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A Lifecycle Model for Autonomous Buses in Public Transport

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Abstract: Automated, driverless buses are an essential part of meeting current challenges in the transportation sector with new, more efficient solutions. Since these systems have not yet been implemented in real operation, several challenges for their developers and operators occur. Some challenges stem from a lack of comprehensive understanding of the bus lifecycle. To address this, this paper presents both a meta-level lifecycle model and detailed descriptions of each phase. A combined approach consisting of a literature review and industry workshops was applied to develop this model. The lifecycle is modeled in an integrated manner as a product-service system, incorporating the product bus and the transportation service perspective, divided into the main phases of planning, development, realization, shared usage, and end of life. A key aspect is the importance of software for the system and data and its feedback from the usage to the engineering phases, especially for the driving software.

Keywords: automated driving, public transport, lifecycle model, product-service systems, systems engineering

1 Introduction and Motivation

The transport sector is currently facing the major challenge of overcoming increasingly high levels of congestion in cities. In addition, climate change is exacerbating the need for new mobility solutions that make transportation more efficient (Ulrich et al., 2019). It is therefore essential to develop and establish new, efficient mobility solutions. An important part is the switch from private to public transportation (Holden et al., 2020). However, this is not yet attractive enough in many areas to encourage people to make the switch from private to public transport. More service offerings in terms of shorter intervals and a larger route network are needed as well as stops close to doorsteps or extensions in rural areas, for which buses represent the system to choose (Millonig and Fröhlich, 2018). However, with the issue of an increasing shortage of skilled workers also reaching the professional group of bus drivers, these growing demands cannot be met by conventional, driver-controlled transport solutions. This must be remedied by automating and networking public transport (Ulrich et al., 2019) by establishing driverless vehicles. However, such systems have not yet been established in real operation, posing several challenges for the developers and operators of such systems (Bucchiarone et al., 2021).

Multiple challenges can be related to the missing comprehensive understanding of the buses' lifecycle: For example, the high costs related to the development and operation not only slow down implementation in pilot projects but also with a view to the future and the question of the extent to which autonomous public transport can remain affordable (Millonig and Fröhlich, 2018). It is a general key aspect of the planning of public transport to estimate all costs along the lifecycle (LC) as accurately as possible, both for defining service contracts as well as a basis in political funding decisions (VDV-Mitteilung 2315, 2010). Only with an exact understanding of all activities related to the bus, a reliable estimation can be reached. Moreover, a lifecycle model (LCM) is needed to holistically investigate the sustainability aspects of these systems (Bucchiarone et al., 2021), such as in a typical lifecycle assessment (LCA). Other disciplines profit from an LCM as well since it represents a common description of the activities related to a system. Therefore, it is often referenced as a basis, e.g., in Systems Engineering (VDI-Richtlinie 2206, 2021).

However, such an overarching LCM has not been established for autonomous buses in literature yet. Therefore, this paper aims to develop such an LCM, resulting in the research question: *How can the lifecycle of an autonomous bus in public transport be modeled? What phases can it be divided into and what do these phases look like in detail?*

2 Methodology

The methodology displayed in Figure 1 is applied to answer the posed research question: at first, a literature review is conducted. Since no specific LCM for autonomous buses is found, the search is focused on LCMs related to vehicles and buses, automotive software, and public transportation systems, supplemented by universal LCMs. Often, LCMs are not found as independent publications, instead, they can be found indirectly, e.g., through total cost of ownership analysis (TCO), lifecycle assessments (LCA), or other comprehensive analyses.

Based on the findings, together with practitioner experts from the public transport industry, an initial LCM is built. This is used as the input for several industry workshops conducted with the essential core stakeholders of buses in public transport, namely a vehicle manufacturer that is currently developing and producing its first prototypes of autonomous buses, a large company operating buses and other public transportation systems, as well as a public transportation association, both operating in a German city of over a million inhabitants. Both of them have been part of pilot projects for the implementation of autonomous buses in their business in the past and are also currently working on such projects. In those workshops, the details of the proposed LCM were discussed intensively and supplemented or modified where necessary, so that a model validated by practitioners can be presented as a result. Each workshop lasted three hours with a different number of attendees given in Figure 1. All attendees are working on projects in the field of autonomous driving and are therefore able to provide valuable expert insights. At first, the meta-level lifecycle was introduced and discussed. Afterward, the dedicated part of the LC for each stakeholder was discussed in detail, namely all phases for hardware and software with the manufacturer, the usage and recycling phase with the operator, and the service perspective with the transport association. The discussions made in each of the three workshops were then combined into the finalized model.

