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System Approach to Manage R&D Validation Process of Advanced Driver-Assistance Systems

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Aim: Apply system thinking to optimize logistic chain for validation of advanced driver assistance systems in modern cars. Demonstrate how even Research & Development for ADAS in cars can benefit from lean manufacturing methods

Content areas:

1. Research on ADAS validation, system thinking, one-piece flow, pull method
2. Description of ADAS validation chain to which will be applied system thinking and selected lean manufacturing methods. Identified its subsystems targets
3. Application of system thinking to design an optimal logistic chain for validation. Application of selected lean manufacturing methods. Results comparison with the original state

Length of thesis: 55 – 65 stran

Recommended literature:

1. LIKER, J. *The Toyota way: 14 management principles.* London: McGraw-Hill, 2004.
2. HOLMAN, D. – WICHER, P. – LENORT, R. – DOLEJŠOVÁ, V. – STAŠ, D. – GIURGIU, I. Sustainable Logistics Management in the 21st Century Requires Wholeness Systems Thinking. *Sustainability.* 2018. v. 10, no. 12, p. 1–26. ISSN 2071-1050.
3. WASCHL, H. – KOLMANOVSKY, I. – WILLEMS, F. *Control Strategies for Advanced Driver Assistance Systems and Autonomous Driving Functions: Development, Testing and Verification.* Cham: Springer International Publishing, 2019.
4. MCKEY, Z. *Think in systems: complexity made simple: the theory and practice of strategic planning, problem solving, and creating lasting results.* CA: CreateSpace Independent Publishing Platform, 2018.
5. MYERSON, P. *Lean supply chain and logistics management.* New York: McGraw-Hill, 2012.

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Mladá Boleslav, date ....

Hereby I would like to thank Ing. David Holman, Ph.D. for his helpful comments and valuable contribution, which he gave me when supervising my Master´s Thesis.

Contents

Acronyms

ACC	Adaptive Cruise Control
ADAS	Advanced Driver Assistance Systems
AEB	Active Emergency Braking
CPU	Central Processing Unit
EU	Europe Union
ETC.	Et Cetera
HIL	Hardware In the Loop
KPI	Key Performance Indicator
LIDAR	Light Imaging Detection And Ranging
R&D	Research & Development
SIL	Software In the Loop
SW	Software
USA	United States of America
VW	Volkswagen

Introduction

Progress in Advanced Driver Assistance Systems or shortly ADAS is today one of the main drivers of innovations in the automotive industry.

Research & Development of ADAS systems and especially its validation represents a strategic issue since those systems directly intervene in driving and are becoming increasingly widespread in todays cars. This represents for the automotive business an important challenge. Human lifes are at stakes. At the same time validation process of ADAS is very painful in terms of time to deliver, costs and people resources.

The author sees in ADAS validation process many similarities with manufacturing. The main diploma thesis goal is to show how system approach and lean manufacturing methods can be applied even in R&D so customer can get ADAS system for their car validated and thus delivered faster, cheaper and with better quality.

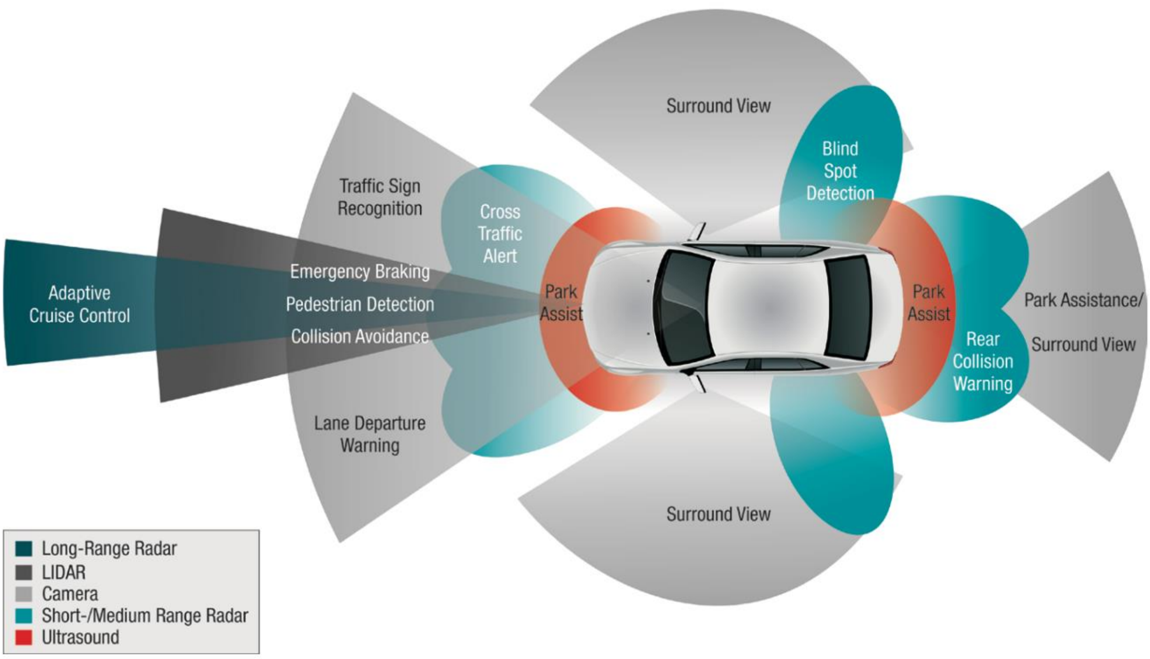
In the first section is presented ADAS validation background together with research on suitable methods to be applied. In the second section is presented concrete ADAS validation project that will be optimized with selected methods. Since the thesis is theoretical without disclosing sensitive information of any company, publicly avaible sources are used together with a few assumptions. The third section describes results after applying the selected methods. In the last fourth section are those results evaluated against defined KPIs.

1. Theory background

In this section one is presented relevant theory research. The theory will be either applied in the following sections to optimize validation chain or has an aim to provide reader with necessary understanding of ADAS business environment and its challenges that have influence on its validation chain, which optimal management is topic of this work.

1.1 Introduction into ADAS

ADAS stands for Advanced Driver Assistence Systems. While this thesis was written in 2019 where developing fully autonomous cars will still take some time, today cars are being equipped with Advanced Driver Assistence Systems which represents the first step toward autonomous driving. In the figure 1 are visualized typical ADAS systems and which sensors they use.



Source: https://www.embedded-vision.com/industry-analysis/technical-articles/ti-vision-sdk-optimized-vision-libraries-adas-systems

Figure 1 Example of ADAS systems

ADAS is an umbrella term for different systems assisting a driver with driving. Can be as simple as passive parking assistance where rear ultrasonic sensors watch distance from an obstacle and driver is informed in form of beap sound about that distance. Or more complex like ACC (Adaptive Cruise Control) that holds certain speed / distance from a vehicle ahead. This system system directly interferes into the driving (Robert Bosch GmbH, 2014, p. 1202).

Validation of those systems is an utmost importance. ADAS systems interfere into driving and consequences when system misbehaves can be fatal for the driver and his surrounding.

Let’s take for example AEB (Active Emergency Braking) displayed in action in the figure 2. The purpose of AEB is to brake a car in a moment when an accident is otherwise unavoidable and avoid or at least mittigate the crash consequences. That system significantly improves safety and saves lifes when for example a driver does not look on the road and a pedestrian jumps in front of the car. Or a car in front of you starts suddenly braking. However, imagine that this system brakes when it should not. Imagine you drive on a highway in 130 km/h and this system accidentally brakes your car. With cars directly behind you on the highway consequences would be fatal.

Source: https://paultan.org/2015/05/14/autonomous-emergency-braking-reduces-collisions-euro-ncap-ancap/

Figure 2 Active Emergency Braking system in action

1.2 Introduction into System Thinking

System thinking is about seeing and optimizing a whole instead of just focusing on its elements.

As described in the article *Sustainable Logistics Management in the 21st Century Requires Wholeness Systems Thinking*: „Systems thinking consists of analysis and synthesis. Analysis focuses on structure. It reveals how things work. Synthesis focuses on function which reveals why things operate as they do. It does not mean that synthesis is more valuable than analysis. It means that they are complementary. Analysis looks into the system; synthesis looks outward to consider the systems environment. Both views assessing the system's understanding and development have the same importance" (Holman et al., 2018, p. 26).

Donella H. Meadows defines in her book *Thinking in Systems* system as "an interconnected set of elements that is coherently organized in a way that achieves something" (Meadows, Wright, 2015, p. 11).

