INTERNATIONAL DESIGN CONFERENCE – DESIGN 2024
https://doi.org/10.1017/pds.2024.260

# Service centric design methodology for integrated robot-infrastructure systems

Abhishek Gupta ✉ and Dietmar Göhlich

Technische Universität Berlin, Germany

✉ abhishek.gupta@tu-berlin.de

**Abstract**

The ongoing development of technology and AI facilitates the emergence of service robots in various application fields. Hence, the development of robot-infrastructure product-service systems (PSS) will become increasingly important. Based on the existing literature we propose a new methodological approach for a joint development of robot and infrastructure in the context of a socio-technical system with various stakeholders. We suggest digital models and physical prototypes to synchronize service and product development. The applicability is demonstrated for autonomous waste management robots.

*Keywords:* *robot-infrastructure systems, smart products engineering, product-service systems (PSS), digital prototyping, requirements management*

## 1. Introduction

Technology and AI advancements are driving the emergence of service robots across diverse fields (Mintrom et al., 2022). Robots, as smart, connected products, incorporate mechatronic functionalities and communicate across systems via the Internet of People, Things and Services (IoPTS) (Tomiyama et al., 2019). Urban robotics necessitates restructuring the surrounding system for autonomous robots to perform services (While et al., 2021). The requirements set forth for service robot development involve a mixture of both product-oriented and service-oriented dimensions, rather than being exclusively aligned with one or the other. Product-Service Systems (PSS) combine physical products and intangible services, strategically designed and integrated to meet specific customer needs (Tukker, 2015). VDI 2206 guides interdisciplinary product development, emphasizing system interconnectivity, digitalization, and integration into the internet of things and services (VDI 2206, 2021). Mechatronic products integrate mechanics, electronics, and software using interdisciplinary methods, while systems engineering offers general approaches to develop such interdisciplinary products (Gräßler & Hentze, 2020; Walden et al., 2015). Early exploration of technology is crucial to prevent unintended consequences, such as excessive energy consumption during operation (Guenat et al., 2022).

This research presents a methodology for synchronous designing of service robots, their additional assistance infrastructure (AAI) and service systems, aligning with broader service goals from initial strategic planning phase. It emphasizes early identification of necessary AAI and service provision, initiating service development concurrently with product and infrastructure development. This approach is essential to obtain precise requirements for autonomous service robots, AAI and service systems. It also integrates digital and physical prototype for product and service development. Our research focus has been derived on the basis of a thorough literature analysis (systematic-mapping review followed by state-of-the art review) of actual methods for synchronized and non-synchronized design and lifecycle phases of robot-infrastructure and service systems, following the approach proposed in Design Research Methodology (DRM) (Blessing & Chakrabarti, 2009).

## 2. State of the art for robot - infrastructure systems

Products evolve from basic mechanical components to complex smart products (Figure 1 (A)), advancing from mechanical to mechatronic products and then to intelligent mechatronic products (IMP). IMPs enable cyber-physical products or systems (CPS) to communicate and network with other products by incorporating features like autonomy and real-time interaction (Tomiyama et al., 2019; VDI 2206, 2021). VDI 2206's new V-Model describes mechatronic and CPS development with a focus on interdisciplinary collaboration and key activities including requirements elicitation, prototyping and final product development. The guideline structures the "holistic product lifecycle" (HPLC) in five phases as shown in Figure 1 (B), including the incorporation of information and communication technology (ICT) (VDI 2206, 2021). The interdependency of product and service is not integrated into the initial two phases of the HPLC (VDI 2206, 2021).

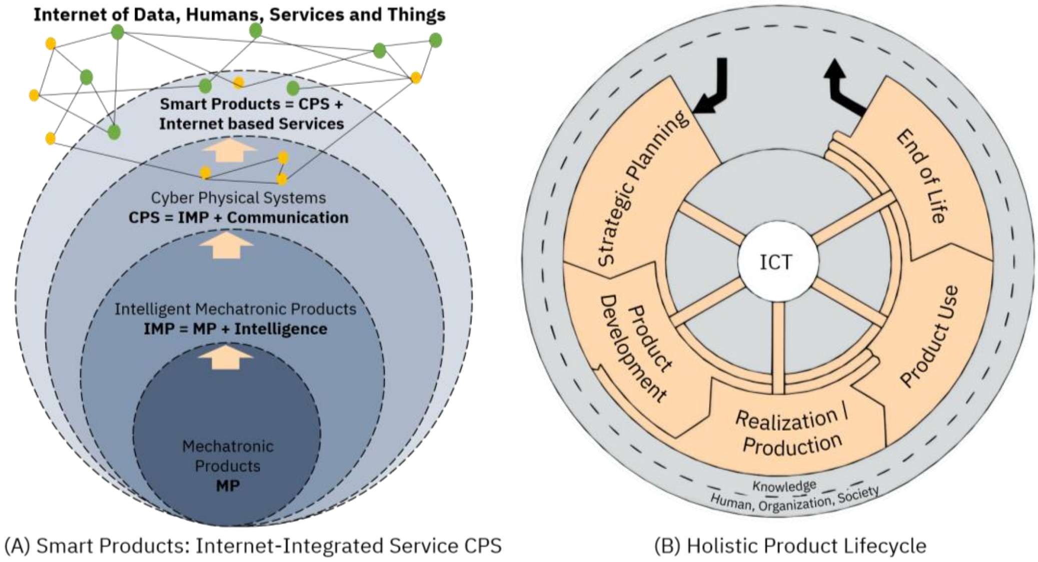



**Figure 1. (A) Evolution of mechatronic products into smart products (Tomiyama et al., 2019) and (B) "Holistic Product Lifecycle" according to (VDI 2206, 2021)**

The IoPTS enables CPS to communicate and integrate internet services, resulting in intelligent and agile smart products, such as smart robots (Tomiyama et al., 2019). These interdisciplinary products and their services can be defined as a system, which is a combination of interacting elements organized to achieve one or more goals (ISO/IEC/IEEE 15288, 2023; Walden et al., 2015). Systems engineering outlays generic methodologies for the development, utilization and retirement of such interdisciplinary products (Walden et al., 2015). Smart products utilize sensors to gather operational and usage data, enhancing service functions like efficient operation and life cycle management, therefore by definition, are considered as PSS (Tomiyama et al., 2019). In this paper, we introduce a methodology for aligning robot-infrastructure with service goals, focusing on a PSS. Subsequent sections detail PSS and robot-infrastructure service designs and integration.