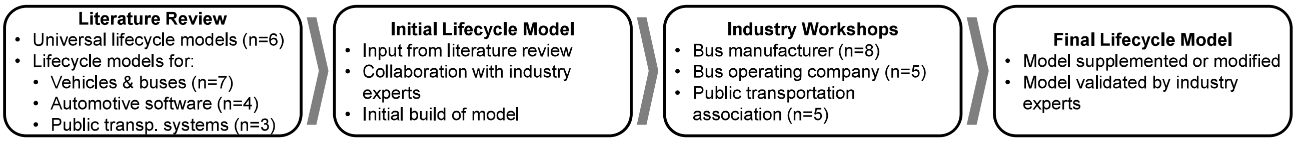


Figure 1: Research procedure

3 State of the Art

As mentioned before, no holistic LCM including all aspects of autonomous buses can be found in literature. However, the literature review also revealed that several LCMs focus on certain parts or phases of the autonomous bus lifecycle. In the following, these already existing models are briefly introduced.

Qureshi et al. (2014) describe a universal LCM that is characterized by not being tied to a specific domain. To develop this model, design processes from a variety of different disciplines and industries, e.g., mechanical engineering, software design, and systems engineering are studied. Subsequently, a common set of product LC phases is derived and integrated into a transdisciplinary framework. This framework consists of five superordinate LC phases: establishing a need, design, implement/realize, use/support, and end-of-life.

LCMs for cars can be found in Rudert and Trumpfheller (2015), Schömann (2012), and Schulz (2014). Although some phases are named differently or omitted in the individual sources, overall a basic structure of the development and production process in the automotive industry can be derived from these sources. It starts with predevelopment activities like product- and goal definition. Next, the basic conceptual design is defined, determined, and validated, followed by the serial development, in which the components of the future car are engineered. Subsequently, serial run-up functions as a binder between serial development and serial production. Serial run-up includes various activities like the manufacturing of prototype vehicles, or coordination with suppliers to ensure a smooth transition to serial production, which is the last presented phase of the development process. LCMs for buses are discussed by Erler (2023) and Faltenbacher (2006). Here, the proposed models are more heterogeneous than the ones for car development. The phases mentioned comprise material extraction and processing, manufacturing/production, distribution, use, maintenance, and end-of-life/disposal. In addition to a basic LCM, Erler (2023) introduces several activities alongside the bus lifecycle, e.g., material acquisition and preventive maintenance. Faltenbacher (2006) developed a bus LCM in order to assess the environmental effects and impacts of three different drive system technologies (diesel, natural gas, hydrogen) for buses. In particular, the subordinate phases of the bus disposal phase are provided: removal of pollutants, disassembly, shredder, and energy recovery.

When looking at process models for the development of software in an automotive context, the V-process according to VDI-Richtlinie 2206 (2021) with its left side representing requirements assessment and design and its right side representing the multiple layers of testing is proposed unanimously (Bock et al., 2019; Burkacky et al., 2021; Staron, 2019; Wolf, 2018). Apart from minor deviations in naming and level of detail between the sources, a general structure of the V-process for automotive software development can be deducted as follows: requirements definition, coarse design, detailed design, module implementation, module test, integration test, system test, and acceptance test. It is stressed, that software in the automotive context is always part of a superordinate mechatronic system and therefore cannot be viewed as an isolated component (Wolf, 2018). Bock et al. (2019) draw attention to new challenges in automotive software development resulting from the development and especially the testing of automated driving (AD) systems. With the rising importance of Artificial Intelligence (AI) in this discipline, there is a growing need for new development methods to address the complexity of future AD. Burkacky et al. (2021) characterize software as the new prime value driver in automotive development, forming the need to implement new methods like agile-at-scale, decoupling software and hardware development, and increasing test automation. To meet these new challenges, Burkacky et al. propose a combined V-process: While systems engineering practices are used for requirements, architecture, integration, and testing on a system level, agile methods are utilized for software component design and testing.

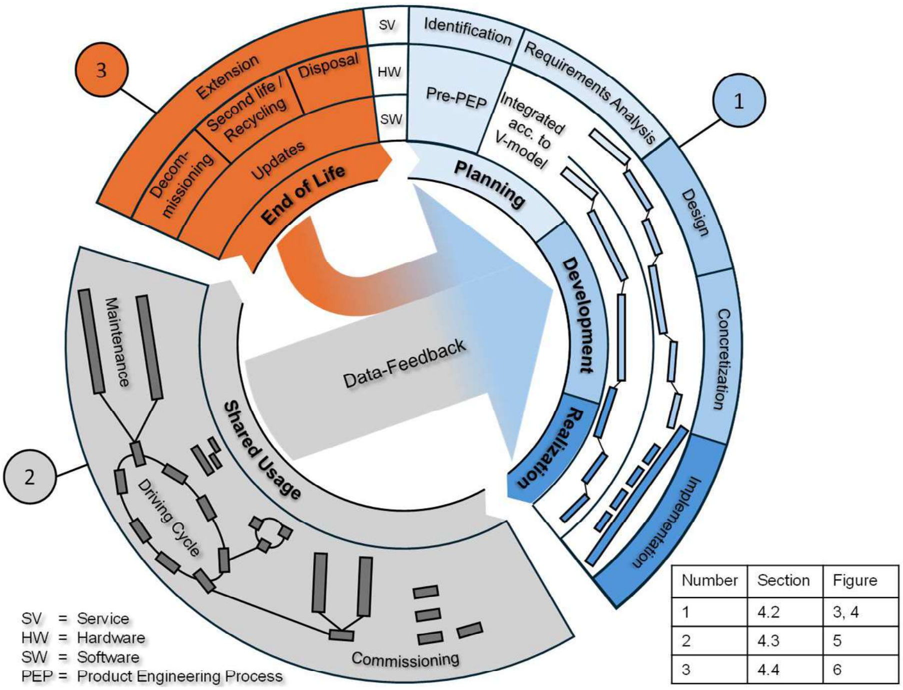
Focusing on the service part of public transportation, mainly two service LCMs are studied. Fischbach et al. (2013) propose a detailed model for integrated service lifecycle management. The model is comprised of seven service-lifecycle phases: identification, requirements analysis, conception, development, implementation, operation, and enhancement. While Fischbach et al. present a more general view of service lifecycles, a comprehensive LCM for the planning of public transportation systems is given by Desaulniers and Hickman (2007), dividing into three main phases (strategic, tactical, and operational planning). While strategic planning focuses on long-term decisions such as designing the network and assigning passengers, tactical planning focuses on mid-term tasks like setting the frequency of routes and providing a service schedule. Finally, operational planning summarizes various activities, that include short-term decisions, e.g., bus parking on a daily basis and driver scheduling on a monthly basis.

