, pp. 80–99.

Elshenawy, M., Abdulhai, B. and El-Darieby, M. (2018), "Towards a service-oriented cyber–physical systems of systems for smart city mobility applications", *Future Generation Computer Systems*, available at:https://doi.org/10.1016/j.future.2017.09.047.

Eris, Ö., Hansen, P.H.K., Mabogunje, A. and Leifer, L. (1999), "Towards a pragmatic ontology for product development projects in small teams", *International Conference on Engineering Design*.

Estrada, A. and Romero, D. (2016a), "A System Quality Attributes Ontology for Product-Service Systems Functional Measurement Based on a Holistic Approach", *Procedia CIRP*, The Author(s), Vol. 47, pp. 78–83.

Estrada, A. and Romero, D. (2016b), "Towards a Cost Engineering Method for Product-Service Systems Based on a System Cost Uncertainty Analysis", *Procedia CIRP*, The Author(s), Vol. 47, pp. 84–89.

Fakhfakh, S., Hein, A.M., Chazal, Y. and Jankovic, M. (2020), "A meta-model for product service systems of systems", *International Design Conference - Design*, pp. 1235–1244.

Fakhfakh, S., Hein, A.M., Jankovic, M. and Chazal, Y. (2019), "Towards an uncertainty framework for Product Service Systems of Systems", *ICED19*.

Fakhfakh, S., Hein, A.M., Kokkolaras, M., Jankovic, M. and Chazal, Y. (2020), *A Review of Product Service Systems (PSS) Modeling Approaches Using the Function-Structure-Behavior Framework*.

Fakhfakh, S., Jankovic, M., Hein, A.M., Chazal, Y. and Dauron, A. (2020), "Proposition of an ontology to support Product Service Systems of Systems Engineering", *Sumitted to Systems Engineering*.

Fang, Z., Davendralingam, N. and Delaurentis, D.A. (2018), "Multistakeholder Dynamic Optimization for Acknowledged System-of-System Architecture Selection", *IEEE Systems Journal*, IEEE, Vol. 12 No. 4, pp. 3565–3576.

Fargnoli, M., Haber, N. and Sakao, T. (2018), "PSS modularisation: a customer-driven integrated approach PSS modularisation: a customer-driven integrated approach", *International Journal of Production Research*, available at:https://doi.org/10.1080/00207543.2018.1481302org/10.1080/00207543.2018.1481302.

Feng, W. (2013), *Strategic Management for Large Engineering Projects :, Engineering Project Organization Conference*, at the Massachusetts Institute of Technology.

Feng, W., Crawley, E.F., de Weck, O., Keller, R. and Robinson, B. (2010), "Dependency Structure Matrix Modelling For Stakeholder value networks", *Dependency and Structure Modelling Conference DSM*, Vol. 501 No. November 2006, pp. 2007–2007.

Fernandes, S.D.C., Rosa, M., Queiroz, C. and Rozenfeld, H. (2018), "An initial prototype of a tool for defining value proposition in the product-service system (PSS) design", *Proceedings of International Design Conference, DESIGN*, Vol. 1, pp. 281–292.

Ferris, T.L.J. (2009), "On the Methods of Research for Systems Engineering", *7th Annual Conferenceon Systems Engineering Research 2009 (CSER 2009)*, Vol. 2009 No. April, p. 7.

Fu, F., Feng, W., Li, Z., Crawley, E.F. and Ni, W. (2011), "A network-based modeling framework for stakeholder analysis of China's energy conservation campaign", *Energy*, Elsevier Ltd, Vol. 36 No. 8, pp. 4996–5003.

Gaiardelli, P., Resta, B., Martinez, V., Pinto, R. and Albores, P. (2014), "A classification model for product-service offerings", *Journal of Cleaner Production*, Vol. 66, pp. 507–519.

Garnier, J., Auzelle, J., Pourcel, C. and Peyrichon, M. (2012), "Service Engineering Life-cycles", *22nd Annual INCOSE International Symposium in Rome*.

Garro, A. and Tundis, A. (2015), "On the Reliability Analysis of Systems and SoS : The RAMSAS Method and Related Extensions", *IEEE Systems Journal*, Vol. 9 No. 1, pp. 232–141.

Ge, B., Hipel, K.W., Yang, K. and Chen, Y. (2014), "A novel executable modeling approach for system-of-systems architecture", *IEEE Systems Journal*, IEEE, Vol. 8 No. 1, pp. 4–13.

Geng, X. and Chu, X. (2012), "A new importance-performance analysis approach for customer satisfaction evaluation supporting PSS design", *Expert Systems with Applications*, Elsevier Ltd, Vol. 39 No. 1, pp. 1492–1502.

Geng, X., Chu, X., Xue, D. and Zhang, Z. (2010), "An integrated approach for rating engineering characteristics' final importance in product-service system development", *Computers & Industrial Engineering*, Elsevier Ltd, Vol. 59 No. 4, pp. 585–594.

Geng, X., Chu, X., Xue, D. and Zhang, Z. (2011), “A systematic decision-making approach for the optimal product – service system planning”, *Expert Systems With Applications*, Elsevier Ltd, Vol. 38 No. 9, pp. 11849–11858.

Gero, J.S. and Kannengiesser, U. (2004), “The situated function-behaviour-structure framework”, *Design Studies*, Vol. 25 No. 4, pp. 373–391.

Gero, J.S. and Kannengiesser, U. (2007), “A function-behavior-structure ontology of processes”, *Artificial Intelligence for Engineering Design, Analysis and Manufacturing: AIEDAM*, Vol. 21 No. 4, pp. 379–391.

Geum, Y. and Park, Y. (2011), “Designing the sustainable product-service integration: A product-service blueprint approach”, *Journal of Cleaner Production*, Elsevier Ltd, Vol. 19 No. 14, pp. 1601–1614.

Giffin, M., de Weck, O., Bounova, G., Keller, R., Eckert, C. and Clarkson, P.J. (2009), “Change Propagation Analysis in Complex Technical Systems”, *Journal of Mechanical Design*, Vol. 131 No. 8, p. 081001.

Goedkoop, M., Van Haler, C., te Riele, H. and Rommers, P. (1999), “Product Service-Systems, ecological and economic basics. Report”, *Report for Dutch Ministries of Envir- Onment (VROM) and Economic Affairs (EZ)*.

Goldbeck, N., Angeloudis, P. and Ochieng, W.Y. (2019), “Resilience assessment for interdependent urban infrastructure systems using dynamic network flow models”, *Reliability Engineering and System Safety*, Vol. 188, pp. 62–79.

Gomes, P., Cavalcante, E., Maia, P., Batista, T. and Oliveira, K. (2015), “A Systematic Mapping on Discovery and Composition Mechanisms for Systems-of-Systems”, *41st Euromicro Conference on Software Engineering and Advanced Applications, IEEE*, pp. 191–198.

Gorod, A., Sauser, B. and Boardman, J. (2008), “System-of-Systems Engineering Management: A Review of Modern History and a Path Forward”, *IEEE Systems Journal*, Vol. 2 No. 4, available at:https://doi.org/10.1109/JSYST.2008.2007163.

