SILESIAN UNIVERSITY OF TECHNOLOGY
FACULTY OF MECHANICAL ENGINEERING
DEPARTMENT OF FUNDAMENTALS OF MACHINERY DESIGN

Doctoral Dissertation

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Engineering knowledge management with the use of the „Digital Twins" method

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Abbreviations used in the automotive industry

APQP – Advanced Product Quality Planning

FMEA – Failure Mode Effect Analysis

DFMEA – Design Failure Mode Effect Analysis

DFSS – Design for Six Sigma

PFMEA – Process Failure Mode Effect Analysis

IATF – International Automotive Task Force

VDA – Verband der Automobilindustrie

AIAG – Automotive Industry Action Group

SUV – Sport Utility Vehicle

ED&T – Engineering, Design and Testing (related to budget)

BOM – Bill of Material

XBOM – Experimental Bill of Material

VOC – Voice of Customer

MLA – Maturity level assurance

PPAP – Production Part Approval Process

SPC – Statistical Process Control

SOP – Start of Production

RFI – Request for Information

DMSO – Design Manufacturing Sign Off

DVP&R – Design Verification Plan and Report

PVP&R – Process Validation Plan and Report

DV – Design Verification

PV – Process Validation

MSA – Measurement System Analysis

Gage R&R – Gage Repeatability and Reproducibility

EFFRA – The European Factories of the Future Research Association

IEC – International Electrotechnical Commission

AMR – autonomous mobile robots

KPI – Key Process Indicator

1. Introduction

1.1. Personal background and motivation for PhD studies

I graduated from the Silesian University of Technology in 2000 from the technical physics faculty with a specialisation in computer aided measurements. I started working for Tenneco company in September 2001 as a Design and Development Engineer in a newly opened Engineering Centre of Tenneco in Gliwice, as one of 8 engineers. The team was a beginning of the Engineering Centre development in Gliwice. The centre was finally growing to the size of nearly 240 employees located in the new engineering centre opened in 2023. Currently, the center is the main and global unit for research and development in the company. Tenneco is a global automotive parts supplier owning currently several brands, including well known shockabsorber brands like Monroe and Öhlins.

At the beginning of my career in the company I was responsible for design and development of electronically controlled semi-active shock absorbers and also for maintenance of test rig software. Then in 2006 I became a supervisor of prototyping and testing team. Parallely, I was participating in Six Sigma Black Belt certification program. My certification project achieved 2nd place CEO award. I became the pioneer implementing Six Sigma approach into Product Engineering in Tenneco company. This activity allowed me to understand engineering processes and methods used in design and development work. One of the most interesting and successfully performed topics was a project on complex tube deformation. The main problem was to optimise design and manufacturing parameters. The idea was to apply exclusively simulations and the parameters obtained from simulations were used directly in the physical experiment delivering the First Time Right results. The project was considered as the breakthrough in Six Sigma implementation in Tenneco and convinced the engineering team and management to continue such development. The PhD thesis is a part of this activity.

Next, the lean training and participation in process improvement projects allowed me to understand not only development processes, but also to gain skills necessary in cooperation within a multidisciplinary team, as well as to determine how to gather inputs from different teams and achieve consensus. Results from various improvement projects were presented in

SAE paper “Lean Product Development. How to Create Flow? Reflection after a 4 Years Implementation in One Business Unit” (Garcia et al., 2016), I was co-author.

Both methodologies gave me the possibility to adjust Six Sigma and Lean tools for specific needs. Basing on gathered experience in leading and facilitating projects I took opportunity to participate in Six Sigma Master Black Belt certification program, and I finished it successfully in 2014. Through several training session run in different regions, including Europe, India and China I have trained more than 400 employees through various Lean and Six Sigma training sessions, delivered not only to engineering teams, but also to other groups, giving the unique opportunity to drive multidisciplinary discussions during training sessions and exchange experience between memebers of Tenneco staff.

Figure 1. Six Sigma Black Belt and Master Black Belt certificates

In 2016 I joined the Global Engineering Operations team and became responsible for some global engineering processes including e.g. Lean and Six Sigma deployment, Advanced Product Quality Planning (APQP), Design rules process, and design risk analysis (DFMEA). Based on my expertise in different areas and Global exposure, I was promoted to Engineering Manager in 2018, and later I took also the role of internal IATF and VDA 6.3 auditor. The contemporary problems in automotive industry to be solved and possibility to implement technologies included in a concept of Industry 4.0 are motivation to determine the topic of PhD thesis. In 2019 I started PhD studies as a cooperation between Tenneco and the Silesian University of Technology.

I hope reading this dissertation will be interesting and inspiring for all readers.

Artur Król

1.2. The dissertation roadmap including current expertise

Engineering knowledge management is a crucial aspect in recently observed changes in the automotive market that led to the significant increase of loads on a vehicle suspension. Results are higher requirements for the strength and durability of shock absorbers. The introduction of the digital twins was managed with a proper definition of the project and efficient use of the tools for business process mapping, known from Lean and Six Sigma methodology.