4 Lifecycle Model

This section is divided as follows: sub-section 4.1 introduces the developed lifecycle model at a meta-level divided into several phases. These phases are presented in detail in the following sub-sections 4.2 to 4.4.

4.1 Meta-level lifecycle model

The introduced LCMs from literature describe a limited view either on only the physical product bus or the service of public transport. However, an essential overall finding is the need to view the autonomous bus as a product-service system (PSS) (Enoch and Potter, 2002). According to Tukker (2004), a PSS can be defined as a combination of tangible products and intangible services designed to work together to fulfill specific customer needs. Here, the product *bus* and the service *public transport* are interdependent, especially in the shared usage phase, to realize the business offering which is the mobility of people. This service offering is the actual subject sold to the customers, but, naturally, depends on the physical bus to be put into effect. Numerous requirements, limitations, and challenges that were discussed with industry experts influencing the service result or at least are affected by the product and vice versa. For this reason, an integrated LC of both *product* and *service* was chosen. Due to its universal applicability, the main phases are based on the presented transdisciplinary framework of Qureshi et al. (2014) and adapted to the present use case. As displayed in Figure 2, the LCM divides into the phases of *planning*, *development*, *realization*, *shared usage*, and *end of life*. A further subdivision is a distinction between *hardware*, *software*, and *service*. While the integration of the service component has already been described above, the subdivision of the product into hardware and software still needs to be explained: the software components form an elementary part of the autonomous vehicle and therefore require intensive consideration. However, the LC of software differs from that of hardware, making integrated considerations possible in parts, but also requiring separate presentations. This visualization also highlights the main components of the autonomous bus in public transport: the service offering, the physical vehicle, and the centrally important driving software.



SV = Service
HW = Hardware
SW = Software
PEP = Product Engineering Process

Number	Section	Figure
1	4.2	3, 4
2	4.3	5
3	4.4	6

Figure 2: Meta-level lifecycle model

The LC is visualized in a circular form to underscore the iterative nature of the processes, highlighting continuous adaptation and improvement. These iterations are not only seen in the updates of software and service offerings but also in the development of the hardware’s next generation. These iterations can occur in parallel, even before the completion of a full cycle. The initial three phases of the LC are closely interlinked, making it challenging to demarcate where one phase ends and another begins, which is illustrated in the overlapping visual representation in the LCM.

A critical aspect of the LC is the feedback of data, which forms the core of the graphic. The use of data, particularly data generated during the usage phase, plays a pivotal role in product improvement. This is most evident in the development of automated driving (AD) software, where data collected from real testing is indispensable. This process is inherently linked with hardware advancements, as the performance and capabilities of the hardware must evolve in tandem with software improvements. The experts also highlighted data feedback as crucial for refining service offerings. In the context of driverless vehicles, the collection and analysis of data are essential for operators to receive customer feedback and potential for improvement, since there is no direct contact person like the bus driver anymore. This data-centric approach is a cornerstone of modern engineering practices discussed extensively in the research field of *data-driven design*.

A comprehensive description of each phase of the LC is provided in the following sections. The visual representation of parallel V-models and the distinct sections within the shared usage phase, as indicated in Figure 2, serves as a reference to contextualize the detailed graphics that follow. These graphics are designed to be self-explaining as far as possible, therefore, not every aspect of them is described textually, rather, pointing out important matters is focused.

4.2 Planning, Development, and Realization

During the Pre-Product Engineering Process (Pre-PEP), the product idea is generated and specified by defining the product's features. After analyzing the market and investigating possible competitors, the requirements are defined. For autonomous buses, especially the introduction of new laws and regulations restricting the system as well as the role of new competitors from software-based companies are important changes in this phase.