### 2.1. Smart products and product service systems engineering

Gräßler & Pottebaum (2022) emphasize the shift from products to service-oriented functionalities, promoting economic value and sustainability. They advocate aligning the "Generic Product Creation System" (gPCS) with Circular Economy (CE) principles, employing strategies like Agile Strategic Planning and Digital Worker and Learning Assistance (Gräßler & Pottebaum, 2022). Similarly, the concept of PSS aims to integrate products and services to meet customer needs while aiming to minimize resource consumption and environmental impact (Kjaer et al., 2019; Tukker, 2015). Kjaer et al. (2019)

outlines a two-step approach that connects PSS to CE strategies by focusing upon resource reduction and specifying the requirements for achieving absolute resource decoupling. PSS combines products with traits like variability, user engagement, stakeholder involvement, and adaptability, posing challenges in defining, analyzing, and predicting future requirements (Song, 2017). Morelli (2006) stresses the importance of collaborative solution-oriented partnerships (SOP) in shaping effective PSS, highlighting designers' crucial role and advocating for customized design methodologies. Digitalization enables Smart PSS and offers interconnected products and services promoting independent interaction and ongoing evolution, enabling tailored services integrated within products (Kuhlenkötter et al., 2017). Smart PSS design methodologies emphasize on information technology (IT) driven value co-creation, closed-loop, and context-awareness design (Cong et al., 2020). Cong et al. (2020) conducted a literature review comparing smart PSS design methodologies, revealing a predominant emphasis on smart products (21 items) over smart services (7 items). Based on their literature review, (Cong et al., 2020) stressed the importance of prioritizing development methodologies for smart PSS from an information (product-sensors or social-sensors based) perspective to enhance sustainability within a CE context.

### 2.2. Product design and service models for autonomous robots

Sostero (2020) defines robots as physical products that perform functionalities autonomously based on the information technology embodied within. Service robots, as one variant of robots, autonomously execute both physical and non-physical tasks by integrating information technology, thus being categorized as smart products (Sostero, 2020). The service requirements to be fulfilled by autonomous service robots have prompted the need for various methods and approaches in scientific and industrial communities to collaborate on the product's design and functionality across various domains, such as the autonomous robot and its service, underlining the necessity to develop them as PSS or smart PSS (Ghim, 2023; T. Wang et al., 2023). Grahle et al. (2020) introduced a scenario-based method for defining initial requirements in Autonomous Mobility on Demand (AMoD) services, incorporating proactive planning and stakeholder feedback for shaping services by autonomous agents. Šabanović (2010) stresses the influence of social and cultural factors on technology, emphasizing the need for a design methodology deeply rooted in the contextual and functional requirements of autonomous service robots. ISO 22166-1 advocates open supply chains in robotics for modular customization and safety (Zou et al., 2022). MARBLE's modular design enhances performance and reusability, while service integration emphasizes social sustainability (Göhlich et al., 2022; Kohl et al., 2020; van der Schoor & Göhlich, 2023). Ostermeier et al. (2022) aimed to optimize last-mile robot-truck delivery services by developing route-planning algorithms to address real-world challenges and operational costs.
The methodologies in section 2 primarily focus on product or service development, overlooking their interrelated development from the outset of autonomous product development. They neglect the necessary assistance infrastructure, treating them as separate entities with independent lifecycles, which can lead to resource wastage during redesign due to application constraints from various stakeholders.

## 3. Service oriented design methodology

According to VDI 2206, the preparation of operator models for utilizing intangible assets (services) occurs during the realization phase of the HPLC (VDI 2206, 2021). The separation of product and service considerations can pose challenges when services require product design changes or additional AAI. Cong et al. (2020) concluded that the current trend of addressing e-services independently underscores the importance of adopting and developing holistic design approaches, considering both physical products and digitalized services within the Smart PSS framework. The proposed methodology emphasizes defining requirements and creating digital prototypes during strategic planning for autonomous robot-infrastructure and service systems, aligning with service goals. This interrelated-products-based-service-thinking approach seeks to streamline the design process for autonomous products, reducing resource consumption across simultaneous product and service lifecycles. It offers a unique perspective by synchronizing the lifecycles of robots, assistance infrastructure, and service systems, diverging from the traditional non-synchronous approaches. Based on these characteristics, the methodology has been named as CLAPS (**C**o-existing **L**ifecycle initiation and management for **A**utonomous **P**roduct-infrastructure and **S**ervice).