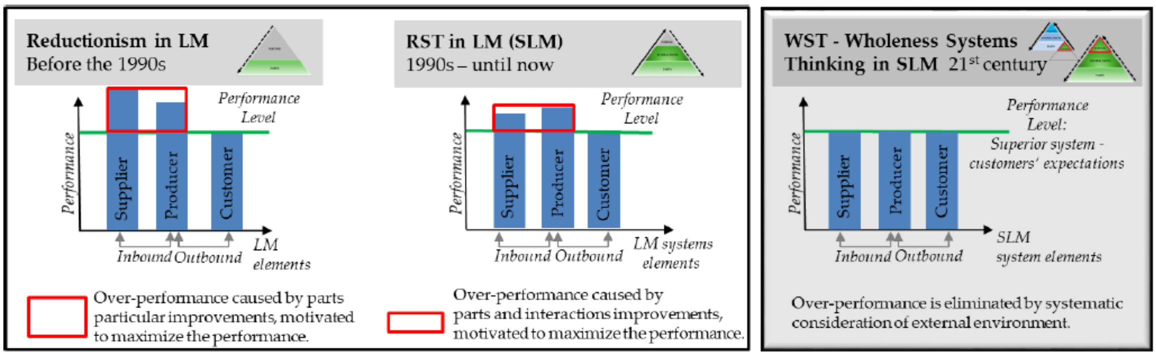
Each system consists of three parts:

1. Elements,
2. Interconnections,
3. Function or purpose.

Elements are in this work subprocesses of ADAS validation chain described below in the chapter 2. For example, data recording, data labeling, validation. Interconnections are how those elements interact between each other. How data are transported. Function or purpose is then the most important system aspect bringing its parts to a commond goal which will be identified in the section 3.

System thinking is in the strong contrast with reductionism, where reductionism focus on maximum economic performance of specific parts or departments instead of the whole. Before the 1990s, reductionism was the norm in the business environment. Focus was to decompose business into individual parts and maximize their performance while minimizing their costs. Reductionism was successful in increasing efficiency of production process till 1990s. In 1990s IT systems as MRP and ERP were implemented and allowed to focus not only on optimization of individual parts, but too on optimization of interactions between them. Reductionism was replaced by system thinking, described as Reductionism System Thinking (RTS) since it still ignores the purpose of the system. RTS understands the system as collection of its parts and interactions. Parts here cannot be understood without reference to the whole. The whole is greater than the sum of its part.

However, RTS approach is not the best in responding in today increasing speed and scope of changes and leads often to overconsumption of resources from the wholeness perspective. Optimal performance should be based on customer expectations and from that expectations should be derived its parts performance with their interactions. That's why authors of *Sustainable Logistics Management in the 21st Century Requires Wholeness Systems Thinking* define the new system thinking approach called as *Wholeness System Thinking (WST)* taking into consideration system purpose.



Source: Holman et al., 2018, p. 5.

Figure 3 Development of the reductionism and system thinking approaches connected with logistic management performance

As you can see in the figure 3 we can distinguish three main approaches in logistic management

- Reductionism – claims that system is defined by sum of its parts. Aim of reductionism is to maximize performance of individual parts. Assumption is that by doing so will maximize even the system performance.
- Reductionism system thinking (RST) – claims that system is defined by sum of its parts and their interaction. Aim of RST is to maximize performance of individual parts and optimize its interaction. Assumption is that doing so will maximize even the system performance.
- Wholeness system thinking (WST) – claims that system is defined primary by its purpose and that system is more than sum of its parts. Aim of WST is to synthetize its purpose and requirements for its performance from the superior system (in the figure 3 represented by customer expectations).

To achieve optimal performance and consumption of resources for a given system one must systematically identify purpose of the superior system. In the contrast, reductionism focuses on particular parts, concrete departments which are then motivated to reach a maximum profit and minimum unit costs. Although this maximizes that department performance, it can jeopardize performance regarding to system purpose. The system purpose is one that none of its parts have. Any part influences the system purpose and the system purpose influences each of its parts.

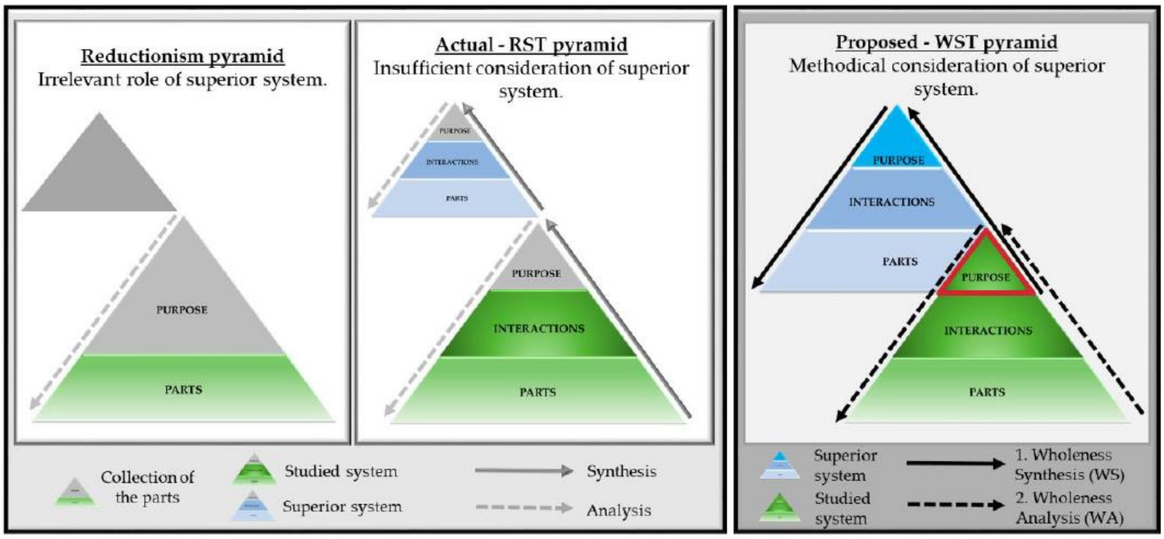
WST approach starts with understanding the system in relationship to the superior system and those steps should be followed:

1. Identifying the superior system
2. Understanding the superior system
3. Identifying the purpose of the studied system in the superior system

The third step translates influence of external environment into appropriate performance of the system.

When the purpose of the studied system in the superior system is identified, analysis of the system should be followed in those steps:

1. Take system apart and analyze its elements from the system purpose perspective
2. Understand each part separately
3. Agregate understanding of its parts and interactions into understanding of the whole system



Source: Holman et al., 2018, p. 8.

Figure 4 Development of the system's purpose role in considering external environment represented by a superior system in reductionism and system thinking pyramid hierarchy

Desribed WST approach will be used in this work in the section 3 to optimize logistic chain for validation of ADAS systems. As highlighted in the figure 4 on the right, we will start from the beginning with the system purpose in the mind. Based on system purpose is then set required performance of system parts and their interaction, considering the role of an external environment – especially the customer.

1.3 Introduction into Supply Chain and Logistic Management

Since we in this diploma thesis optimize ADAS logistic validation chain, we need to define what logistic chain means.

Myerson uses the following definition of logistic chain and supply chain
"Supply chain management encompasses the planning and management of all activities involved in sourcing, procurement, conversion, and logistics management. It also includes the crucial components of coordination and collaboration with channel partners which can be suppliers, intermediaries, third-party service provides, and customers." (Myerson, 2012, p. 287)

In another words, Myerson defines logistic as part of supply chain. If we optimize transport time of data from place A to place B, then we optimized logistic chain. In contrast, when we optimize transport of information containing what goods needs to be produced and transported and what goods not, then it's according to Myerson not optimization of logistic chain, rather optimization of higher level called supply chain. However, for purposes of this diploma thesis we will consider both cases to be simply part of logistic chain and will use this term for the rest of the thesis.

To improve logistic chain companies has the following options:

1. Focus on adding value from customer perspective. Could be faster response, faster delivery.
2. Focus on reducing non-value-added activities and inventory reduction

(Myerson, 2012)

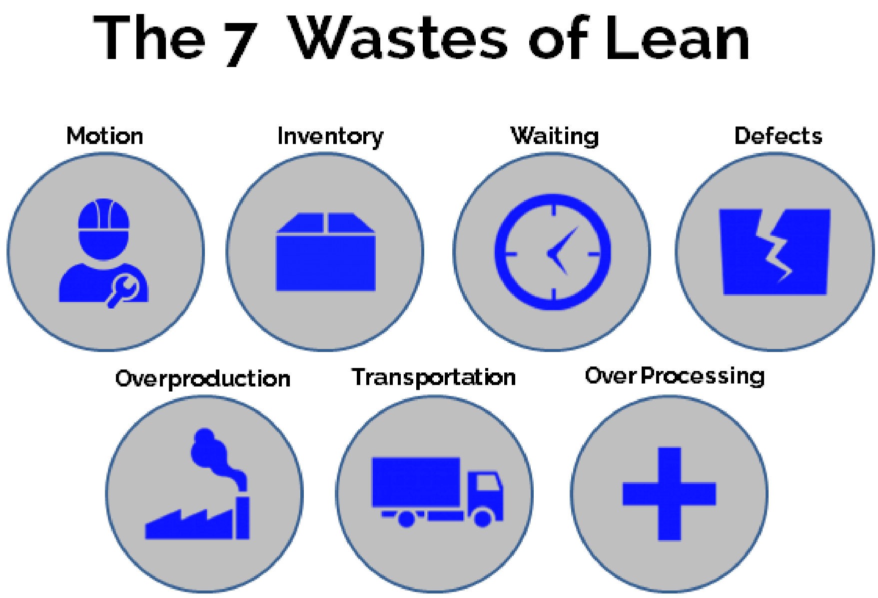
1.4 Introduction into Lean Manufacturing Methods

Lean manufacturing is management philosophy derivered from the Toyota Production System. The goal of the lean manufacturing is continuous improvement that focuses on identifying and eliminating waste. Waste is non-value-added activity from customer perspective.

