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Department of Management and Economics

Innovation of the Validation Process of Advanced Driver Assistance Systems and Automated Driving Systems

Inovace validačního procesu pro pokročilé asistenční systémy řidiče a automatizované jízdní systémy

Master's Thesis

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Study program: N2301 Mechanical Engineering
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MASTER'S THESIS ASSIGNMENT

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2. Analytical part - management of development processes, technological and legislative aspects of ADAS/ADS implementation in automotive, current trends in validation approaches
3. Design part - design of the validation process, economic evaluation of benefits
4. Discussion and recommendations, conclusion

Bibliography / sources:

Winner H, Hakuli S, Lotz F, Singer C. Handbook of Driver Assistance Systems. Springer International Publishing, Cham. 2016. ISBN 978-3-319-12351-6.

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Weber J. Automotive Development Processes. Springer, Berlin Heidelberg. 2009. ISBN 978-3-642-01252-5.

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DECLARATION OF HONOUR

I hereby declare that this master's thesis titled "Innovation of the Validation Process of Advanced Driver Assistance Systems and Automated Driving Systems" is my own work and all used literature is properly cited in the References.

In Prague on 31st July 2020

Ing. Petr Cink, M.Sc.

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Abstract: The aim of this thesis is to analyse managerial, process, technological and legislation aspects as well as current trends in the validation of advanced driver assistance systems and automated driving systems, and based on that propose the concept of the innovated validation process of mentioned systems, at the company Porsche Engineering Services s.r.o., incorporating the state-of-the-art technological tools and effective managerial methodologies.

Anotace: Cílem této práce je analyzovat manažerské, procesní, technologické a legislativní aspekty, jakož i současné trendy ve validaci pokročilých asistenčních systémů řidiče a automatizovaných jízdních systémů, a na základě této analýzy navrhnout koncept inovovaného validačního procesu zmíněných systémů ve společnosti Porsche Engineering Services s.r.o., který zahrnuje nejmodernější technologické nástroje a efektivní manažerské metodiky.

CONTENTS

1. INTRODUCTION

1.1. Background

Nowadays, the automotive industry experiences significant changes. As disruptive technologies (such as artificial intelligence or internet of things) enhance with the endlessly increasing pace the automotive development is at the beginning of the biggest revolution ever after 130 years of incremental changes following a linear development path. Electrification, automated driving, connectivity and shared mobility are four substantial trends, which will likely reshape the automotive industry in the next 10 to 15 years. [1]

Motivation for Automated Driving

The implementation of automated vehicles (AVs) to the real-world traffic represents the opportunity to bring solutions to various safety, social, economic and environmental challenges. According to [2], 1.35 million people die each year in traffic accidents, which represents 2.2 % of all deaths globally. In consequence, road crashes cost 518 billion USD globally. This corresponds to 1-2 % annual GDP of individual countries. [3] Since 94 % of serious crashes are due to human error, AVs have the potential to save lives, reduce injuries and costs connected to vehicle crashes. [4] Drivers in the USA spend on average 8 hours and 22 minutes per week with driving. [5] With AVs, the travelling time might be spent more effectively with work or relaxation and also drivers' stress could be reduced. AVs have also potential to increase fuel efficiency and reduce emissions, improve independent mobility for non-drivers, for example, children or elderlies and support vehicle sharing, which would reduce total ownership and travel costs. [6]

Road to Full Automation

In 2015, Oliver Wyman in [7] predicted that there will be two types of advanced self-driving vehicles on the road by 2025:

1. Semi-automated vehicles with a driver behind the steering wheel equipped with functions that can take over on a motorway or in a traffic jam.
2. Vehicles with fully autonomous capabilities operating in closed areas such as airport terminals, university campuses or specially defined city zones without any driver.

Even though there have already been launched some pilot projects demonstrating AVs in action such as Waymo's robot taxi fleet operating in the suburbs of Phoenix [8], these vehicles can be in service only in good weather conditions and under remote operators support. Another example of Tesla's effort to introduce the Autopilot [9] able to take a coast-to-coast ride across the USA on its own seems to be far from the reality since its features can be rather considered as a hands-on driver assistance system requiring supervision of the fully attained driver. These examples indicate that it will take some more time till the Oliver Wyman's predictions will become mainstream.

The road to fully automated driving will most likely progress through various levels of automation depending on different legislation and technical aspects. SAE International has defined J3016 standard [10] defining six levels of driving automation from no automation (SAE Level 0) to full automation (SAE Level 5). The overview of these levels is shown in Figure 1.1. The levels of driving automation can be categorized into two groups. Levels from 0 to 2 are considered as driver support features, so-called Advanced Driver Assistance Systems (ADAS), while levels from 3 to 5 represents Automated Driving Systems (ADS). The main difference between these two is that with ADAS the driver must always supervise the support features and be ready to intervene in case of danger event to maintain safety, whereas when the ADS is engaged the driver does not need to pay attention and can relax.

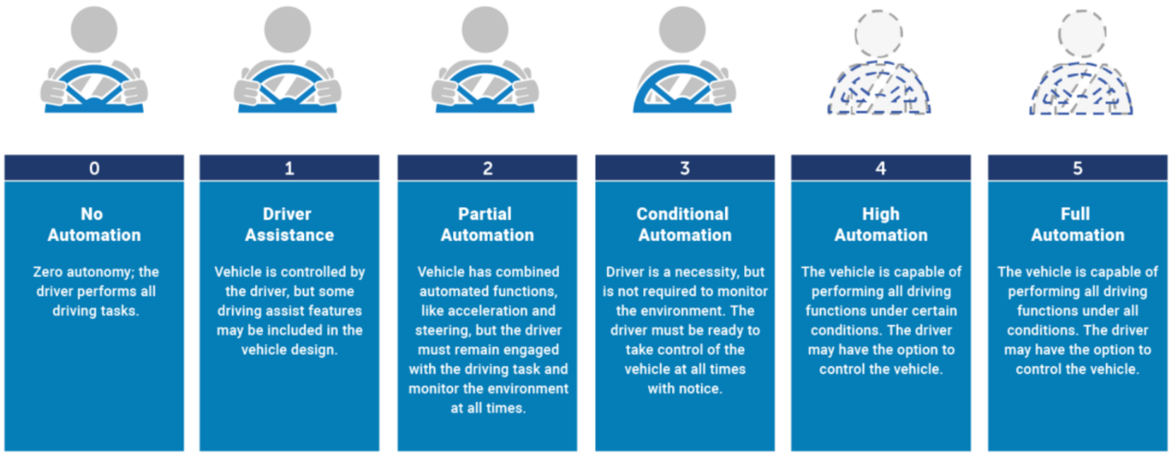


Figure 1.1: SAE Automation Levels [4]

Further, all automation levels are described in more detail and some example features are also presented. Level 0 features (e.g. lane departure warning, blind-spot warning or automatic emergency braking) are just providing warnings and momentary assistance. At Level 1, the driver is provided with steering (lane keeping) or acceleration/brake (adaptive cruise control) support. Level 2 is the combination of lane-keeping and adaptive cruise control and the driver is then assisted in lateral as well as longitudinal direction. From Level 3 the vehicle can drive on its own under limited weather or infrastructural conditions. The example of Level 3 function is a traffic jam chauffeur, where the driver must drive when the required conditions are not met. From Level 4 the driver will not be required to take over driving. Level 4 vehicles will be designed for usage at special infrastructural conditions (local driverless taxi services) and will not necessarily need pedals or steering wheel. Finally, with Level 5 automation functions, vehicles will be able to drive everywhere in all conditions.

1.2. Problem Definition

The fundamental prerequisite of ADAS and ADS functionality is environmental perception. Different types of sensors need to be used to compensate for their individual shortcomings and decrease overall uncertainty to acquire an accurate picture of the vehicle's surrounding. The example of sensors coverage combined from various cameras, ultrasonic sensors and radar is shown in Figure 1.2. The raw data from all of these sensors (and other eventual sensors, for example, LIDAR or GPS) have to be fused and processed in the central processing unit to obtain information about vehicle localization and detected objects (roads, vehicles, pedestrians, etc.). Decision-making algorithms then determine driven path and initiate appropriate vehicle's actuators such as motor, brakes or steering mechanism.

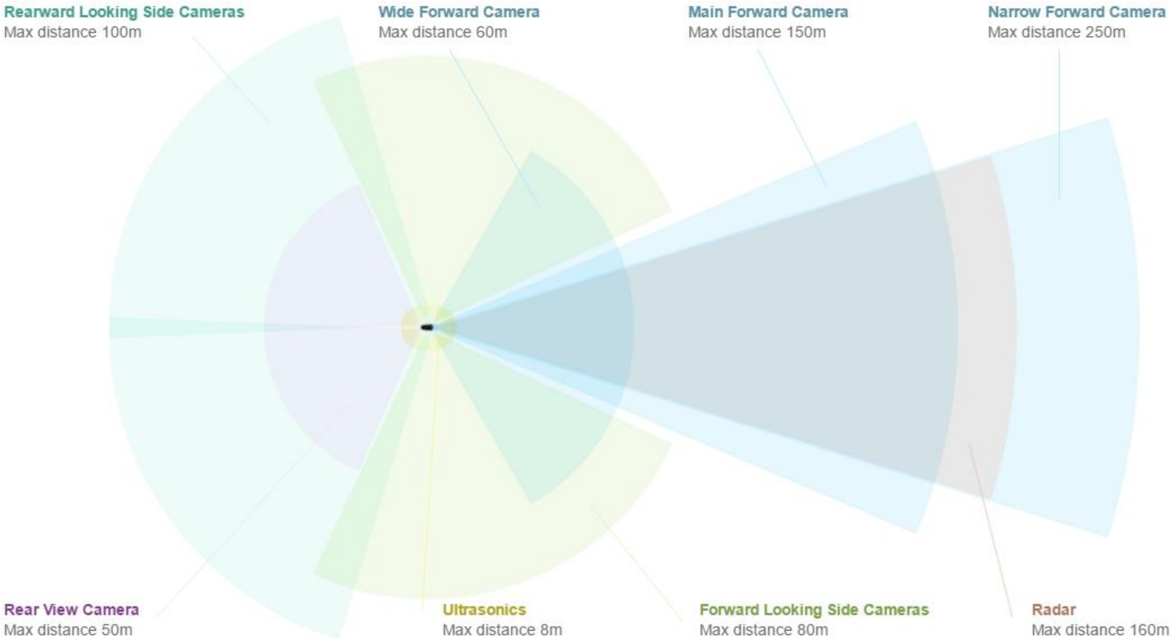


Figure 1.2: Advanced Sensor Coverage [9]

With increasing automation level, the complexity of ADAS and ADS increases exponentially. It is, however, necessary to demonstrate that these systems are reliable and safe in every complex driving situation in order to achieve acceptance among customers and regulatory authorities. [11] The problem is that the systems with environmental perception require a much broader scope of testing than ever before. According to [12], fully automated vehicles would have to be driven 65 million miles to demonstrate statistically significantly, that their failure rate of crashes per mile is 20 % lower than the failure rate of a human driver. It would take 3 years of non-stop driving to a fleet of 100 vehicles at an average speed of 25 miles per hour. It is clear that it is not feasible to rely just on driving these miles and alternative methods need to be used to supplement real-world testing. Furthermore, it will not be applicable to use traditional requirement specifications due to the complexity of real-world traffic situations. There will be therefore a need for agile development and situation-dependent testing. [13] Moreover, the legislation aspects of AVs are still evolving and regulations are far from any standardized form, which brings big uncertainty to developers. Since the traditional validation approaches are not practicable anymore for the development of highly automated vehicles, the validation methods, tools and processes need to be revised and innovated to speed up the transition to the fully automated driving system.

1.2.1. Research Questions

The previously defined problem was translated into the form of research questions, which enable its better understanding. The questions are organized to the form of main research question broken down into four sub-questions. These questions are important statements that identify the phenomenon to be studied and provide guidance for the process innovation.

Main Research Question

- *Which methods need to be implemented to the validation process of ADAS and ADS to support their effective development?*

Sub-Questions

- *Which managerial and organizational methodologies should be incorporated?*
- *Which technological tools should be used?*
- *What are the legislative aspects influencing the development of ADAS and ADS?*
- *What are the current trends in the validation approaches?*

1.3. Thesis Objective

The objective of this thesis is to analyse managerial, process, technological and legislation aspects as well as current trends in the validation of ADAS and ADS, and based on that propose the concept of the innovated validation process of ADAS and ADS, at the company Porsche Engineering Services s.r.o., incorporating the state-of-the-art technological tools and effective managerial methodologies.

1.4. Thesis Outline

After introducing the background, problem definition and objectives in this chapter, the analytical part based on the research questions follows in chapter 2. It introduces the overview of different aspects of the validation of ADAS and ADS, essential for understanding the concerned topic which is important to be able to achieve defined thesis objective.

Chapter 3 is devoted to the design part. Firstly the company Porsche Engineering Services s.r.o and its context is presented. Afterwards, the current validation process is introduced and analysed. Then, the innovated validation process of ADAS and ADS is proposed based on the outcomes of the analytical part and specified requirements. At the end of this chapter, the benefits of the proposed innovated validation process are evaluated.

In chapter 4, some remarks on the proposed innovation of the validation process are discussed and recommendations regarding the future work and possible first steps of implementation are stated.

Finally, in chapter 5, the conclusions are stated.

2. ANALYTICAL PART

The analytical part aims to introduce the overview of different aspects essential for understanding the concerned topic, which is important to be able to achieve defined thesis objective. It is based on the previously mentioned research questions in section 1.2.1. The focus will be given to managerial and process, technological as well as legislation aspects. In the end, the current trends in validation approaches will be presented.

2.1. Managerial and Process Aspects

Since the automotive industry is one of the most competitive business sectors, it is crucial to manage its activities in the most efficient way. The managerial aspects of process-driven development are therefore further introduced as a key factor of the ability to deliver competitive automotive systems.

2.1.1. Quality Management System

According to [14], the meaning of the word “quality” can be perceived from two different points of view. Firstly, it is about delivering products that meet customer needs. This approach increases customer satisfaction and makes products salable, which has a major effect on revenues. Secondly, it is about avoiding failures. Focusing on this type of quality reduces rework, error rates and waste, which has a positive impact on costs.

Quality management aims to strive for fulfilment of previously mentioned quality objectives, which leads to higher profitability and sustained growth of an organization. Quality management activities, which are further described in the following paragraph, incorporate quality planning, quality control, quality assurance and quality improvement. To manage everyday operations in a structured manner, the organizational structure, processes, procedures and resources needed to accomplish these activities form a quality management system (QMS). [15]

Quality planning refers to establishing quality objectives (both qualitative and quantitative), identifying quality requirements applicable to products as well as processes and developing QMS, which involves the establishment of product development and its support processes including their plan for execution. Quality control deals with the monitoring of processes to ensure desired quality requirements and activities to correct eventual deviations. Quality assurance comprises systematic activities that can provide confidence to management and customers that the product quality requirements will be met. It requires that the strategy to demonstrate achievement of quality requirements is well planned. Finally, quality improvement aims for enhancement in the effectiveness as well as efficiency of processes and for enhancement in the extent of fulfilment of product quality requirements. It is important to think about quality improvement as a never-ending process, because customer's requirements and also business competition evolves in time with ever-increasing pace. [15]

The widely accepted international standard ISO 9001 [16] specifies the requirements on the establishment of QMS and serves as a reference model for the foundation of management processes in an organization. The compliance of an organization's QMS with this standard demonstrates the ability to consistently fulfil the needs and expectations of customers. The standard is based on seven quality management principles: customer focus, leadership, engagement of people, process approach, improvement, evidence-based decision making and relationship management. The quality management activities described in the previous paragraph are in ISO 9001 organized to the so-called Plan-Do-Check-Act (PDCA) cycle. This cycle can be applied to the entire QMS as a whole as well as to all particular processes within an organization. The representation of the structure of ISO 9001 in the PDCA cycle shown in Figure 2.1 clearly demonstrates the importance of QMS as a link between customer requirements and QMS's results in form of customer satisfaction with products and services fulfilling desired quality. [17]

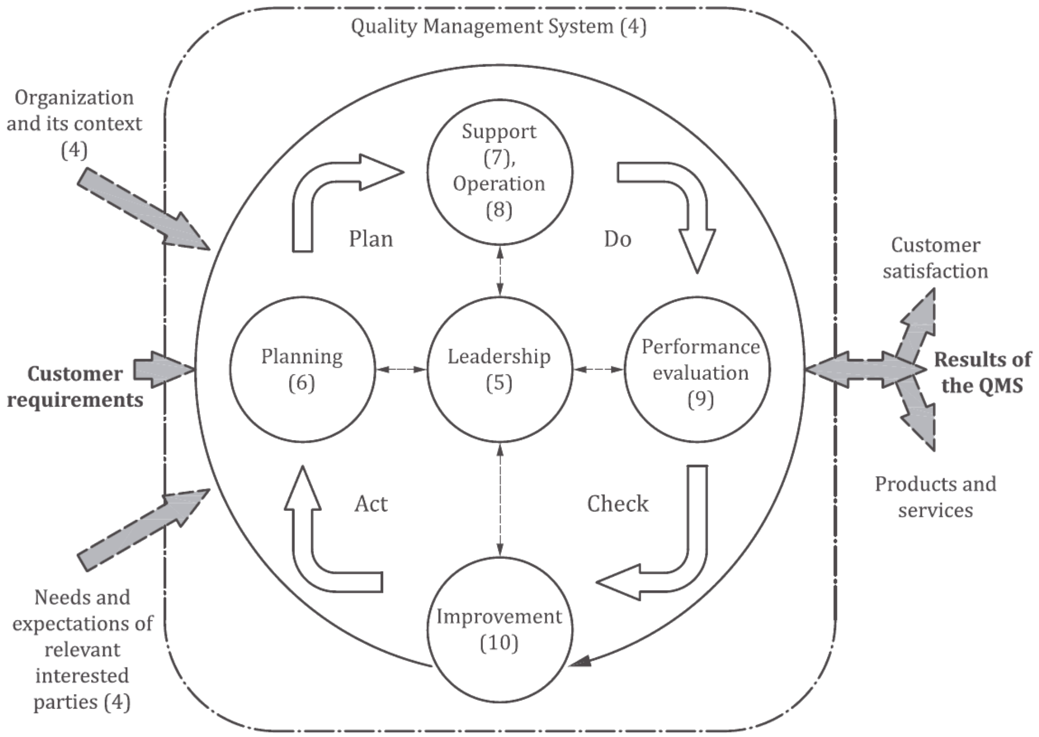


Figure 2.1: Representation of the Structure of ISO 9001 in the PDCA Cycle [16]

2.1.2. Process Approach

The process approach is one of the principles of ISO 9001. A single process is a set of interconnected activities that utilize input resources and transforms them into output products. The scheme of a single process is shown in Figure 2.1. Both inputs and outputs can be matter, energy or information and they are actually the same thing, because the output of one process might be input to another process. It could include software and hardware as well as services or requirements etc. There can be, for example, development, innovation, production and countlessly more processes established within a company. The main purpose of organizing these activities into processes is to transform them into repeatable routines, which increases productivity and helps to sustain the consistent quality of process outputs. [18]

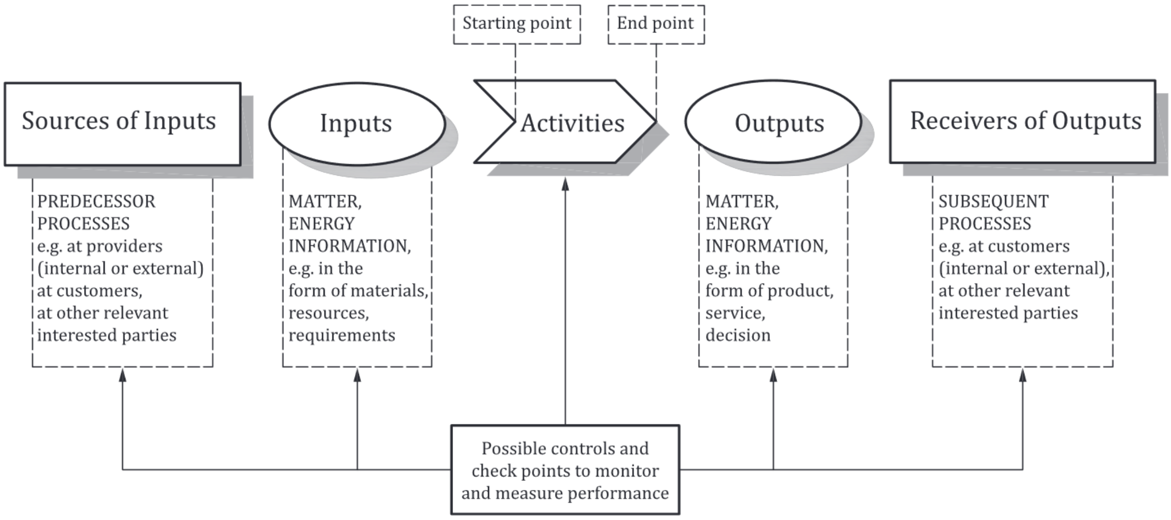


Figure 2.2: Schematic Representation of the Elements of a Single Process [16]