The integrated development of software and hardware in mechatronic systems such as autonomous buses is a complex, multi-domain task requiring a suitable integrated process model. One of the most prominent is the process reference model of Automotive SPICE (VDA, 2023), describing the overall systems engineering with a dedicated V-process and domain-specific aspects such as software and hardware engineering with individual V-processes. For the LCM presented in this paper, the hardware and software engineering domains have been identified as central and thus are depicted as two individual but connected V-processes. This proposed integrated V-process has also been confirmed by the consulted industry experts. Through its structure, the V-process allows for fast iterations and ensures seamless compatibility through the integration of development and testing by emphasizing verification and validation at each stage.

Hardware V-processes are already well established. Though crucial for the realization of the overall mechatronic product, it is therefore assumed that the hardware V-process itself is not heavily affected by the introduction of AD functions. Nonetheless, minor changes are to be expected as various sensors and actors have to be integrated. With the implementation of AD functionality highly dependent on the development of cutting-edge driving software, the focus in the development stage is drawn to the software V-process and the integration of software and hardware to form a reliably functioning system. The expected changes in the software domain are therefore discussed in the following.

The proposed software V-process is particularly important in the development of AD functionalities, because of its emphasis on testing, verification, and validation of the developed software. To ensure the safety of AD functionalities, these software components have to be tested extensively, which is no longer possible solely through real-world test drives as the tests require huge amounts of data. This aspect substantiates the importance of data feedback from the usage phase and the overall role of data within the development and realization. Besides the central role of data itself, a second pillar to meet the challenges of AD testing are the established methods of X-in-the-loop (XiL) and Scenario-based testing. XiL methods can be summarized as virtual testing methods simulating the environment of a unit under test. Depending on what this unit under test is, the methods can be differentiated as, e.g., Model-in-the-loop (MiL), Software-in-the-loop (SiL), Hardware-in-the-loop (HiL), and Vehicle-in-the-loop (ViL) (Moten et al., 2018). Detailed descriptions of XiL approaches can be studied in the corresponding literature, e.g., (Reisgys et al., 2022). XiL approaches are utilized throughout the whole integrated V-process with MiL, SiL, and HiL being applied at rather early development stages and ViL being used as a bridge to real-life test drives (Miquet and Frings, 2024).

When the testing environment is provided by XiL-methods, it must still be determined which test cases the unit under test will be tested on. Here, scenario-based testing comes into play. According to Nalic et al. (2020) a scenario "describes the chronological sequence of still images represented by scenes and can be enriched by actions and events (e.g. overtaking maneuvers)". Nalic et al. further describe how data-driven approaches that rely on real measurement data are one of the two main approaches to the generation of concrete scenarios. It therefore once again becomes clear, how important the feedback of usage data is for filling a scenario database to use for AD validation.

Hence XiL and scenario-based-test methods should not be seen as two independent, but rather two complementing methods in the validation of automated driving systems. This is also confirmed by Reisgys et al. (2022) with the description of the "Scenario-based X-in-the-loop Test". The two mentioned methods can be incorporated seamlessly into the V-process, as shown by Reisgys et al. (2022) and Miquet and Frings (2024), which further stress the importance of a combined view on the HW/SW-development process. Figure 3 shows this integrated V-process with XiL and scenario-based testing approaches.