Both *Liker* in his book *The Toyota Way* and *Paul Myerson* in his book *Lean Supply Chain and Logistics Management* defines eight types of waste that are visualized in the figure 5.

1. Inventory Waste
   Inventory waste is caused by extensive inventory. Inventory costs money to be produced, to be stored, to be transported around.
2. Transportation or Movement Waste
   Transportation waste is movement of material from one place to another. Customer does not care about how much movement is done before he receives his product. Transport adds non-value to the product and company pays for it.
3. Motion Waste
   Motion waste is for example too much travel between workstations or machine movements.
4. Waiting Waste
   Waiting waste is idle time when input to perform work is missing.
5. Overproduction Waste
   Overproduction waste is the most serious of all wastes. It's producing more than is required, sooner than is required. Overproduction leads to high levels of inventory which hides many problems of organization.
6. Overprocessing Waste
   Overprocessing waste represents too much of perfection. Example can be painting areas that customer does not care about.
7. Defect or Error Waste
   Defect waste costs much more than expected in following series of rework, extra paperwork, unplanned work. The later the defect is detected, the higher the consequences.

8. Behavioural (or underutilized Employees)
   Behavioural waste represents unmotivated employees whose potential company fails to utilize.



Source: https://leanmanufacturingsecrets.com/elimination-of-the-seven-wastes-of-lean-manufacturing/

Figure 5 The 7 Wastes of lean visualized

Eliminating those wastes can be done through implementation of Lean Tools. However, the main principle of lean manufacturing is to focus on value for the customer. This approach will cause the wastes to literally dissolve (Myerson 2012), (Liker, 2004).

1.4.1 Law of the minimum

Source: https://www.taurus.ag/micronutrient-deficiency-and-yield/

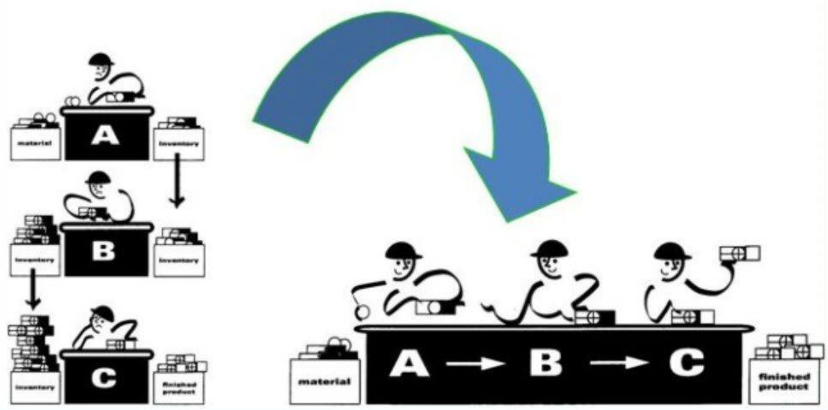
Figure 6 Barrel with unequal staves on which Liebig explained the law of the minimum

One of the key principles to avoid wasting was stated by Justut von Liebig in Law of the Minimum. “It doesn’t matter how much nitrogen is avaible to the grain, he said, if what’s short is phosphorus. It does no good to pour on more phosphorus, if the problem is low potassium. Bread will not rise without yeast, no matter how much flour it has. Children will not thrive without protein, no matter how many cabohydrates they eat. Companies can’t keep going without energy, no matter how many customers they have – or without customers, no matter how much energy they have“ (Meadows, Wright, 2015, p. 101).

Liebig used the image of the barrel with unequal staves as in the figure 6 to explain how plant grow is limited by the element that is in the shortest supply. The same as is level of water in the barrel limited by the shortest stave.

The important conclusion is that there is always in a given time a bottleneck that determines the system output and is very important to identify and primary optimize this bottleneck.

1.4.2 One-piece flow method



Source: https://www.latestquality.com/one-piece-flow/

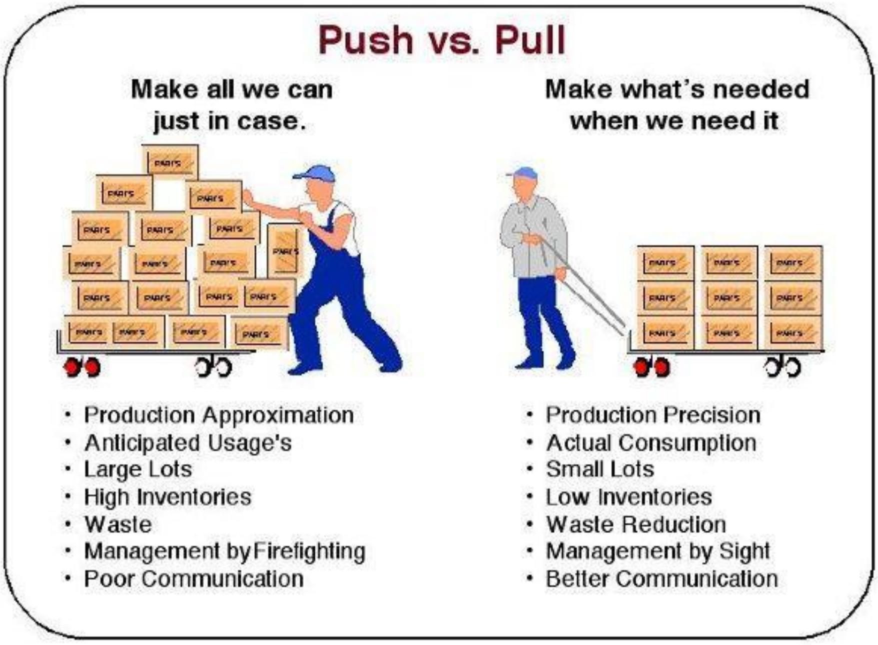
Figure 7 One-piece flow versus batch production

One-piece flow is in the figure 7 represented on the right. It’s a technique leading to increased quality, early fault detection and waste reduction. In standard manufacturing each workstation works with batches. This is called batch manufacturing and is represented in the figure on the left. Pile of inventory on input, pile of inventory on output. This can be beneficial in certain circumstances, however it brings with it high risk of defects waiting hidden in the inventory.

To demonstrate one-piece flow principle let’s say that material is transferred between workstation A and B and between B and A in a batch of 50 pieces. Let’s say machine in workstation A has undetected defect producing defective outputs. The defect will affect and be detected on workstation C. However, before the first defective output will get in station C and gets detected, another 100 defective materials will be produced in meantime.

With one-piece flow only one another defective material would be produced before defective part would get in workstation C and be detected. Thus, with one piece flow defects are detected early which leads to increased quality. Since no inventory is involved, one-piece flow helps to reduce lead time and inventory (Myerson, 2012).

1.4.3 Pull method



Source: https://www.industryweek.com/cloud-computing/push-vs-pull-manufacturing-kanban-pull-system-right-your-company

Figure 8 Pull system versus push system

Pull is represented in the figure 8 on the right. In pull you produce nothing till there is demand. In contrast in push workstations you produce, and you hope that there will be demand. This is represented in the figure on the left. Since with pull only what is needed is produced, pull helps to reduce overproduction and with it following all other types of waste like excessive inventory, overprocessing, transport waste and so on. At the same time pull leads to shorter lead times. In practise usually combination of pull and push is used (Myerson, 2012).

1.5. Main challenges of ADAS validation for automotive companies

Although proper ADAS validation is crucial for each system to ensure safety on roads, at the same time it takes enormous time, costs and people efforts. There are several reasons for this.

1.5.1 Nature of ADAS testing is mostly statistical

With deterministic testing one simply tests a specific edge-case scenario where result determines if requirement is passed or not. In deterministic systems, passing the test once means that test will be passed every time. Example of such a test for AEB is display in the figure 9.

Source: https://press.zf.com/press/en/releases/release_2565.html

Figure 9 Predefined test of AEB for cyclist detection

However, with ADAS systems it’s more difficult. The first issue is that’s almost impossible to figure-out and design in advance all situations that can happen in real traffic. The second is that ADAS systems are by their nature often non-deterministic systems. That means that when system react in the right way during the first time, it can react in the wrong way during the second time. The reason is that output is dependent on exact sequence of inputs the system received from the World.

Another challenge is that all the edge-cases are simply not defined. Typical requirements for ADAS systems thus are expressed statistically (Waschl, Kolmanovsky, Willems, 2019).

To understand statistical testing, we need to define a few terms. True positive is when AEB should be activated but was not. False positive is when car braking should be not activated but was activated. This metrics are widely used in statistical testing and displayed in confusion matrix in the table 1.

Table 1 Confusion Matrix

	Actual - True/False	
Predicted – Positive/Negative	True Positive	False Positive
	False Negative	True Negative

Source: https://towardsdatascience.com/taking-the-confusion-out-of-confusion-matrices-c1ce054b3d3e

In requirements for ADAS system two important things needs to be defined. What is required rate (e.g. x% of true positive) and what is dataset to which those rates will be related. Example of a car collecting data in real traffic can be seen in the figure 10.