Interrelated processes and their interactions should be systematically documented in a quality manual, which ensures their easy transferability to different employees and locations. The structure of process documentation follows a top-down approach and is shown in Figure 2.3. The outline of processes is firstly presented in the high-level product development process map. Than follows documentation of process procedures with

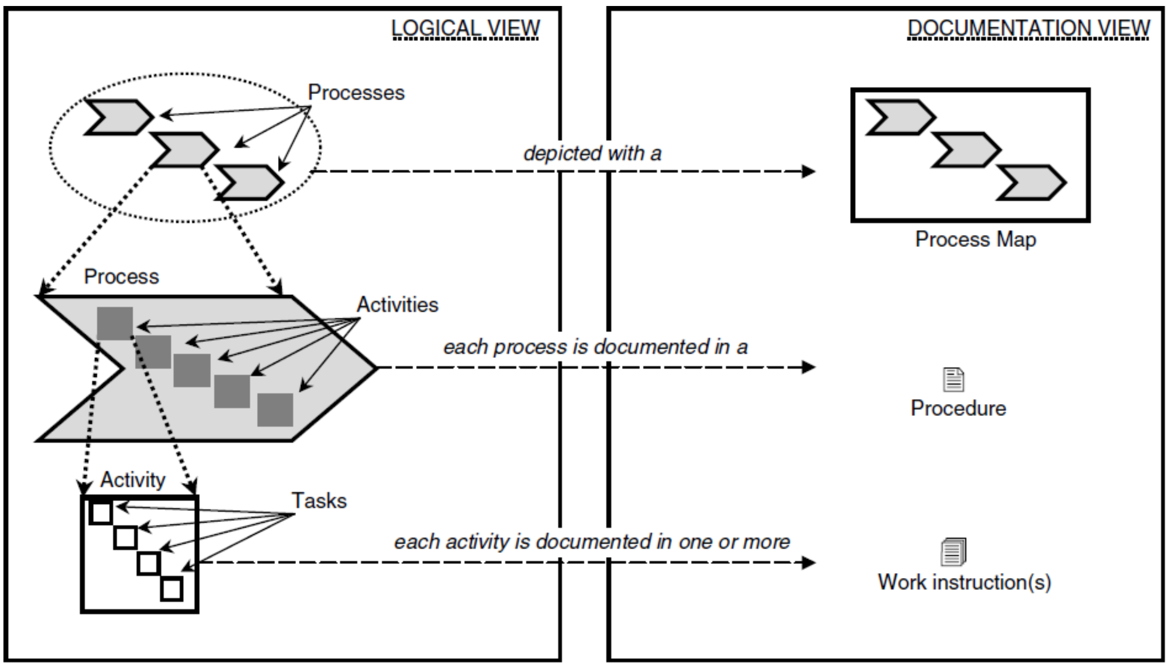


Figure 2.3: Relationship between Process Documentation and Processes, Activities, and Tasks [15]

defined scope, inputs, outputs, responsibilities and acceptance criteria. In the end, the step-by-step work instructions for every task are described in detail. [15]

For the understandable communication of process procedures are often used annotations prescribed by the standard Business Process Model and Notation (BPMN) 2.0. [19] It provides a set of descriptive elements and base practices to simply communicate process information between all users such as business analysts, process implementers and technical developers as well as customers and suppliers. It, therefore, closes the gap between business process design and their implementation. The example of a collaboration diagram for procedure description demonstrating the usage of different BPMN elements (flow objects, data, connection objects, swimlanes and artefacts) is shown in Figure 2.4.

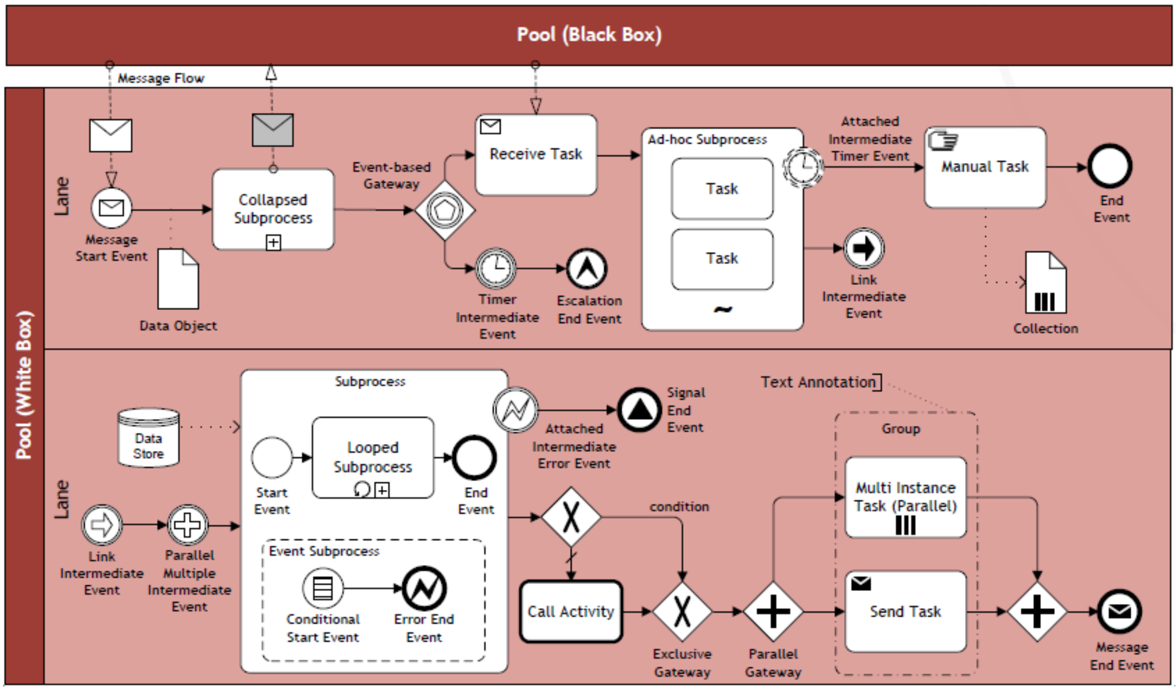


Figure 2.4: Collaboration Diagram [20]

2.1.3. V-Model

V-model is the term for the development process typical for systems engineering within the automotive domain. This designation is due to its shape, which is apparent in Figure 2.5. It describes a chronological sequence of activities grouped into two branches, where the descending branch represents the definition and design phase, while the ascending branch depicts the test and integration phase. The arrows symbolize connections between appropriate levels of both branches in the sense that the created subsystems are verified according to instructions and test cases specified during the definition phase. The process starts with the definition of customer requirements, which are translated into logical architecture. Then the development proceeds with a gradual decomposition of complexity from the development of technical architecture to the detailed design of single components. Implementation is a bridge between two phases and means that software is embedded into hardware. Then the single components are integrated and verified step by step until the entire vehicle system is complete. In the end, it is possible to validate the vehicle's conformity against customer requirements. [21]

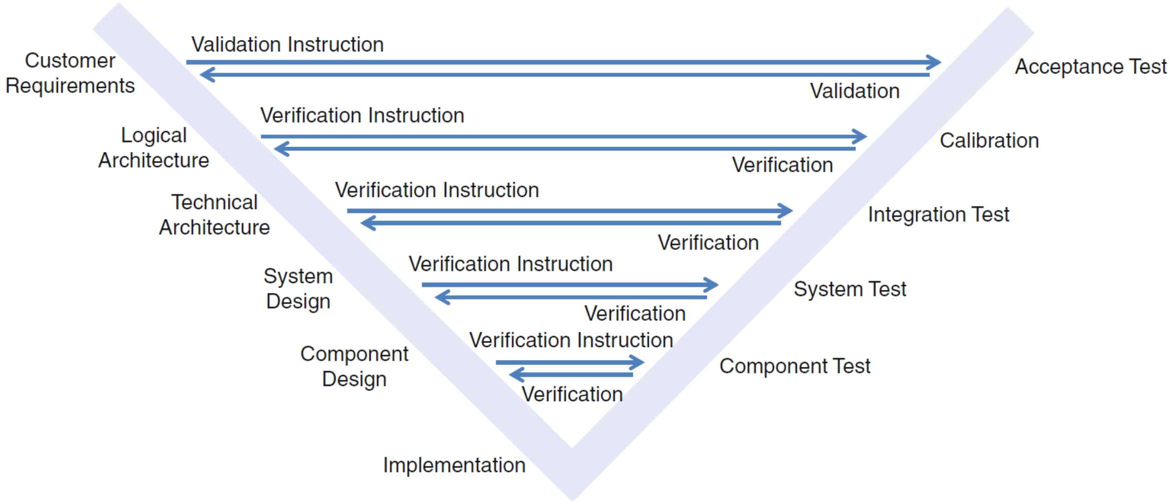


Figure 2.5: Development Process According to the V-Model [21]

Even though the V-model provides very systematic and easy to understand approach of managing projects requiring uncompromising quality assurance, it also has particular limitations. It is supposed that requirements are fixed at the beginning of the project, but they often change several times during the development. It is also not possible to verify the system, before all its sub-components are completed. The design and integration phases therefore usually iterate, which leads to prolonged release and increased costs. [22]

2.1.4. Development Process Standards

Development of automotive systems is supported by various domain-specific standards and guidelines. Since the software development processes shall be comprehensible and capable to ensure creation and maintenance of high quality and functional safe ADAS and ADS software, the standards providing structures, strategies and methods enabling to set up such processes are therefore introduced in this section.

Automotive SPICE

Automotive SPICE stands for Automotive Software Process Improvement and Capability Determination (ASPICE). It is a process reference and assessment model [23] derived specifically for automotive domain from generic international standard ISO/IEC 15504 and serves as a framework for designing and assessing software development processes of electronic control units and embedded systems. However, ASPICE additionally provides structure to the development process of entire mechatronics products and defines procedures for project management, requirements management, configuration management, risk management, supplier qualification etc. [24]

The ASPICE process reference model shown in Figure 2.6 provides a set of processes, which are organized into primary, organizational and supporting life cycle process categories and at a second level into process groups devoted to a different type of activities. The core of the primary life cycle processes consisting of system and software engineering process groups is organized according to V-model. Particular processes are described by process ID and name. For each process are further specified process purpose, process outcomes, base practices and output work products. The process purpose specifies functional objectives, which should ensure expected positive results of the process performance listed as a process outcomes. Base practices represents exemplary activities needed to accomplish the process outcomes and together with exemplary output work products serves as process performance indicators. [23]

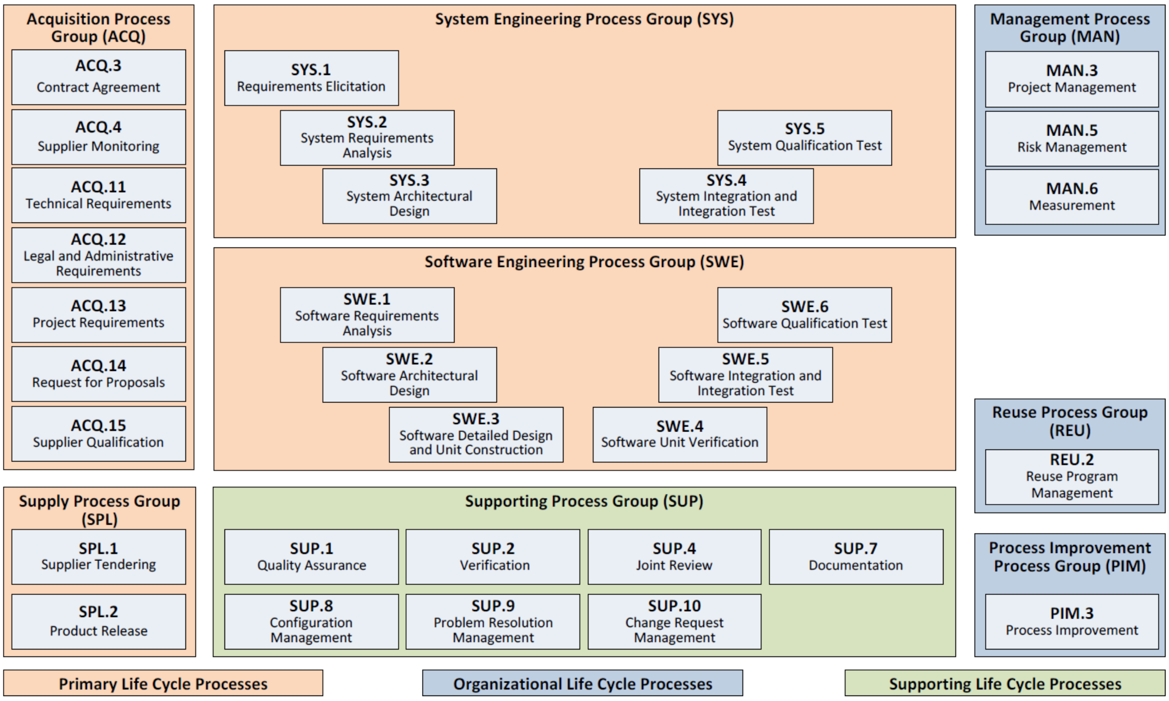


Figure 2.6: Automotive SPICE Process Reference Model - Overview [23]

The determination of process capability according to process assessment model consists of process and capability dimensions. The process dimension is based on previously mentioned indicators (defined by the process reference model) which are prescribed for all processes to evaluate the extent to which these processes are performed. The capability dimension then determines different capability levels according to indicators identical for all processes. ASPICE uses six capability levels from 0 to 5 named ascendingly as incomplete, performed, managed, established, predictable and optimizing. The capability levels are further subdivided into process attributes defining particular aspects of process capability. Process attributes are rated according to four-point scale: N (not achieved), P (partially achieved), L (largely achieved) and F (fully achieved). The certain capability level is achieved if the ratings of corresponding process attributes are at least L and ratings of all process attributes of the lower capability levels are F. [25]

Functional Safety and Safety of the Intended Functionality

Functional safety is an aspect of a technical product determining its correct and safe function with regard to predictable human errors, hardware failures and operational inconstancies. As a measure of sufficient safety level is used the tolerable risk limit, which needs to be higher than actual risk defined as the product of damage severity and the probability of its occurrence. [21]

Functional safety requirements for the development of safety-critical electrical, electronic and programmable systems in road vehicles such as ADAS and ADS are incorporated in international standard ISO 26262 [26]. The overview of the scope of this standard is shown in Figure 2.7. ISO 26262 provides definitions, guidelines and methods to empower functional safety into a product in the form of comprehensive safety lifecycle structured along the V-model covering all phases from product conception and development to production and use. The prescribed actions support analysis

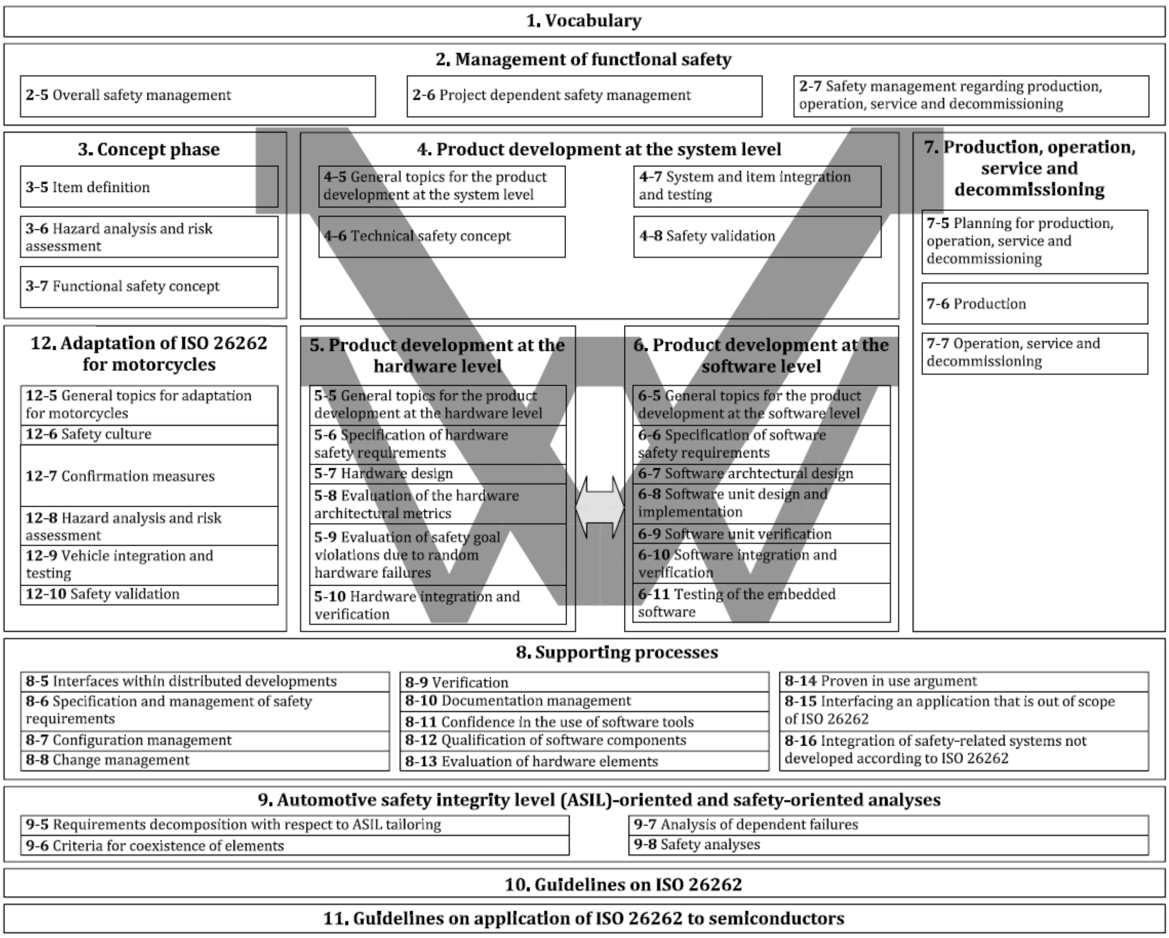


Figure 2.7: Overview of the ISO 26262 Series of Standards [26]

and evaluation of possible failures, derive measures to reduce the number of possible errors and their effects and provide evidence that functional safety objectives are achieved. The risk-based approach uses the automotive safety integrity levels (ASIL) to classify potential safety risks. The levels range from the lowest risk potential ASIL A to the highest one ASIL D with additional quality management level marked as QM for the risks classified below ASIL A, for which the regular measures of quality management are sufficient and further application of ISO 26262 is not required. [26]

Even though ISO 26262 deals with the safety risks that arise from random hardware and systematic faults of electrical and electronic systems, it does not cover the potential risks related to hazardous behaviour caused by the failures resulting from technological limitations of sensors and actuators, the performance limitations of a system or foreseeable misuse of intended functionality. These risks are related specifically to the systems sensing the environment or using the complex machine learning algorithms, which may face to insufficient robustness of the function in diverse environmental conditions (unpredictable traffic situation or unfavourable weather). It is also important that the driver properly understands the functional limitations e.g. while supervising the vehicle with activated SAE Level 2 ADAS. The absence of mentioned unreasonable risks is characterised by the safety of the intended functionality (SOTIF). The requirements on SOTIF are specified by the international standard ISO/PAS 21448 [27], which is currently under development. The overview of the activities promoted by this standard is shown in Figure 2.8. These activities are complementary to those prescribed by ISO 26262 and draw attention to the systematic risk-based testing and comprehensive validation focused on identified hazards related to SOTIF. The practices realized by SOTIF are foreseen as a normative support for the advanced realization of automated driving. [28]

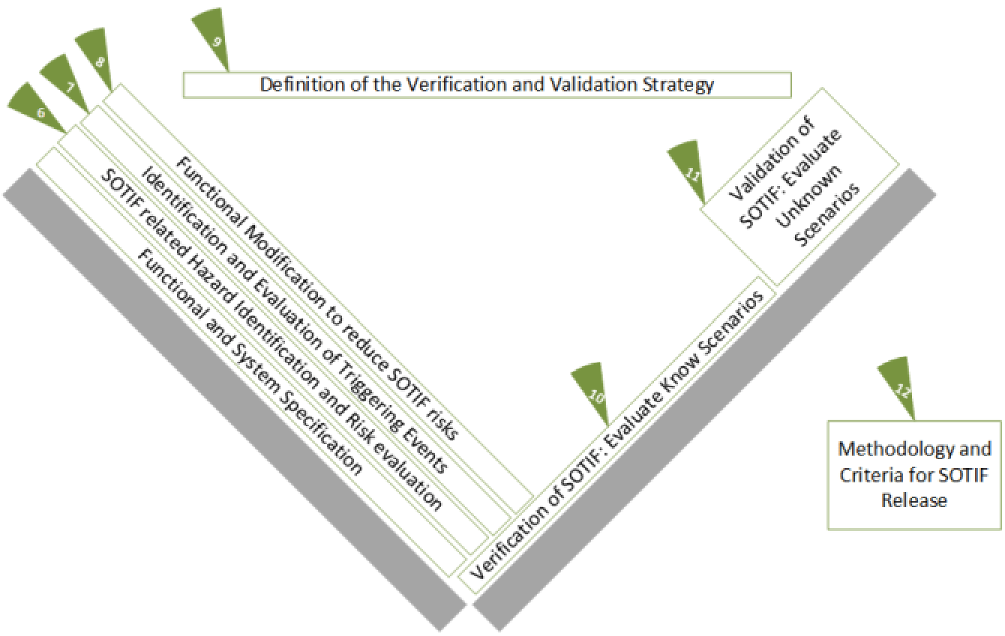


Figure 2.8: Overview of the structure of the standard ISO/PAS 21448 [28]