## 3.1. Generalized methodology and interrelated product and service lifecycle

CLAPS enhance the HPLC (Figure 1 (B)) by introducing **five additional phases** in the strategic planning and development phase. It also modifies realization/ production, use, and end of life phases for the autonomous service robot, additional assistance infrastructure (AAI), and service system, synchronizing their lifecycles as interrelated products throughout. It can be incorporated into the HPLC (Figure 2) for developing robot, AAI and their service systems. The **first phase (1)** analyzes stakeholder input, represented by a brief use-case description. It examines the current service process for automation by an autonomous product, focusing on socio-technical aspects and identifying key stakeholders and domain expertise. **Second phase (2)** collects requirements for the autonomous robot and service in the service-event area (SEA), creating and evaluating a digital robot prototype for service suitability. Deficiencies may trigger adjustments or new developments for AAI for collaborative service. In the **third phase (3)**, an operation management system is designed for optimizing the service goal, such as minimizing energy consumption and service time, and is simulated in the designated SEA to assess its alignment with the robot and AAI. In the **fourth phase (4)** adjustments are made to the digital prototypes and requirements, ensuring iterative refinement. If successful, the requirements are specified in the **fifth phase (5)** and the output initiates the modified product and service development, emphasizing their interconnected and iterative evolution with integrated ICT for knowledge sharing.

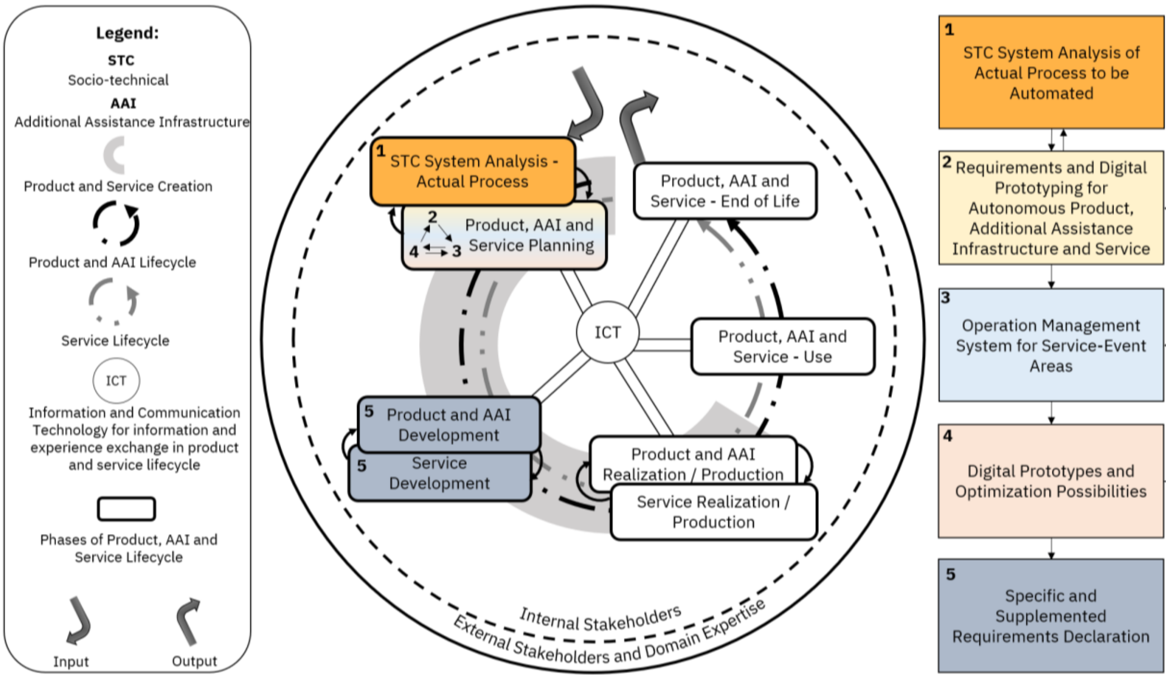



**Figure 2. Incorporation of methodology in the holistic product lifecycle (adapted from VDI 2206: 2021)**

The **realization/ production phase** is split into two interrelated and synchronous phases for autonomous product, AAI, and service system as components of a PSS. The **use phase** utilizes the components of PSS, and the **end-of-life phase** also integrates the impact of all components as interrelated products.

## 3.2. Specific methodology for robot-infrastructure product service system

This section provides a thorough explanation of the first five iterative phases within CLAPS, explaining the processes involved (illustrated in Figure 3). The stakeholder's defined use-case is the input for the methodology. The goal is to analyze the current service-process system intended for replacement by autonomous agents in the **first phase**. This analysis identifies key elements, stakeholders, and issues for automation within the socio-technical system. Albers & Rapp (2022) suggests a similar descriptive model for new system development, based on socio-technical systems theory. This analysis promotes collaborative Solution-Oriented Partnerships (SOP). CONSENS aids in gathering requirements by understanding the service environment, identifying stakeholders, and defining application scenarios (Kaiser, 2014). Figure 3 contrasts projects using the proposed methodology (highlighted green) with ongoing projects with physical prototypes (labelled as Standard Physical Prototype Development (SPP)). Requirements for these ongoing projects are typically comprehensively documented in requirements document and initial solution concept document, covering product goals, end-user needs, and service goals for autonomous products, leveraging product development expertise (Göhlich et al., 2021). In the **second phase**, general requirements for the autonomous robot and their functionalities are to be established to align with SEA operational characteristics and specific service goals, such as minimizing energy consumption. These are also based on the results of the first phase as the input for the second phase. The process involves creating a preliminary PSS design using methodologies such as Integration Definition for Function Modelling (IDEF0). IDEF0 is recommended, as it helps in transforming interconnected requirements as functions (Morelli, 2006). An initial requirement analysis ensures these requirements are suitable for the intended product development in the designated service context (Bender & Gericke, 2021). These analyses may reveal complex needs, constrained by external stakeholders, such as city speed limits affecting delivery speed or precise delivery times requiring customer data collection. These needs underscore the importance of having assistance infrastructure that aids the autonomous robot in fulfilling the service without breaching the constraints and requirements of related stakeholders. Subsequently, digital prototypes for autonomous products and supporting infrastructure are to be developed using methodologies such as the Digital and Virtual Product Creation methodology from (Gräßler & Pottebaum, 2022). Along with the digital prototypes, the functional models can also be simulated for extracting important characteristics of the functionalities such as energy consumption, service time to perform the functionality etc. Insights from SPP projects can be incorporated during the initial requirement analysis phase, allowing for potential digital process implementation via the CLAPS instead of continued physical prototype development.