Example requirements could be that the false-positive detection rate is no greater than a preset rate and that the false-negative detection rate in no greater than a preset rate. To prove this rate, cars then collect real trafic data on roads for a given car model and ADAS system.

Specific example as requirements for AEB system could be:

Dear ADAS system supplier,

deliver us your AEB system that fulfills our x conditions (could be for example detection range up to 50 meters)

Next show us that:
False Positive rate of your AEB system is under 0.0000001%.
False Negative rate of your AEB system is under 40%
Prove us this on the following dataset. Real traffic data containing 100 000 km in Germany. 50 000 km in Japan. In each country 50 % must be highways, 25 % city traffic, 25 % country traffic. At least 10 % must be recorded in snow, at least 25 % in sunny weather, at least 25 % in rainy weather.

You can see that AEB is kind of system called high precision model where main goal is to avoid false positives. Worse consequences have for us to trigger false positive – to activate emergency braking when no danger situation exist than to miss activation of AEB when accident occurs. The reason is that activating emergency braking when no danger situation exists could be fatal on highways, not speaking about trust of drivers in a given car when car would suddenly brake on occasion for no apparent reason.

Source: https://www.glassdoor.co.uk/Photos/Velodyne-LiDAR-Office-Photos-IMG1886528.htm
Figure 10 Car collecting data in real traffic for statistical testing

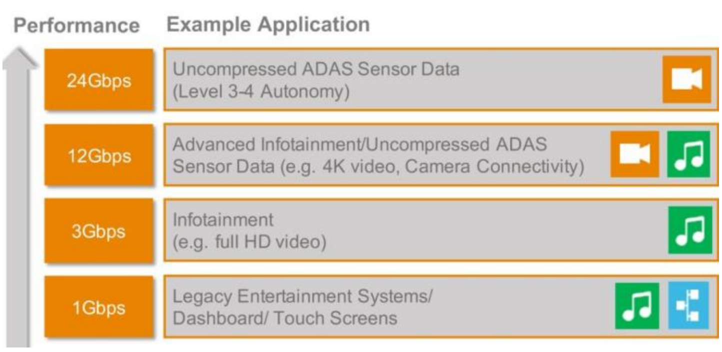
1.5.2 Huge amount of test hours to be driven

Consider a fleet of one million vehicles operated one hour per day (10^6 hours per days). Consider safety target one catastrophic computing failure in the fleet each 1000 days. Then safety target between catastrophics failures is 10^9 hours. To validate this catastrophics failure rate target one must conduct more than 10^9 hours of test drives in real traffic.

This kind of testing needs to be done for each ADAS system that company wants to sell. In case of autonomous cars, for each car model. This brings enormous pressure to organize this process efficiently (Choi et al., 2019).

1.5.3 Car data occupies huge amount of space

As number of sensors in cars increase, so amount of data being produced as visible in the figure 11. Specific amount of data depends on sensors being used in cars. The most data are in general produced by camera sensors, followed by LIDAR sensors. This represents significant challenge for storing such amount of data after they are recorded. Company producing ADAS sensors needs to store this data to validate its ADAS system and after that keep them due to legislation reasons so they can proof for example 15 years from now how they validated this ADAS system. For us it means important conclusion that we will later use, that transferring all recorded data via mobile network from car to R&D center is not feasible due to huge amount of data it represents.



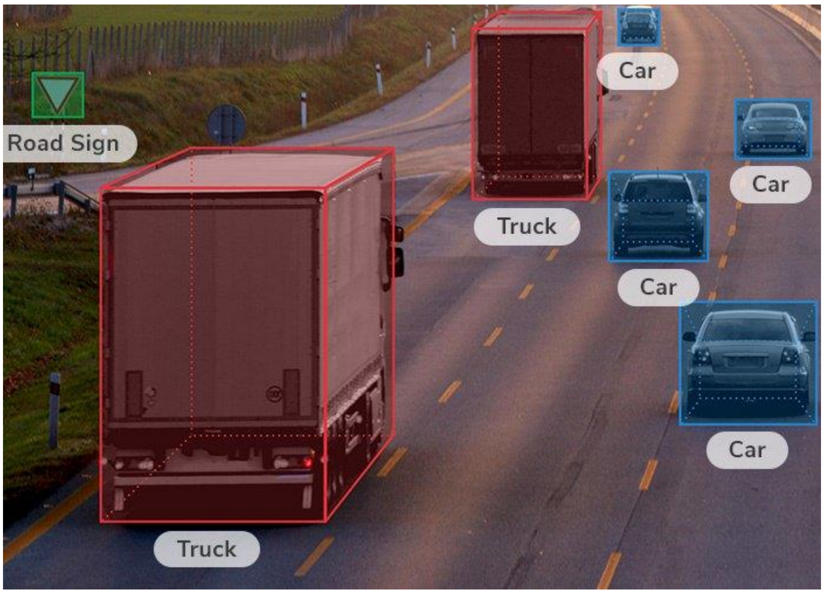
Source: https://www.autonomousvehicleinternational.com/wp-content/uploads/2018/10/05-Performance-cropped-1078x516.jpg

Figure 11 Increasing requirements for data handling in modern cars

1.5.4 Labeling of data is very expensive

Labeling (can be called in the industry too as annotation) is a work where humans go through each recording and label them. The result of this labeling is shown in the figure 12. Let's say we have ACC system automatically maintaining a safe distance from the vehicle ahead. Then during annotation human would annotate each vehicle in recording and road signs to don't exceed a speed limit. This human detection is then used as ground-truth which is in the end compared with ADAS system output.

If you would collect 10^9 hours of car recording, then you would need to annotate 10^9 hours of car recordings. Annotation ratio depends on function and automation, but let's say it's 1:120. Meaning that to annotate the one minute of recording you will need 120 minutes. Means we will spend $10^9 * 2$ hours on annotation itself for this case. Since this is done by people, costs are enormous and the process needs to be properly managed.



Source: https://www.cloudfactory.com/hubfs/img/micro/labeled-bounding-box.jpg

Figure 12 Image annotation – objects and road signs detection

1.6 Trends in ADAS validation industry

Since ADAS industry is relatively new field it‘s quickly evolving and we can observe a few important trends for the industry that will be described in this chapter.

1.6.1 Using virtual simulations

Since collecting data on roads with real cars in such a huge amounts needs significant time and brings enormous expenses, there is a trend to use simulation data instead (see figure 13). In addition, testing in virtual environments allows to create corner case scenarios that in real traffic would be difficult and dangerous to record. Example is sudden jump of pedestrian in front of a car. Volkswagen intensively focused on this area claims „it is conceivable that in future millions of test kilometers required for validating automated driving could be completed in virtual environments.“ (Volkswagen Group, 2018)

Source:
https://www.tesis.de/fileadmin/user_upload/Virtual_testing_city_environment_adas_functions.jpg

Figure 13 Simulation in virtual environment

1.6.2 Automatization of labelling process

Companies attempt to reduce costs and time by using algorithms to pre-label recorded data. Humans in that case do just final check instead of whole scene labelling. For pre-labelling are often used machine learning and deep learning algorithms.

1.6.3 Focus on validation process orchestration

Since validation proces is complex, run for a given system in multiple locations and data to be managed are enormous, validation process orchestration is utmost importance for automotive companies involved in ADAS systems. Next important topics are for companies data lifecycle management and complying with law regulations.

This diploma thesis is focused on exploring wheather applying system approach and lean manufacturing methods, specifically one-piece flow and pull typically used in manufacturing can be beneficial even for ADAS systems validation.

2 Description of validation chain to be improved

In this section two is presented a concrete validation chain which we will try in the next section three improve by application of the theory described in the section one, specifically the system approach, one-piece flow and pull method.

To be able to evaluate application of each method, a concrete ADAS validation chain is described with its problems and their enumerations. As the basic is used publicly avaible general description of validation chain described by Philosys company. That explains the validation activity behind, its subprocesses and relationships between them. However, this is not enough to evaluate effects of our methods. For that purpose is this general validation chain put into context of a specific validation project. There are described concrete recording locations, annotation suppliers' locations, transport times, and issues with their costs. Those cases are based on the author's ADAS validation industry experience. Numbers are however chosen arbitrary and does not represents any specific company data.

2.1 General description of ADAS validation chain

In this chapter is presented general ADAS validation chain as is described by Philosys company. Philosys process description was selected since that company has wide experience in ADAS validation topics where they offer their solution called VALassistPRO exactly for workflow management of this validation chain. This chapter is then basic for system thinking approach applied in the next section three.