2.1.5. Agile Methodology

The automotive industry currently transforms into the software-centric domain with increasing implementation of ADAS and ADS to the vehicles. As the complexity and interdependency of the automotive software increase and their release cycles shorten more and more, it is getting very difficult to specify all requirements and create accurate development plan upfront. The traditional plan-driven approach becomes to be unsustainable and agile methodology is, therefore, beginning to be applied to the automotive software development. [29]

Agile methodology has its origin in the software industry and relies on continuous iteration of development and testing throughout the development project lifecycle rather than on fixed planning at the beginning of this project. In Figure 2.9, the agile methodology is compared with the waterfall model, which is similar to V-model because of its sequential character. The inconvenience of the waterfall model is its resistance to change due to rigid planning usually supported by heavy documentation where even small uncertainty in the requirements can cause large-scale failure at the end of the project. On the other hand, agile methodology breakdowns the final outcome into partial pieces, which are worked out in the short development iterations (sprints) ongoing over time in a cyclic pattern with a defined period. The sprints are organized according to the agile development framework named Scrum, which is based on “short bursts” of intense productivity of closely collaborating cross-functional teams. The preliminary and intermediate iteration outcomes of each sprint are presented to stakeholders in order to validate the iteration’s result and gain early feedback, which is crucial for revision of requirements and determination of what needs to be advanced or changed in further development steps. Such a change-driven approach is fundamental especially for large scale projects with higher uncertainty. [30]

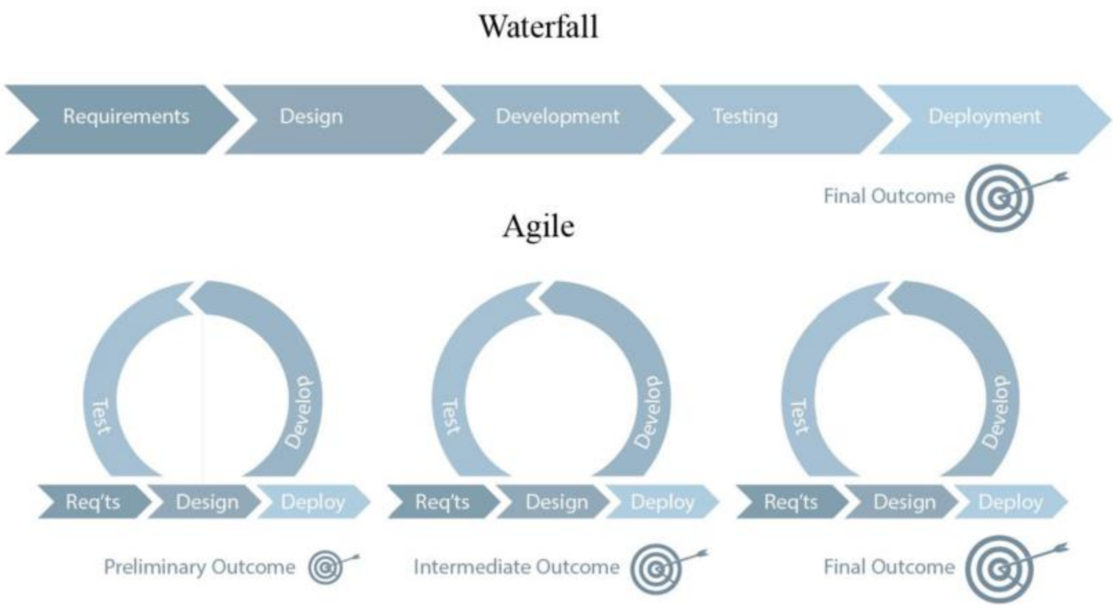


Figure 2.9: Agile Project Management vs Waterfall Project Management [30]

For the purpose of managing the work, agile methodology uses product and sprint backlogs, which are shown in Figure 2.10. Product backlog is continously evolving list of work items that are planned to be done in order to develop or maintain certain procuct. The work items should be ordered according to their relative business priority, breaked down into interconnected and concesutive tasks and should contain all necessary details about requirements and targeted release dates. The tasks are then transferred into a sprint backlog during a sprint planning with aim to realize them as effectivelly as possible. During a sprint, the tasks move across *to-do*, *in-progress* and *done* sections of sprint backlog in accordance to their status. [31]

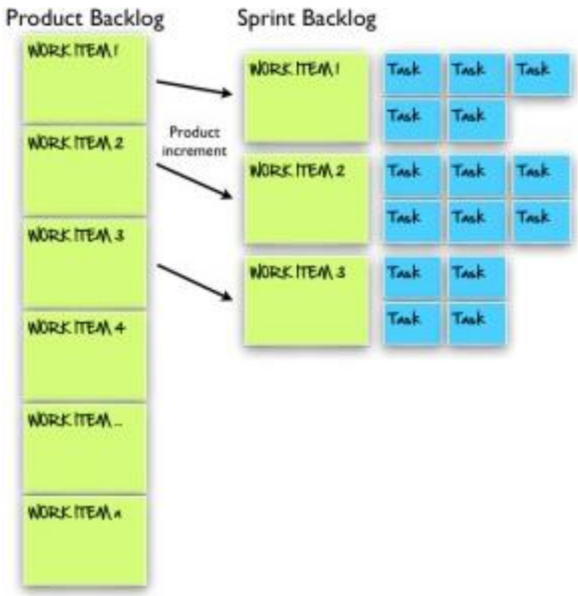


Figure 2.10: Product Backlog and Sprint Backlog Working Together [31]

The structure of a typical development team based on agile methodology is shown in Figure 2.11. The core of the team, also called the scrum team, consist of product owner, scrum master and development team. The product owner is responsible for managing the product backlog. He needs to specify and prioritize the items in the product backlog and needs to make sure that the product backlog is sufficiently transparent and that the rest of the team understands the work items enough. The scrum master is responsible for sprint organization and maximization of the value created by the scrum team. The scrum master also provides guidance to the team and ensures that agile practices are followed. The development team comprise cross-functional, self-organizing professionals, who work on the completion of tasks. The external players outside the scrum team are subject matter experts (SMEs) supporting the team with domain-specific expertise, a business owner who is typically sponsoring the development activities, and stakeholders to whom is delivered the output product so it is important to communicate with them to ensure that the most valuable requirements are met. [32][33]

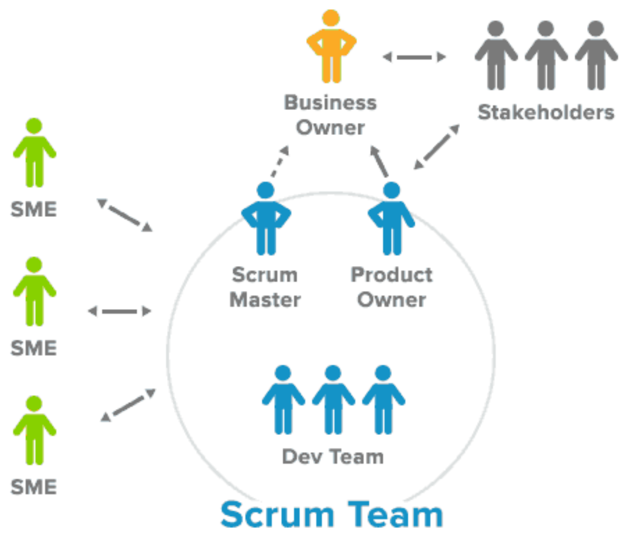


Figure 2.11: Scrum Team [33]

The implementation of agile methodology into the development of automotive software can decrease time to market, increase cost efficiency and productivity, help to handle complexity and develop products that meet customers' need more closely. Nevertheless, the introduction of agile methods in the automotive domain is sometimes hindered as it is argued that software development has to be in sequence with hardware development without compromising quality and safety. However, integration of agile elements into ASPICE, functional safety and SOTIF processes supporting quality and safety consistency does not bring any contradictions since these standards separate the software development from the system level. As the modern vehicles are connected to the internet, the software can be installed with usage of over-the-air (OTA) updates, which enables to fix software bugs and upgrade operating system even after the vehicle is deployed to the market. The innovative functions of ADAS or ADS can be therefore realized much faster with this flexible approach. [34][35] As an example can be seen the practice of Tesla, which offers from the hardware point of view vehicles with potentially full self-driving capability, but the particular software features are continuously upgraded through the OTA updates as they evolve. [9]

2.2. Technological Aspects

As the level of automation in the vehicles increases, these vehicles can cope with the increasingly complicated driving situations and their ADAS and ADS get more and more complex. This brings new challenges to their validation. The extent of required testing to demonstrate that the AVs are sufficiently safe is not practicable anymore with traditional approaches. The most important technological tools needed for enhanced deployment of AVs are therefore presented in this chapter.

2.2.1. Virtual Reality

As it was mentioned in chapter 1.2, it is not possible to rely just on driving in real traffic to demonstrate that AVs are sufficiently safe. To handle the complexity of interaction between ADAS or ADS and surrounding environment and speed up the development of AVs, real-world testing needs to be supplemented by virtual test drives. Such approach enables to place the simulation model of AV into a virtual urban environment with roads, intersections, traffic signs, surrounding vehicles and pedestrians so the vehicle's behaviour can be simulated as in the real world. The visualization of test drive in virtual reality (VR) is shown in Figure 2.12. [36]

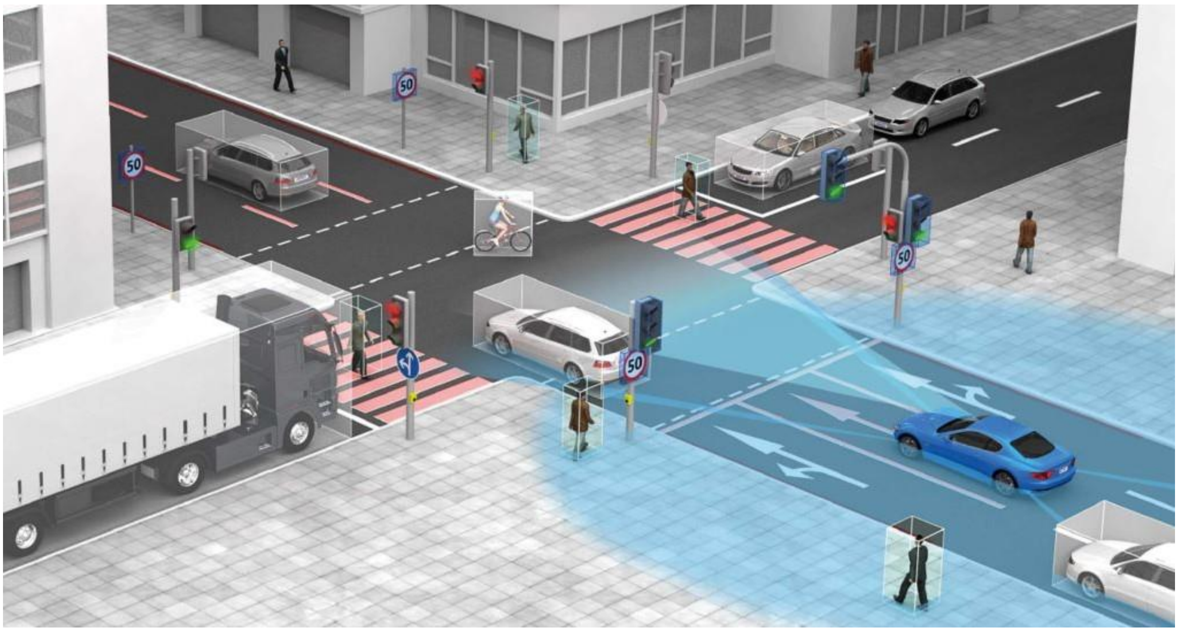


Figure 2.12: Virtual Road Traffic [36]

Since VR enables to interact with the digital environment as it would be real, it has been widely used for simulation of activities e.g. training of pilots on flight simulators, which would otherwise be dangerous and expensive in reality. As the technology improves, virtual scenes can be rendered with physically realistic effects accounting for different weather and lighting conditions. Physically correct distribution of light patterns and realistic imagining of light reflections on virtual objects enables to generate input data for simulation models of vehicle sensors that are practically indistinguishable from reality. The environmental perception abilities of optical and radar-based sensor systems and interactions between AV and its surrounding environment in critical driving situations can be therefore tested in VR without any safety risks. The tremendous advantage of VR is a possibility to generate a comprehensive database with a wide range of odd cases and near-accident situations, which occur very rarely in real-world driving. These scenarios can be used not only for reproducible testing and validation of ADS but also exhaustive training of neural networks to optimize the object detection algorithms to improve their robustness against unlikely events in real-life application. As a result, the usage of VR can significantly reduce time, costs and safety risks of the development of ADAS and ADS and contribute to more rapid deployment of fully automated vehicles. [37][38]

2.2.2. Scenario-Based Specification

The purpose of ADS is to control a self-driving vehicle in an open world environment without a need of human driver attention. However, the operation of AVs in complex real-world conditions that are continuously changing is much more challengeable in comparison to traditional industrial robots operating in a fixed place and stable conditions. The ADS need to be sufficiently flexible to handle an uncountable amount of all possible traffic situations occurring while driving in real environment. From the requirements engineering perspective, it is not feasible to cover specifications on intended functionality with the traditional text-based, solution-oriented requirements. Specifications by means of scenarios should be therefore introduced as a goal-based requirements to realistically represent relevant real-world situations. Once the scenarios are developed, they can directly serve as a test cases in all development stages. Even though scenarios have been already used in accidentology and consumer testing, they need become a corner stone of verification, validation and certification of AVs in order to speed up their deployment. [13][39]

Due to the variety of different stakeholders (OEMs, suppliers or regulators) that are involved in the development of AVs, there is a need for harmonized systematic description of scenarios into a standardized form. The scenario model shown in Figure 2.13 distributes the content of scenarios into six independent layers, whose systematic description is

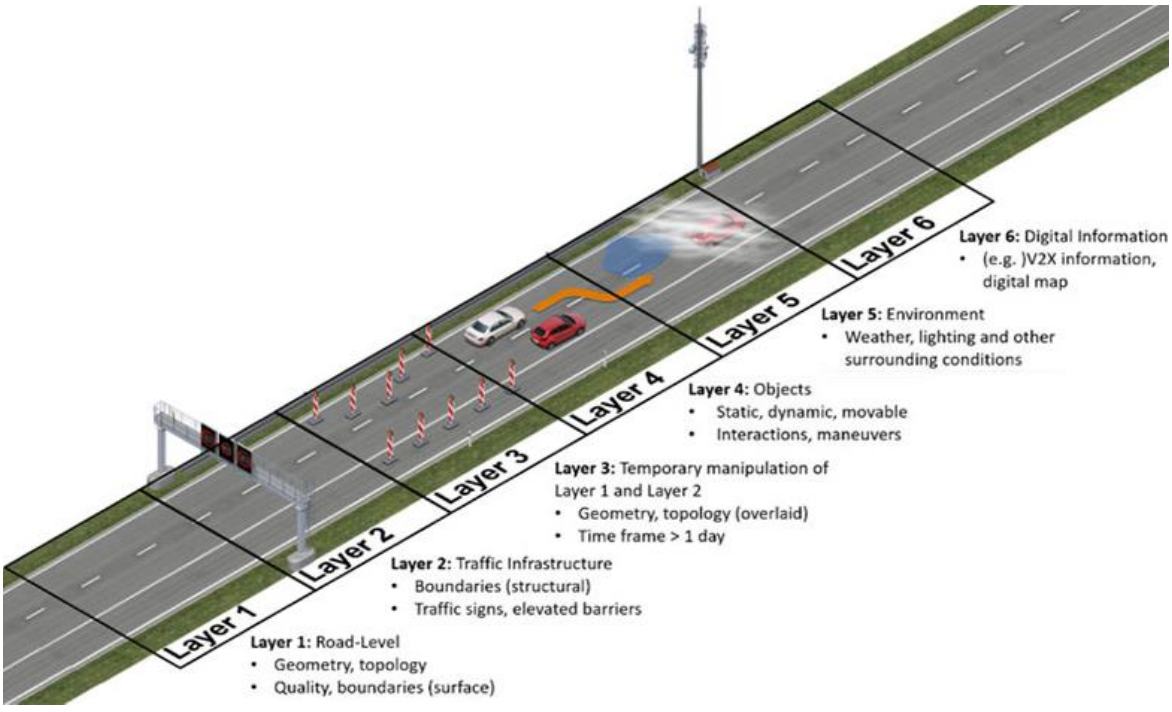
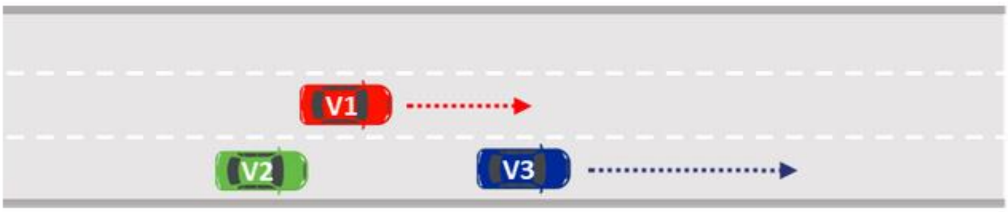


Figure 2.13: Model for a Systematic Description of Scenarios with Six Independent Layers [40]

defined by the set of standards including OpenCRG [41], OpenDRIVE [42] and OpenSCENARIO [43]. OpenCRG is a file format for the description of road surfaces in the road-level layer 1 with the consideration of weather impact in layer 5. On top of that, OpenDRIVE defines a precise description of road networks, traffic infrastructure and temporary traffic changes covered by layers 1 to 3. OpenSCENARIO then describes the dynamic behaviour of objects in layer 4 such as vehicles or pedestrians and environment conditions in layer 5.

OpenSCENARIO uses domain-specific language, which enables a parameterizable description of acts in scenarios and their variable execution. The description of scenarios can contain different level of information in various development phases. Based on the level of abstraction, it is distinguished between functional, logical and concrete scenarios. Functional scenarios are specified in the concept phase and must be expressed in a natural language using defined vocabulary and terms so they can be understand by human experts. Logical scenarios are expressed in domain-specific language and include parameter spaces for different system states. Concrete scenarios contain certain parameter values and must not leave possibilities for different interpretations. The example of logical scenario described by OpenSCENARIO notation with parameterizable modifiers of speed and position influencing scenario's dynamics is shown on the description of the vehicle's 3 motion relative to the other vehicles in Figure 2.14. Once the space of parameters and evaluation criteria are defined, the concrete scenarios can get tested as test cases in the simulation. [43]




```
v3.drive(p) with:
  lane(right_of: v1)
  speed([7..15]kph, faster_than: v1)
  position([20..70]m, ahead_of: v1)
  position([10..30]m, ahead_of: v2)
  lane(same_as: v2)
  lateral([10..25]cm, left_of: v2)
```

Figure 2.14: Modifiers Describing V3 *Relative to the Other Vehicles [43]*

2.2.3. XiL Approach

Using the X-in-the-Loop (XiL) methods is a well-established approach for testing of automotive embedded software. The X is devoted to the particular functional units (model, software, hardware or vehicle) developed along the V-model sequence as it is indicated in Figure 2.15. The XiL approach is based on continuous testing of these functional units integrated into the testing framework as soon as they are available. It enables to discover possible shortcomings of the product quality in the early stages of the development, when it is relatively cheap to adapt the requirements specification. Moreover, after that the XiL testing framework is established, its infrastructure can be easily reused for the development of other systems, which has a positive economic effect on overall development costs of ADAS and ADS. [44]

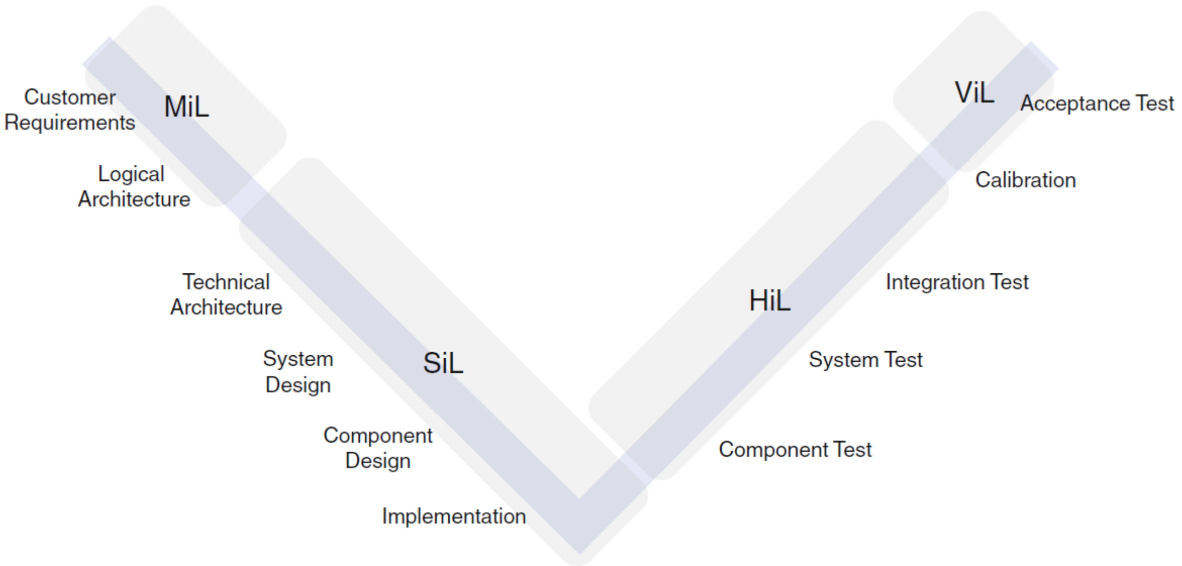


Figure 2.15: In-the-Loop Methods in the V-Model [21]

The XiL approach usually combines the usage of virtual simulation models and real components. Having a virtual vehicle prototype placed into virtual reality as described in section 2.2.1 enables to integrate a single component to the virtual environment and test it as it would be placed in the real vehicle. The gradual transition of particular elements, which are continuously integrated into the XiL testing framework along the V-model, from virtual to real world is presented in Table 2.1. The transition from pure simulation in the

Table 2.1: Gradual Transition from Virtual to Real World [21]

	MiL	SiL	ECU HiL	System HiL	Chassis dynamo-meter	ViL	Test drive
Functional code	V	R	R	R	R	R	R
Control unit	V	V	R	R	R	R	R
System	V	V	V	R	R	R	R
Vehicle	V	V	V	V	R	R	R
Driver	V	V	V	V	V/R	V/R	R
Driving dynamics	V	V	V	V	V	R	R
Driving experience	V	V	V	V	V	R	R
Road	V	V	V	V	V	R	R
Traffic/environment	V	V	V	V	V	V	R

V virtual, R real

beginning of the development process to real test drive before deployment is described further. [21]

Model-in-the-loop (MiL) method enables to test model-based software algorithms up to the logical system architecture. Created models are integrated into a simulation environment tested in virtual test drive. It enables easy and transparent communication with the customer in order to confirm the specification of requirements.