Grüninger, M., Fox, M.S. and Gruninger, M. (1995), “Methodology for the Design and Evaluation of Ontologies”, *International Joint Conference on Artificial Inteligence (IJCAI95), Workshop on Basic Ontological Issues in Knowledge Sharing*, pp. 1–10.

Guariniello, C. and Delaurentis, D.A. (2013), “Dependency analysis of system-of-systems operational and development networks”, *Procedia Computer Science*.

Guariniello, C., Mockus, L., Raz, A.K. and Delaurentis, D.A. (2019), “Towards Intelligent Architecting of Aerospace System-of-Systems”, *IEEE Aerospace Conference Proceedings*, IEEE, Vol. 2019–March, pp. 1–11.

Haase, R.P., Pigosso, D.C.A. and McAloone, T.C. (2017), “Product/Service-System Origins and Trajectories: A Systematic Literature Review of PSS Definitions and their Characteristics”, *Procedia CIRP*, The Author(s), Vol. 64, pp. 157–162.

Haber, N., Fargnoli, M. and Sakao, T. (2018), “Integrating QFD for product-service systems with the Kano model and fuzzy AHP Integrating QFD for product-service systems with the Kano model and fuzzy AHP”, *Total Quality Management*, available at:https://doi.org/10.1080/14783363.2018.1470897org/10.1080/14783363.2018.1470897.

Haeberle, D., Imran, S., Husen, C. Van and Droll, C. (2016), "Product-Service Systems across Life Cycle A New Approach for the Development of Services for Industrial Product- Service Systems", *Procedia CIRP*, Elsevier B.V., Vol. 47, pp. 353–357.

Hajimohammadi, A., Cavalcante, J. and Gzara, L. (2017), "Ontology for the PSS Lifecycle Management", *Procedia CIRP*, The Author(s), Vol. 64, pp. 151–156.

Haley, B.M., Dong, A. and Tumer, I.Y. (2016), "A Comparison of Network-Based Metrics of Behavioral Degradation in Complex Engineered Systems", *Journal of Mechanical Design, Transactions of the ASME*, Vol. 138 No. 12, pp. 1–11.

Hamel, J.M. and Azarm, S. (2011), "Reducible Uncertain Interval Design by Kriging Metamodel Assisted Multi-Objective Optimization", *Journal of Mechanical Design*, available at:https://doi.org/10.1115/1.4002974.

Hamraz, B., Caldwell, N.H.M. and Clarkson, P.J. (2012), "A Multidomain Engineering Change Propagation Model to Support Uncertainty Reduction and Risk Management in Design", *Journal of Mechanical Design*, Vol. 134 No. October 2012, pp. 1–14.

Han, S.Y. and Delaurentis, D. (2013), "Development interdependency modeling for system-of-systems (SoS) using Bayesian networks: SoS management strategy planning", *Procedia Computer Science*, Elsevier B.V., Vol. 16, pp. 698–707.

Hänsch, F., Pereira, D. and Borges, A. (2016), "Product-service systems characterization based on life cycle : application in a real situation", *Procedia CIRP*, Elsevier B.V., Vol. 47, pp. 418–423.

Hara, T., Arai, T. and Shimomura, Y. (2009a), "A Method to Analyze PSS from the Viewpoints of Function , Service Activity , and Product Behavior", *Proceedings of the 19th CIRP Design Conference–Competitive Design. Cranfield University Press*, pp. 1–2.

Hara, T., Arai, T. and Shimomura, Y. (2009b), "A CAD system for service innovation : integrated representation of function , service activity , and product behaviour", *Journal of Engineering Design*, Vol. 4828, available at:https://doi.org/10.1080/09544820903151715.

Hara, T., Arai, T., Shimomura, Y. and Sakao, T. (2009), "Service CAD system to integrate product and human activity for total value", *CIRP Journal of Manufacturing Science and Technology*, Vol. 1, pp. 262–271.

Hause, M. (2010), "The unified profile for DoDAF/MODAF (UPDM) enabling systems of systems on many levels", *2010 IEEE International Systems Conference Proceedings, SysCon 2010*, No. September, pp. 426–431.

Hein, A.M., Chazal, Y., Boutin, S. and Jankovic, M. (2018), "A Methodology for Architecting Collaborative Product Service System of Systems", *13th Annual Conference on System of Systems Engineering (SoSE). IEEE*, pp. 53–59.

Hein, A.M., Jankovic, M., Feng, W., Farel, R., Yune, J.H. and Yannou, B. (2017), "Stakeholder power in industrial symbioses: A stakeholder value network approach", *Journal of Cleaner Production*, Elsevier Ltd, Vol. 148, pp. 923–933.

Hein, A.M., Poulain, B., Jankovic, M., Chazal, Y. and Fakhfakh, S. (2018), "Product Service System

Design in a System of Systems Context: a Literature Survey", *International Design Conference*, pp. 2891–2902.

Heppelmann, J.E. (2014), "How Smart, Connected Products Are Transforming Competition", *Harvard Business Review*, No. November.

Heppelmann, J.E. (2015), "How Smart, Connected Products Are Transforming Companies", *Harvard Business Review*, No. October.

Hepperle, C., Orawski, R., Nolte, B.D., Mörtl, M. and Lindemann, U. (2010), "An integrated lifecycle model of product-service-systems", *Proceedings of the 2nd CIRP IPS2 Conference*, pp. 159–166.

Hernandez, R., Kreye, T.; and Pigosso, M.; (2018), *Typology of Uncertainties in the Development Process of Product-Service Systems, 25th Annual EurOMA Conference*, available at: http://www.inderscience.com/link.php?id=43140.

Herrmann, C., Kuntzky, K., Mennenga, M., Royer-Torney, M., Bergmann, L., Herrmann, C., Kuntzky, K., et al. (2010), "Joint Framework for Product Service Systems and Life Cycle Management", *CIRP International Conference on Industrial Product Service Systems*, pp. 353–359.

Herzog, M., Meuris, D., Bender, B. and Sadek, T. (2014), "The nature of risk management in the early phase of IPS2 design", *Procedia CIRP*, available at:https://doi.org/10.1016/j.procir.2014.02.010.

Horvath, I. (2012), "Beyond Advanced Mechatronics: New Design Challenges of Social-Cyber-Physical Systems", *ACCM-Workshop on Mechatronic Design*, pp. 0–20.

Horvath, I. and Gerritsen, B.H.M. (2012), "Cyber-Physical Systems : Concepts , Technologies and Implementation Principles", *TMCE*, pp. 19–36.

Huang, J., Seck, M.D. and Gheorghe, A. (2016), "Towards trustworthy smart cyber-physical-social systems in the era of Internet of Things", *2016 11th Systems of Systems Engineering Conference, SoSE 2016*, available at:https://doi.org/10.1109/SYSOSE.2016.7542961.

Hussain, R., Lockett, H., Vijaykumar, G. and Vasantha, A. (2012), "A framework to inform PSS Conceptual Design by using system-in-use data", *Computers in Industry*, Elsevier B.V., Vol. 63 No. 4, pp. 319–327.