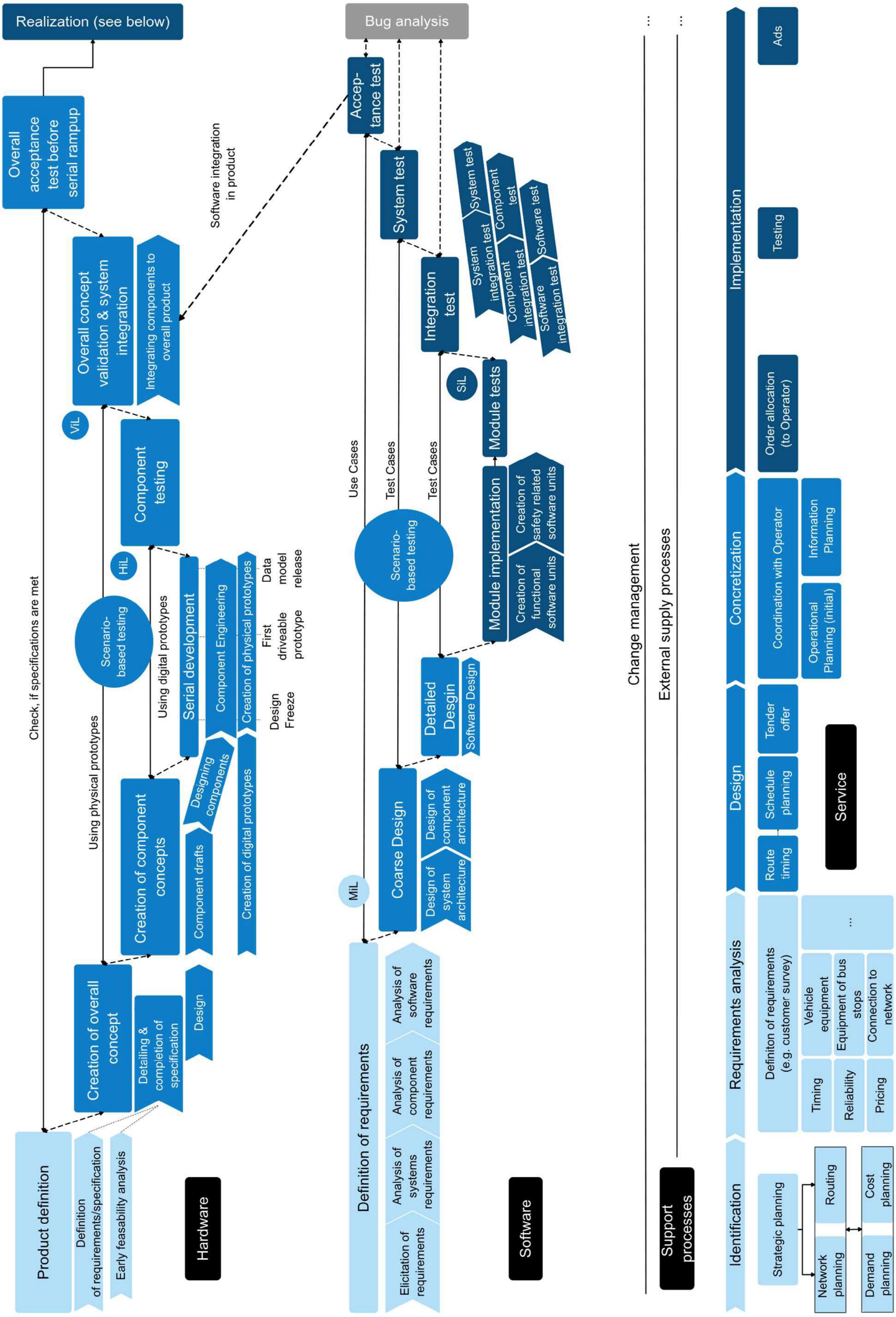


Figure 3: Integrated development and implementation phase

The advancements made in the development of AD systems are heavily linked to the progress of AI, as AI methods have numerous applications in the field of AD functionalities. AD systems must act appropriately in the given driving situation without relying on a human fallback. Current AI methods such as Machine Learning, Deep Learning, and Reinforcement Learning are applied in various AD tasks like perception of the vehicle's surroundings, localization and mapping of the vehicle, decision making, and path planning (Ma et al., 2020). Due to the significance of AI methods, it is important to look at the expected changes in the integrated development process of mechatronic systems resulting from the addition of AI-based software components. In its latest version, the development process of Machine Learning systems is added to the Automotive SPICE process reference model mentioned above, introducing the phases of ML requirements analysis, architecture, training, and testing (VDA, 2023). A similar process model for ML development can be found in the work of Nascimento et al. (2019), naming phases of Data Handling and Model Building. Through looking at these ML process models it becomes apparent that ML systems heavily rely on a huge amount of data, especially during training and testing, further confirming the importance of data-feedback during the autonomous bus lifecycle. Additionally, this data dependency makes ML systems unique in their development, which leads to the fact that already established Software Engineering (SE) development processes might not be transferred to the development of ML models without adaptations, as examined by Lorenzoni et al. (2021). With current approaches to ML modeling based on the SE development process, the authors identified various gaps in the proposed processes and a lack of detail in the description of the individual stages and used techniques. These challenges ultimately lead to diverging views on how the existing SE development processes must be adapted for ML systems, with one view stating that new processes are needed, and others denying this need (Lorenzoni et al. 2021). Although one possible integration of ML components in the software development process is given in (VDA, 2023), it, therefore, remains unsure if this proposed process will prevail in the future development of AD systems. Consequently, there is no specific ML development process integrated into the LCM presented in this paper.

Regarding the service perspective, the boundaries of limited driver availability as described in the motivation section no longer apply, allowing new possibilities in routing and networking planning, however, at the same time, new limitations occur, such as new vehicle boundaries like the suitability to installed digital systems and communication paths. Overall, the pricing must be pointed out as an important aspect since currently, the industry experts stated that a detailed cost prediction for autonomous buses is currently not available. During the development of the service, an initial operational planning with the operator is needed. Operational planning encompasses a range of activities, including short-term decisions such as daily bus parking arrangements and monthly driver scheduling, whereas strategic planning focuses on long-term decisions. Further, it must be concretized which information will be communicated within the stakeholders, such as the customer, the operator, and others. To implement a public transportation service, it is tendered, operators can apply for it and are afterward selected with the detailed processes behind it differing locally. Out of the industry experts, it is described that these processes have a very long-time aspect in common, therefore making them inflexible. However, with the rapid changes in software development, these processes could need to be adapted to allow faster adaptation to new technologies. Further, a new aspect of the service implementation is test drives required to validate the functioning of the overall entangled PSS, e.g., validating the functioning of the AD features in the specific environment or the communication platforms for service operation.