Software-in-the-loop (SiL) method integrates a functional code, which can be generated from previously developed model-based algorithm, into a detailed simulation platform with architecture comparable to real hardware. At this point, all software components can be tested before that any hardware is available and the correctness of requirements on individual components can be verified. Moreover, having a virtual prototype of the complete vehicle enables to perform exhaustive testing and verification of the whole system with virtual test drives, which is much flexible, faster and cheaper.

Hardware-in-the-loop (HiL) method implements developed software into actual hardware. The target hardware can be either a single electronic control unit (ECU) or a complete system with sensors and actuators connected to the test bench. The functionality of real single components, as well as whole systems, can be therefore verified with the simulation before the vehicle prototype is ready.

Vehicle-in-the-loop (ViL) is the state-of-the-art method for efficient validation of ADAS and ADS integrated into the real vehicle. The advantage of the ViL method against real test drives is that it uses a virtual environment as an input to the system, which enables reliable and reproducible traffic simulation of critical driving manoeuvres without any safety concerns. The test driver therefore sees augmented or virtual reality. The simulation can be run either on a chassis dynamometer or test track. However, the usage of the dynamometer is limited only to longitudinal applications such as adaptive cruise control. The actual position of the real vehicle is synchronized with the position in the virtual environment with the usage of GPS and inertial sensors. Virtual environment can be

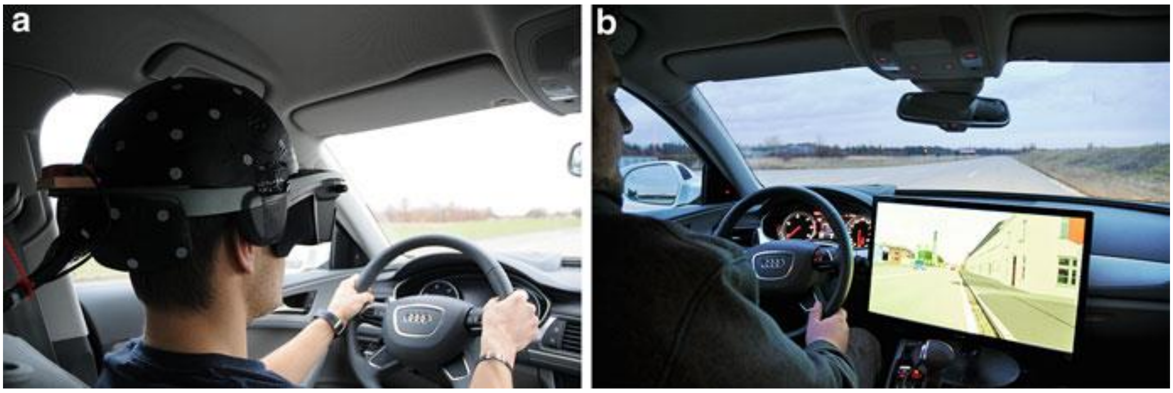


Figure 2.16: Potential Visualization Forms in the ViL [21]

visualized to the driver with a virtual reality headset or a screen as shown in Figure 2.16. The first option is more suitable for realistic evaluation of driver's interactions with ADAS or ADS, whereas screen visualization is sufficient for evaluation of system functionality and parameter calibration with emphasis on driving dynamics rather than driving behaviour.

Even though the XiL approach in combination with virtual reality enables to validate ADAS and ADS more efficiently with lower risks, real test drives will still be needed for several reasons. Firstly, to be able to develop a database of critical scenarios for simulations, these scenarios need to first occur in the real world. The database, therefore, needs to be updated for new cases so the probability of accident continually decreases. Secondly, especially simulations of environment sensors are still not perfectly accurate because of insufficient details of virtual reality due to limited computational power. Thirdly, the subjective assessment of the systems will be always more relevant in real test drives.

2.2.4. Test Automation

The scope of required verification and validation activities magnifies rapidly with increasing assistance and self-driving abilities of ADAS and ADS. In order to improve the agility of automotive systems development processes and shorten release cycles of software updates, test automation along the XiL framework is a necessary step to increase the testing efficiency. For this purpose, the Extended Automation Method (EXAM) brings the platform-independent interface for test management. With EXAM, it is possible to

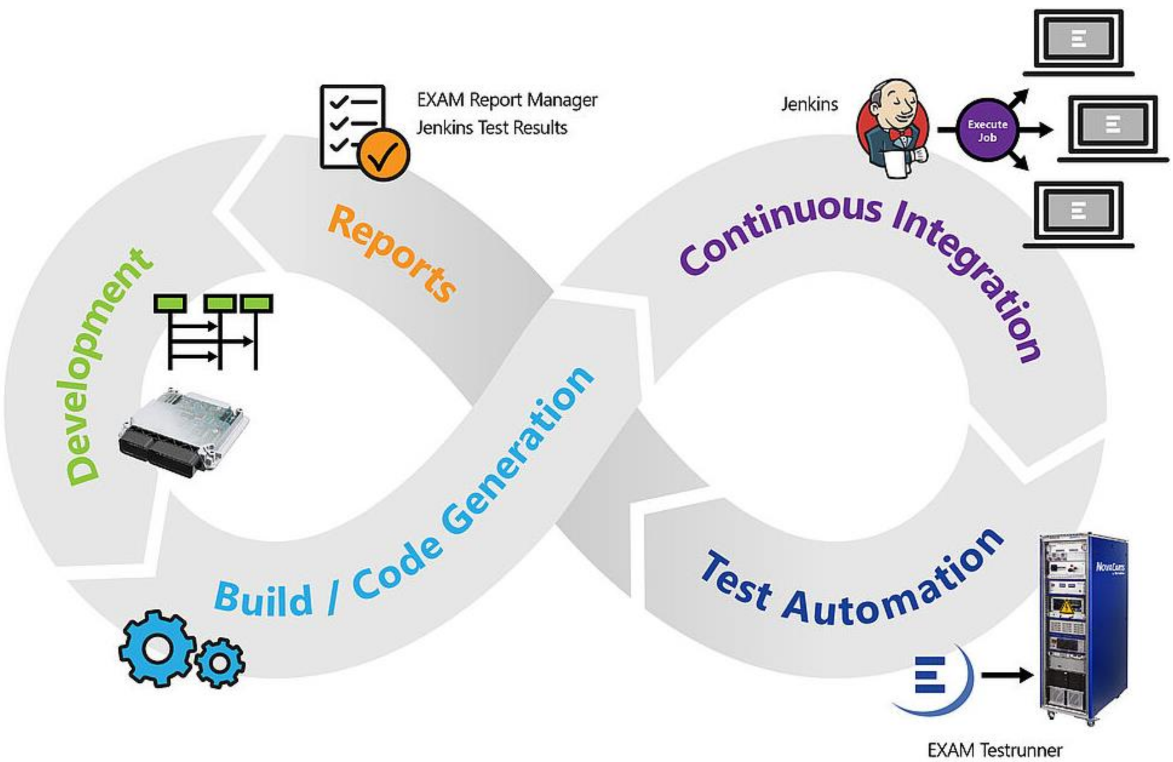


Figure 2.17: Continuous Integration with EXAM [46]

integrate various tools supporting test processes into continuous testing toolchain as shown in Figure 2.17. Such a toolchain enables automated creation, execution and evaluation of test cases in a very short time and feedback on each development iteration can be therefore obtained much faster, which improves the agility of the whole development process. [45][46]

The potential of test automation can be also foreseen in connection with testing of self-adaptive algorithms of AVs based on artificial intelligence, which are dynamic at run-time. It would be beneficial to automate collection and labelling of data acquired from the operation of AVs to improve the robustness of self-driving algorithms in real-time. The test systems itself should also learn from these data to adapt certain test criteria and facilitate the testing processes. [47]

2.3. Legislation Aspects

The well-established legislation creates an essential prerequisite for broad acceptance of highly and fully automated systems. Currently, the legal framework compiles complex network of regulations and industry-accepted standards on a national as well as international level. Especially the differences in national regulations represent unnecessary obstacles in the development of ADS. Car manufactures, therefore, aim for an internationally harmonized legal framework which would enable unified clarifications to the liability, ethical and homologation issues. [48][49] Also, public regulators have an interest in accelerating the adoption of a regulatory framework since it could bring the economic potential to generate European added value worth approximately 148 billion euros. [50]

2.3.1. Liability Issues

As there is a shift in responsibilities for driving tasks from driver to ADS with increasing automation level according to Figure 1.1, liabilities in the event of an accident should also shift toward ADS providers. The traditional three-pillar liability system combining liabilities of drivers, owners and manufactures offers the well-balanced distribution of risk and ensures reliable protection of victims. The driver alongside the owner is liable for consequences resulting from the omission of the duties arising from the operation of the vehicle whereas manufactures are liable for damages caused by a product fault. [48] The liability for accidents caused by SAE Level 3+ vehicles at the time of operation under ADS should be allocated directly to the ADS component and software suppliers, rather than to car manufactures or mobility service providers. [51] Due to complexity of ADS systems (which might be developed by many suppliers) as well as the complex causal links leading to the accident, the tracing technology (similar to flight recorders known from aviation industry) should be introduced. This would help to investigators and insurancers to establish the reasons for accidents and thus assign liability. [50]

2.3.2. Ethical Issues

Because ADS need to take over the decision making, there might arise new moral questions during the development of new self-driving algorithms. How self-driving cars should prioritize someone's lives in situations when they need to choose which life should be spared at the expense of someone else's life in the event of an unpredictable corner case when there isn't any other way how to avoid an accident? Should be rather spared life of elderly or youthful pedestrian? Should be spared lives of pedestrians over passengers? It was found that answers to these questions vary across the cultures. For example, people from western countries are more likely to spare the young at the contrast of people from East Asian countries, which prefer to spare the old due to the greater respect to elderlies. However, the great bias can be also found in between opinions of Japanese which prefer to save pedestrians, while Chinese would rather spare passengers. Further discussion (which would also incorporated risk analysis instead of just defining who will be spared or not) is therefore needed before deployment of ethical issues to specific regulations. [52]

2.3.3. Legislation Framework

Several countries aim to establish legislation framework timely to attract companies developing ADS. The proactive approach of regulators supporting initiation of pilot projects and enabling testing of ADS in real traffic can create innovative business ecosystem with high added value.

The German approach is driven by the Strategy for Automated and Connected Driving, which was issued in 2015 and urge the need for legal certainty in the deployment of AVs. Based on this, the ethics commission was established and in 2017 issued report [53] comprising ethical rules for automated and connected vehicular traffic e.g. the top priority is the protection of human life before damage to animals or any property; it is strictly prohibited to prioritize lives based on age, gender etc., but it may be justifiable to program ADS so it reduces the number of injuries; liability for damage caused by activated ADS is governed by product liability and it must be distinguishable whether ADS is being used. Moreover, the Road Traffic Act was amended in 2017 and is considered to be the most innovative traffic law in the world. It changes the rights and duties of drivers of SAE Level 3 and 4 vehicles. It states that the driver (which is still on board) may divert its attention from environment perception under certain conditions when ADS is active. The driver can, therefore, rely on the ADS functionality and will not be liable in case of its failure. [54]

In the USA, where the world's leading companies in AVs development are based, the federal approach to AVs deployment is specified by the report [55] of the United States

Department of Transportation. The approach is based on defined principles such as prioritizing safety, keeping technology-neutral policy, supporting pilot programs, protecting mobility freedom, modernizing regulations and encouraging a consistent regulatory and operational environment on the national level. However, actual significant control of the states over the transport policies prevents to successfully centralize legislative framework. Individual states, therefore, need to work hard to support AVs development. The example of successful cooperation between state regulators and the commercial company is Waymo's pilot project in Arizona mentioned in section 1.1. [56]

It is in favour of car manufactures that the legal framework is internationally harmonized. The cornerstone of international regulatory harmonization is United Nation's Vienna Convention on Road Traffic from 1968. Originally, it was assumed that a driver is responsible and in control of the vehicle in traffic. In 2016 was accepted the amendment admitting operation of AVs, which conform UN regulations and allows the driver to override and switch of the ADS. [48] In 2019, the International Alliance for Mobility Testing and Standardization (IAMTS) was founded to interconnect various stakeholders in AVs development. It aims to develop best practices in testing and validation methods and provide the industry with a set of physical and virtual test environments, which would help to establish a commonly accepted framework of regulations at a global scale. [57]

2.3.4. Six-Point Approach

Since there are currently no regulations that would deal with the effectiveness and safety of ADS concerning their actual deployment on the road, TÜV SÜD (which is also a member of IAMTS) came with so-called "six-point approach" [49] for developing homologation and approval regulations for AVs. This approach aims to establish effective safety assessment of AVs incorporating the use of simulations combined with physical testing and real-world driving to assess ADS against appropriately defined regulatory requirements. The scheme of the proposed framework is shown in Figure 2.18 and its stages are described next.

Firstly, the assessment framework should be designed as state-of-the-art. Since it is not feasible to rely just on real-world driving, it is important to establish testing approach as scenario-based, where the structure of relevant and critical scenarios would account for potentially millions of driving kilometres and it would be possible to use virtual simulations in combination with physical testing as a basis for assessment framework.

Secondly, testing scenarios should be compiled into an up-to-date globally and freely accessible database sustained by an independent institution. It would enable to develop safe AVs more quickly with reduced risk and also support the establishment of globally harmonized regulatory safety requirements for homologation.

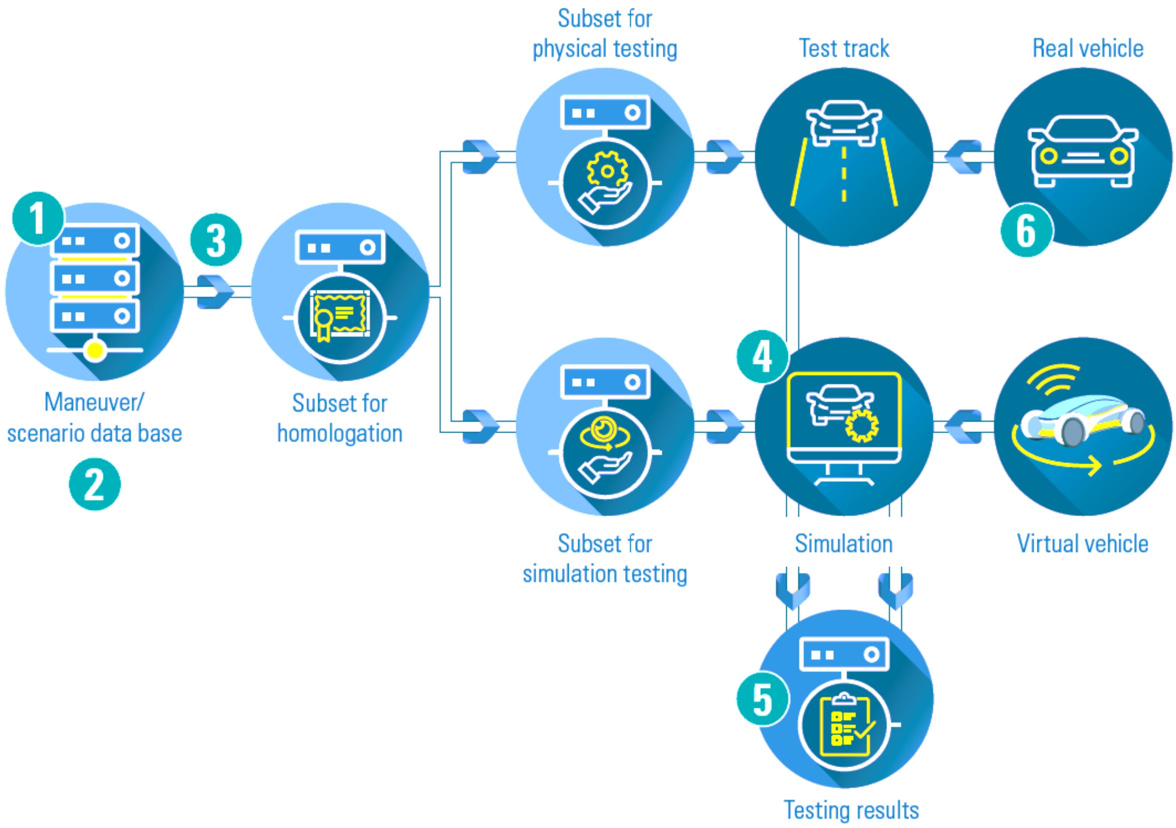


Figure 2.18: A Six-Point Approach to Empower Homologation of Automated Vehicles [49]

Thirdly, it should be defined (based on criticality metrics), which scenarios from the database will be used as a subset for homologation and which pass/fail criteria will be used as threshold metrics for each use case so that it sufficiently demonstrates the safety of ADS under test.

Fourthly, the virtual simulation should be integrated into the homologation process to support large-scale testing of requirements. However, it is also important to prove the validity of a virtual vehicle model on various levels from sensor perception to vehicle dynamics so that it ensures the trustworthiness of simulation.

Fifthly, the assessment of functional safety and SOTIF based on ISO 26262 and ISO/PAS 21448 should be enforced directly to the homologation process. Even though, the compliance with these guidelines is currently not mandatory, it is essential for introduction of AVs.

Sixthly, real-world driving is essential as a final validation of ADS functionality. It should be audited by regulators and any issues discovered during field testing should be publicly reported (with safety-related data recorded in a vehicle) to institution sustaining scenario database, which could be then continually refined. This approach would, therefore, help to speed up the deployment of AVs to real traffic.

2.4. Current Trends in Validation Approaches

Nowadays, several industry-driven initiatives are pursuing to come up with common, cost-effective and state-of-the-art verification and validation methodology, which would enable to enhance the deployment of safe and reliable AVs that would be acceptable by society. PEGASUS [40] and ENABLE-S3 [13] are two notable research projects bringing together industrial and academic partners to develop a set of reusable technology bricks and a common methodology for scenario-based verification and validation toolchain. Since these two projects are the key drivers of current trends in validation approaches, their main outcomes will be presented next.

2.4.1. PEGASUS Project

The Project for the Establishment of Generally Accepted quality criteria, tools and methods as well as Scenarios and Situations (PEGASUS) [40] addresses a joint research supported by German government focused on verification and validation methodology of SAE Level 3+ automated driving functions. The overview of the PEGASUS assessment method is shown in Figure 2.19. It consists of five basic process elements including definition of requirements, data processing, information storage and processing in a database, assessment of the highly automated driving functions and finally argumentation. The sequence of these elements is further described in more detail.