Idrissi, N.A., Boucher, X. and Medini, K. (2017), "Generic Conceptual Model to Support PSS Design Processes", *Procedia CIRP*, available at:https://doi.org/10.1016/j.procir.2017.03.055.

INCOSE. (1966), *Systems Engineering Handbook*, *Journal of the Franklin Institute*, Vol. 281, available at:https://doi.org/10.1016/0016-0032(66)90450-9.

Ingram, C., Payne, R., Perry, S., Holt, J., Hansen, F. and Couto, L. (2014), "Modelling Patterns for Systems of Systems Architectures", *IEEE International Systems Conference Proceedings*, pp. 146–153.

Järvinen, P. (2007), "Action research is similar to design science", *Quality and Quantity*, Vol. 41 No. 1, pp. 37–54.

Kalawsky, R.S., Joannou, D., Tian, Y. and Fayoumi, A. (2013), "Using architecture patterns to architect and analyse systems of systems", *Conference on Systems Engineering Research (CSER)*, Vol. 16, pp. 283–292.

Kalawsky, R.S., Tian, Y., Joannou, D., Sanduka, I. and Masin, M. (2013), “Incorporating architecture patterns in a SoS optimization framework”, *Proceedings - 2013 IEEE International Conference on Systems, Man, and Cybernetics, SMC 2013*, IEEE, pp. 1726–1731.

Katina, P.F., Keating, C.B., Zio, E. and Gheorghe, A. V. (2016), “A Criticality-based Approach for the Analysis of Smart Grids”, *Technology and Economics of Smart Grids and Sustainable Energy*, Vol. 1 No. 1, available at:https://doi.org/10.1007/s40866-016-0013-2.

Keating, C.B. and Katina, P.F. (2011), “Systems of systems engineering: prospects and challenges for the emerging field”, *International Journal of System of Systems Engineering*, available at:https://doi.org/10.1504/IJSSE.2011.040556.

Keshavarzi, E., McIntire, M. and Hoyle, C. (2017), “A dynamic design approach using the Kalman filter for uncertainty management”, *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, available at:https://doi.org/10.1017/S0890060417000051.

Kim, Y.S. (2020), “A representation framework of product – service systems”, *Design Science*, Vol. 6, pp. 1–40.

Kim, Y.S., Lee, S.W. and Koh, D.C. (2011), “Representing product-service systems with product and service elements”, *ICED 11 - 18th International Conference on Engineering Design - Impacting Society Through Engineering Design*, Vol. 4 No. August, pp. 390–399.

Kim, Y.S., Wang, E. and Park, M.W. (2009), “Value- Function -Structure modeling in an ontological representation of Product-Service Systems”, *International Conference on Engineering Design*, pp. 359–370.

Kimita, K., Sakao, T. and Shimomura, Y. (2018), “A failure analysis method for designing highly reliable product-service systems”, *Research in Engineering Design*, available at:https://doi.org/10.1007/s00163-017-0261-8.

Kimita, K., Sugino, R., Rossi, M. and Shimomura, Y. (2016), “Framework for Analyzing Customer Involvement in Product-Service Systems”, *Procedia CIRP*, The Author(s), Vol. 47, pp. 54–59.

Kimita, K., Watanabe, K., Hara, T. and Komoto, H. (2015), “Who realizes a PSS?: An organizational framework for PSS development”, *Procedia CIRP*, Vol. 30, pp. 372–377.

Kinder, A., Barot, V., Henshaw, M. and Siemieniuch, C. (2012), “System of Systems:‘Defining the system of interest’”, *Proc. of the 2012 7th International Conference on Systems of Systems Engineering*, No. July, pp. 463–468.

Kölsch, P., Herder, C.F., Zimmermann, V. and Aurich, J.C. (2017), “A Novel Concept for the Development of Availability-Oriented Business Models”, *Procedia CIRP*, The Author(s), Vol. 64, pp. 340–344.

Komoto, H. and Tomiyama, T. (2008), “Integration of a service CAD and a life cycle simulator”, *CIRP Annals*, Vol. 57 No. 1, pp. 9–12.

Kreye, M.E. (2011), *Uncertainty Analysis in Competitive Bidding for Service Contracts*, University of Bath.

Kreye, M.E., Goh, Y.M. and Newnes, L.B. (2018), “Uncertainty perception in bidding for Product-Service Systems under competition”, *Journal of Purchasing and Supply Management*, available at:https://doi.org/10.1016/j.pursup.2017.10.003.

Kujawski, E. (2013), "Analysis and critique of the system readiness level", *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, Vol. 43 No. 4, pp. 979–987.

Kumar, A.A., Trinh, G.C. and Sakao, T. (2013), "How is Uncertainty Perceived and Managed in Design by PSS Providers? - Relation to PSS Types Provided", *The Philosopher's Stone for Sustainability*, Springer, Berlin, Heidelberg, pp. 91–96.

Kwan, S. and Müller-Gorchs, M. (2011), "Constructing Effective Value Propositions for Stakeholders in Service System Networks", *Proceedings of SIGSVC Workshop*, Vol. 11 No. 2011, pp. 1–23.

Labrousse, M. and Bernard, A. (2008), "FBS-PPRE, an Enterprise Knowledge Lifecycle Model", *Methods and Tools for Effective Knowledge Life-Cycle-Management*, pp. 285–305.

Lane, J.A. and Bohn, T. (2013), "Using SysML Modeling To Understand and Evolve Systems of Systems", *Systems Engineering*, Vol. 16 No. 1, pp. 87–98.

Laurischkat, K. and Viertelhausen, A. (2017), "Business Model Gaming: A Game-Based Methodology for E-Mobility Business Model Innovation", *Procedia CIRP*, The Author(s), Vol. 64, pp. 115–120.

Lay, G. (2003), "Betreiben statt Verkaufen: Häufigkeit des Angebots von Betreibermodellen in der deutschen Investitionsgüterindustrie", *ECONSTOR*.

Lay, G., Schroeter, M. and Biege, S. (2009), "Service-based business concepts: A typology for business-to-business markets", *European Management Journal*, available at:https://doi.org/10.1016/j.emj.2009.04.002.

Lee, J. and Hong, Y.S. (2017), "Bayesian network approach to change propagation analysis", *Research in Engineering Design*, Springer London, Vol. 28 No. 4, pp. 437–455.

Lee, S., Geum, Y., Lee, S. and Park, Y. (2015), "Evaluating new concepts of PSS based on the customer value: Application of ANP and niche theory", *Expert Systems with Applications*, Elsevier Ltd, Vol. 42 No. 9, pp. 4556–4566.

Li, H., Ji, Y., Gu, X., Qi, G. and Tang, R. (2012), "Module partition process model and method of integrated service product", *Computers in Industry*, Elsevier B.V., Vol. 63 No. 4, pp. 298–308.

Li, T., He, T., Wang, Z. and Zhang, Y. (2016), "A QFD-Based Evaluation Method for Business Models of Product Service Systems", *Mathematical Problems in Engineering*, Vol. 2016, available at:https://doi.org/10.1155/2016/8532607.