The hardware realization phase described in Figure 4 is likely to stay similar to current buses in its structure: after acquiring all necessary inputs, the components are manufactured and assembled. However, the role of suppliers must be emphasized as a core change. Components like lidar and radar sensors, cameras, or actuators will increase in number and therefore importance for the overall assembly. These components are typically purchased parts and must be focused on during the procurement and assembly processes and can result in a shift of the suppliers' individual impact on the overall product.

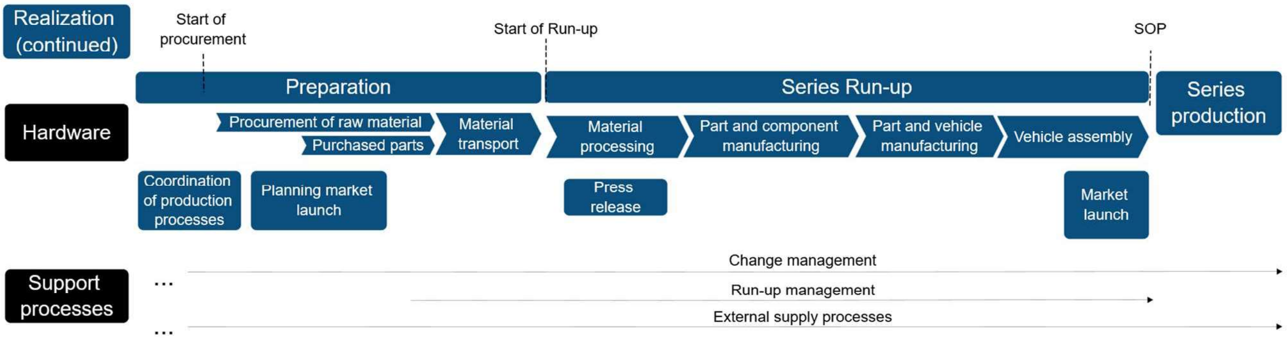


Figure 4: Hardware realization phase

4.3 Shared Usage

The shared usage phase is the core phase of the lifecycle since the PSS is put into its designated effect. It can be separated into three main phases: commissioning, driving cycle, and maintenance. At first, the bus must be registered to be allowed into operation. Especially the approved operational area is a significant new aspect. Currently, approvals are only given to a very tightly limited area on a street or city area level in contrast to the general approvals given to regular vehicles.