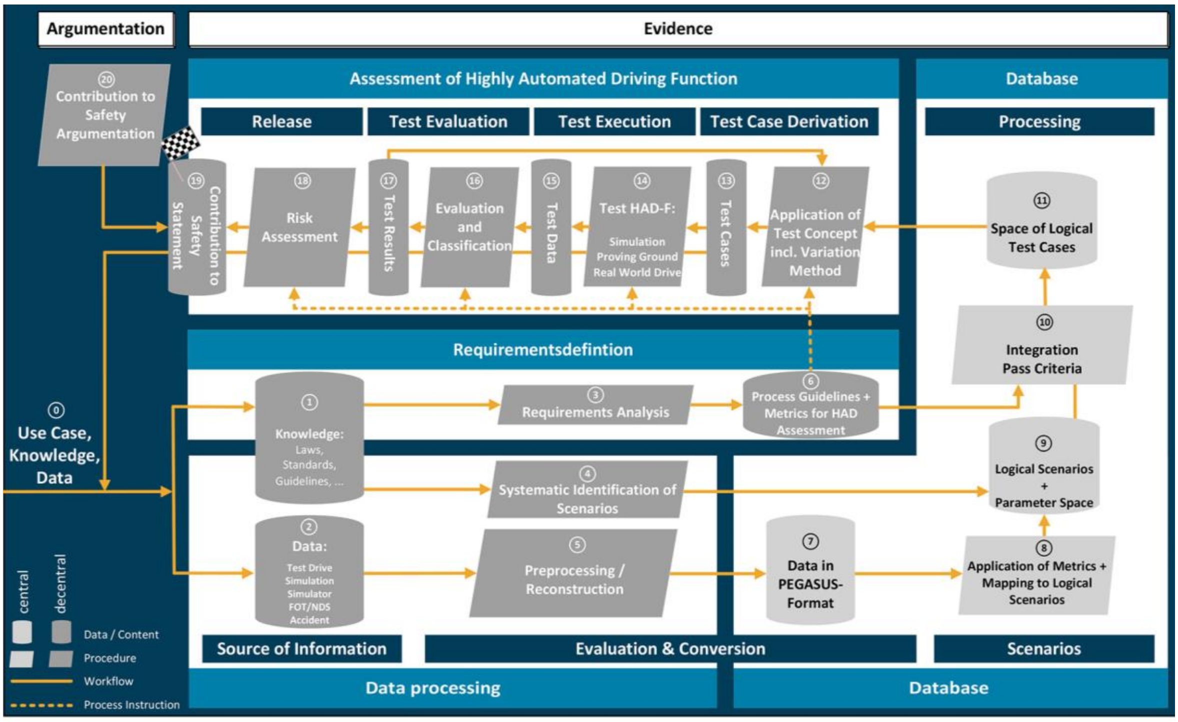


Figure 2.19: The PEGASUS method [40]

The goal of the first four elements is to provide evidence about a safety statement of an evaluated system, which will serve as a safety argumentation before release. In the data processing element, the logical scenarios are systematically identified based on abstract knowledge of laws, standards etc. or reconstructed from recorded driving data of accidents or corner cases. The scenarios must be processed into common input format such as OpenSCENARIO. The requirements are defined in parallel with data processing based on abstract knowledge. These requirements serve as evaluation criteria of scenarios so certain test cases can be created. The requirements are also used to design the assessment process. The database element creates a complete space of logical test cases with defined parameter spaces for different scenario parameters and integrated pass/fail criteria. In the fourth element, the space of logical test cases is executed in the simulation along the XiL framework and selectively validated on proving ground to assess the highly automated driving function. The results are then compared with pass/fail criteria and are used in combination with field test drives for a risk assessment to define a safety statement. In the end, the evidence about the safety of the evaluated system is compared with predefined safety argumentation and the outcomes are potentially used to upgrade the requirements and scenario database so the safety of AVs can continuously improve.

2.4.2. ENABLE-S3 Project

ENABLE-S3 [13] is a cross-national European project conducting research on a modular framework for validation and verification of automated cyber-physical systems across six application domains including automotive. As a result, ENABLE-S3 delivers generic test architecture, which is schematically shown in Figure 2.20. This test architecture

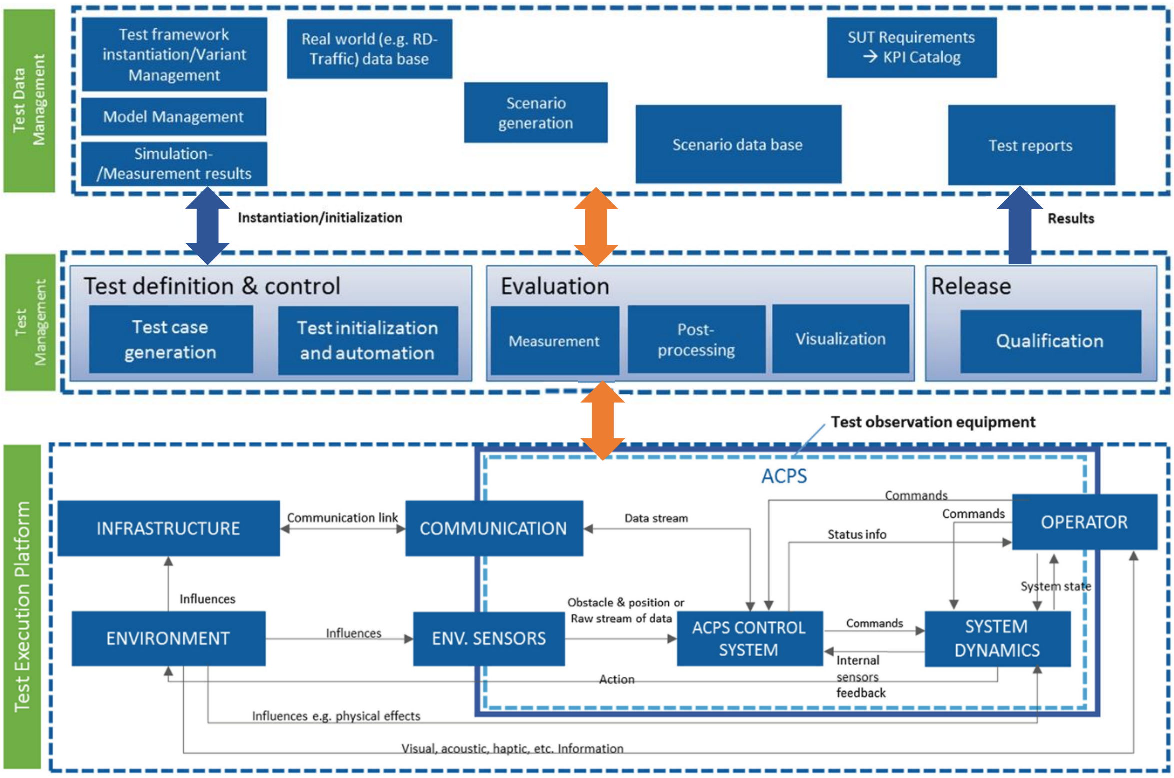


Figure 2.20: ENABLE-S3 Generic Test Architecture [13]

consists of three main layers including the test data management, test management and test execution platform. It aims to integrate different technology bricks to support validation activities from the acquisition of scenarios and simulation models to the execution of test cases and generation of reports.

The ENABLE-S3 further stresses importance to the implementation of the independent application domain on top of two branches of traditional V-model as shown in Figure 2.21. This domain should represent a collection of knowledge about the intended usage of systems to be developed and should provide a scenario database for the purpose of requirements specification as well as verification and validation activities.

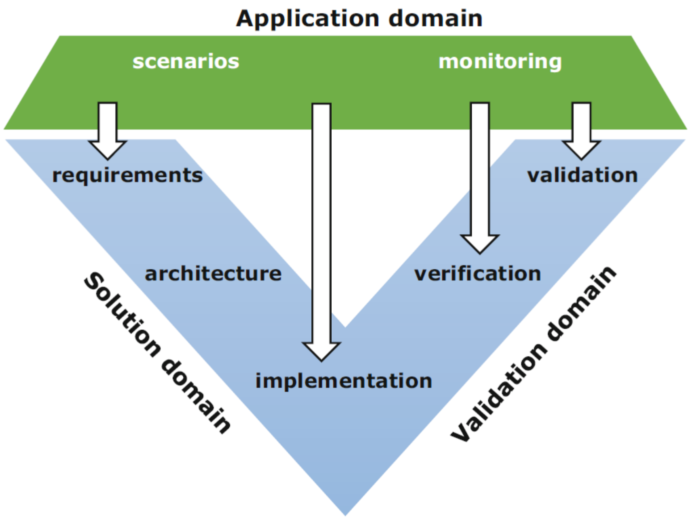


Figure 2.21: Triangle Model Showing Uses for Scenarios [13]

The project also encourages standardization activities, which is an important prerequisite for the usage of virtual validation environments for homologation and certification. It proposes a standardized scenario description using OpenSCENARIO and standardization of sensor model interfaces to provide compatibility between different development frameworks.

2.5. Summary of Findings

In this section, the summary of findings in the form of answers to previously defined research questions is presented. These answers provide guidance for the innovation of the validation process of ADAS and ADS presented in chapter 3.

- *Which managerial and organizational methodologies should be incorporated?*

The validation process should comply with the Automotive SPICE process reference model, which is a domain-specific quality management standard for automotive software development. The validation process should be compliant with functional safety and safety of intended functionality standards ISO 26262 and ISO/PAS 21448 respectively to be able to demonstrate sufficient safety level of developed systems. Moreover, the agile methodology practices should be incorporated into the development activities of automotive software to support its efficient development.

- *Which technological tools should be used?*

The usage of virtual reality and scenario-based specification for virtual verification and validation along the XiL testing framework is necessary to cope with the ever-increasing scope of required testing of ADAS and ADS. To enhance the rapid deployment of AVs to real traffic, these technological tools should be integrated into the continuous testing interface enabling test automation.

- *What are the legislative aspects influencing the development of ADAS and ADS?*

Even though the regulators are still working on a sufficiently mature legislation framework that would enable fully automated driving, there can be found local activities supporting testing of AVs in pilot projects. The international organizations aim to establish a commonly accepted framework of regulations at a global scale. The six-point approach is a promising proposal of state-of-the-art concept of assessment framework for homologation and approval of AVs.

- *What are the current trends in the validation approaches?*

PEGASUS and ENABLE-S3 are two notable research projects, which were identified as the key drivers of current trends in validation approaches. The PEGASUS assessment method provides the interface to acquire evidence about the safety of an evaluated system. ENABLE-S3 project delivers generic test architecture to support the integration of different technology bricks, stresses the importance to the implementation of the application domain on top of V-model and encourages standardization of scenario description and sensor model interfaces.

3. DESIGN PART

This chapter deals with the concept proposal of the innovated validation process of ADAS and ADS in the company Porsche Engineering Services s.r.o. with regard to the knowledge acquired in the analytical part.

In the beginning of this chapter, the company Porsche Engineering Services s.r.o as well as its context is introduced. The current validation process of ADAS and ADS is then described and analysed based on the specified assumptions. Required improvements are further defined and proposed changes are implemented into the innovated validation process structure, whose procedures are described. In the end, the benefits of innovated validation process are evaluated.

3.1. Introduction of the Company

Porsche Engineering
driving technologies

Figure 3.1: Company Logo [59]

3.1.1. Company Details

Company name	Porsche Engineering Services, s.r.o.
Headquarters	Radlická 714/113a 158 00 Prague 5 The Czech Republic
Founded	27th August 2001
Business form	Limited liability company
Number of employees	146
Revenue	334 million CZK
Operating income	38 million CZK
Net income	28 million CZK

Note: Data as of fiscal year 2018 according to the last annual report [58]

3.1.2. Characteristics of the Company

Porsche Engineering Services, s.r.o. (PES or the company) is a Prague-based subsidiary of German parent company Porsche Engineering Group GmbH with headquarter in Weissach. PES was founded in 2001 as a result of cooperation between Czech Technical

University in Prague and the company Dr.-Ing. h.c. F. Porsche AG. PES provides a wide range of research and development engineering services in the field of automotive industry and focuses on the development of complete vehicle systems, car body structures, chassis components and concepts, function and software development, electronics design and electronics integration. [59]

The company has been continually growing since its foundation and especially in recent years recorded a rapid increase in all key figures as it can be seen in Figure 3.2. There was established a new development site in Ostrava in 2018 to continue with its expansion of operations within the Czech Republic. The company aims to further extend its know-how and competences especially in the fields of electromobility, automated driving and artificial intelligence to be able to support its customers in the development of these cutting-edge technologies and pursue the trends in future-oriented mobility.

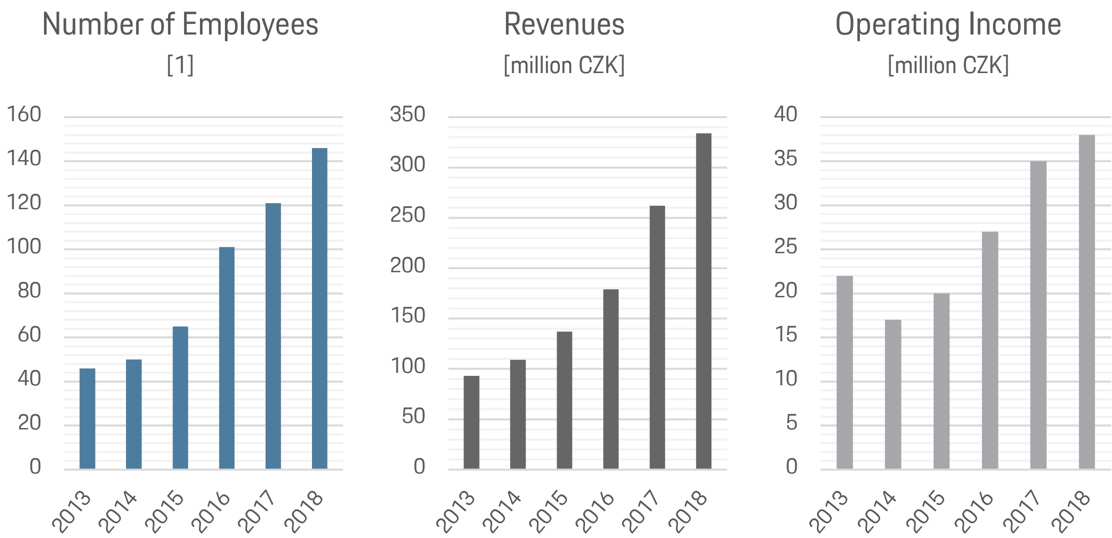


Figure 3.2: Evolution of Key Figures of the Company [data from 58]

3.1.3. Portfolio of Services

Complete Vehicle Systems Development

- Development of high-voltage systems such as battery modules, cooling systems, power electronics, fast-charge infrastructure and packaging of these systems into the vehicle
- Complete life cycle development of heating, ventilation and air conditioning components and systems with integration into the vehicle
- Noise, vibration and harshness analysis
- Thermo-management development comprising CFD simulations and validation measurements

- Aerodynamics performance development

Car Body Structures Development

- Design of car body structures from single modules to complete body-in-white, closures or battery pack frame with focus on lightweight design and ergonomics
- Structural simulations to perform stiffness, strength and fatigue analysis
- Passive safety simulations to evaluate crashworthiness or pedestrian protection

Chassis Development

- Chassis design of parts and assemblies
- Chassis testing and optimization (multi-body simulations, FEM analysis)
- Braking systems optimization
- Driving dynamics testing (system integration tests, vehicle handling tests)

Function and Software Development

- Model-based function development of battery management, active chassis, electric and hybrid powertrain systems using Matlab and Simulink
- Control systems development using traditional PID control schemes as well as modern methods e.g. neural networks
- Hand-coded software development in C/C++ or Python from low level codes to major projects e.g. software solution for charging infrastructure
- Functional safety and software quality management to ensure compliance with ISO 26262 and ASPICE standards

Electronics Design

- Development activities comprising complete development lifecycle of electronics including electric circuit design, embedded software development and testing
- Consultancy on legislative and normative standards application, worldwide certification, reliability calculations and FMEA

Electronics Integration

- Validation of automotive software embedded in electronics hardware

- HiL testing of powertrain and active chassis, car connectivity, advanced driver assistance and interior vehicle systems
- Development of software tools and simulation models for virtual testing of ADAS
- Modelling and real-time simulation of vehicle network architectures

3.1.4. Context of the Company

Porsche Engineering Services, s.r.o. is one of the international subsidiaries of Porsche Engineering Group GmbH which has over 1000 employees (from which more than 70 % accounts for engineers) in total with all other subsidiaries in Germany, Romania, China and Italy. Porsche Engineering Group GmbH is fully owned by automobile manufacturer Dr.-Ing. h.c. F. Porsche AG which is also the main customer. Porsche Engineering Group GmbH provides Dr.-Ing. h.c. F. Porsche AG with support in product development processes and engineering as well as supporting services. Since Dr.-Ing. h.c. F. Porsche AG is part of one of the world-biggest automotive groups Volkswagen AG, there is a straightforward vertical connection in ownership structure between PES and Volkswagen AG as shown in Figure 3.3. [60]

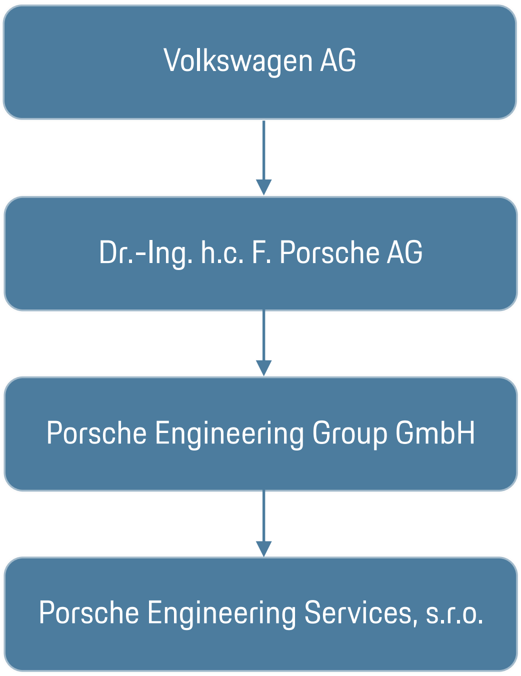


Figure 3.3: Ownership Structure

Volkswagen AG includes twelve brands of motor vehicles from seven European countries. Among these brands belong Volkswagen, SEAT and ŠKODA in volume segment; Audi as a premium brand; Bentley, Bugatti, Lamborghini and Porsche as representatives of the super-premium segment; Volkswagen Commercial Vehicles, Scania and MAN as commercial vehicles brands and finally Ducati as a motorcycle manufacturer. Besides these vehicle manufactures, the automotive division of Volkswagen AG comprises several development companies e.g. Porsche Engineering Group GmbH, Digiteq Automotive, s.r.o. (subsidiary of ŠKODA AUTO a.s. operating in the Czech Republic) or Car.Software organization etc. The connection of these companies, schematically presented in Figure 3.4, creates an extensive ecosystem of strategical partnership across the group resulting in collaboration and transfer of technologies. This is beneficial for Porsche Engineering Group GmbH, because its know-how and resources can be better utilized across (and not only) the whole group Volkswagen AG.

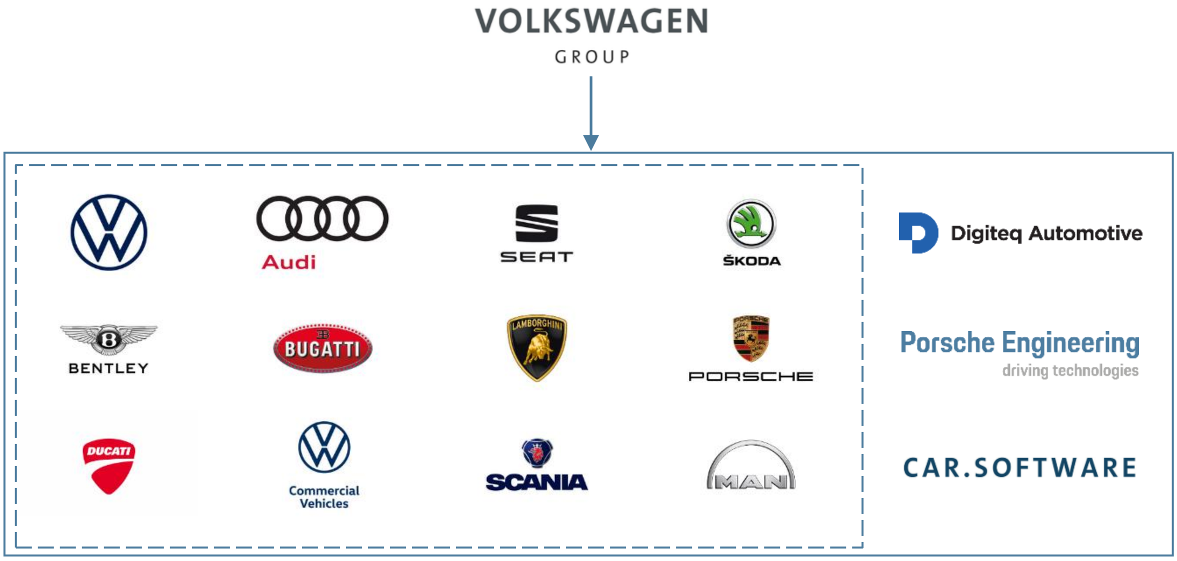


Figure 3.4: Context of Porsche Engineering

The special opportunity for whole Porsche Engineering Group GmbH represents the foundation of Car.Software organization operating from 2020 as an independent business unit of Volkswagen AG to integrate and centralize the associates and subsidiaries to develop automotive software and digital ecosystems. Car.Software will comprise five domains as shown in Figure 3.5, from which Porsche will be primarily responsible for Vehicle Motion & Energy division developing powertrain, chassis, energy and charging software functions. The objective of Car.Software is to establish uniform software architecture across all brands, develop standard vehicle operating system “vw.os” enabling connection to the Volkswagen Automotive Cloud, develop standardized infotainment platform, unify all ADAS into one compact system communicating with software functions connecting powertrain, chassis and charging systems and finally a develop digital ecosystem of mobile services and digital business models. On behalf of that, there should be more than 10000 employees by 2025 in Car.Software organization to increase the share of in-house software development from less than 10 % to at least 60 % by then. [61] Porsche Engineering Group GmbH can be foreseen as a strategic partner to shape Car.Software organization, which would allow PES to take advantage in this partnership to further growth, especially in the fields of automated driving and artificial intelligence.