Li, Y., Wang, Z., Zhong, X. and Zou, F. (2018), "Identification of influential function modules within complex products and systems based on weighted and directed complex networks", *Journal of Intelligent Manufacturing*, Springer US, available at:https://doi.org/10.1007/s10845-018-1396-9.

Lim, C.H., Kim, K.J., Hong, Y.S. and Park, K. (2012), "PSS Board: A structured tool for product-service system process visualization", *Journal of Cleaner Production*, Elsevier Ltd, Vol. 37, pp. 42–53.

Lim, S.L. and Ncube, C. (2013), "Social Networks and Crowdsourcing for Stakeholder Analysis in System of Systems Projects", *International Conference on System of Systems Engineering*, pp.

13–18.

Lim, S.L., Quercia, D. and Finkelstein, A. (2010), “StakeNet: Using social networks to analyse the stakeholders of large-scale software projects”, *Proceedings - International Conference on Software Engineering*, Vol. 1, pp. 295–304.

Lindahl, M., Sakao, T., Sundin, E. and Shimomura, Y. (2009), “Product / Service Systems Experiences : an International Survey of Swedish , Japanese , Italian and German Manufacturing Companies”, No. April, pp. 74–81.

Liu, Z., Ming, X., Song, W., Qiu, S. and Qu, Y. (2018), “A perspective on value co-creation-oriented framework for smart product-service system”, *Procedia CIRP*, Elsevier B.V., Vol. 73, pp. 155–160.

Long, H.J., Wang, L.Y., Shen, J., Wu, M.X. and Jiang, Z.B. (2013), “Product service system configuration based on support vector machine considering customer perception”, *International Journal of Production Research*, available at:https://doi.org/10.1080/00207543.2013.778432.

Long, H.J., Wang, L.Y., Zhao, S.X. and Jiang, Z.B. (2016), “An approach to rule extraction for product service system configuration that considers customer perception”, *International Journal of Production Research*, available at:https://doi.org/10.1080/00207543.2015.1078012.

Luo, J. (2015), “A simulation-based method to evaluate the impact of product architecture on product evolvability”, *A Simulation-Based Method to Evaluate the Impact of Product Architecture on Product Evolvability*, available at:https://doi.org/10.1007/s00163-015-0202-3.

Luo, J. (2017), “System-of-systems innovation : Proactive methods for conception and strategies for implementation”, *Journal of Enterprise Transformation*, Taylor & Francis, Vol. 0 No. 0, pp. 1–25.

Luo, J., Baldwin, C.Y., Whitney, D.E. and Magee, C.L. (2012), “The Architecture of Transaction Networks : A Comparative Analysis of Hierarchy in Two Sectors”, *Industrial and Corporate Change*, Vol. 21 No. 6, pp. 1307–1335.

Mahmood, A. and Montagna, F. (2012), “System of Systems Architecture Framework (SoSAF) for production industries”, *Proceedings - 2012 7th International Conference on System of Systems Engineering, SoSE 2012*, IEEE, No. July, pp. 537–542.

Mahut, F., Daaboul, J., Bricogne, M. and Eynard, B. (2015), “Survey on product-service system applications in the automotive industry”, *IFAC-PapersOnLine*, Elsevier Ltd., Vol. 28 No. 3, pp. 840–847.

Maier, M.W. (1996), “Architecting Principles for Systems-of-Systems”, *INCOSE International Symposium*, Vol. 6 No. 1, pp. 565–573.

Maleki, E., Belkadi, F. and Bernard, A. (2017), “Systems Engineering as a Foundation for PSS Development Project: Motivations and Perspectives”, *Procedia CIRP*, Elsevier B.V., Vol. 64, pp. 205–210.

Maleki, E., Belkadi, F. and Bernard, A. (2018), “Industrial Product-Service System modelling base on Systems Engineering: Application of sensor integration to support smart services”, *IFAC-PapersOnLine*, Vol. 51 No. 11, pp. 1586–1591.

Maleki, E., Belkadi, F., Van der Zwaag, B.J. and Bernard, A. (2017), “A sensor ontology enabling service implementation in Industrial Product-Service Systems”, *IFAP*.

Malik, B.A., Aftab, A. and P.M., N.A. (2019), “Mapping of PSS Research: A Bibliometric Analysis”, *DESIDOC Journal of Library & Information Technology*, Vol. 39 No. 1, pp. 23–30.

Mannweiler, C. and Aurich, J.C. (2012), “Modularization of Products and Services for Configuring Product-Service Systems”, *The Philosopher’s Stone for Sustainability*, pp. 37–41.

Mannweiler, C., Siener, M. and Aurich, J.C. (2010), “Lifecycle Cost oriented Evaluation and Selection of Product-Service System Variants”, *Proceedings of the 2nd CIRP IPS2 Conference*.

Mansouri, M., Gorod, A., Wakeman, T.H. and Sauser, B. (2009), “Maritime Transportation System of Systems management framework: a System of Systems Engineering approach”, *Int. J. Ocean Systems Management*, Vol. 1 No. 2, pp. 200–226.

Manzini, E. and Vezzoli, C. (2003), “A strategic design approach to develop sustainable product service systems: Examples taken from the ‘environmentally friendly innovation’ Italian prize”, *Journal of Cleaner Production*, Vol. 11 No. 8 SPEC., pp. 851–857.

Marrone, M. and Hammerle, M. (2018), “Smart Cities: A Review and Analysis of Stakeholders’ Literature”, *Business and Information Systems Engineering*, Springer Fachmedien Wiesbaden, Vol. 60 No. 3, pp. 197–213.

Martín-Peña, M.L., Pinillos, M.J. and Reyes, L.E. (2017), “The intellectual basis of servitization: A bibliometric analysis”, *Journal of Engineering and Technology Management - JET-M*, Vol. 43, pp. 83–97.

Matschewsky, J., Kambanou, M.L. and Sakao, T. (2018), “Designing and providing integrated product-service systems–challenges, opportunities and solutions resulting from prescriptive approaches in two industrial companies”, *International Journal of Production Research*, Taylor and Francis Ltd., Vol. 56 No. 6, pp. 2150–2168.

Maurer, M., Gerdes, J.C., Lenz, B. and Winner, H. (2016), *Autonomous Driving: Technical, Legal and Social Aspects*, *Autonomous Driving: Technical, Legal and Social Aspects*, available at:https://doi.org/10.1007/978-3-662-48847-8.

Maussang, N., Zwolinski, P. and Brissaud, D. (2008), “Evaluation of Product-Service Systems During Early Design Phase”, *Manufacturing Systems and Technologies for the New Frontier*, Springer., London, pp. 547–552.

Maussang, N., Zwolinski, P. and Brissaud, D. (2009), “Product-service system design methodology: from the PSS architecture design to the products specifications”, *Journal of Engineering Design*, Vol. 20 No. 4, pp. 349–366.

Maxwell, D., Sheate, W. and Vorst, R. Van Der. (2006), “Functional and systems aspects of the sustainable product and service development approach for industry”, *Journal of Cleaner Production*, available at:https://doi.org/10.1016/j.jclepro.2006.01.028.