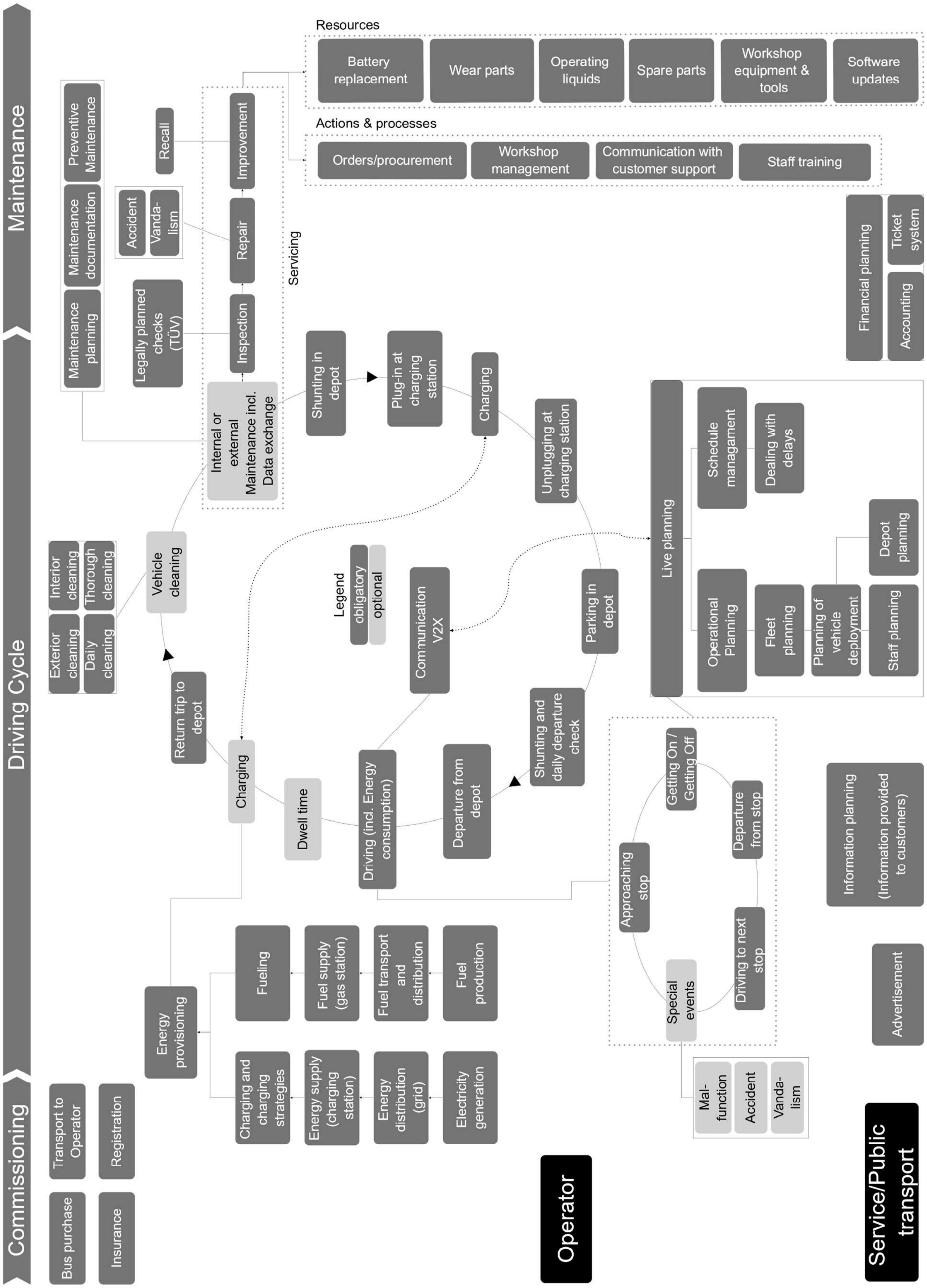


Figure 5: Shared Usage phase

The driving cycle can be simplified as such: the bus leaves the depot, drives its route, is either recharged on the route or in the depot, returns to the depot, is checked and if necessary maintained, and parked, before the cycle restarts. In parallel, live planning takes place, including operational planning as described in the previous section. During the driving cycle, there are optional aspects that can take place, which are colored in light grey in Figure 5, such as cleaning operations, maintenance, or special events like accidents or vandalism. Autonomous buses are expected to be electric vehicles (EV) only, still, this model is given completeness by also showing the fuel path at the energy provisioning phase. For the recharging of the EVs, several strategies exist: Either, the vehicle is charged in the depot of the operator, or during the driving cycle. The latter can be divided into in-motion charging (IMC) (Trolleybus) or opportunity charging (OC) at stop points on the driving route. However, IMC is only available in a few cities and the OC is very complex in its planning and requirements for infrastructure, therefore, the most used strategy is depot charging (Jefferies and Göhlich, 2020). The industry experts consolidated for this paper confirmed this observation. When returning to the depot, currently, specialized shunting drivers take over for parking and other maneuverings. Either, the autonomous vehicles still allow manual control or must be able to maneuver in these tight spaces to lose the necessity for a shunting driver. Further, the departure control of the vehicles could also be automated with specialized systems.

Out of the several aspects of maintenance, three must be pointed out: first, the need for new training for the employees in the workshops regarding EV and the growing software importance, and second, the importance of data feedback for the realization of predictive maintenance. If suitable data is available, repair intervals, spare part orders, and other workshop management aspects can be adapted to the real condition of the vehicles and processes overall automated. Not only for predictive maintenance reasons and the already described importance of feedback to the development phase, the role of data as visualized in Figure 2 must be emphasized in this phase. Sufficient data communication and related data management are essential for conducting live planning operations, technically supervising autonomous vehicles, providing customers with the needed information, and other digitalized processes. Third, software updates are estimated to be constantly taking place, while smaller updates such as map updates can be provided over-the-air, bigger software updates for the driving software are predicted by the experts to be conducted in workshops by connecting the bus to a computer. However, this aspect could change with the advancements of digitalization. Another aspect to be mentioned is the role allocation of operator and service planning, which can vary in every city. In the example of the industry partners in this paper, in the inner-city part, both operator and overall service planning are mostly combined in one company, whilst in the outer parts of the city, smaller operating companies and the service planning are distributed over separate stakeholders.

4.4 End of Life

The End of Life concludes the LC. As visualized in Figure 6, hardware, software, and service must be described separately.