Figure 3.5: The Car.Software Organization [61]

3.2. Current Validation Process of ADAS at the Company

For the activities related to the validation of ADAS at PES is responsible ADAS and Vehicle Architecture team (EIA team) in the Electronics Integration department. The EIA team comprises six test development engineers working in pairs on three currently ongoing projects, whose organizational structure is shown in Figure 3.6, concerning the integration

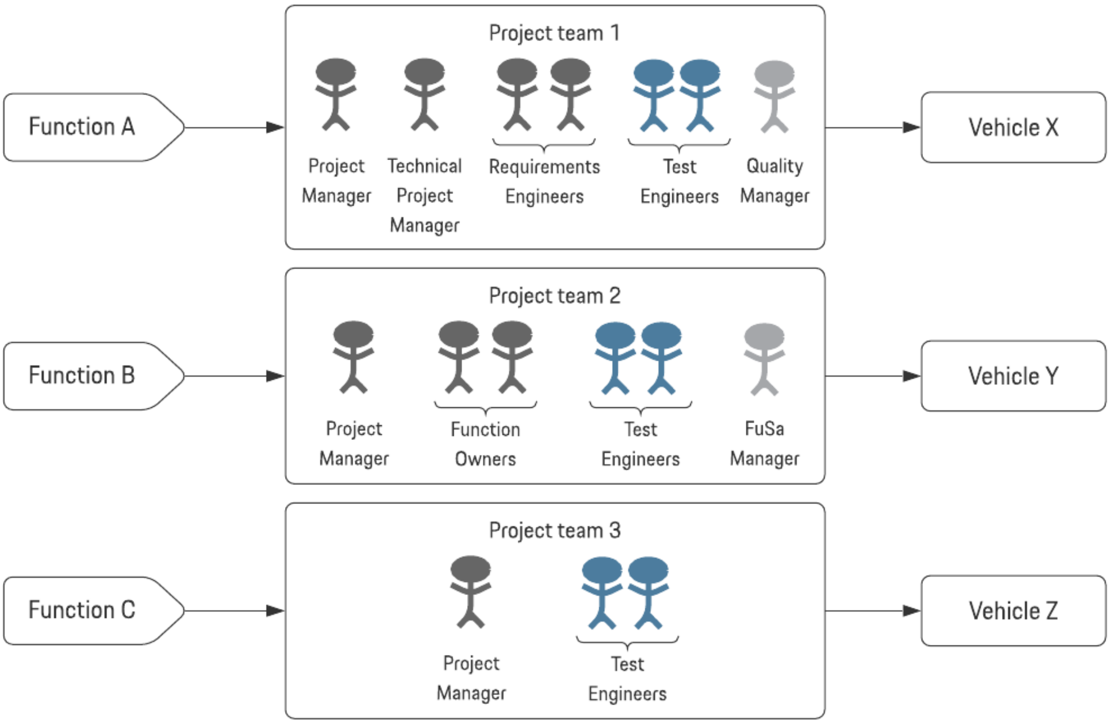


Figure 3.6: Organizational Structure of Validation Projects

of ADAS functions into the vehicles. Besides the test development engineers from the EIA team, who are responsible for **core processes** comprising validation activities, there are also roles responsible for **management** and **support processes**. The scope of these processes is described in the next section. The aim of these projects is to ensure that certain ADAS functions (such as automated parking assistant or adaptive cruise control) are properly integrated into the specific vehicle and provide evidence about their compliance with specified requirements.

As can be seen in Figure 3.6, each of the validation projects is to some extent specific from many points of view. While the first project deals with validation of in-house developed system function so the validation activities of EIA team are therefore part of a bigger development project, another two projects deal with validation of ADAS integrated by suppliers. Also, the structure of **managing** and **supporting** roles varies depending on the complexity and importance, and therefore allocated budget, of the system to be validated. The managerial methodology also varies across the projects. Even though the internal Software Quality Management Handbook defining standard-compliant (concerning ASPICE and Functional Safety) procedure of development processes is established, only the first project with complete in-house development is managed accordingly to this manual.

3.2.1. Process Map of Ongoing Validation Projects

Despite the mentioned differences in the projects, the processes related to the validation of ADAS were captured in the generalized process map presented in Figure 3.7. The process map is partially based on ASPICE structure and is divided into **management**, **core** (which are the responsibility of the EIA team) and **support** processes. The scope of these processes is described next.

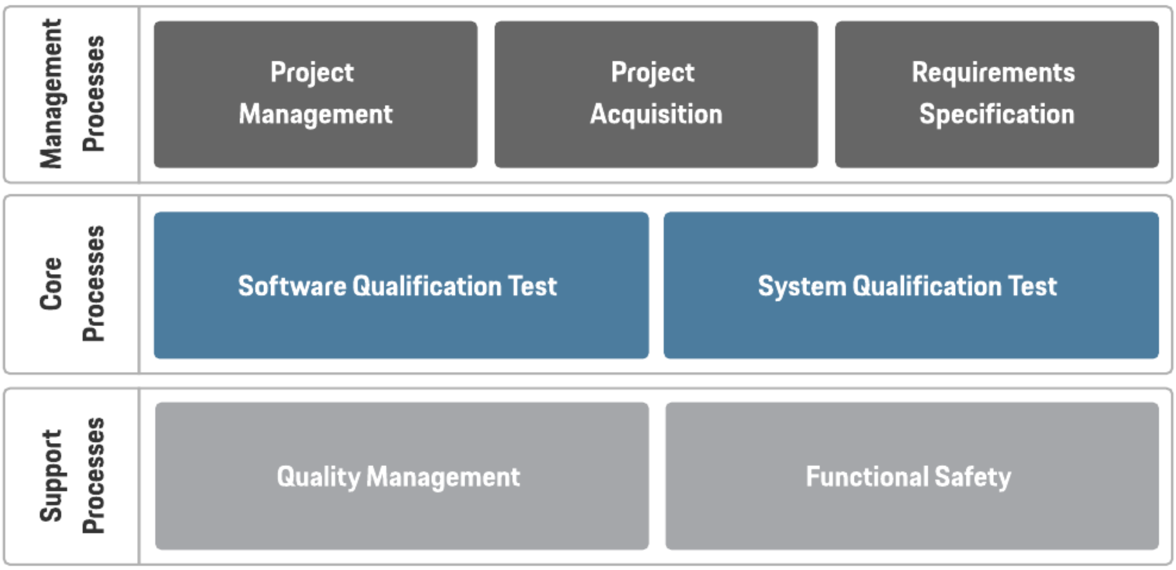


Figure 3.7: Processes Related to the Validation of ADAS

Management Processes

The purpose of the Project Management process is to specify activities leading to the fulfilment of project objectives with regards to the release plan and allocated resources. The ASPICE base practices of the Project Management process comprise the definition of the project scope; definition of project life cycle; evaluation of the project feasibility; definition, monitoring and adjustment of project activities, schedule as well as project estimates and resources; assurance of required skills, knowledge and experience within the project team; setting up the project interface; management of risks; assurance of consistency; writing the documentation including the project plan, schedule, work breakdown structure, list of stakeholders etc.; reviewing and reporting the progress.

The Project Acquisition represents processes of ASPICE Acquisition Process Group aiming to support external (with the involvement of third-party supplier outside the organisation) as well as internal (between subsidiaries and different departments) customer-supplier cooperation and define the desired work product. It incorporates a definition of project requirements to ensure adequate planning and control of project activities; establishment of technical requirements determining functional and non-functional specification; definition of legal and administrative requirements; negotiation and approval of contract agreement; and supplier monitoring to continuously assess whether the agreed requirements are fulfilled.

The Requirements Specification represents defining processes from ASPICE System and Software Engineering Process Groups and comprises elicitation of desired stakeholder needs and requirements to set a basis for work product specification, and system and software requirements analysis to provide detailed system as well as software requirements specification.

The responsibilities for performing the management processes widely vary between the validation projects. The best-distributed responsibilities are in the first project with in-house development, where Project Management is performed by the project manager, Project Acquisition by technical project manager and Requirements Specification by two requirements engineers. In the second, there is project manager handling Project Management and two function owners performing Project Acquisition as well as Requirements Specification. In the third project, there is only one project manager responsible for all management processes.

Core Processes

The core processes represent validation activities performed by the EIA team, from which two test engineers are assigned to each project. It comprises Software and System Qualification Test processes, which are the last stages in the Software as well as System Engineering Process Groups of ASPICE. The main focus of EIA team is given to Software Qualification Test process providing evidence about the compliance of embedded software integrated into ECU (based on the software testing primarily performed on ECU HiL test benches) with specified software requirements. On the contrary, EIA team holds only minor role in the System Qualification Test process and rather provides support to the customer, which performs test drives to provide evidence that ADAS integrated into a vehicle complies with specified system requirements. The structure of these two processes is in general very similar and varies only in the level of details. Since the primary concern of the EIA team is the Software Qualification Test process, it is therefore further described in detail in section 3.2.2.

Support Processes

The support processes provide independent and objective assurance that development processes and their products comply with quality and functional safety policies. Each validation project should, therefore, have a quality manager to be responsible for the Quality Management process as well as a functional safety manager to handle responsibilities related to the Functional Safety process. A quality manager is a process owner of previously described processes and provides support to the project team regarding the methods and base practices based on ASPICE. Functional safety manager coordinates the development of ADAS according to ISO 26262 standard, develops safety concepts, specifies safety requirements and carries out safety analysis activities. The activities performed by the quality and functional safety managers enable to handle the validation projects with better quality and safe approach. However, in the currently ongoing ADAS validation projects handled by the EIA team, just the first project has only quality manager and the second project only functional safety manager.

3.2.2. Software Qualification Test Process

The Software Qualification Test process represents the main workload for the EIA team and its objective is to ensure that the software of ADAS integrated into ECU meets specified software requirements. The process details and description of Software Qualification Test procedure are presented next.

Process Details

Process owner	Quality manager
Process performer	Two test engineers
Inputs	Projects plan Release plan Software requirements Integrated software
Outputs	Test plan Test specification Test result Review and traceability record Communication record
Resources	ECU HiL test bench Real-time testing SW Traffic and environment simulation SW

Software Qualification Test Procedure

The procedure of Software Qualification Test is based on the base practices of ASPICE and its scheme is shown in Figure 3.8. Even though the procedure represents a sequence of activities, iterations may occur in the procedure since the software requirements can change during the validation process. The individual activities are further described.

Develop software qualification test strategy

The software qualification test strategy is developed with regards to the customer's release plan and project plan provided by a project manager. The strategy should include a regression test strategy for re-testing in the case that the software requirements either integrated software are changed over time. The software qualification test strategy is documented in the test plan.

Develop specification for software qualification test

The specification for software qualification test is developed according to the software qualification test strategy and software requirements provided by the requirements engineer or function owner. It includes the development of test cases in the form of logical scenarios based on the verification criteria.

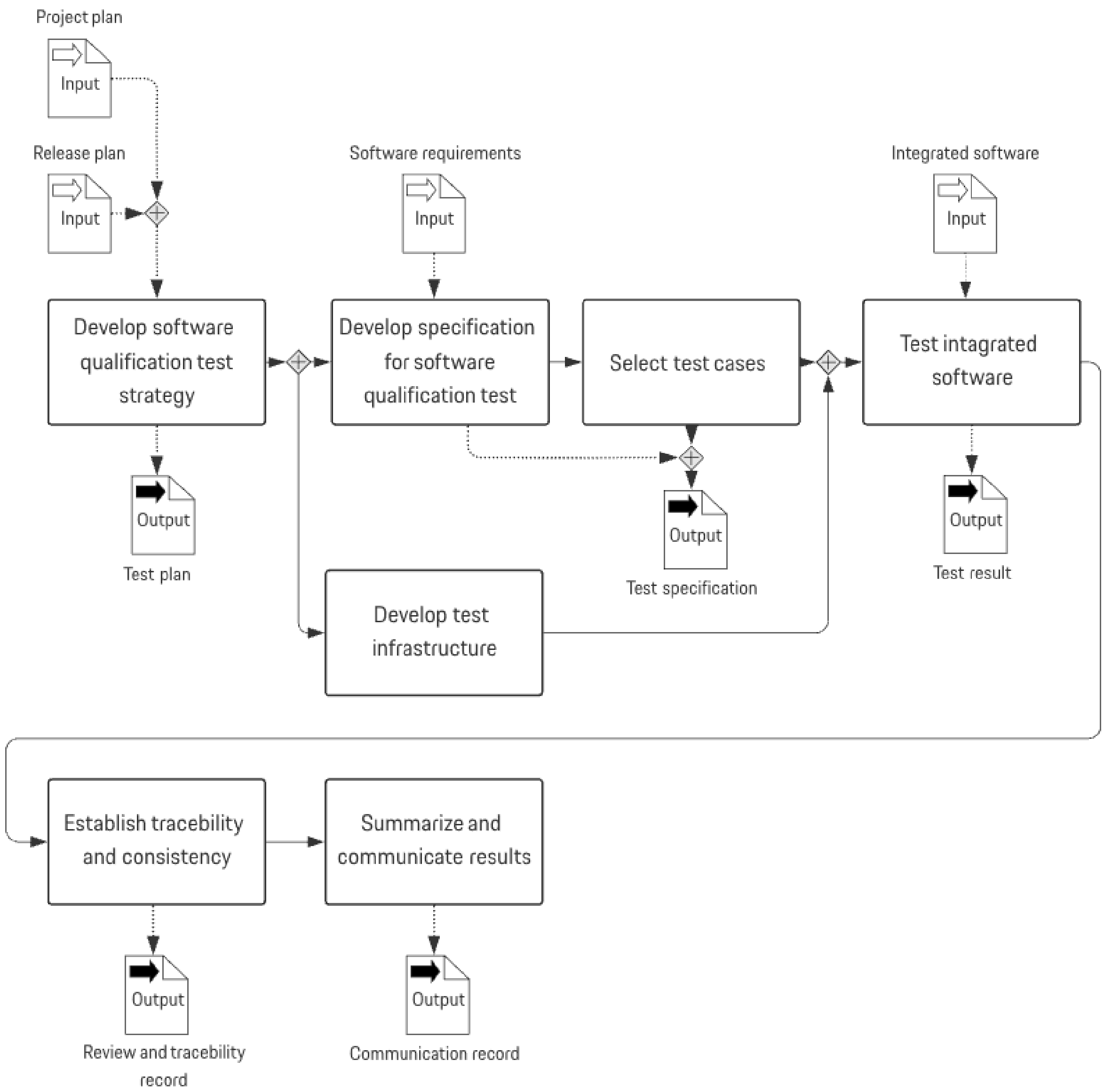


Figure 3.8: Software Qualification Test Procedure

Select test cases

The selection of test cases comprises the implementation of a set of parameters transforming logical scenarios into executable concrete scenarios, which should have sufficient coverage to demonstrate compliance of tested software with the software requirements.

Develop test infrastructure

Development of test infrastructure is a complementary activity to the actual qualification test procedure. It includes development of ECU HiL test bench and configuration of the software environment for the execution of the tests. The development of ECU HiL test bench could be also outsourced.

Test integrated software

The selected test cases are executed on the ECU HiL test bench to test the integrated software delivered by a supplier or internal development team. The output logs are documented in the test result.

Establish traceability and consistency

There should be established bidirectional traceability and consistency between the software requirements, test cases included in the test specification and software qualification test results. It should be documented in the review and traceability record.

Summarize and communicate results

The software qualification test results are summarized and communicated to the involved stakeholders so they can determine consequences. The communication with stakeholders should be backed up in the communication record.

3.3. Analysis of Current Validation Process

In this section, the current validation process of ADAS at the company is analysed based on the assumed validation aspects (which are specified in the next section) of more advanced ADAS and ADS coming to the market in the foreseeable future. This analysis serves as a starting point for the proposal of the innovated validation process.

3.3.1. Assumptions about the Future Aspects of ADS Validation

Even though, the current validation process suits well for currently ongoing projects focused on validation of ADAS functions such as automated parking assistant or adaptive cruise control, it might soon face new challenges. The assumptions about the future aspects of ADS validation are therefore specified to be able to analyse shortcomings of the current validation process with regards to the future outlook. The further presented assumptions are based on the findings presented in the analytical part and take into account 5 years horizon.

- There will be required much broader scope of testing since advanced ADS will be highly dependent on environmental perception and usage of artificial intelligence, which will allow them to cope with much more complex situations. (See section 1.2.)

- The operational design domain of ADS will be evolving continually and ADS software will need to be regularly upgraded through the OTA updates even after the deployment of vehicles to the market. (See section 2.1.5.)

- ADS will use uniform software architecture and will operate on standard vehicle operating system “vw.os”. Most of that software will be developed inside Volkswagen AG. (See section 3.1.4.)

3.3.2. Inconsistencies between Future Aspects of ADS Validation and Current Validation Process

There can be found several inconsistencies between assumed future aspects of ADS validation specified in the previous section and current validation process. In currently ongoing projects, there have been needed hundreds of test cases to ensure that the integrated ADAS software meets specified software requirements and these test cases have been executed mostly manually. However, the number of required test cases can easily increase to thousands and even millions with upcoming ADAS and ADS based in greater extent on environmental perception and artificial intelligence. For this reason, it will not be feasible to execute all the test cases manually anymore and it will be therefore necessary to execute the tests with usage of test automation. This will get even more apparent, if we assume that testing will need to be executed on weekly or even daily basis, because of continuous OTA updates of ADAS and ADS software aiming to react on the evolving specification of operational design domain.

From the organizational point of view, it seems to be unsustainable to further continue with current organizational project structure, where are two test engineers assigned to projects with fixed scope lasting about one to two years. It leads to very uneven utilization of working capacity, especially in initial project phases, when there are not available any requirements and it is therefore difficult to work on test specification. Besides that, test engineers need to face various activities, which require different skills. It can be beneficial for engineer’s professional development if he can handle the development of test specification and scenarios, development of test infrastructure as well as execution of tests and communication of results, but it is not very productive and it can get even impossible in a large scale. It might be therefore beneficial to adopt agile methodology and distribute the development activities resulting from continuously evolving operational design domain across complete EIA team (where team members would specialize on certain type of activities) using a product and sprint backlogs, which could bring better utilization of working capacity in the team. This would require to break down all activities into the smallest possible pieces, link their continuity and also to work with unified development interface.

However, there is not any unified development interface or test infrastructure in the present and every project, therefore, need to develop its own one purpose interface, which must be compatible with certain input format of integrated ADAS software delivered by various suppliers. Considering the assumptions that future ADAS and ADS will use uniform software architecture and will operate on standard vehicle operating system "vw.os", the implementation of unified development interface and test infrastructure would lead to better overall quality and shorter validation times. Moreover, the unified development interface and test infrastructure might be used along all validation cycle from SiL simulations to test drives, since it is assumed that the software will be developed mostly internally.

Another shortcoming can be seen in the creation of test scenarios. Even though the scenario-based testing have already been used in first projects at PES, the creation of scenarios is currently based on traditional text-based requirements, which are often unclear and very extensive for a description of operational design domain. This will get even worse with the increasing complexity of operational design domain of upcoming ADAS and ADS. It might be beneficial to use scenarios directly as a cornerstone specifying operational design domain according to legislative requirements and data collected from real-world traffic. Traditional requirements could be therefore directly linked to the scenario database and could serve just for the specification of parameters of certain vehicle configuration. The executable test cases could be then generated from specified parameters and scenarios contained in the scenario database. Moreover, since SOTIF is not currently actively used at PES, its practices should be incorporated into a process of creation and maintenance of operational design domain.