2.1.1 Philosys company introduction

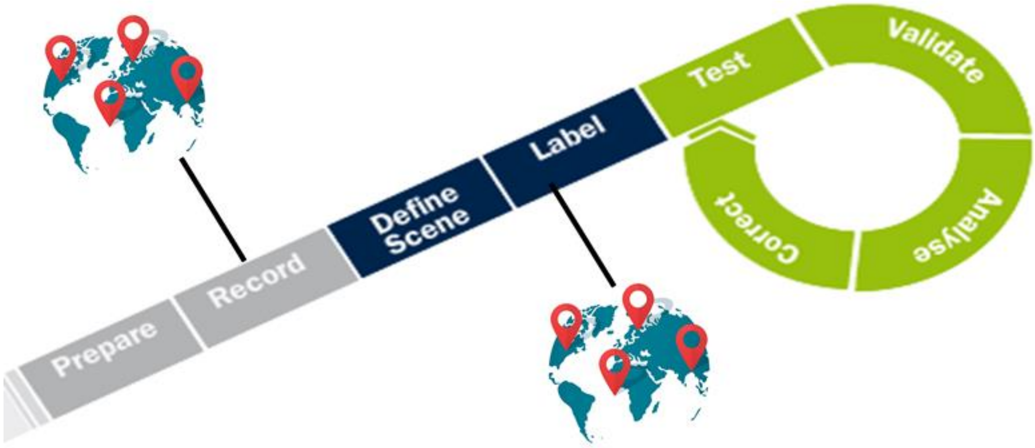
Since Philosys process description was selected for this thesis as the description of general ADAS validation chain, the company is in this chapter introduced in a few words.

Philosys is a Germany SW company founded in 1988 focused on area of automotive and ADAS. Offering contains solutions for topics like automotive software, driving simulation, assistance systems, annotation services.

Philosys process description was selected since it has wide experience in ADAS validation topics where they offer their solution called VALassistPRO that provides a framework workflow system, which supports the validation of camera based ADAS systems. At the same time Philosys is one of the leaders in the area of software solution for ADAS annotation topics which software solution for annotations you can see in the Figure 16 (Philosys, 2019).

2.1.2 General description of ADAS validation chain

In the figure 14 is ADAS validation chain described by Philosys. Complemented by World maps with location icons in the figure 14 ilustrating the fact that activities for recording and labeling usually run in multiple countries for a given ADAS system, adding complexity and necessity to manage it properly.



Source: https://www.philosys.de/en/products/valpro

Figure 14 ADAS validation process described by Phylosis

You can see in the Figure 14 eight subprocesses that we will call in this work subsystems from now. The first subsystem called *prepare* represents preparation of cars for recording. In this step are prepared and installed recording devices on recording cars, defined KPIs for a given ADAS system, datasets to be collected etc. Since this is not ongoing activity, we will not focus on this part in this work and will start from *recording* part representing a car collecting data. Next *defining scenes* represents activity of defining things like in which weather was a given recording recorded. We will consider this part to be contained in the record subsystem. *Labeling* is then about analyzing car recordings and telling what was recorded. Typical labeling activity can be object marking. After labeling goes recording to be processed into *test and validate* subsystem. Subsystem *analyze and correct* is then triggered only when testing activity detects an error of algorithm for a given recording. All described subsystems are described more in details in the next chapter.

The record subsystem description

In the record part a car or usually multiple cars drive and collect data in real traffic. The car needs to have the same setup as the final car. For example, to verify that AEB based on front laser sensor will work on VW Passat, you need to record this data in real traffic with VW Passat with front laser placed in the same position as will be in final car that will be sold to customers. Example of a car collecting data in real traffic is in the figure 16 where you can see widely used LIDAR sensor from Velodyne company mounted on the top.

As often happens, an algorithm released in the first SW release is not perfect and is beeing improved as more and more data are collected. With keeping that collected data, when next version of for example AEB software is released, correct behaviour of that algorithm can be verified on previously recorded data. It’s possible because new AEB software release affects AEB computing unit logic and might affects its output for a given input. However, the input itself or in another words what a given LIDAR seen for a given drive remains not affected by new AEB software release, thus can be reused again. In contrast, when new LIDAR version is released with new hardware, accuracy etc. then must be done new recordings with this new sensor setup.

During the car recording happens the first classification of data being recorded. For example, if there is a requirement for weather there is a co-driver who labels in which weather condition is the recording being produced. Or can be done by automatic tools which based on GPS location and weather forecast for that area label this automatically. This information is not always precise and could be corrected in labeling step. However, the first information about the recording and how it fits to requirements is created in this step. Those complicates management, since one cannot simply plan all drives 100% upfront with knowing what exactly will be recorded.

Concrete scenes to be recorded are usually up to agreement between ADAS system supplier and car manufacturer and have influence on complexity of this part. It’s different complexity to manage collecting data with its logistic in one country like Germany and between collecting data for a given model car in EU, USA and Asia.

Source: https://www.glassdoor.co.uk/Photos/Velodyne-LiDAR-Office-Photos-IMG1886528.htm

Figure 15 Car collecting data in real traffic for statistical testing

The label subsystem description

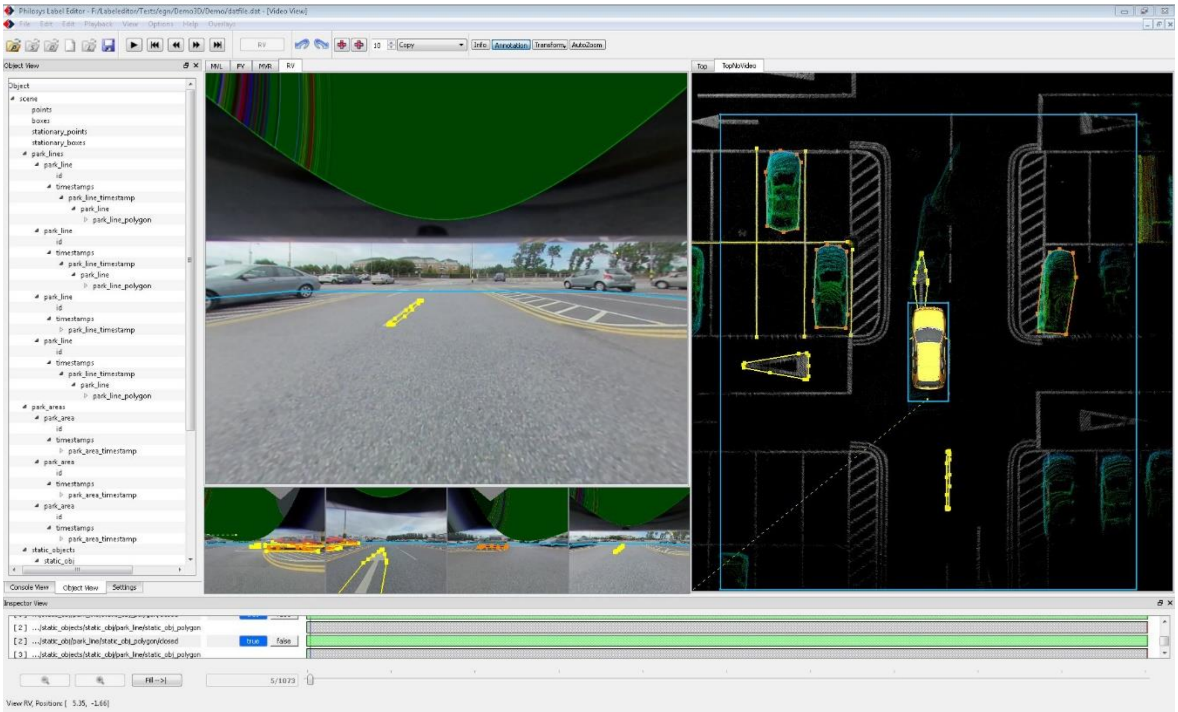
The aim of labeling is to provide ground truth for a given ADAS system. In ADAS system validation you run embedded system with its algorithm against data recorded in the previous step and compares that output with expected output created in this labeling step.

In labelling part (or called too as annotation) humans go through recordings and label them. Terms labelling and annotation are in this work used interchangeable. What exactly is labeled depends on concrete function that system should provide to customer.

Let’s stay we have AEB based on laser sensor. Then human needs to go through recordings and label each car, each pedestrian and each static object detected. This activity is human labour very intensive and expensive. Very often multiple annotation suppliers are involved which brings significant demands for logistic management. In addition, not having data to annotate equals to situation when there is a factory full of employes who has nothing to produce.

Labeling provides an important information in relation to the data collection requirements. It might fix for example weather or country information that was set in car recording. Or it can add additional classification required by customer that was not known till know for example number of pedestrians. Those complicates the management, since one cannot simply know 100% what data were collected regarding to requirements before the labeling is done.
Since labeling is one of the most expensive and human labor-intensive parts, companies try to automate this as much as possible using machine learning and neural networks to pre-annotate recordings, however final confirmation that algorithm annotated it properly needs to be done by human in the end.

One of the tools widely used in the industry for labeling is Philosys Label Editor shown in the figure 17. You can see on the left what camera recorded and on the right point cloud of a laser sensor which is then being labeled. In the picture three cars and three round boundaries are labeled.



Source: https://www.philosys.de/en/newsen/292-philosys-labeleditor-release-43en

Figure 16 Labeling tool Philosys Label Editor

The test and validate subsystem decription

In this part displayed in the figure 18 test engineers run ADAS system against test data and output is then compared with expected output set in the labeling step. This part tells you how your system is going in comparision with requirements regarding true positives, false positives and any other metrics that were set.