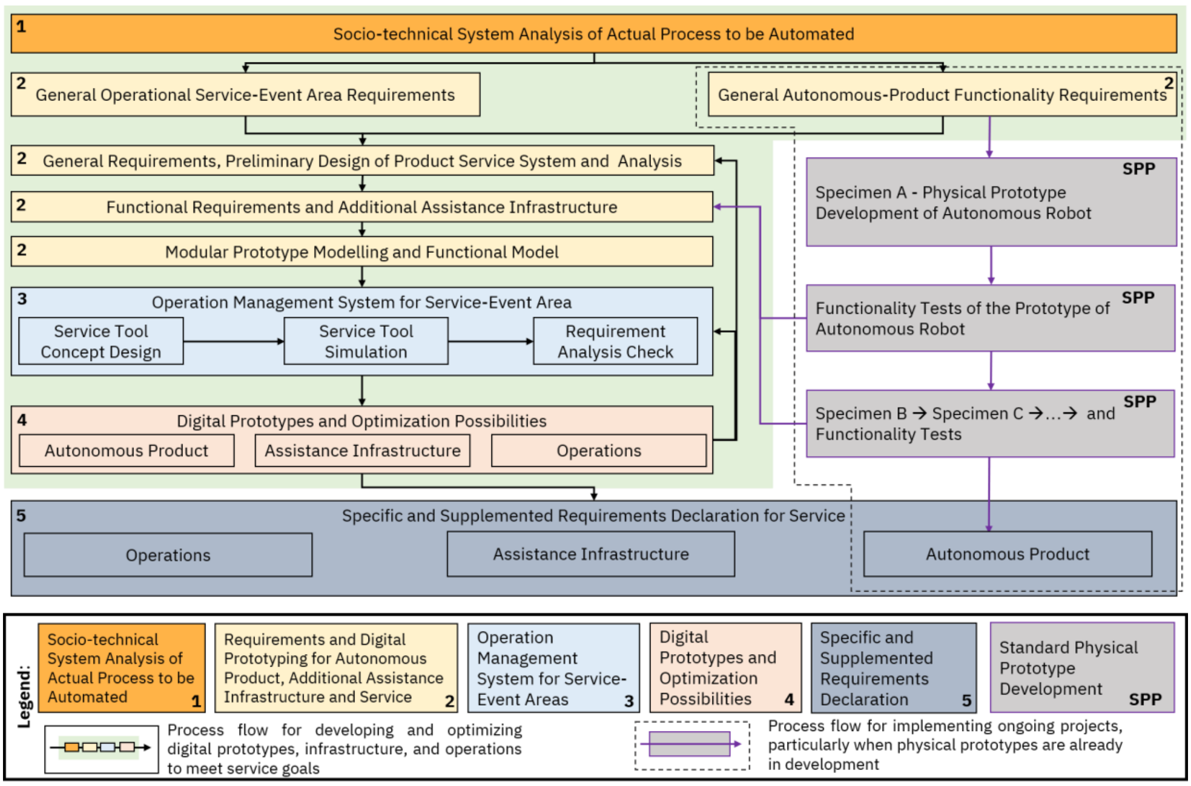



**Figure 3. CLAPS Processes in the first five phases of the methodology**

In **third phase**, the process involves designing an operation management system for SEAs by conceptualizing the operational tool based on service goals, characteristics, and functionalities.

Designing the framework can utilize Design Research Methodology (DRM), which clarifies research goals, understands design factors, develops support, and evaluates effectiveness (Blessing & Chakrabarti, 2009; Saldierna & Lino, 2010). The smart service framework integrates service robot functionalities, additional assistance infrastructure (from phase two), and service features into a functional model. Utilizing the Methodology for Smart Service Architecture Definition (MESSIAH) facilitates this process, amalgamating approaches from PSS design, Smart Service design, and MBSE (Halstenberg et al., 2019). Mathematically simulating the designed operation management framework using functional characteristics from phase two allows analysis of alignment with service goals, potentially revealing further optimization possibilities for digital prototypes. If further optimization is deemed necessary, based on the analysis of results from the simulated service tool in the third phase, then the optimizations in the **fourth phase** should be aligned with the overall service goal. In the **fifth phase**, the requirement document (for SPP-based projects) or the requirement model (for the specified MBSE methodology) is updated, resulting in a preliminary specifications document (Göhlich et al., 2021) or an updated requirements model for the MBSE-based approach. This process also involves an updated solution concept, delineating requirements for the autonomous robot, AAI, and the service system's development, while outlining their interdependence in integrated development. The results act as an input in phase 5 for the interrelated development of product, AAI and service.

## 4. Validation: Application for use-case MARBLE

For demonstrating the applicability of CLAPS, a service robot in the field of waste management has been taken into consideration. The Mobile Autonomous Robot for Litter Emptying (MARBLE) project at the Technical University of Berlin has developed a functional prototype of a service robot capable of autonomously emptying street litter-bins (Göhlich et al., 2022). The MARBLE prototype (Figure 5 (a)) follows the Modular Product Architecture (MPA), emphasizing efficient product development based on requirements management (Göhlich et al., 2021; Göhlich & Fay, 2021; Göhlich et al., 2022).