McKay, A. and Kundu, S. (2014), “A representation scheme for digital product service system definitions”, *Advanced Engineering Informatics*, Elsevier Ltd, Vol. 28 No. 4, pp. 479–498.

Medini, K. and Boucher, X. (2019), “Specifying a modelling language for PSS Engineering – A development method and an operational tool", *Computers in Industry*, Elsevier B.V., Vol. 108, pp. 89–103.

Meier, H., Roy, R. and Seliger, G. (2010), "Industrial Product-Service systems-IPS2", *CIRP Annals - Manufacturing Technology*, Vol. 59 No. 2, pp. 607–627.

Meier, H., Völker, O. and Funke, B. (2011), "Industrial Product-Service Systems (IPS2) : Paradigm shift by mutually determined products and services", *International Journal of Advanced Manufacturing Technology*, Vol. 52 No. 9–12, pp. 1175–1191.

Michaelis, M.T. (2013), *Co-Development of Products and Manufacturing Systems Using Integrated Platform Models*, Chalmers University of Technology.

Mikusz, M. (2014), "Towards an Understanding of Cyber-Physical Systems as Industrial Software-Product-Service Systems", *Procedia CIRP*, Elsevier B.V., Vol. 16, pp. 385–389.

Mitchell, R.K., Agle, B.R. and Wood, D.J. (1997), "Toward a Theory of Stakeholder Identification and Salience : Defining the Principle of Who and What Really Counts", *Academy of Management Review*, Vol. 22 No. 4, pp. 853–886.

Mohsin, A., Janjua, N.K., Islam, S.M. and Valdemar Vicente Graciano, N. (2019), "Modeling Approaches for System-of-Systems Dynamic Architecture : Overview , Taxonomy and Future Prospects", *Architecture*, Vol. 13, pp. 49–56.

Mohsin, A., Janjua, N.K., Islam, S.M.S., Vicente, V. and Neto, G. (2019), "A Taxonomy of Modeling Approaches for Systems-of-Systems Dynamic Architectures : Overview and Prospects", *Proceedings of the 14th International Conference on System of Systems Engineering (SoSE)*.

Mok, K.Y., Shen, G.Q. and Yang, J. (2014), "Stakeholder management studies in mega construction projects : A review and future directions", *JPMA*, Elsevier Ltd, Vol. 33 No. 2, pp. 446–457.

Mont, O. (2002), "Clarifying the concept of product – service system", *Journal of Cleaner Production*, Vol. 10, pp. 237–245.

Morelli, M.D., Eppinger, S.D. and Gulati, R.K. (1995), "Predicting Technical Communication in Product Development Organizations", *IEEE Transactions on Engineering Management*.

Morelli, N. (2003), "Product-service systems, a perspective shift for designers: A case study - The design of a telecentre", *Design Studies*, Vol. 24 No. 1, pp. 73–99.

Mougaard, K., Howard, T.J., McAloone, T.C., Neugebauer, L. and Bey, N. (2012), "Establishing collaborative networks for the conceptualisation of PSS", *Proceedings of International Design Conference, DESIGN*, Vol. DS 70, pp. 249–258.

Mourtzis, D., Fotia, S., Gamito, M. and Neves-silva, R. (2016), "PSS Design Considering Feedback from the Entire Product-Service Lifecycle and Social Media", *Procedia CIRP*, Elsevier B.V., Vol. 47, pp. 156–161.

Mourtzis, D., Fotia, S. and Vlachou, E. (2016), "PSS Design Evaluation via KPIs and Lean Design Assistance Supported by Context Sensitivity Tools", *Procedia CIRP*, The Author(s), Vol. 56, pp. 496–501.

Muller, G. (2016), "Are stakeholders in the constituent systems SoS aware ?", IEEE.

Muller, G. (2018), "The challenge of increasing heterogeneity in Systems of Systems for architecting", *2018 13th Annual Conference on System of Systems Engineering (SoSE)*, IEEE, No. Sec VI, pp. 521–526.

Müller, P., Schulz, F. and Stark, R. (2012), "Guideline to elicit requirements on industrial product-service systems", *Proceedings of the 2nd CIRP IPS2 Conference 2010; 14-15 April; Linköping; Sweden*, pp. 109–116.

Neely, A., Benedetinni, O. and Visnjic, I. (2011), "The servitization of manufacturing : Further evidence", *18th European Operations Management Association Conference, Cambridge*, No. July, pp. 1–10.

Neves-silva, R., Pina, P., Spindler, P., Pezzotta, G. and Mourtzis, D. (2016), "Supporting context sensitive lean product service engineering", *Procedia CIRP*, Elsevier B.V., Vol. 47, pp. 138–143.

Nielsen, C.B., Larsen, P.G., Fitzgerald, J., Woodcock, J. and Peleska, J. (2015), "Systems of Systems Engineering", *ACM Computing Surveys*, available at:https://doi.org/10.1145/2794381.

Nilsson, S. and Lindahl, M. (2016), "Product-Service Systems across Life Cycle A Literature Review to Understand the Requirements Specification ' s Role when Developing Integrated Product Service Offerings", *Procedia CIRP*, The Author(s), Vol. 47, pp. 150–155.

Noy, N.F. and McGuinness, D.L. (2001), "A Guide to Creating Your First Ontology", *Biomedical Informatics Reseach*, pp. 7–25.

O'Connor, G.C. and Rice, M.P. (2013), "A comprehensive model of uncertainty associated with radical innovation", *Journal of Product Innovation Management*, available at:https://doi.org/10.1111/jpim.12060.

OECD. (2015), "Urban Mobility System Upgrade: How shared self-driving cars could change city traffic", *International Transport Forum*, pp. 1–36.

OECD. (2020), "Smart Cities and Inclusive Growth", No. July, pp. 1–59.

Oppong, G.D., Chan, A.P.C. and Dansoh, A. (2017), "A review of stakeholder management performance attributes in construction projects", *International Journal of Project Management*, Elsevier Ltd, APM and IPMA, Vol. 35 No. 6, pp. 1037–1051.

Orellano, M., Medini, K., Lambey-Checchin, C. and Neubert, G. (2019), "A system modelling approach to collaborative PSS design", *Procedia CIRP*, Elsevier B.V., Vol. 83, pp. 218–223.

Van Ostaeyen, J., Van Horenbeek, A., Pintelon, L. and Duflou, J.R. (2013), "A refined typology of product-service systems based on functional hierarchy modeling", *Journal of Cleaner Production*, pp. 261–276.

Osterwalder, A. and Pigneur, Y. (2010), "Business Model Generation: A Handbook for Visionaries, Game Changers, and Challengers", *A Handbook for Visionaries, Game Changers, and Challengers*, Vol. 5 No. 7, p. 288.

Paparistodimou, G., Duffy, A., Whitfield, R.I., Knight, P. and Robb, M. (2020), "A network tool to analyse and improve robustness of system architectures", *Design Science*, No. May, pp. 1–40.

Pape, L., Agarwal, S. and Dagli, C. (2015), "Selecting Attributes , Rules , and Membership Functions for Fuzzy SoS Architecture Evaluation", Vol. 61, pp. 176–182.