3.4. Concept Proposal of the Innovated Validation Process

This section presents the concept proposal of the innovated validation process of ADAS and ADS at PES. The concept proposal aims to overcome the shortcomings of the current validation process presented in the previous section. These shortcomings are next transformed into requirements on the innovated validation process.

3.4.1. Requirements on the Innovated Validation Process

- The generation and execution of test cases should be automated.
- There should be established unified development interface and infrastructure for complete validation cycle.
- The organizational structure of validation activities should be based on agile methodology.
- The scenario-based specification should become a cornerstone of operational design domain requirements.
- The SOTIF practices should be used for the development of operational design domain.

3.4.2. Proposal of Innovated Organizational Structure

Since the current model of project-driven development with fixed desired outcomes at the beginning of the project is not suitable for a dynamic development environment, there must first come major organizational change to be able to handle the development of ADAS and ADS capable to adapt to ever-evolving operational design domain. On behalf of that, it would be beneficial to transition to product-oriented operating model enabling better agility.

The shift to the product-oriented development targets several behavioural changes. Instead of focusing on detailed planning in advance, it pursues principles of agile methodology and a value-driven approach reflecting actual demand. It means that new items are continuously added to a product backlog and then scheduled for sprints according to relative business priority. It is also important that end-user is regularly involved in validation activities, e.g. ViL testing or test drives, so his feedback can be gathered at every sprint and not just at the end of a project. Regarding the product teams, they should be dedicated to their products for the complete life cycle from prototype development to work on continuous upgrades after release. It means that the team should be funded annually based on a strategic agreement and not just a project contract. This would also elevate the role of PES from service provider to business partner. The transition to product-oriented development has the potential to improve collaboration, agility and mainly ability to develop better ADAS and ADS. [62]

The innovated organizational structure following the principles of product-oriented development is presented in Figure 3.9. The main difference in comparison with the project-oriented organizational structure in Figure 3.6 is that the product (function) teams are dedicated to certain ADAS or ADS function and are responsible for its integration into complete vehicle portfolio, which is expected to be feasible considering the assumption that the ADAS and ADS will use uniform software architecture. The individual function teams are managed by function owners and scrum master and comprise closely collaborating team members from different development domains. (Please, note that the number of teams, as well as team members, is just illustrative.) The team members from each development domain are further grouped into different development units supervised by technical leads and supported by subject matter experts. The stand-alone interface & infrastructure (I&I) team is responsible for development and maintenance of the unified development I&I shared by all function teams. The quality and functional safety managers are supporting the development process in a similar manner as in the current organizational structure. At the highest level, the top management roles are represented by the system owner, agile coach and technical manager. The processes performed by the teams and roles in the organizational structure are further described in the next section.

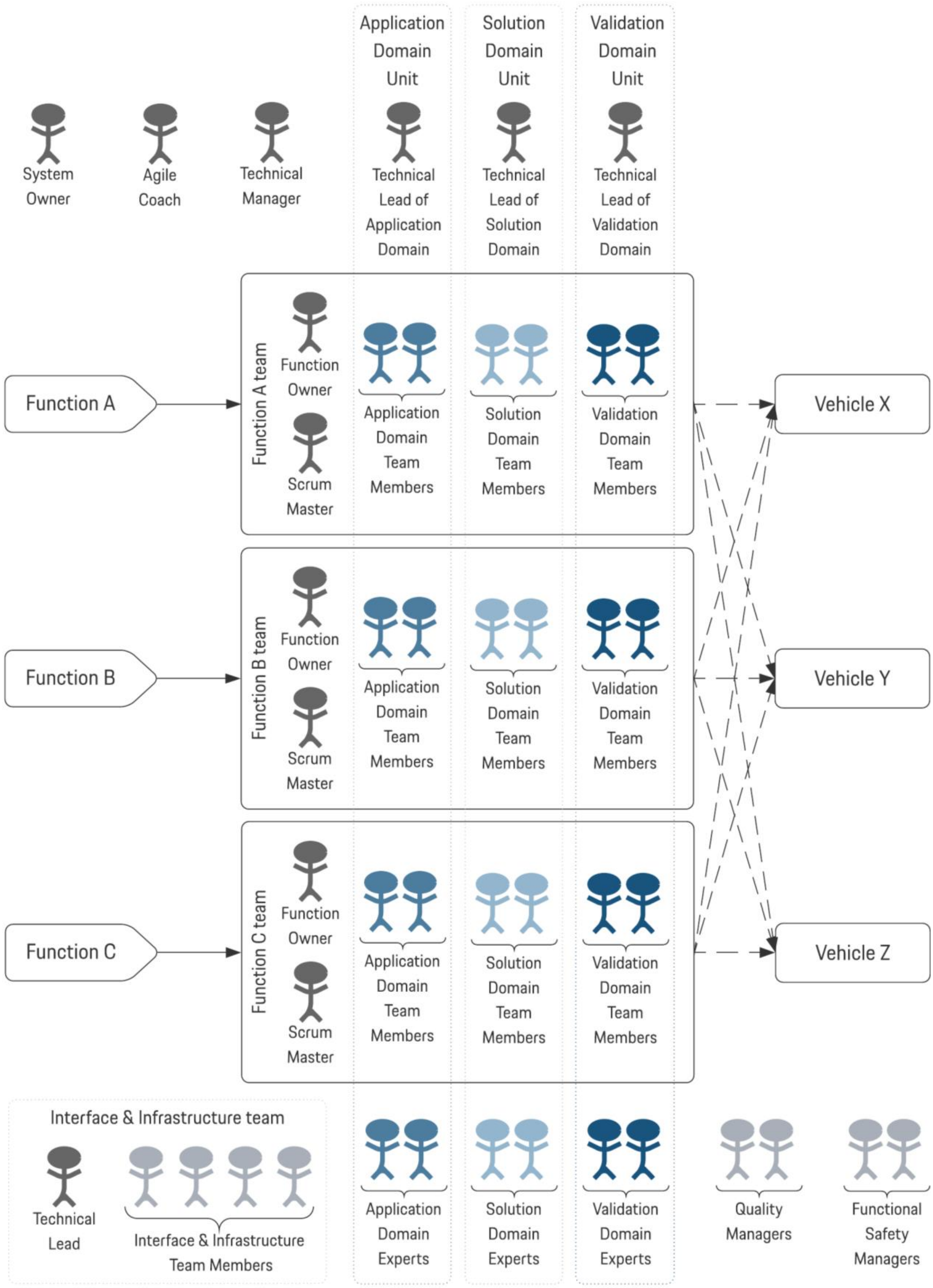


Figure 3.9: Proposed Innovated Organizational Structure

3.4.3. Proposal of Innovated Process Structure

The proposed innovated process map is presented in Figure 3.10 and reflects the requirements on the innovated validation process specified in section 3.4.1. The structure of the process map distinguishes management, core and support processes, whose scope is described next.

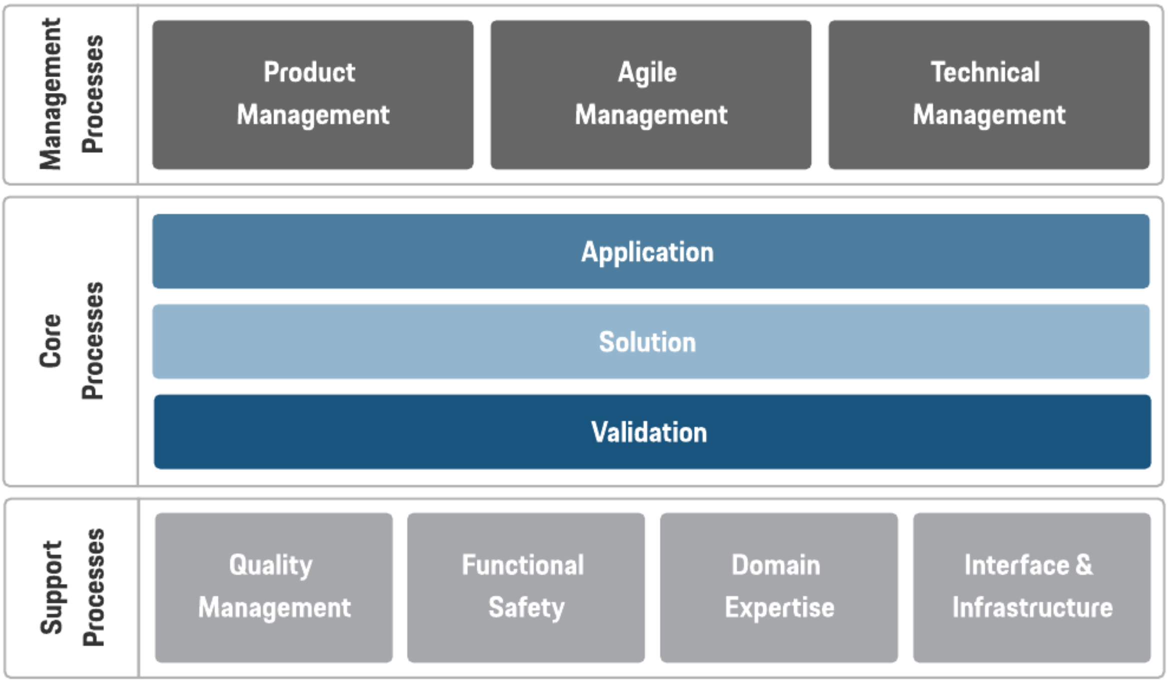


Figure 3.10: Proposed Innovated Process Map

Management Processes

The management processes include product, agile and technical management processes, which are further individually described. The managerial roles performing these processes are for better comprehensibility illustrated in Figure 3.11.

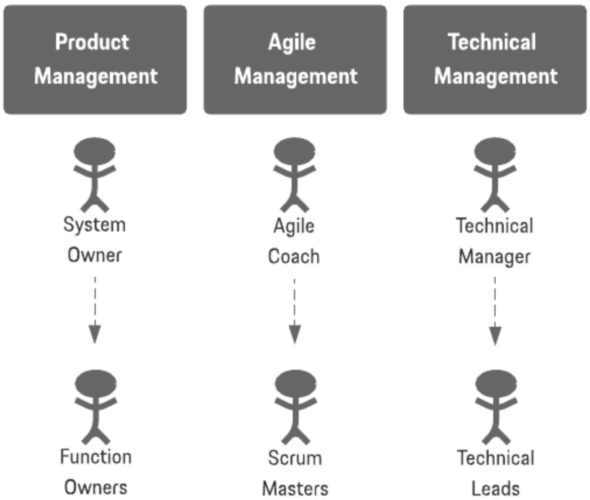


Figure 3.11: Managerial Roles

Product Management

The Product Management process aims to specify what and why is going to be developed. Function owners are responsible for the complete life cycle of certain ADAS or ADS functions from early specification to the product release as well as continuous maintenance and upgrades. Function owners need to acquire expectations of stakeholders and end-users, all requirements based on legislation and guidelines and translate them into the specification of work items to be added into the product backlog. The work items should create a work breakdown structure of interconnected and consecutive tasks with specified requirements and deadlines. Function owners need to closely communicate with scrum masters and development team members to make sure that everyone understands what needs to be developed. Function team members are also responsible for continuous acquisitions of customers' feedback on developed features to ensure they meet customers' expectations. System owner is then responsible for the integration of individual functions into complete ADAS or ADS, represents the role of Product Management process owner and works closely with function owners to ensure that development of all functions is aligned with product strategy.

Agile Management

The purpose of the Agile Management process is to facilitate agile methodology in the development processes. This process comprises a wide range of activities performed by scrum masters and agile coach. Scrum masters are responsible for sprint planning, organization of daily scrums and sprint reviews, and guiding the development team members and function owners in the usage of agile practices and tools. Agile coach, who is the process owner of the Agile Management process, facilitates the structure of agile teams, supports technical leads in the integration of agile principles into individual development processes, coaches agile teams in the agile methodology, collaborates closely with scrum masters on the establishment of agile culture, and pursues continuous improvement.

Technical Management

Technical Management process aims to manage individual development processes, establish standardized procedures and ensure their continuous improvement. The responsibility of technical leads is to manage individual development processes, ensure necessary resources for development activities, organize meetings with development unit members to identify opportunities for process improvement, and support development unit members in their professional development. Technical manager owns the Technical Management process, collaborates with technical leads on a definition of process metrics of individual development processes, and cooperates with system owner and agile coach to identify possible bottlenecks in the development processes.

Core Processes

There were applied three major modifications to the structure of core processes in comparison to the current process map in Figure 3.7. First of all, based on the triangle model proposed in ENABLE-S3 project shown in Figure 2.21, the application domain was implemented alongside to the validation process in order to establish scenario-based specification as a cornerstone defining operational design domain, and to unify and streamline the procedure of test strategy and test specification development. Secondly, the solution domain representing software development process was added next to the application and validation domain processes to enable close collaboration between all function team members as it is illustrated in Figure 3.9 and to facilitate factual agile operation. This should be feasible considering the assumption that software will be developed mostly internally. Thirdly, the core processes comprise the complete validation cycle from SiL testing to test drives to streamline the validation process. The core processes, therefore, include three closely interconnected development processes, which are described in detail in section 3.4.4.

Support Processes

The support processes include on top of Quality Management and Functional Safety processes, which are already present in the current process map, also Domain Expertise and Interface & Infrastructure processes. The scope of these processes is described next.

Quality Management

The Quality Management process owned and performed by quality managers aims to define quality strategy, policies and guidelines prescribing the requirements on documentation of processes in the innovated process map. The responsibility of quality managers is not to own individual managerial, core as well as support processes, but to provide support to management representatives and technical leads who own these processes to establish, document and maintain their processes. All these processes should have prescribed process performance metrics to enable their monitoring. The quality manager should also assure that all processes are properly documented, comply with required standards and are continuously improved.

Functional Safety

The purpose of the Functional Safety process remains similar to the present one. The aim is to provide independent and objective assurance that all development processes and their products comply with functional safety policies. The responsibility of functional safety manager, who is the owner of this process, is to develop safety concepts, specify safety requirements, carry out safety analysis activities and assure that development processes comply with ISO 26262 standard. He should also promote functional safety culture across the company.

Domain Expertise

The Domain Expertise processes are owned by technical leads and performed by subject matter experts from different development domain units. These processes are complementary to individual development processes and aim to provide a unified approach in the identification and implementation of new methods into the development processes. SMEs should regularly review the development process with development team members and technical leads to identify its possible shortcomings, actively search for state-of-the-art methods and pursue their implementation to continuously improve the development process. SMEs should also collaborate with I&I team on tasks related to the development and maintenance of the development I&I.

There should be covered various domain-specific expertise by SMEs. In the application domain unit, there should be experts on SOTIF, scenario-based specification, legislation and relevant standards, definition of assessment metrics, and statistic methods such as design of experiments. The solution domain experts might be experts in image processing, artificial intelligence, control engineering, embedded software, etc. The validation domain unit should comprise experts on software testing, test automation, XiL testing methods, and simulations.

Interface & Infrastructure

The purpose of the Interface & Infrastructure process, which is performed by the I&I team and owned by its technical lead, is to develop, integrate and maintain the unified development I&I shared by all function teams. The operation of the I&I team should be based on agile methodology so the development or maintenance requests from subject matter experts of different development units could be added into the I&I product backlog and then processed based on the defined prioritization. The I&I team members should also ensure that the development I&I is properly documented.

The I&I itself comprise development interface, test infrastructure and database infrastructure necessary for the development of ADAS and ADS. The detailed overview of individual components of the development I&I is shown in Figure 3.12.

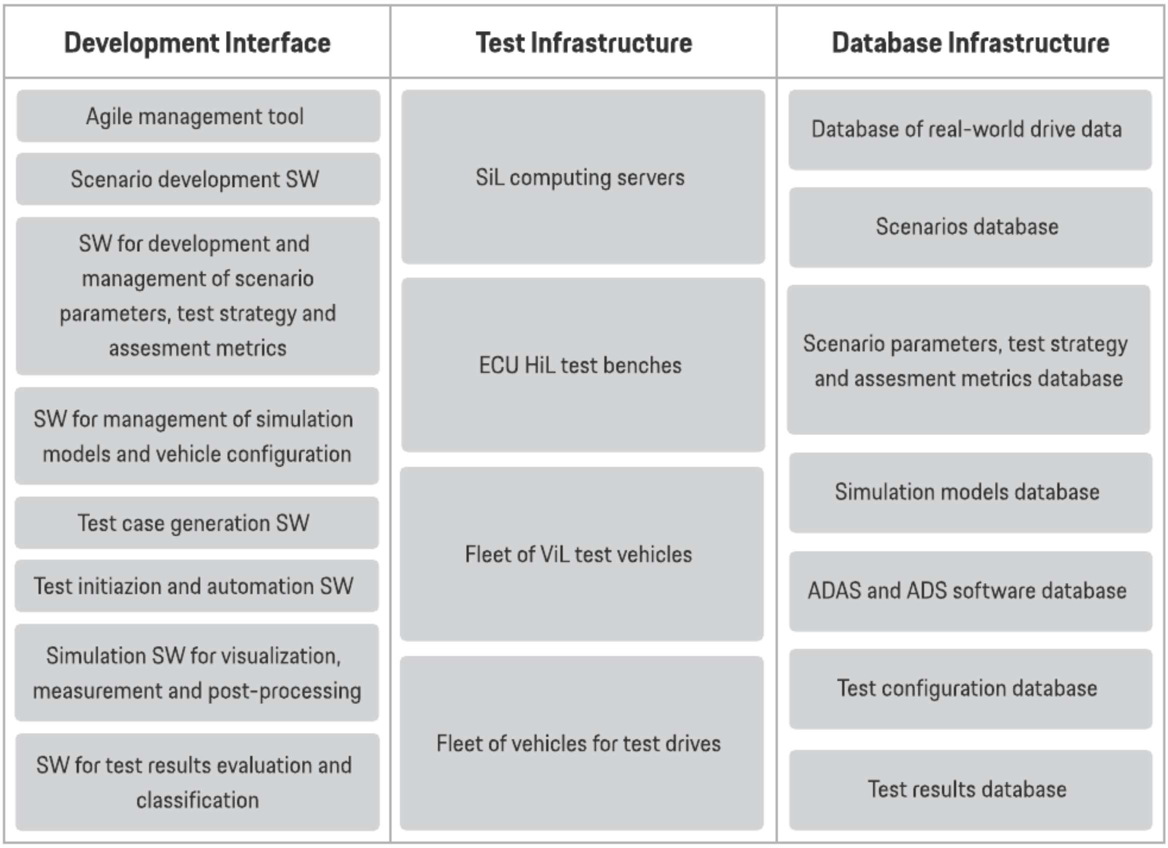


Figure 3.12: Components of Development Interface & Infrastructure

3.4.4. Proposal of Innovated Core Processes

The proposed innovated procedure of core processes is introduced in Figure 3.13. The procedure represents a sequential flow of activities leading to the completion of certain work item. The details of processes and descriptions of procedures of individual development domains are presented next.