### 4.1. Phase 1 and Phase 2: MARBLE and assistance infrastructure

The methodology begins with a socio-technical analysis of the LB emptying process using an MBSE model, specifically using CONSENS and Magic Systems of Systems Architect 2022x software. $CO_2$ emissions and service costs are studied, revealing significant emissions and costs from service vehicles. Essential service elements are identified for replacement by the MARBLE service robot. Functional and design requirements are established based on use-case provided information. MARBLE's functional model, created with IDEF0, details functions hierarchically. Due to space and speed limitations, MARBLE's SPP design can't manage more than four 50% full litter-bins (LBs) without intermediate transfer. Hence, we propose a Mothership (MS), an AAI vehicle. Digital prototypes for MARBLE and the MS comply with VDI 2206 and are created in SOLIDWORKS 3D CAD software.

### 4.2. Phase 3: Operation management system as service

Digital prototypes of the robot and MS provided initial energy consumption and operation time parameters, validated through MATLAB and Python simulations, aiming to reduce both parameters as a service goal. Based on insights from the first phase of MBSE-based socio-technical analysis, task allocation and route planning for MARBLE and the MS have been selected to design the operation management system. The decision to prioritize route planning for assessing energy consumption and operation time as measurable success factors of the service was strengthened by following DRM approach similar to that outlined in Saldierna & Lino (2010). To establish a functional model for the service system integrating MARBLE's functionalities, AAI and operational management tool like route planning, the MESSIAH approach was utilized. It facilitated the establishment of interrelated functionalities among the service components, forming the basis for a functional model for smart PSS. For SEA Monbijou Park, Berlin, with 51 LBs, a management system framework was established, with a physical layer defining robot, MS, and SEA characteristics, and a platform layer using algorithms to optimize routes for minimal energy consumption and operation time based on LB positions and 50% filling levels (Bräutigam et al., 2022). Routes considered MARBLE's limited garbage storing capacity.

## 4.3. Phase 4: Digital prototypes and optimization possibilities

Phase 3 analysis revealed a mismatch with service goals and an assumption about 50% filling levels of LB fullness that might not be true in reality. To address these issues, three solutions were considered: the first involved a fleet of MARBLE robots and a redesigned MS prototype (Figure 4 (A)), which reduced operational time but increased energy consumption (Gupta, van der Schoor, & et al., 2022).

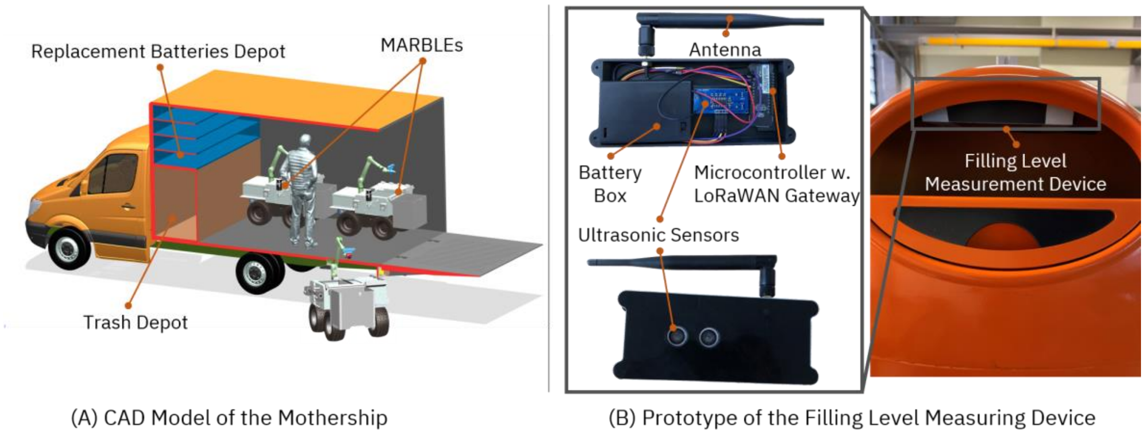



**Figure 4. Prototypes for mothership and smart litter-bin as additional assistance infrastructure**

Secondly, adding an aluminum-alloy cover to the MARBLE compressor (Figure 5 (C)) increased garbage storage to seven LBs, reducing energy use by 34% and operation time by 30% with the route planning service. Thirdly, by substituting the costly robot arm with a magnetic lock system (Figure 5 (B)), energy use was reduced up to 37% and operational time up to 30% with integrated route planning.