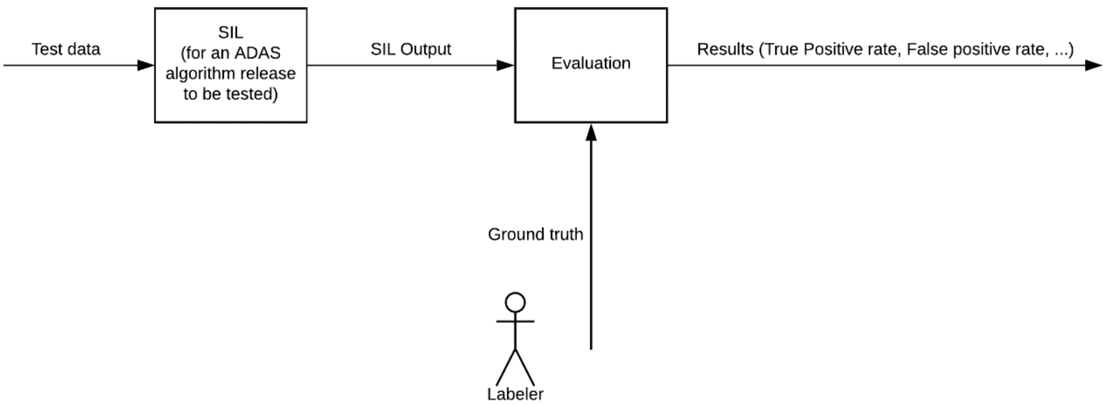


Figure 17 Testing activity flow

Testing can be dividend into HIL and SIL testing. HIL testing stands for Hardware In the Loop and is executed on the same embedded system as will be integrated in the car. The advantage is that you execute test with the same hardware limitations, CPU power and memory as will be in the car. The disadvantage is the necessity to prepare and operate testing hardware.

SIL testing stand for Software In the Loop and can be executed on any computer with enough computing power. The advantage of SIL testing is that it's quick and cheap to execute test of a new algorithm with your computer in comparision with HIL. The disadvantage is that it's not the same as physical embedded device that will be integrated in the car so might happen that SIL will pass, but HIL will fail for some cases.

In practise is used combination of both SIL and HIL. SIL is easier to deploy, faster and less expensive. On the other hand, HIL is more reliable as it represents the real conditions with its hardware limitations (Waschl, Kolmanovsky, Willems, 2019).

In the interest of test engineers is proper quality of input data from car recording and labeling subsystem otherwise their results are not accurate and rootcause needs to be examined in the next steps called as *Analyze and Correct* which requires additional non value-added work.

Analyze and Correct subsystem description

These steps happen in the case there is a mismatch between ADAS algorithm output and expected ground truth labeled by labelers. In that case the rootcause must be identified, if possible corrected and then retested again. In this section can be generated valuable feedback to the ADAS system performance and discoveries about its limitations. Could be found things like poor system performance in rainy weather. However, when the rootcause is error in annotation or in car recording itself, then it's non-valued added work resulting in waste we aim to avoid.

2.2 Specific validation project

The chapter above explains the activity behind ADAS validation, but it's not enough to evaluate effects of our methods which is done in the next chapter three. For that purpose, is this general validation chain put into context of a specific validation project. There are described concrete recording locations, annotation supplier's locations, transport times, and issues with their costs. Those cases are based on the author's ADAS validation industry experience. Numbers are however chosen arbitrary and does not represents any specific company data.

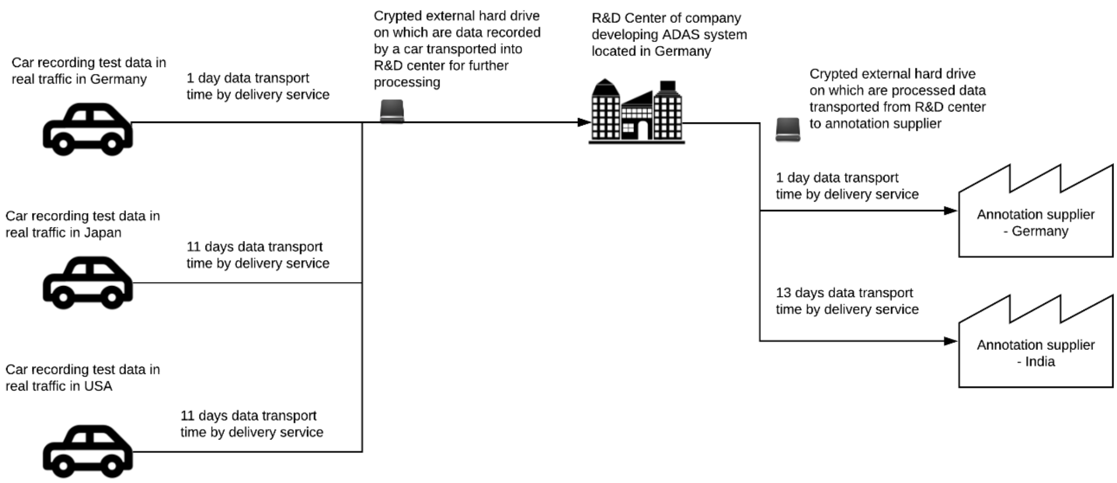


Figure 18 Initial logistic system setup as comparison baseline

In the figure 19 is presented a specific project on which we will evaluate benefits of methods applied. There are three cars collecting data in Germany, Japan, USA. After each day of recording sends a car recorded data crypted on external hard drive by post service to the R&D center located in Germany. This transport takes from 1 day for car recording in Germany, to 11 days for cars recording in Japan and USA. In R&D center are data processed and then send for annotation to two annotation suppliers. One annotation supplier is located in Germany with transport time 1 day. The second, much more cost effective annotation supplier, is located in India with the transport time of 13 days. Annotation results are small files, let's assume that annotation supplier delivers them immediatelly after their completion to the R&D center over the internet.

Next let's assume the following for our specific project:

- Internal data logistic in R&D center on external hard drives adds additional 10 days of lead time.
- During a project happens that car records for weeks with undetected error in a recording device. Multiple causes. Could be driver mistake. Could be software mistake. Could by because of reference sensor installed on the top of the car being deviated from its predefined position. This happens on average for 32 days of recording and has direct costs for that extra recording 416 000 € during validation of one ADAS system.
- During a project happens that annotators annotate wrongly specific scenes. Could be annotator mistake. Could be omitment in annotators training. Could be not defined annotation rules for that specific situations. This happens on average for 21 days of annotation work and has direct costs for that extra labeling 1.659mil € during validation of one ADAS system.
- During a project happens that car records scenes that are already fulfilled in requirements. For example, a requirement for 25 000 km on highways exists and car records in total 35 000 km on highway instead of focusing on remaining 25 000 km in countryside. This happens on average for 13 days of recording work and has direct costs for that extra recording 169 000 € during validation of one ADAS system.
- During a project happens that annotators annotate scenes that are already fulfilled in the requirements. For example, a requirement for 25 000 km on highways exists and labelers label in total 35 000 km on highway instead of focusing on remaining 25 000 km in countryside. This happens on average for 10 days of labeling and has direct costs for that extra labeling 790 000 € during validation of one ADAS system.

2.3 The problem with the current status

Before we move into the next section three and try to improve this specific case by applying system approach and lean manufacturing methods like one-piece flow and pull method, let's stress the motivation to do so. Time efforts and costs to validate an ADAS system are for automotive industry enormous. Milions of € per combination system & car only for validation of an ADAS system on roads. Let's explore in the next section how system approach and lean manufacturing methods can help with this.

Source: https://towardsdatascience.com/defining-a-data-science-problem-28c21d817c0b?gi=835ee2a04752

Figure 19 The problem lies in huge lead time and costs for validation of each ADAS system

3 Application of selected methods

The section three is about applying the selected methods described in the section one, specifically system approach, one-piece flow and pull method. Results are applied and compared against the initial state in the section two. Their evaluations in terms of defined KPIs happens in the section fourth.

Each method applied, specifically system thinking, one-piece flow and pull principle is described here in its own chapter.

3.1 Application of System Approach

We apply in this section Wholness System Thinking described in the sectione one to identify relationships between the superior system and the validation chain. From that is in this section derived the main system purpose and KPIs to be optimized. As the next step is done analysis of its subsystem in relation to the system purpose.

3.1.1 The system purpose identification

In this chapter we identify the system purpose. The system here represents the validation chain described in the chapter above. We apply what was described in the chapter on system thinking in the section one. As the first step we identify the superior system. Then we seek to understand the superior system. In the last step is identified the purpose of the studied system in relation to the superior system.

Following those steps, the first question is, what is the superior system. As the final superior system can be considered car maker ordering ADAS system into his vehicles. When we go deeper, we can see another superior system in form of internal SW development team developing algorithm for the customer. Thus, two superior systems were identified, car maker ordering the ADAS system and internal SW team of ADAS supplier developing an algorithm for the customer.

When we identified the key superior systems, the next questions to ask is what is for them important in the system. For internal SW team it's definitely the lead time to get feedback on their new algorithm and accuracy of that feedback. For the customer who ordered ADAS system into their vehicles it's too keep the defined quality, minimize the lead time when they get their system delivered and minimize the costs. Ordering priorities is up to each company, we will for this work consider ADAS system validation time as the most important target, followed by costs reduction while keeping the required quality.

3.1.2 Analysis of the system elements

After defining the system purpose in the chapter above, this chapter takes the system apart and analyzes its elements from the system purpose perspective. The chapter aims to understand each part separately so in the end can be agregated understanding of the parts and interactions into understanding of the whole system. Each identified subsystem target is highlighted in the points below.