Park, Y., Geum, Y. and Lee, H. (2012), "Toward integration of products and services: Taxonomy and typology", *Journal of Engineering and Technology Management - JET-M*, Elsevier B.V., Vol. 29 No. 4, pp. 528–545.

Parnar, B.L., Freeman, R.E., Harrison, J.S., Wicks, A.C., DeColle, S. and Purnell, L. (2010), "Stakeholder Theory: The state of the art", *The Academy of Management Annals*, Vol. 4 No. 1, pp. 403–445.

Parraguez-Ruiz, P. (2015), *A Networked Perspective on the Engineering Design Process*, Technical University of Denmark.

Parraguez, P., Steven, D. and Maier, A. (2015), "Information Flow Through Stages of Complex Engineering Design Projects : A Dynamic Network Analysis Approach", *IEEE Transactions on Engineering Management*, available at:https://doi.org/10.1109/TEM.2015.2469680.

Paula, A., Seidel, J., Seliger, G. and Kohl, H. (2016), "Sustainability factors for PSS business models", *Procedia CIRP*, Elsevier B.V., Vol. 47, pp. 436–441.

Petitdemange, F., Borne, I. and Buisson, J. (2018), "Modeling system of systems configurations", *13th Annual Conference on System of Systems Engineering (SoSE)*, pp. 392–399.

Pezzotta, G., Cavalieri, S. and Gaiardelli, P. (2012), "A spiral process model to engineer a product service system : An explorative analysis through case studies", *CIRP Journal of Manufacturing Science and Technology*, CIRP, Vol. 5 No. 3, pp. 214–225.

Pezzotta, G., Cavalieri, S. and Romero, D. (2018), "Collaborative product-service systems engineering: Towards an active role of customers and stakeholders in value co-creation", *2017 International Conference on Engineering, Technology and Innovation: Engineering, Technology and Innovation Management Beyond 2020: New Challenges, New Approaches, ICE/ITMC 2017 - Proceedings*, Vol. 2018–Janua, pp. 1247–1254.

Pezzotta, G., Pinto, R., Pirola, F. and Ouertani, M.Z. (2014), "Balancing product-service provider's performance and customer's value: The SErvice Engineering Methodology (SEEM)", *Procedia CIRP*, available at:https://doi.org/10.1016/j.procir.2014.01.008.

Pezzotta, G., Pirola, F., Pinto, R., Akasaka, F. and Shimomura, Y. (2015), "A Service Engineering framework to design and assess an integrated product-service", *Mechatronics*, Elsevier Ltd, Vol. 31, pp. 169–179.

Pezzotta, G., Pirola, F., Rondini, A., Pinto, R. and Ouertani, M.-Z. (2016), "Towards a methodology to engineer industrial product-service system – Evidence from power and automation industry", *CIRP Journal of Manufacturing Science and Technology*, Vol. 15, pp. 19–32.

Pezzotta, G., Regazzoni, D., Cavalieri, S. and Rizzi, C. (2011), "Enhancement in Industrial PSS Design based on TRIZ: a Case Study", *Proceedings of the 3rd CIRP IPSS Conference CIRP IPSS Conference*, pp. 225–230.

Piccolo, S.A. (2019), *Analysis and Modelling of Engineering Systems Using Data Science and Network Science*, Technical University of Denmark.

Pieroni, M.D.P., Marques, C.A.N., Moraes, R.N., Rozenfeld, H. and Ometto, A.R. (2017), "PSS Design

Process Models: Are They Sustainability-oriented?", *Procedia CIRP*, Vol. 64, pp. 67–72.

Pinho, N.F. De. (2015), *Designing Complex Services for Multiple Stakeholders : An Application to Electronic Health Records*, Universidade do Porto.

Pinto, H.S. and Martins, J.P. (2004), "Ontologies: How can They be Built?", *Knowledge and Information Systems*, Vol. 6 No. 4, pp. 441–464.

Piontek, F.M. and Müller, M. (2018), "Literature Reviews : Life Cycle Assessment in the Context of Product-Service Systems and the Textile Industry", *Procedia CIRP*, The Author(s), Vol. 69 No. April, pp. 758–763.

Pirayesh, A., Doumeingts, G., Seregni, M., Gusmeroli, S., Westphal, I., Gonzalez, L., Hans, C., et al. (2018), "Conceptual Framework for Product Service Systems", *Systems*, Vol. 6 No. 20, available at:https://doi.org/10.3390/systems6020020.

Plassat, G. (2010), "Megacities on the move, sustainable urban mobility in 2040".

Qu, M., Yu, S., Chen, D., Chu, J. and Tian, B. (2016), "State-of-the-art of design , evaluation , and operation methodologies in product service systems", *Computers in Industry*, Elsevier B.V., Vol. 77 No. 127, pp. 1–14.

Raja, V. (2019), *On the Design of Functionally Integrated Aero-Engine Structures Modeling and Evaluation Methods for Architecture and Complexity*, Chalmers University of Technology.

Raman, R. and Drsouza, M. (2018), "Learning framework for maturing architecture design decisions for evolving complex SoS", *13th System of Systems Engineering Conference, SoSE 2018*, pp. 350–357.

Reason, P. and Bradbury, H. (2001), "Handbook of action research Introduction : Participative Inquiry and Practice", *London: Sage Publications*.

Reed, M.S., Graves, A., Dandy, N., Posthumus, H., Hubacek, K., Morris, J., Prell, C., et al. (2009), "Who's in and why? A typology of stakeholder analysis methods for natural resource management", *Journal of Environmental Management*, Elsevier Ltd, Vol. 90 No. 5, pp. 1933–1949.

Reim, W., Parida, V. and Ortqvist, D. (2015), "Product e Service Systems (PSS) business models and tactics - a systematic literature review", *Journal of Cleaner Production*, Vol. 97, available at:https://doi.org/10.1016/j.jclepro.2014.07.003.

Reim, W., Sjödin, D.R. and Parida, V. (2014), "Trust or Control: How to Manage Behavioural Uncertainty for Industrial Product-Service System Provision?", *International CINet Conference: Operating Innovation-Innovating Operations 07/09/2014-09/09/2014.*

Sabbagh, O., Nizam, M., Rahman, A. and Ismail, W.R. (2016), "Methodology implications in automotive product – service systems : a systematic literature review", *Total Quality Management & Business Excellence*, Vol. 3363 No. February, available at:https://doi.org/10.1080/14783363.2016.1150169.

Sahin, F., Sridhar, P., Horan, B., Raghavan, V. and Jamshidi, M. (2007), "System of systems approach to threat detection and integration of heterogeneous independently operable systems", *Conference Proceedings - IEEE International Conference on Systems, Man and Cybernetics*, pp. 1376–1381.

Sakao, T. and Lindahl, M. (2012), “A value based evaluation method for Product/Service System using design information”, *CIRP Annals - Manufacturing Technology*, CIRP, Vol. 61 No. 1, pp. 51–54.

Sakao, T., Panshef, V. and Dörsam, E. (2009), “Addressing Uncertainty of PSS for Value-Chain Oriented Service Development”, *Introduction to Product/Service-System Design*, pp. 137–157.