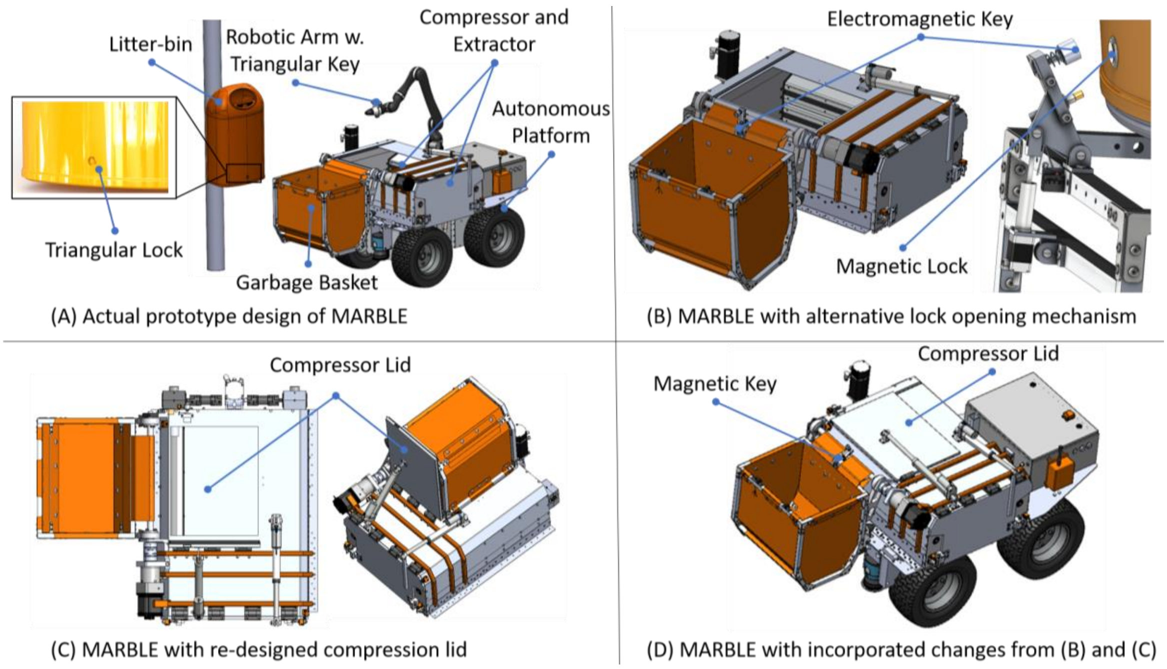
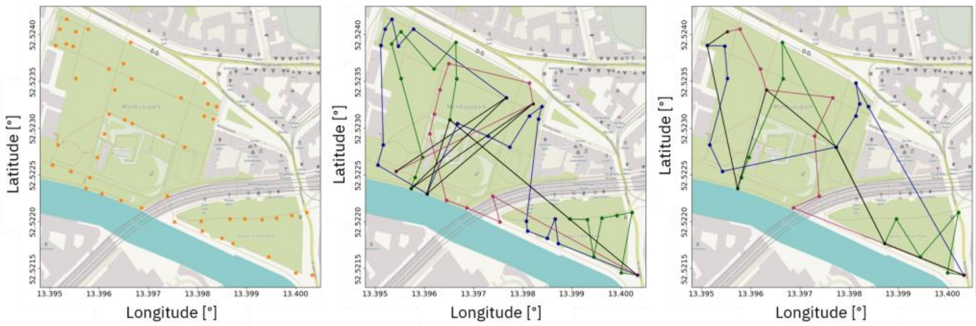



**Figure 5. Different variants of MARBLE's digital prototypes for efficient service**

Still with these possible solutions, the problem of unknown filling levels of LBs persisted. Wang et al. (2018) suggested a data-driven approach for smart PSS by analyzing user behavior. Therefore, transforming LBs to smart prototypes (Figure 4 (B)) with real-time fill data saved 13% energy for a single MARBLE with MS (Gupta, Kremer, & et al., 2022). Smartening Berlin's LBs costs 87 € per unit. We manually collected data from 51 LBs for three weeks, achieving 83% accurate filling predictions, and integrated this into the route planning algorithm. We introduced a machine learning (ML) based Simulated Rebalancing based Route Planning (SRRP) strategy, deferring LB emptying below 25% full until the next day, resulting in a significant 45% energy reduction and a 30% decrease in overall operation time (Pollak et al., 2024). Figure 6 depicts MARBLE and redesigned MARBLE fleet routes with SRRP, indicating energy consumption of 3.51 kWh and 2.14 kWh, and operation times of 1.22 hours and 0.96 hours, respectively. Compared to a single MARBLE without MS and non-SRRP, redesigned MARBLE and its fleet with MS and SRRP significantly reduces energy consumption by 66.95% and operation time by 75.19% respectively.

| Scenario | MARNLE Fleet w. MS | Re-designed MARBLE Fleet (C+AL) w. MS and SRRP |
|---|---|---|
| Energy Consumption | 3.51 kWh | 2.14 kWh |
| Operation Time | 1.22 Hours | 0.96 Hours |




(A) Litter Bins in Monbijou Park (B) Route – Fleet w. MS (C) SRRP - Fleet w. MS

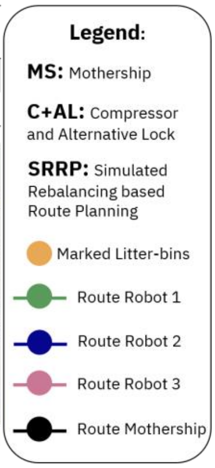



**Figure 6. Operation routes for SEA with a fleet of MARBLEs and mothership**

### 4.4. Phase 5: Specific requirements for the product and service development

Specified additional MARBLE requirements involve compressing a minimum of seven 50% full LBs and simplifying the LB operating mechanism. A mothership is essential, and accurate LB filling data is crucial. The mothership should prioritize automated garbage transport with MARBLE, and SEA adjustments should align LB densities with high-visited areas. Feedback mechanism from the compressing machine can assure reliability, especially when combined with the SRRP approach. These modified requirements are further used as inputs in the product, AAI and service development phase.

## 5. Discussion and outlook

We introduced the CLAPS methodology to incorporate the lifecycle driven requirements in early product development phases. CLAPS methodology takes into account co-existing lifecycles of autonomous robots, AAI, and operation management service systems as interrelated components. In comparison to researched methodologies, which treat these components separately, by concretizing interrelated requirements upfront, CLAPS minimize the need and risk for late design changes. Demonstrated in project MARBLE, CLAPS utilized ML and other service management algorithms for further improvements of fleet operation, by reducing energy consumption and operational time, validating its effectiveness in achieving service goals.