Record subsystem targets:

- Collect only scenes that are needed to fulfill the required dataset and avoid wasting.
- Minimize „walking time waste“ as car rides between location of recording and location of data processing.
- Detect errors as soon as possible, so car does not spend time with recording. Example can be the situation when car continue to record with a sensor that stoped to work properly.
- Transport results as soon as possible to place where they will be futher processed and labeled.

Label subsystem targets:

- Receive data in proper quality, so that data can be handled without wasting time with corrupted recordings.
- Produce labeling in the quality demanded by customer.
- Fully utilize dedicated amount of people hired to do labeling, so no time is wasted by not having data to label. This is especially important when considering significant amount of people involved in the labeling activity.
- Minimize handling of data logistic so labeler can focus on labeling instead of doing non value-added activities like moving data.
- Transport results as soon as possible to place where they will be processed for testing.

Test, validate subsystem targets:

- Receive labeling in proper quality that can be used for testing, so no time is wasted by handling corrupted data.
- Produce statistic results for an ADAS algorithm version as soon as possible, so the SW team developing the ADAS algorithm gets early feedback and can react.
- Minimize handling of data logistics so test engineer can fully focus on testing activity.

Analyze, Correct subsystem targets:

- Having labeled data in such a quality that there are no errors caused by mistakes in labeling.
- Minimize handling of data logistic so test engineer can fully focus on rootcause analysis.
- Minimize transportation time of data between this step and futher reprocessing in testing part.

3.1.3 KPIs based on system approach

Based on identified system targets two main KPIs were chosen:

1. KPI: Reduction of Lead time between recording of data and ADAS system performance feedback

   - so company gets feedback to an ADAS system performance sooner
   - so customer gets an ADAS system delivered sooner

2. KPI: Reduction of Costs that it takes to finish an ADAS system validation

   - so company makes bigger profit
   - so customer can get an ADAS system cheaper and makes bigger profit on a final car

3.1.4 System approach results

Considering system purpose and each subsystem targets identified above seems that transportation times are burden for the whole system and their reduction together with reduction of need of data logistic handling would benefit to each processing part and at the same time reducing the lead time. Since lead time reduction is identified as one of our mains KPIs, we will focus on reduction of transporation time.

In manufacturing one can reduce transportation time by putting workstations together. This is not fully applicable here since recording locations are project depent and moving R&D center is not feasible. Instead, we will utilize the fact that goods beeing transported are in fact digital. They can be transported quickly over internet networks and be stored in a cloud accessible for processing to everyone involved – especially to R&D center and annotation suppliers.

Setting up cloud storage and system solutions to manage data governance and lifecycle is very interresting, but complex topic that this work will not focus on. Using cloud solution brings in this case many strategical advantages to the company. However, in this thesis we will just focus on benefits of this solution regarding to transportation time reduction.

The situation after application of system approach and integration of cloud solution is described in the figure 20 below.

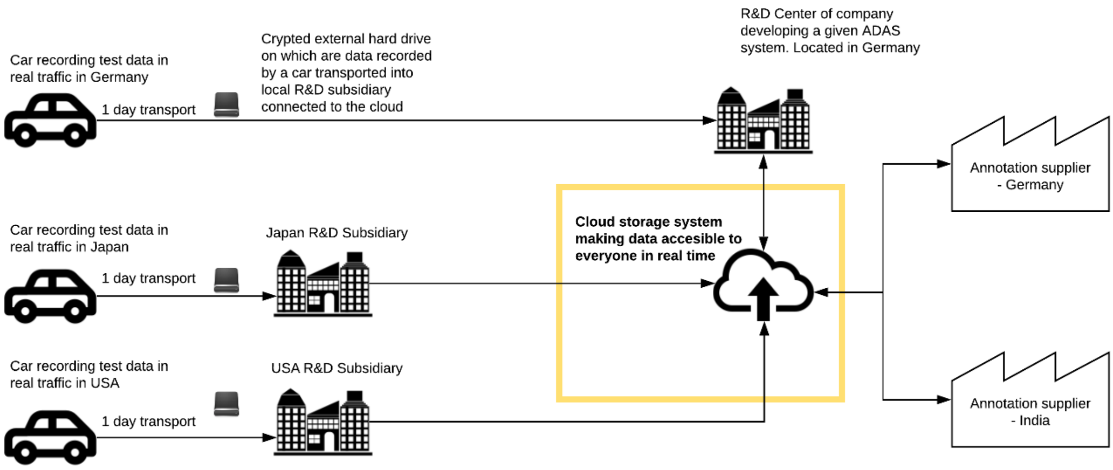


Figure 20 Logistic system setup after application of system approach

In the figure 20 you can see now that the time from car recording in Japan to R&D center was reduced from 11 days to 1 day. Both Japan and USA cars here send data directly to R&D subsidiary in a given location which takes only 1 day. We assume here that company producing ADAS system is multinational organization that has subsidiaries in Japan and USA that can be connected to the company cloud and take care about data upload. Thus, data are immediatelly accesible for further processing of R&D Center located in Germany. Next, we assume that driver has no option to connect to the cloud himself and upload data. Thus, that one day is there simply for inter-Japan transport between car recording location and that subsidiary in Japan.

At the same time, the time to transport data for labeling to annotation supplier was reduced to zero instead of 13 days for supplier in India. Although in another part of the World, supplier in India still access the same cloud storage.

Further transport time reduction was achieved by removing the need for internal transports in R&D center between testing, validation, analyze and correct processing. This reduction was estimated to be 10 days.

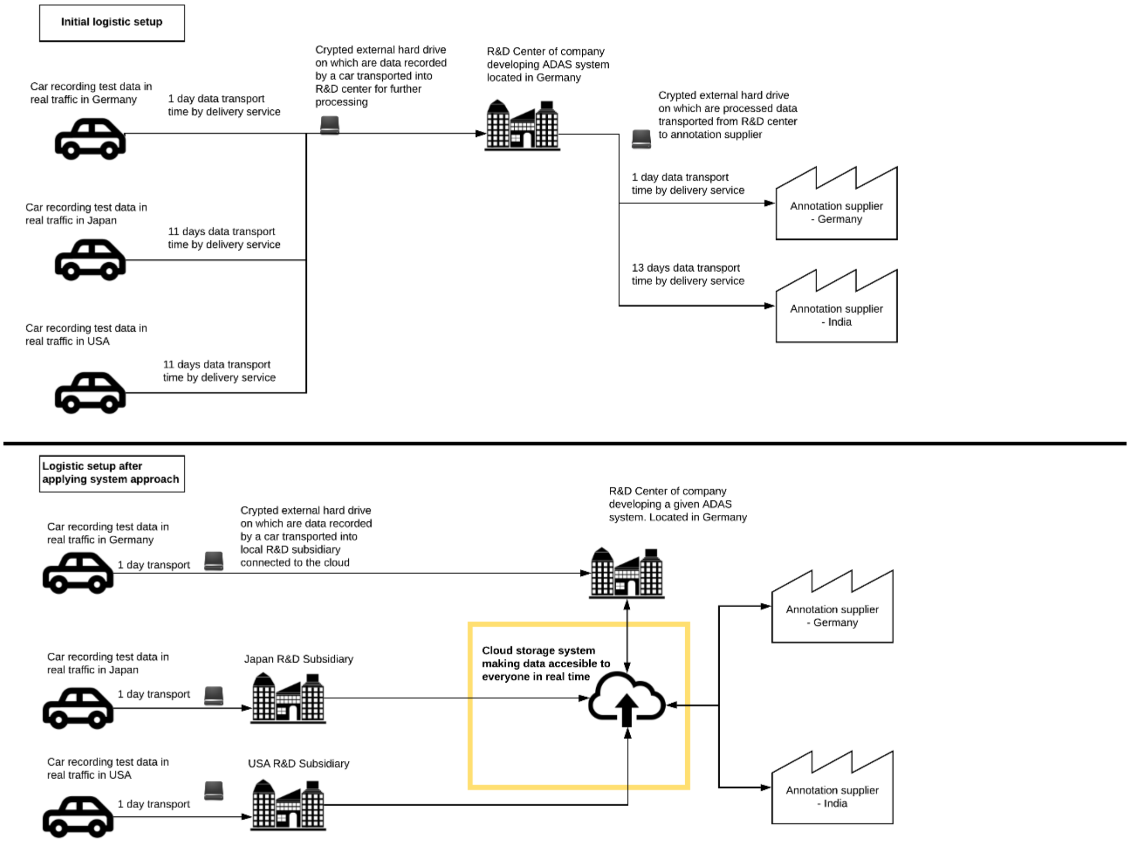


Figure 21 Comparision between initial system setup and the new one

In the figure 21 you can see in one place initial state versus new logistic chain with integrate cloud storage. Results described above are then evaluated in the section four.

3.2 Application of One-Piece Flow

Having one-piece flow from car recording to next processes would be very beneficial in terms of earlier quality problem detection we have in our initial setup defined in the section 2 instead of piling them up in the inventory. Possible solution could be to transport data from car online over mobile network. The problem with this approach is that data recorded by car has significant size as described in the chapter 0 and transferring them over network would take significantly more time that it currently takes to transfer them over post service to the R&D center.