Sakao, T. and Shimomura, Y. (2007), “Service Engineering : a novel engineering discipline for producers to increase value combining service and product”, *Journal of Cleaner Production*, Vol. 15, pp. 590–604.

Sakao, T., Shimomura, Y., Sundin, E. and Comstock, M. (2009), “Modeling design objects in CAD system for Service/Product Engineering”, *CAD Computer Aided Design*, Elsevier Ltd, Vol. 41 No. 3, pp. 197–213.

Sanduka, I. and Obermaisser, R. (2014), “Model-based development of Systems-of-Systems with real-time requirements”, *Proceedings - 2014 12th IEEE International Conference on Industrial Informatics, INDIN 2014*, IEEE, pp. 188–194.

Sarica, S. and Luo, J. (2019), “An Infinite Regress Model of Design Change Propagation in Complex Systems”, *IEEE Systems Journal*, IEEE, Vol. 13 No. 4, pp. 1–9.

Sassanelli, C., Pezzotta, G., Pirola, F., Terzi, S. and Rossi, M. (2016), “Design for Product Service Supportability (DfPSS) approach : a state of the art to foster Product Service System (PSS) design”, *Procedia CIRP*, The Author(s), Vol. 47, pp. 192–197.

Saunders, M., Lewis, P. and Thornhill, A. (2009), *Research Methods for Business Students, Harlow, UK, Financial Times Prentice Hall*.

Sauser, B. and Boardman, J. (2008), “Taking Hold of System of Systems Management”, *Engineering Management Journal*, Vol. 20 No. 4.

Sauser, B., Boardman, J. and Gorod, A. (2009), “System of Systems Management”, *System of Systems Engineering: Innovations for the 21st Century*, pp. 191–217.

Schenkl, S.A., Sauer, R.M. and Mörtl, M. (2014), “A Technology-centered Framework for Product-Service Systems”, *Procedia CIRP*, Elsevier B.V., Vol. 16, pp. 295–300.

Scholze, S., Teresa, A. and Stokic, D. (2016), “Novel Tools for Product-Service System Engineering”, *Procedia CIRP*, The Author(s), Vol. 47, pp. 120–125.

Shen, J., Erkoyuncu, J.A., Roy, R. and Wu, B. (2017), “A framework for cost evaluation in product service system configuration”, *International Journal of Production Research*, Taylor & Francis, Vol. 55 No. 20, pp. 6120–6144.

Shimomura, Y., Hara, T. and Arai, T. (2009), “A unified representation scheme for effective PSS development”, *CIRP Annals - Manufacturing Technology*, Vol. 58 No. 1, pp. 379–382.

Son, S. and Cho, J. (2017), “Social Network Analysis of Collaborative R & D activities in Pharmaceutical Industry - Topological Properties of EU ’ s Innovative Medicines Initiative-”, *International Journal of Applied Engineering Research*, Vol. 12 No. 20, pp. 9799–9806.

Song, W. (2017), “Requirement management for product-service systems : Status review and future trends”, *Computers in Industry*, Elsevier B.V., Vol. 85, pp. 11–22.

Song, W., Ming, X., Han, Y., Xu, Z. and Wu, Z. (2015), "An integrative framework for innovation management of product-service system", *International Journal of Production Research*, Taylor & Francis, Vol. 53 No. 8, pp. 2252–2268.

Song, W. and Sakao, T. (2016), "Service conflict identification and resolution for design of product-service offerings", *Computers and Industrial Engineering*, Elsevier Ltd, Vol. 98, pp. 91–101.

Song, W. and Sakao, T. (2017), "A customization-oriented framework for design of sustainable product / service system", *Journal of Cleaner Production*, Elsevier Ltd, Vol. 140, pp. 1672–1685.

Song, W., Wu, Z., Li, X. and Xu, Z. (2015), "Modularizing product extension services: An approach based on modified service blueprint and fuzzy graph", *Computers and Industrial Engineering*, Elsevier Ltd, Vol. 85, pp. 186–195.

Sosa, M., Mihm, J. and Browning, T. (2011), "Degree Distribution and Quality in Complex Engineered Systems", *Journal of Mechanical Design*, Vol. 133 No. 10, p. 101008.

Sosa, M.E., Eppinger, S.D., Pich, M., McKendrick, D.G. and Stout, S.K. (2000), "Factors that Influence Technical Comminication in Distributed Product Development: An Empirical Study in the Telecommunications Industry", *IEEE Transactions on Engineering Management*, Vol. 49 No. 1, pp. 45–58.

Stalker, R. (2002), "A function-behaviour-structure framework for the lifecycle of an artefact", *Creativity and Cognition 4*, p. 6.

Suh, N.P. (2001), *Axiomatic Design: Advances and Applications*, Mit-Pappal.

Summers, J.D. and Eckert, C. (2013), "Interviewing as a method for data gathering in engineering design research", pp. 1–19.

Susman, G. and Evered, R.D. (1978), "An Assessment of the Scientific Merits of Action Research", *Administrative Science Quarterly*, Vol. 23 No. 4, pp. 582–603.

Talebpour, A. and Mahmassani, H.S. (2016), "Influence of connected and autonomous vehicles on traffic flow stability and throughput", *Transportation Research Part C: Emerging Technologies*, Elsevier Ltd, Vol. 71, pp. 143–163.

Tekinerdogan, B. (2016), "On devising an architecture framework for system-of-systems", *ACM International Conference Proceeding Series*, No. July, pp. 1–6.

Thunnissen, D.P. (2003), "Uncertainty Classification for the Design and Development of Complex Systems", *3rd Annual Predictive Methods Conference*, pp. 1–16.

Tran, T. and Park, J.Y. (2016), "Development of a novel set of criteria to select methodology for designing product service systems", *Journal of Computational Design and Engineering*, available at:https://doi.org/10.1016/j.jcde.2015.10.001.

Tran, T.A. and Park, J.Y. (2014), "Development of integrated design methodology for various types of product – service systems", *Journal of Computational Design and Engineering*, Elsevier Masson SAS, Vol. 1 No. 1, pp. 37–47.

Travassos, G.H. (2009), "Action Research Use in Software Engineering: an Initial Survey", *Systems Engineering*, pp. 414–417.

Tukker, A. (2004), "Eight Types of Product Service Systems", *Business Strategy and the Environment*, Vol. 13, pp. 246–260.

Tukker, A. (2015), "Product services for a resource-efficient and circular economy - A review", *Journal of Cleaner Production*, Elsevier Ltd, Vol. 97, pp. 76–91.

Tukker, A. and Tischner, U. (2006), "Product-services as a research field: past, present and future. Reflections from a decade of research", *Journal of Cleaner Production*, Vol. 14 No. 17, pp. 1552–1556.

Uday, P. and Marais, K. (2015), "Designing Resilient Systems-of-Systems: A Survey of Metrics, Methods, and Challenges", *Systems Engineering*, Vol. 18 No. 5, pp. 491–510.

Uschold, M. and King, M. (1995), "Towards a Methodology for Building Ontologies", *Workshop on Basic Ontological Issues in Knowledge Sharing*, No. July.