Further implementation of realization/ production, use, and end-of-life phases for the MARBLE service components within CLAPS is essential for complete validation. CLAPS has been defined for general autonomous robot-infrastructure, hence enabling the comprehensive design of other service robots and smart products by establishing comprehensive requirements for the product, its AAI, and services. For the methodology's enhancement, it is crucial to ensure sustainability by uniformly evaluating all dimensions across diverse design concepts (Gräßler & Hesse, 2022; van der Schoor & Göhlich, 2023). Incorporating approaches from (Stark, 2022), such as the linking of virtual product creation to PSS features, including maintenance, repair and overhaul, across product and service lifecycles, can contribute to methodological evolution. Large-scale CPS for smart robots, designed as a System of Systems (SoS), can improve complex robot-infrastructure and service systems by integrating MBSE approaches into the proposed methodology, beyond the approach undertaken in this research work. Lastly, it is important to assess the proposed methodology using quantitative key-performance indicators. Rondini et al. (2020) introduces the Engineering Value Assessment (EVA) method for PSS evaluation, including trade-off identification through Importance-Performance Analysis from consumer and producer perspectives. Currently we are implementing and refining such approaches to validate our methodology, incorporating aspects like synchronized lifecycles from designers' and users' perspectives.

## Acknowledgement

The authors thank Mr. Paul Anderer, Mr. Anton Pollak, Mr. Gian Tegel, Mr. Tobias Umland and Mr. Imtiaz Yousuf for their contributions. This research was part of the MARBLE project under the Berlin Program for Sustainable Development - BENE, supported by the European Regional Development Fund (#1247-B5-O).

## References

Albers, A., & Rapp, S. (2022). Model of SGE: System Generation Engineering as Basis for Structured Planning and Management of Development. In *Design Methodology for Future Products* (pp. 27–46). Springer, Cham. https://doi.org/10.1007/978-3-030-78368-6_2

Bender, B., & Gericke, K. (2021). Entwickeln der Anforderungsbasis: Requirements Engineering. In *Pahl/Beitz Konstruktionslehre* (pp. 169–209). Springer Vieweg, Berlin, Heidelberg. https://doi.org/10.1007/978-3-662-57303-7_7

Blessing, L. T. M., & Chakrabarti, A. (2009). *DRM, a Design Research Methodology*. http://83.136.219.140:8080/handle/123456789/89

Bräutigam, J., Gupta, A., & Göhlich, D. (2022). Simulated Annealing-based Energy Efficient Route Planning for Urban Service Robots. In *2022 26th International Conference on Methods and Models in Automation and Robotics (MMAR).* IEEE. https://doi.org/10.1109/mmar55195.2022.9874325

Cong, J., Chen, C.-H., &, et al. (2020). A holistic relook at engineering design methodologies for smart product-service systems development. *Journal of Cleaner Production*, *272*, 122737. https://doi.org/10.1016/j.jclepro.2020.122737

Ghim, Y.-G. (2023). *A Product-Service System Approach for Designing Mobile Robots.* Industrial Designers Society of America. https://www.researchgate.net/profile/Yong-Gyun-Ghim-2/publication/374163793

Göhlich, D., Bender, B., Fay, T.-A., & Gericke, K. (2021). Product Requirements Specification Process in Product Development. *Proceedings of the Design Society*, *1*, 2459–2470. https://doi.org/10.1017/pds.2021.507

Göhlich, D., & Fay, T.-A. (2021). Arbeiten mit Anforderungen: Requirements Management. In *Pahl/Beitz Konstruktionslehre* (pp. 211–229). Springer Vieweg, Berlin, Heidelberg. https://doi.org/10.1007/978-3-662-57303-7_8

Göhlich, D., Syré, A. M., van der Schoor, M. J., &, et al. (2022). Design Methodologies for Sustainable Mobility Systems. In *Design Methodology for Future Products* (pp. 123–144). Springer, Cham. https://doi.org/10.1007/978-3-030-78368-6_7

Grahle, A., Song, Y.-W., &, et al. (2020). Autonomous Shuttles for Urban Mobility on Demand Applications – Ecosystem Dependent Requirement Elicitation. *Proceedings of the Design Society: DESIGN Conference*, *1*, 887–896. https://doi.org/10.1017/dsd.2020.100

Gräßler, I., & Hentze, J. (2020). The new V-Model of VDI 2206 and its validation. *At - Automatisierungstechnik*, *68*(5), 312–324. https://doi.org/10.1515/auto-2020-0015

Gräßler, I., & Hesse, P. (2022). Approach to Sustainability-Based Assessment of Solution Alternatives in Early Stages of Product Engineering. *Proceedings of the Design Society*, *2*, 1001–1010. https://doi.org/10.1017/pds.2022.102

Gräßler, I., & Pottebaum, J. (2022). From Agile Strategic Foresight to Sustainable Mechatronic and Cyber-Physical Systems in Circular Economies. In *Design Methodology for Future Products* (pp. 3–26). Springer, Cham. https://doi.org/10.1007/978-3-030-78368-6_1

Guenat, S., Purnell, P., &, et al. (2022). Meeting sustainable development goals via robotics and autonomous systems. *Nature Communications*, *13*(1), 3559. https://doi.org/10.1038/s41467-022-31150-5

Gupta, A., Kremer, P., &, et al. (2022a). Intelligent Route Planning for Autonomous Service Robots using Communicating Smart Dustbins. In *ICC 2022 - IEEE International Conference on Communications.* IEEE. https://doi.org/10.1109/icc45855.2022.9838510

Gupta, A., van der Schoor, M. J., &, et al. (2022b). Autonomous Service Robots for Urban Waste Management - Multiagent Route Planning and Cooperative Operation. *IEEE Robotics and Automation Letters*, *7*(4), 8972–8979. https://doi.org/10.1109/lra.2022.3188900

Halstenberg, F. A., Lindow, K., & Stark, R. (2019). Leveraging Circular Economy through a Methodology for Smart Service Systems Engineering. *Sustainability*, *11*(13), 3517. https://doi.org/10.3390/su11133517

ISO/IEC/IEEE 15288 (2023-5). *ISO/IEC/IEEE 15288:2023 - Systems and software engineering— System life cycle processes:* Second Edition. The International Organization for Standardization.