Application Domain Process Details

Process owner	Technical lead of application domain
Process performer	Application domain team members
Inputs	Work item specification Laws and standards Real-world drive data
Outputs	Functional scenarios Logical scenarios Concrete scenarios Test strategy Assessment metrics and criteria

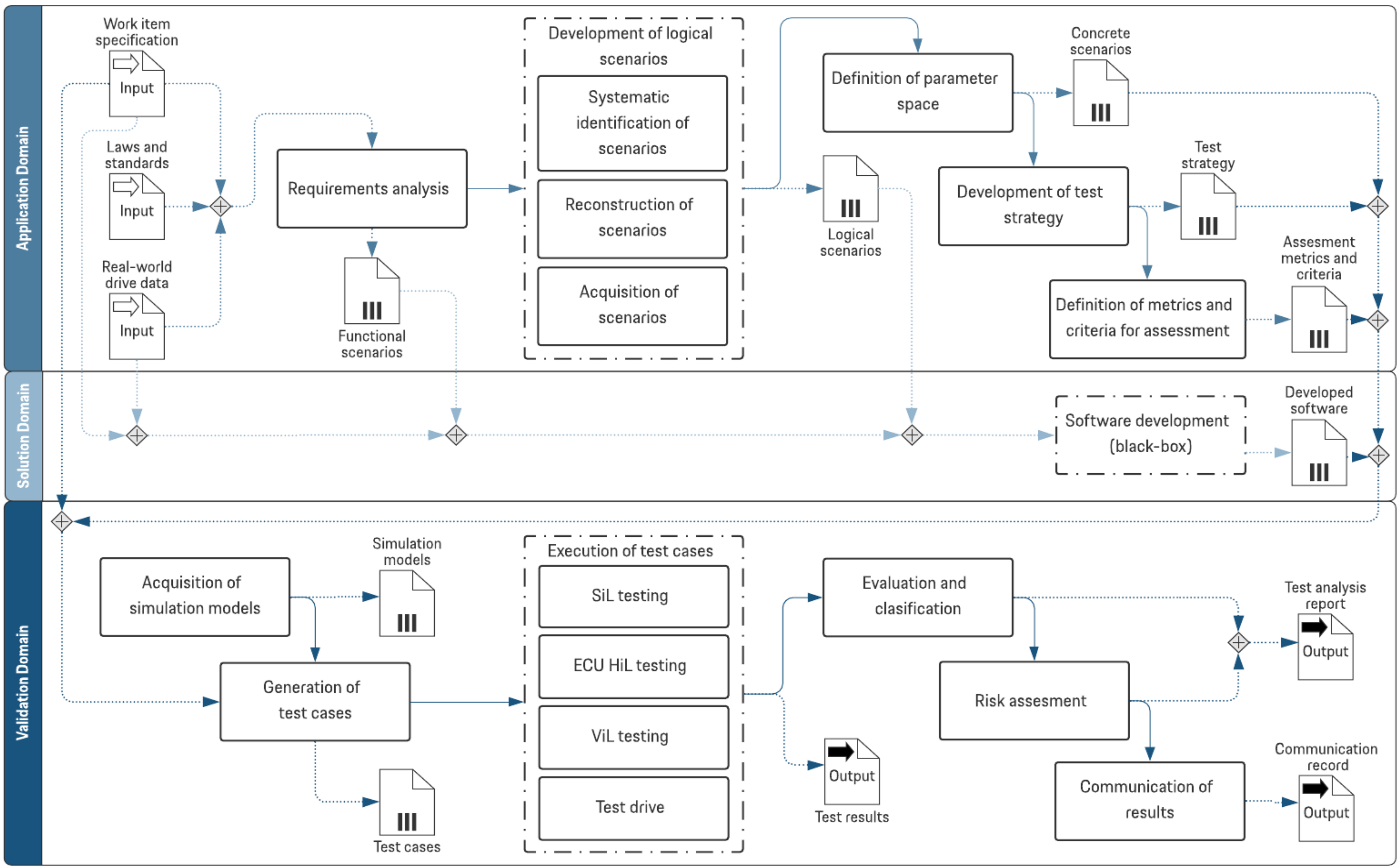


Figure 3.13: Innovated Procedure of Core Processes

Resources Agile management tool
Scenario development SW
SW for development and management of scenario parameters, test strategy and assessment metrics

Application Domain Procedure

Requirements analysis

Requirements analysis acquires knowledge from laws and regulations of countries where the ADAS or ADS should be released, relevant standards (ISO/PAS 21448 and ISO 26262) and real-world drive data to define functional scenarios based on the work item specification provided by function owner.

Development of logical scenarios

Logical scenarios can be developed in three different ways. They can be systematically identified based on the knowledge acquired in requirements analysis, reconstructed from real-world drive data (especially from crashes or corner cases) or acquired from a specialized provider.

Definition of parameter space

In this step, certain parameter values are defined to specify concrete scenarios, which must not be interpretable in a different way. There should be used statistical methods, e.g. design of experiments, to determine a set of scenarios, which would cover the space of all possible scenarios as efficiently and conclusively as possible.

Development of test strategy

The development of test strategy comprise definition of testing scope at individual testing stages from SiL testing (which is fastest and cheapest, but also less trustworthy) to test drives (which are most time-consuming and expensive, but most reliable). There should be therefore assigned all specified concrete scenarios for SiL testing and the number of assigned scenarios to be tested should decrease step by step such that only minimum of selectively chosen scenarios will get tested on test drives.

Definition of metrics and criteria for assessment

The evaluation metrics and pass/fail criteria to assess the performance of tested ADAS and ADS software are defined concerning the requirements of work item specification, laws and standards. As a result, the specified evaluation metrics and criteria should be linked to each concrete scenario.

Solution Domain Process Details

Process owner	Technical lead of solution domain
Process performer	Solution domain team members
Inputs	Work item specification Real-world drive data Functional scenarios Logical scenarios
Outputs	Developed software
Resources	Agile management tool SW development tools

Solution Domain Procedure

The solution domain comprise development of ADAS or ADS software, based on work item specification and defined scenarios. Real-world drive data can be used for training of algorithms. Since the solution domain is not the main area of interest in this thesis, the software development is considered as a black-box.

Validation Domain Process Details

Process owner	Technical lead of validation domain
Process performer	Validation domain team members
Inputs	Work item specification Concrete scenarios Test strategy Assessment metrics and criteria Developed software
Outputs	Simulation models Test cases Test results Test analysis report Communication record
Resources	Agile management tool SW for management of simulation models and vehicle configuration Test case generation SW Test initiation and automation SW

Simulation SW for visualization, measurement and post-processing

SW for test results evaluation and classification

SiL computing servers

ECU HiL test benches

Fleet of ViL test vehicles

Fleet of vehicles for test drives

Validation Domain Procedure

Acquisition of simulation models

The simulation models of a vehicle, to which the ADAS or ADS software is supposed to be integrated, need to be acquired for the purpose of SiL and ECU HiL testing. The simulation models need to correspond with certain vehicle configuration defined in the work item specification.

Generation of test cases

Once the concrete scenarios, test strategy, assessment metrics and criteria, developed software, and simulation models are available, complete set of executable test cases (or instructions in case of test drive) can be generated.

Execution of test cases

The testing of ADAS and ADS software can be done in four different ways based on the work item specification and test strategy depending at which phase the development process occurs. SiL testing, ECU HiL testing can be executed remotely on SiL computing servers or ECU HiL test benches respectively with the usage of the test initiation and automation SW. ViL testing and test drives take place on a test track and are performed by test drivers according to the generated sequence of test cases or test instructions.

Evaluation and classification

The test results are evaluated according to the defined assessment criteria and classified as passed, passed with a warning and failed. As a result, the test report is generated. The bidirectional traceability and consistency between test results, test cases and work item specification is guaranteed since the generation process is automated.

Risk assessment

The risk assessment determines whether the identified residual risks are acceptable with regards to SOTIF. The conclusions of risk assessment and recommendations regarding the ADAS or ADS software function release are documented in the test analysis report.

Communication of results

The validation results are communicated to the function development team and involved stakeholders. The communication should be backed up in the communication record.

3.5. Economic Evaluation of Benefits

In this section, the benefits, and to some extent also necessity, of proposed transformation of the validation process are evaluated. The focus is devoted to the implementation of unified development interface and infrastructure and adoption of agile methodology.

3.5.1. Benefits of Implementation of Unified Development Interface and Infrastructure

As it was already mentioned in section 1.2., it is not feasible to validate the correct functionality of ADAS and ADS just with the usage of test drives. Therefore, the scenario-based testing in combination with XiL approach is already widely used to validate the ADAS and ADS functionality effectively. However, as it was discussed in section 3.3.2., the validation of ADAS and ADS based in greater extent on environmental perception requires testing with the usage of extensive scenario database. The implementation of unified development interface and infrastructure enabling continuous integration and automated generation, execution and evaluation of test cases was therefore proposed to substitute manual execution of test cases currently used in PES on ADAS validation projects. The necessity of this implementation is justified on the example of SAE Level 2 motorway pilot.

In Figure 3.14, there are shown 6 basic functional scenarios describing operational design domain of SAE Level 2 motorway pilot, which assists the driver in given tasks. Considering that each functional scenario can account for 10 different traffic scenarios and

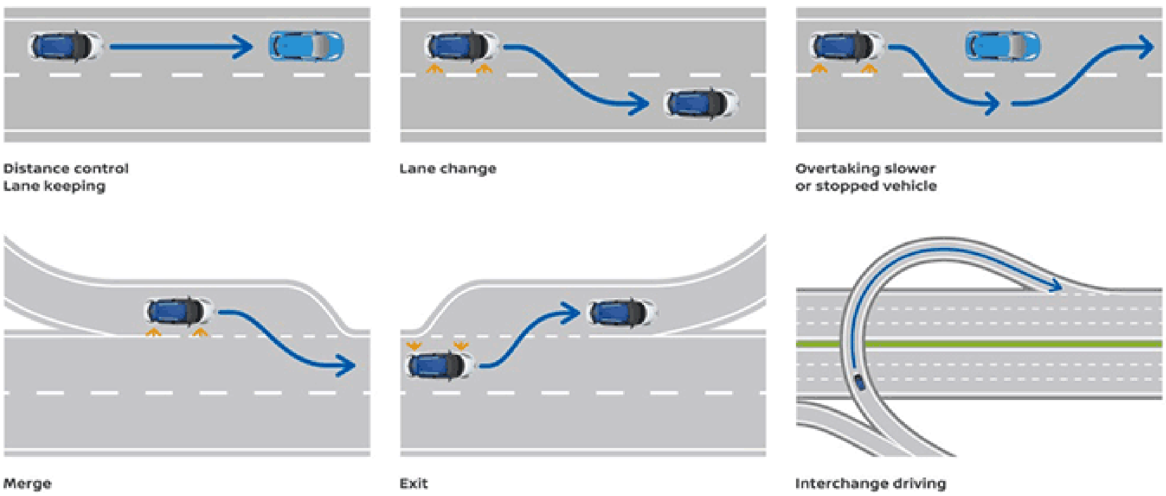


Figure 3.14: Piloted Drive Features [63]

10 different road configurations, there can be 100 logical scenarios per each functional scenario. Considering very optimistic estimation that each logical scenario can comprise 10 parameters (e.g. initial vehicle speed, speed of surrounding vehicles, initial distance from other vehicle, weather conditions etc.) and that for each parameter will be chosen 10 values from parameter space, there can be 100 concrete scenarios per each logical scenario. It means that there would be 60 thousand concrete scenarios representing the definition of the operational design domain. Considering, again very optimistically, that the motorway pilot software would be integrated into 3 different vehicles, where each of them would have 3 different configurations, there would be 540 thousand test cases, which would need to be executed to validate the correct functionality of motorway pilot. The estimation of the number of test cases is summarized in Table 3.1.

Table 3.2: Estimation of the Number of Test Cases

	6	functional scenarios
x	100	logical scenarios per each functional scenario
x	100	concrete scenarios per each logical scenario
=	**60 000**	**concrete scenarios in total**
x	3	different vehicles
x	3	vehicle configurations
=	**540 000**	**test cases in total**

Let’s assume that these test cases would be tested with the usage of SiL simulation and that each test case would be executed manually. Considering the time needed to prepare and execute the simulation 30 seconds and simulation time for each test case 5 seconds, it would take over 5 thousand hours of engineer’s productive time (almost 3 years spent at work). With the usage of engineer’s hourly labour cost (estimated in Appendix A), it can be obtained that 6.4 million CZK would be wasted only on labour cost and just one SiL testing.

Of course, that the estimations stated above are just hypothetical, but it clearly demonstrates the need for the usage of unified development interface and infrastructure enabling continuous integration and test automation. Even if the mentioned SiL simulation would be automated, there would be needed 100 parallel computational units to get a result of these 540 thousand test cases in 7.5 hours, which can be already considered as a reasonable time. Moreover, the SAE Level 3+ ADS, where it would need to be accounted for even more scenarios incorporating e.g. modifications of temporary construction sites or pedestrian detection, would require much more robust computational infrastructure.

3.5.2. Benefits of Adoption of Agile Methodology

The proposal of agile product-driven development conceivably represents the most significant change in comparison to the current project-driven approach. Possibly the greatest benefit of adoption of the agile approach is appropriately illustrated in Figure 3.15. In the current traditional approach, the requirements specification always strictly defines which features (as well as their desired quality) should be included in ADAS integrated into a vehicle. The release plan also specifies a time schedule according to the start of production and project plan defines cost items according to the allocated budget. However, during the development phase, complications usually occur, which is getting more and more common as the complexity of ADAS increases. As the deliveries are getting behind the schedule, the budget is operationally increasing to prevent late delivery. Moreover, the quality of features needs to be sometimes compromised to finish the integration on time. On the other hand, the agile approach based on continuous delivery does not strictly specifies ADAS features to be released beforehand. The releases are planned according to actual business priority with regards to available fixed resources. This approach is much more sustainable and enables to deliver ADAS features only if the desired quality is achieved. From the economic point of view, the resources can be better utilized and stable cash flow can be sustained. Moreover, potential increases in development cost can be based on strategical decisions rather than operational needs.

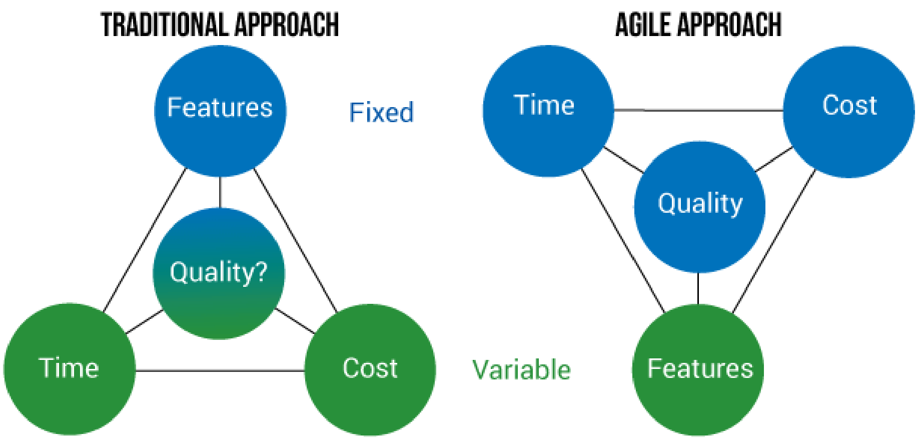


Figure 3.15: Comparison of Traditional and Agile Approach [64]

4. DISCUSSION ANS RECOMMENDATIONS

4.1. Discussion

The increased incorporation of ADAS and ADS into vehicles has potential to improve safety and comfort in our everyday life. It also represents a big business opportunity to car manufactures and mobility providers. It can be said that the development of ADAS and ADS can completely reshape the automotive industry. Nevertheless, automotive companies developing ADAS and ADS need to face big challenges, which require significant changes in established approaches. The proposed transformation of the validation process in this thesis is definitely significant and it would require not only big investments, but also enormous organizational effort from everyone involved. Strong leadership and teamwork will be a strong decisive factor of success.

Even though the innovation of the validation process of ADAS and ADS was primarily proposed for the purposes of PES, the applied principles could serve to other companies as well. Considering the ownership structure in Figure 3.3, it might be even beneficial for Volkswagen AG, if the development activities would be distributed throughout the Group. For example, from the financial point of view, it would make sense if Car.Software would take responsibility for the development of big part of unified development interface and infrastructure, scenarios, or ADAS and ADS software, which could be further shared by all companies in the Group.

In the analytical part, ASPICE was identified as a helpful standard providing process structure and methods to develop automotive software with high quality. Even though it does not bring any contradictions with the agile approach, there were found some friction points with the implementation of the application domain based on ENABLE-S3 project. Current version of ASPICE does not seem to be compatible with scenario-based specification. It might be therefore recommendable to imply some extension into ASPICE, which could bring better support to the development of software of ADAS and ADS based in greater extent on environmental perception.

4.2. Recommendations

This thesis can be foreseen as an initiator of further discussions and initiatives regarding the innovation of the validation process of ADAS and ADS at PES. There can be outlined several areas of future work (perhaps for another thesis assignments) on top of this thesis. It might be interesting to work out a detailed business case examining the feasibility of the proposed innovation of the validation process, which could serve, among other things, as a basis for discussion with Porsche Engineering Group GmbH and Dr.-Ing. h.c. F. Porsche AG. In [65], Stanglmeier presents a matrix-based analytical approach of economic assessment of virtual validation processes in the automotive development, which could fit for such evaluation. There could be also worked out detailed designs of each of the development domains in the innovated process map as well as the design of the unified development interface and infrastructure.

It would be appropriate to establish regular communication with Porsche Engineering Group GmbH and Dr.-Ing. h.c. F. Porsche AG to synchronize know-how and bidirectionally share experiences regarding the validation processes. It might be also beneficial to initiate communication with Car.Software to discuss possible cooperation and with Audi to possibly acquire their know-how and experiences regarding the "Artemis" project [66], which is a pilot project aiming to establish agile development processes for complete vehicle development and is expected to be a blueprint for future use throughout the Group.

Regarding the action that might be taken directly by the EIA team, it would be appropriate to initiate regular team meetings devoted to discussions about the validation processes. It might be furthermore beneficial to establish a working group, which would incorporate also software developers, quality and functional safety managers and could specify concrete action steps pursuing the proposed innovation of the validation process. One of the first steps could be the development of a unified test automation framework based on EXAM, for example. For this, there could be used experiences from other teams of Electronics Integration department, which have already been using test automation. Next, there might be established standardized structure of a scenario database or strategy to define assessment metrics and criteria. It is also important to continuously follow rapidly evolving trends in validation approaches and legislation updates.

From the very beginning of the implementation of changes, it should be pursued for continuous improvement of the validation processes as well as development interface and infrastructure. A concept of Kaizen and PDCA method can be used for the control of continuous improvement. It is important to define key performance indicators to measure the performance of processes. For example, it could be mean time to develop a concrete scenario, the number of SiL simulations per day, utilization rate of HiL test benches, daily executed test cases per employee, cost allocated to one execution of test case etc. In the end, even smallest everyday improvements will lead to big improvements in a long-term not only in the validation processes, but also in functionality of ADAS and ADS itself.

5. CONCLUSIONS

The aim of this thesis was to analyse managerial, process, technological and legislation aspects as well as current trends in the validation of ADAS and ADS, and based on that propose the concept of the innovated validation process of ADAS and ADS, at the company Porsche Engineering Services s.r.o., incorporating the state-of-the-art technological tools and effective managerial methodologies.

The analytical part based on the main research question *''Which methods need to be implemented to the validation process of ADAS and ADS to support their effective development?''* provides insight into the managerial, process, technological and legislation aspects of the validation of ADAS and ADS, and the current trends in the validation approaches. The acquired knowledge, which is summarized in section 2.5., serves as a basis for the proposal of the innovation of the validation process of ADAS and ADS.

The design part firstly introduces the company Porsche Engineering Services s.r.o. and its context. Afterwards, the current validation process of ADAS at the company is presented and analysed with regard to defined assumptions about the future aspects of ADS validation. The identified inconsistencies were further translated into the requirements on the innovated validation process. The concept proposal of the innovated validation process is based on agile product-driven development; implementation of unified development interface and infrastructure enabling continuous integration and test automation; implementation of application domain responsible for scenario-based specification; close collaboration with software developers from solution domain; and validation domain covering complete validation cycle from SiL testing to test drives. In the end, the benefits, and also necessity, of proposed innovation are evaluated.

Based on the conclusions above, it can be stated that the thesis objective was fulfilled. The outcomes of this thesis can be foreseen as an initiator of further discussions and initiatives regarding the innovation of the validation process of ADAS and ADS at Porsche Engineering Services s.r.o. I personally believe that the presented principles can become a cornerstone of further expansion of Porsche Engineering Services s.r.o. in the field of automated driving. Hopefully, it might bring some little contribution enabling to fasten the implementation of automated vehicles to the real-world, which could improve safety and comfort in our everyday life.

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NOMENCLATURE

ADS	Automated Driving Systems
ADAS	Advanced Driver Assistance Systems
ASIL	Automotive Safety Integrity Levels
ASPICE	Automotive Software Performance Improvement and Capability Determination
AV	Automated Vehicle
BPMN	Business Process Model and Notation
CFD	Computational Fluid Dynamics
ECU	Electronic Control Unit
EIA	Electrical Integration – ADAS and Vehicle Architecture
EXAM	EXtended Automation Method
FuSa	Functional Safety
FEM	Finite Element Method
GDP	Gross Domestic Product
GPS	Global Positioning System
HiL	Hardware-in-the-Loop
I&I	Interface & Infrastructure
LIDAR	Light Detection and Ranging
MiL	Model-in-the-Loop
OTA	Over the Air
PEGASUS	Project for the Establishment of Generally Accepted quality criteria, tools and methods as well as Scenarios and Situations
PDCA	Plan Do Check Act
PES	Porsche Engineering Services, s.r.o.
QMS	Quality Management System
SiL	Software-in-the-Loop
SME	Subject Matter Expert
SW	Software
UN	United Nations
ViL	Vehicle-in-the-Loop
VR	Virtual Reality
XiL	X-in-the-Loop

APPENDIX A: ESTIMATION OF ENGINEER'S HOURLY LABOUR COST

For the estimation of engineer's hourly labour cost at PES, the following formula is used

$$Hourly\ Labour\ Cost = \frac{\frac{Personal\ Cost + Allocated\ Overhead}{(1 - Estimated\ Internal\ Work\ Rate)}}{Capacity} \quad [CZK/hour],$$

where *personal cost* [CZK/month] is considered as a sum of average monthly salary increased for social and health insurance; *allocated overhead* [CZK/month] represents monthly selling, general and administrative expenses per employee; *internal work rate* [-] is an estimated rate of time devoted to internal meetings and administration; and *capacity* [hours/month] is an engineer's time spent at work per month.

Using the data from [58], the engineer's hourly labour cost can be obtained

$$Hourly\ Labour\ Cost = \frac{\frac{88004\ + 68138}{(1 - 0.2)}}{160} = \mathbf{1220\ [\boldsymbol{CZK/hour}]}$$

Please note that this is just estimate based on data from the publicly available annual report [58] and it does not reflect the actual amount used for internal purposes.