However, we can still partly implement one-piece flow and get its benefits by sending over mobile network only one sample in regular intervals that will be processed with the priority. Thus, sample is sent regularly over internet and processed via the whole chain so potential error is immediately found out. That is feasible for mobile network and in case that problem affecting all recording arises, it will be detected quickly. The rest will be produced and send in batches as before.

After an annotation part can be one-piece flow implemented fully. Annotation is in general the slowest element from that time, slower than SIL and HIL processing and sets the tact. In addition, data are now shared immediately via cloud avaible for futher processing. Thus, everytime an annotation is produced, it’s immediately processed for SIL or HIL testing and potential error is immediately found out.

3.3 Application of Pull method

Everything is basically already based on pull sice all requirements and planning to fulfill them comes from requirements set by customer or by internal customer, representing a stakeholder who want to sell this system with these parameters. However, there is an option for improvement and it's in term of quicker feedback on what was collected versus requirements. As was described in the description of car recording and annotation part, there is an uncertainty what exactly was recorded. This uncertainty can be for example caused by difference in weather forecast versus real weather or if target to collect specific number of pedestrians exists, it's hard to predict it upfront. This uncertainty is minimized after data were collected since some parameters were briefly labeled by co-driver and removed after the recording was annotated. We can ensure quicker feedback by updating the catalogue in real time from cars over the internet and from annotation immediately after it's finished.

4. Evaluated results

In this section four are methods, which application is described in the section three, evaluated in terms of defined KPIs as lead time reduction and direct costs reduction for one-piece flow and pull method. Evaluation is based on comparison with the initial state described in the section two where are described problems of that solution with their delay and costs impact. Tables below contain the problems that were solved by application of a given method and that problems delays and costs impacts being removed by that.

4.1. Evaluation KPIs

Based on identified system targets in the section three, two KPIs were chosen. Evaluated methods are then evaluated based on those KPIs.

KPI 1. Reduction of Lead time between recording of data and ADAS system performance feedback

- so company gets feedback to an ADAS system performance sooner
- so customer gets an ADAS system delivered sooner

KPI 2. Reduction of Costs that it takes to finish an ADAS system validation

- so company makes bigger profit
- so customer can get an ADAS system cheaper and makes bigger profit on a final car.

4.2. Evaluated application of System Approach

Table 2 Results after applying system approach

Solved problem	Lead time reduction
Transport car to R&D center	10 days transport from car USA, Japan into R&D center, Germany
Transport R&D center to annotation supplier	13 days transport from R&D center to annotation supplier in India
Internal data transports in R&D center	10 days internal data transports in R&D site
Total effect	**33 days**

Taking into consideration the system purpose with its subsystem targets led to focus on data logistic time reduction. By sharing data over the cloud system instead of transporting them via post service saves 33 days of lead time in comparison with the initial status as shown in the Table 2.

4.3. Evaluated application of One-Piece Flow

Table 3 Results after applying one-piece flow

Solved problem	Solution	Lead time reduction	Direct costs reduction
Car recording for weeks with undetected error in the recording device	Sample is sent regularly over internet and processed via whole chain so potential error is immediately found out	32 days	416 000 €
Annotators annotating wrongly for three weeks before defects are found out	Immediately after annotation is done it‘s automatically processed via the whole chain so potential error is immediately found out	21 days	1 659 000 €
Total effect		**53 days**	**2 075 000 €**

By partly implementing one-piece flow, overstepping batch production and sending sample data from car regulary over the internet to be processed with priority we solved one of the cases evaluated in the initial baseline for 32 days delay and cost of 416 000 €. Similarly, for the case where annotators annotate wrongly for three weeks before defects are found out and applying that delivered annotations are immediately processed via the whole chain so feedback for potential error is quickly received. In total it results in lead time reduction of 53 days and direct costs reduction of 2 075 000 € against our comparison baseline defined in the section two.

4.4. Evaluated application of Pull method

Table 4 Results after applying pull method

Solved problem	Solution	Lead time reduction	Direct costs reduction
Cars recording already covered scenes	Catalogue with predefined targets updated in real-time from cars over internet	13 days	169 000 €
Annotators annotating scenes that are already fulfilled	Catalogue with predefined targets updated in real-time with annotation results over internet	10 days	790 000 €
Total effect		**23 days**	**959 000 €**

By application of pull principle and making work triggered more by real demand than by projected demand and updating catalogue in real time from cars over the internet we solved one of the cases evaluated in the initial baseline for 13 days delay and costs of 169 000 €. Similarly, for the case where annotators annotate scenes that are already fulfilled and applying that catalogue targets are updated in real-time with annotation results over the Internet. In total it results in lead time reduction of 23 days and direct costs reduction of 959 000 € against our initial situation defined in the section two.

4.5. Evaluated results summary

Table 5 Results summary

Benefits for each ADAS system being validated	**Lead time reduction**	**Direct costs reduction**
System approach – making data accessible from one place via cloud solution	33 days	Not included in this work
Applying partly One-Piece Flow	53 days	2 075 000 €
Applying partly Pull method	23 days	959 000 €
Total effect	**109 days**	**3 034 000 €**

The Table 5 summarizes results achieved for the company validating ADAS system which uses the initial process described in the section two. Results in the Table 5 were created by merging results from the Table 2 representing results for application of system approach, Table 3 representing results for application of one-piece flow and Table 4 representing results for application of pull method. Costs for applying principles used in one-piece flow and pull method section are neglibile regarding to saved amounts and the application of that methods brings significant benefits in terms of lead time and costs reduction. However, costs might represent a factor for implementing the cloud solution where company needs to carefully consider primary how it fits in its long-term strategy for data lifecycle management etc.

In every case applying system approach and lean manufacturing methods resulted for our case in the following benefits:

1. Company gets feedback on each ADAS system performance sooner
2. Customer (OEM) gets an each ADAS system delivered sooner
3. Company reduces costs and makes bigger profit

Although exact application needs to be tailored to specific ADAS company situation, application of principles as system approach and lean manufacturing methods traditionally used in manufacturing, seems to be worth consideration even to Research & Development departments producing ADAS systems. At least based on results for the case study described in this work.

Conclusion

In the first section was presented ADAS validation background together with research on suitable methods to be applied, especially system approach, one-piece flow, pull method. In the second section was presented concrete ADAS validation chain that was in the next chapter three optimized with the selected methods. Since the thesis is intentionally theoretical without disclosing sensitive information of any company, publicly avaible sources were used together with a few assumptions. In the next section three were applied the selected methods. In the last forth section was application of each method evaluated in terms of identified KPIs.

Main KPIs were identified based on system thinking, specifically the lead time reduction and the costs reduction. Improvement in lead time and costs reduction were then caused mostly by reducing transportation times by using centralized cloud storage to transfer car recordings and by increasing feedback speed, so potential errors can be detected and solved in early stage.

Applying system approach and lean manufacturing methods, specifically one-piece flow and pull system, shown in our case study positive results where customer can get ADAS system for their car validated and thus delivered faster, cheaper and with better quality. For purposes of this thesis only the direct effects on ADAS validation were calculated, however for futher research could be interresting to take into calculation even side effects for example the quicker feedback on ADAS SW algorithm release.

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List of figures and tables

List of Figures

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List of attachments

This diploma thesis contains no attachments.

ANOTAČNÍ ZÁZNAM

AUTOR	**Bc. Jan Marčan**		
STUDIJNÍ OBOR	6208T088 Business Administration and Operations		
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VEDOUCÍ PRÁCE	**Ing. David Holman, Ph.D.**		
KATEDRA	**KLRK - Katedra logistiky a řízení kvality**	**ROK ODEVZDÁNÍ**	**2019**

POČET STRAN	**52**
POČET OBRÁZKŮ	**21**
POČET TABULEK	**5**
POČET PŘÍLOH	**0**

STRUČNÝ POPIS	**Cílem diplomové práce bylo ukázat, jak mohou být systémový přístup a lean manufacturing metody využity také v R&D validaci ADAS systémů, aby zákazník dostal ADAS systém validovaný pro své auto dřívě, tudíž doručené rychleji, levněji a s větší kvalitou.** **K demonstraci potenciálních benefitů byl vytvořen model původního systému. Výsledky aplikace každé metody byly poté porovnány s tímhle původním systémem a vyčísleny v lead time a přímých nákladech.** **Výsledky ukázaly značné zmenšení lead timu a nákladů.**

KLÍČOVÁ SLOVA	**ADAS validace, ADAS, systémový přístup, lean manufacturing, management logistických řetězců**

ANNOTATION

AUTHOR	Bc. Jan Marčan		
FIELD	6208T088 Business Administration and Operations		
THESIS TITLE	System Approach to Manage R&D Validation Process of Advanced Driver-Assistance Systems		
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SUMMARY	The diploma thesis goal was to show how system approach and lean manufacturing methods can be applied even in R&D for validation of ADAS systems, so customer can get ADAS system for their car validated and thus delivered faster, cheaper and with better quality. To demonstrate potential benefits, initial baseline system was set. Each method application was then compared against this initial baseline and evaluated in terms of lead time reduction and direct costs reduction. Results showed significant lead time and costs reduction.

KEY WORDS	ADAS validation, ADAS, system approach, lean manufacturing, supply chain management