Kaiser, L. (2014). *Rahmenwerk zur Modellierung einer plausiblen Systemstruktur mechatronischer Systeme: Doktorarbeit.* Universität Paderborn. https://core.ac.uk/download/pdf/50517459.pdf

Kjaer, L. L., Pigosso, D. C. A., &, et al. (2019). Product/service-systems for a Circular Economy: The Route to Decoupling Economic Growth from Resource Consumption? *Journal of Industrial Ecology*, *23*(1), 22–35. https://doi.org/10.1111/jiec.12747

Kohl, J. L., van der Schoor, M. J., Syré, A. M., & Göhlich, D. (2020). Social Sustainability In The Development Of Service Robots. *Proceedings of the Design Society: DESIGN Conference*, *1*, 1949–1958. https://doi.org/10.1017/dsd.2020.59

Kuhlenkötter, B., Wilkens, U., &, et al. (2017). New Perspectives for Generating Smart PSS Solutions – Life Cycle, Methodologies and Transformation. *2212-8271, 64,* 217–222. https://doi.org/10.1016/j.procir.2017.03.036

Mintrom, M., Sumartojo, S., Kulić, D., &, et al. (2022). Robots in public spaces: Implications for policy design. *Policy Design and Practice*, *5*(2), 123–139. https://doi.org/10.1080/25741292.2021.1905342

Morelli, N. (2006). Developing new product service systems (PSS): methodologies and operational tools. *Journal of Cleaner Production*, *14*(17), 1495–1501. https://doi.org/10.1016/j.jclepro.2006.01.023

Ostermeier, M., Heimfarth, A., & Hübner, A. (2022). Cost-optimal truck-and-robot routing for last-mile delivery. *Networks, 79*(3), 364–389. https://doi.org/10.1002/net.22030

Pollak, A., Gupta, A., & and Göhlich, D. (2024). Optimized Operation Management With Predicted Filling Levels of the Litter Bins for a Fleet of Autonomous Urban Service Robots. *IEEE Access*, *12*, 7689–7703. https://doi.org/10.1109/access.2024.3352436

Rondini, A., Bertoni, M., & Pezzotta, G. (2020). At the origins of Product Service Systems: Supporting the concept assessment with the Engineering Value Assessment method. *CIRP Journal of Manufacturing Science and Technology*, *29*, 157–175. https://doi.org/10.1016/j.cirpj.2018.08.002

Šabanović, S. (2010). Robots in Society, Society in Robots. *International Journal of Social Robotics*, *2*(4), 439–450. https://doi.org/10.1007/s12369-010-0066-7

Saldierna, C., & Lino, M. (2010). The Design Research Methodology as a Framework for the Development of a Tool for Engineering Design Education. *12th International Conference on Engineering and Product Design Education - When Design Education and Design Research Meet,* 298–303. https://www.designsociety.org/publication/30186/

Song, W. (2017). Requirement management for product-service systems: Status review and future trends. *Computers in Industry*, *85*, 11–22. https://doi.org/10.1016/j.compind.2016.11.005

Sostero, M. (2020). *Automation and Robots in Services: Review of Data and Taxonomy* (JRC Working Papers Series on Labour, Education and Technology 2020/14). Seville: European Commission, Joint Research Centre (JRC). https://www.econstor.eu/handle/10419/231346

Stark, R. (2022). *Virtual Product Creation in Industry: The Difficult Transformation from IT Enabler Technology to Core Engineering Competence*. Springer. https://link.springer.com/chapter/10.1007/978-3-662-64301-3_4 https://doi.org/10.1007/978-3-662-64301-3_4

Tomiyama, T., Lutters, E., Stark, R., & Abramovici, M. (2019). Development capabilities for smart products. *CIRP Annals*, *68*(2), 727–750. https://doi.org/10.1016/j.cirp.2019.05.010

Tukker, A. (2015). Product services for a resource-efficient and circular economy – a review. *Journal of Cleaner Production*, *97*, 76–91. https://doi.org/10.1016/j.jclepro.2013.11.049

van der Schoor, M. J., & Göhlich, D. (2023). Integrating sustainability in the design process of urban service robots. *Frontiers in Robotics and AI*, *10*, 1250697. https://doi.org/10.3389/frobt.2023.1250697

VDI 2206 (2021). *Development of mechatronic and cyber-physical systems*. Beuth-Verlag GmbH.

Walden, D. D., Roedler, G. J., & Forsberg, K. (2015). Incose Systems Engineering Handbook Version 4: Updating the Reference for Practitioners. *INCOSE International Symposium*, *25*(1), 678–686. https://doi.org/10.1002/j.2334-5837.2015.00089.x

Wang, T., Yue, W., Yang, L., &, et al. (2023). A User Requirement Driven Development Approach for Smart Product-Service System of Elderly Service Robot. In D. Harris & W.-C. Li (Eds.), *Lecture notes in computer science Lecture notes in artificial intelligence: Vol. 14018, Engineering psychology and cognitive ergonomics* (pp. 533–551). Springer. https://doi.org/10.1007/978-3-031-35389-5_37

Wang, Y., Blache, R., Zheng, P., & Xu, X. (2018). A Knowledge Management System to Support Design for Additive Manufacturing Using Bayesian Networks. *Journal of Mechanical Design*, *140*(5), Article 051701. https://doi.org/10.1115/1.4039201

While, A. H., Marvin, S., & Kovacic, M. (2021). Urban robotic experimentation: San Francisco, Tokyo and Dubai. *Urban Studies, 58*(4), 769–786. https://doi.org/10.1177/0042098020917790

Zou, Y., Kim, D., &, et al. (2022). Towards robot modularity — A review of international modularity standardization for service robots, *148*, 103943. https://doi.org/10.1016/j.robot.2021.103943