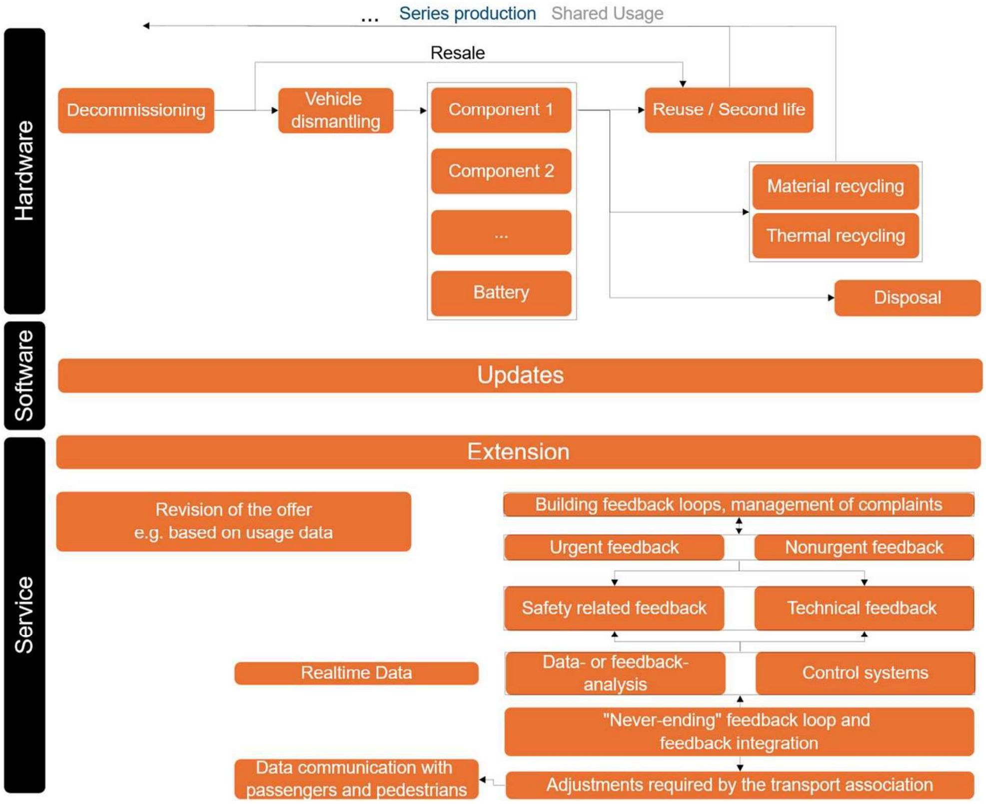


Figure 6: End of Life phase

The software simply will be updated at a certain point, which can be seen as its older version's end of life. The hardware can either be reused in a second lifecycle, such as is currently state of the art, or dismantled, recycled, and disposed. For the former, it must be addressed that a simple selling of the buses to other countries and a second-life operation might not be possible with autonomous buses, due to the strong legal limitations, unsuitability with technical systems in other cities, or simply the uneconomic need for updates in hard- and software.

The aspect of battery recycling of EVs is a large research field on its own, it plays an important role in the buses hardware recycling but cannot be described in detail in this paper. To know about the exact remaining lifetime of each component, the constant data feedback during the usage phase is important. Through the smartification of single components, they can each be individually treated in the recycling process. The extension and revision of the service offer highly relies on the right data availability, especially coming from customer feedback and complaints, knowledge about the offerings generated through the data collected during the usage phase, e.g., about its occupancy and adjustments required by the overall transport association. It emphasizes once more the importance of data feedback through suitable communications and management along the whole lifecycle of the bus.

5 Summary and Discussion

In this paper, a detailed lifecycle model for an autonomous bus is presented, describing all the sub-phases in detail and therefore offering a nuanced and holistic view of the lifecycle in question. It is divided into the main phases of planning, development, realization, shared usage, and end of life. Most importantly, it is modeled integrated as a product-service-system (PSS) also including the transportation service perspective. This is necessary since the product (bus) and the service (public transport) are highly interdependent in various requirements, limitations, and challenges that impact both, particularly evident during the shared usage phase. The business offering, which revolves around the service of people's mobility, relies on the physical bus for implementation. This finding can be transferred to public transportation systems in general. The lifecycle is modeled as circular with an emphasizing description of data feedback which is crucial in each phase.

A main new aspect of autonomous buses poses the increasing importance and role of software along the lifecycle, especially during planning, development, and realization. It is a crucial part of these new systems and therefore focused in the modeling of these stages by presenting an integrated V-model approach for hardware and software. Especially the importance of testing and validation relying on the availability of suitable data must be emphasized. The aspect of data feedback also runs through the following phases highlighting the need for a dedicated focus on this at all lifecycle stages. The shared usage phase represents the central stage of the product-service system (PSS) lifecycle and can be subdivided into three primary stages: commissioning, driving cycle, and maintenance. Here, the new role of technical supervision of autonomous vehicles must be pointed out. The end of life is described separately for hardware, software, and service, with recycling aspects relevant to the hardware, updates to the software, and adaptions based on customer feedback and usage data to the service perspective.

It must be discussed that the proposed model is a forecast for the future since autonomous buses are not established in regular operation yet. Therefore, the views might be biased by present best practices and other forms of best practices might occur over time, for example in the planning, development, and realization phase where the integrated V-model is a best practice at the moment, also confirmed by the industry experts, however, other approaches like agile development could prevail. Further, the impact of Artificial Intelligence (AI) on all phases, especially during development, is recently discussed intensively, possibly requiring changes in the methods and approaches that are currently state of the art. Overall, it can be concluded that the proposed model must be re-evaluated once such systems are established in real operation, nevertheless, it represents the current view on this future topic validated by numerous industry experts. These experts represent the view of several stakeholders along the lifecycle, however, only one operator and transport association from one large city is included here, further validation with other involved stakeholders in other cities or countries could pose further steps for this research.

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