Varvasovszky, Z. (2000), "Stakeholder analysis : a review", *Health Policy and Planning*, Vol. 15 No. 3, pp. 239–246.

Vasantha, G.V.A., Roy, R., Lelah, A. and Brissaud, D. (2012), "A review of product-service systems design methodologies", *Journal of Engineering Design*, Vol. 23 No. 9, pp. 635–659.

Velamuri, V.K., Neyer, A.K. and Möslein, K.M. (2011), "Hybrid value creation: A systematic review of an evolving research area", *Journal Fur Betriebswirtschaft*, Vol. 61 No. 1, pp. 3–35.

Vezzoli, C., Ceschin, F., Carel, J. and Kohtala, C. (2015), "New design challenges to widely implement ' Sustainable Product - Service Systems ' *", *Journal of Cleaner Production*, Elsevier Ltd, Vol. 97, pp. 1–12.

Waidelich, L., Bulander, R., Richter, A., Kölmel, B. and Glaser, P. (2019), "A Systematic Literature Review on Product-Service Systems Classifications and Types", *ICETE*, pp. 83–94.

Walsh, H.S., Dong, A. and Tumer, I.Y. (2018), "The role of bridging nodes in behavioral network models of complex engineered systems", *Design Science*, Vol. 4, pp. 1–28.

Walsh, H.S., Dong, A. and Tumer, I.Y. (2019), "An Analysis of Modularity as a Design Rule Using Network Theory", *Journal of Mechanical Design, Transactions of the ASME*, Vol. 141 No. 3, pp. 1–10.

Wang, P.., Ming, X., Wu, Z., Wang, L. and Wu, Z.Y. (2011), "Modular Development of Product Service Systems", *Concurent Engineering: Research and Applications*, Vol. 19 No. 85, available at:https://doi.org/10.1177/1063293X11403508.

Wang, P.P., Ming, X.G., Li, D., Kong, F.B., Wang, L. and Wu, Z.Y. (2011), "Status review and research strategies on product-service systems", *International Journal of Production Research*, Vol. 49 No. 22, pp. 6863–6883.

Wang, P.P., Ming, X.G., Wu, Z.Y., Zheng, M.K. and Xu, Z.T. (2014), "Research on industrial product – service configuration driven by value demands based on ontology modeling", *Computers in Industry*, Vol. 65, pp. 247–257.

Wang, X. and Durugbo, C. (2013), "Analysing network uncertainty for industrial product-service delivery: A hybrid fuzzy approach", *Expert Systems with Applications*, available at:https://doi.org/10.1016/j.eswa.2013.01.062.

De Weck, O., Eckert, C. and Clarkson, J. (2007), "A classification of uncertainty for early product and system design", *Guidelines for a Decision Support Method Adapted to NPD Processes*, pp. 159–160.

Weiller, C. and Neely, A. (2013), "Business Model Design in an Ecosystem Context", *British Academy of Management Conference*, pp. 1–21.

Welp, E.G., Meier, H., Sadek, T. and Sadek, K. (2008), "Modelling Approach for the Integrated Development of Industrial Product-Service Systems", *In Manufacturing Systems and Technologies for the New Frontier*, Springer,., London, pp. 525–530.

Wiesner, S., Freitag, M., Westphal, I. and Thoben, K. (2015), "Interactions between Service and Product Lifecycle Management", *Procedia CIRP*, Elsevier B.V., Vol. 30, pp. 36–41.

Williams, A. (2007), "Product service systems in the automobile industry : contribution to system innovation ?", *Journal of Cleaner Production*, Vol. 15 No. 11–12, pp. 1093–1103.

Wu, D., Rosen, D.W., Panchal, J.H. and Schaefer, D. (2016), "Understanding communication and collaboration in social product development through social network analysis", *Journal of Computing and Information Science in Engineering*, Vol. 16 No. 1, pp. 1–10.

Wynn, D.C., Caldwell, N.H.M. and Clarkson, P.J. (2010), "Can Change Prediction help prioritise Redesign Work in Future Engineering Systems", *Proceedings of the 11th International Design Conference DESIGN 2010*, pp. 1691–1702.

Wynn, D.C., Caldwell, N.H.M. and John Clarkson, P. (2014), "Predicting Change Propagation in Complex Design Workflows", *Journal of Mechanical Design*, Vol. 136 No. 8, available at:https://doi.org/10.1115/1.4027495.

Yang, L., Xing, K. and Lee, S.-H. (2010), "A New Conceptual Life Cycle Model for Result-Oriented Product-Service System Development", *IEEE International Conference on Service Operations and Logistics, and Informatics*, pp. 23–28.

Yang, R.J. and Zou, P.X.W. (2014), "Stakeholder-associated risks and their interactions in complex green building projects : A social network model", *Building and Environment*, Elsevier Ltd, Vol. 73, pp. 208–222.

Yin, D., Ming, X., Liu, Z. and Zhang, X. (2020), "A Fuzzy ANP-QFD Methodology for Determining Stakeholders in Product-Service Systems Development from Ecosystem Perspective", *Sustainability*, Vol. 12 No. 8, p. 3329.

Yip, M.H., Phaal, R. and Probert, D.R. (2012), "Value co-creation in early stage new product-service system development", pp. 287–298.

Yoonyee, P. and Sang, B.J. (2017), "Need network analysis: A process to understand the stakeholder need structure in multi-actor service systems", *Proceedings of the International Conference on Engineering Design, ICED*, Vol. 4 No. DS87-4, pp. 693–702.

Zedan, S. and Miller, W. (2018), "Quantifying stakeholders ' influence on energy efficiency of housing : development and application of a four-step methodology", *Construction Management and Economics*, Routledge, Vol. 6193, pp. 1–19.

Zhang, L. (2015), "Applying System of Systems Engineering Approach to Build Complex Cyber Physical Systems", *Advances in Intelligent Systems and Computing*, available at:https://doi.org/10.1007/978-3-319-08422-0_88.

Zhang, W. and Banerji, S. (2017), "Challenges of servitization: A systematic literature review", *Industrial Marketing Management*, available at:https://doi.org/10.1016/j.indmarman.2017.06.003.

Zhang, Y., Liu, X., Wang, Z. and Chen, L. (2012), "A service-oriented method for system-of-systems requirements analysis and architecture design", *Journal of Software*, Vol. 7 No. 2, pp. 358–365.

Zhang, Z., Xu, D., Ostrosi, E., Yu, L. and Fan, B. (2017), "A systematic decision-making method for evaluating design alternatives of product service system based on variable precision rough set", *Journal of Intelligent Manufacturing*, available at:https://doi.org/10.1007/s10845-017-1359-6.

Zhu, Q.Q., Jiang, P.Y., Huang, G.Q. and Qu, T. (2011), "Implementing an industrial product-service system for CNC machine tool", *International Journal of Advanced Manufacturing Technology*, Vol. 52 No. 9–12, pp. 1133–1147.

Zine, P.U., Kulkarni, M.S., Chawla, R. and Ray, A.K. (2014), "A framework for value co-creation through customization and personalization in the context of machine tool PSS", *Procedia CIRP*, available at:https://doi.org/10.1016/j.procir.2014.01.005.