The dissertation is related to the management of the engineering knowledge gathered during product design and development. The problem description concerns mainly the increase of suspension loads mentioned above. However, there are also other problems related to engineering knowledge management and strong requirements to decrease the time of development of new products. There are different approaches implemented in the automotive industry to characterize enumerated problems. To elaborate efficient solutions several concepts and contemporary technological trends were considered. One of them is a very wide concept of the Industry 4.0. The possibilities to implement some technologies included in this concept were characterized in the consecutive chapters. As the result of the PhD project a solution based on the implementation of a digital twin was elaborated. The detailed characteristics of the problem and consecutive steps of the elaborated approach implementation together with verification results were presented in the second part of the thesis. The conclusions and further plans were discussed in the final parts of the dissertation.

The PhD dissertation roadmap presented in Figure 2 characterizes the project elements and explains the connection with the current state of expertise and contemporary problems in automotive industry to be solved as well as a personal development interests and development path of the author.

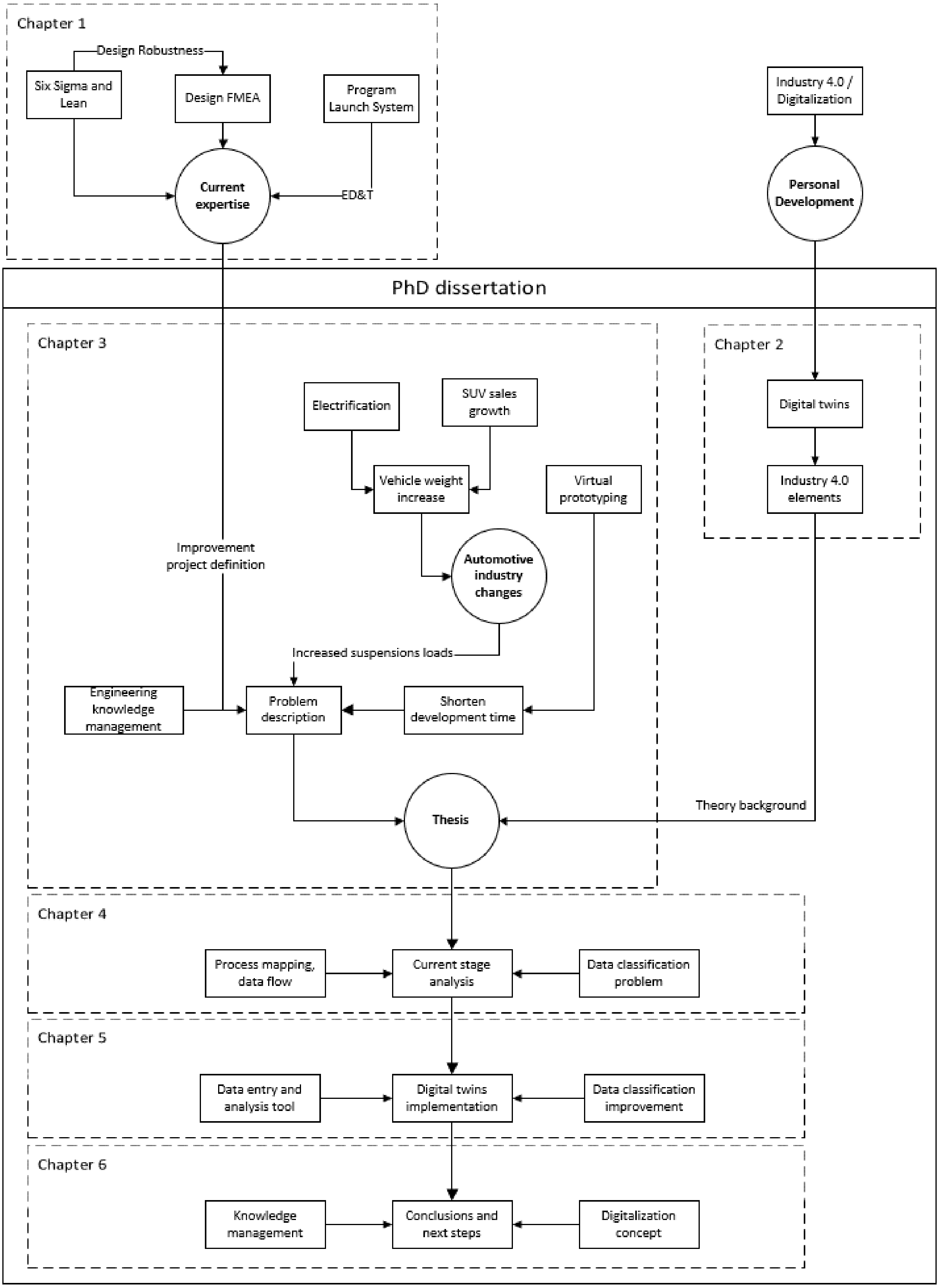


Figure 2. PhD roadmap

1.3. Product development process and knowledge management.

The PhD dissertation is focused on improving engineering knowledge management in the automotive industry. The main idea elaborated as the result of the PhD project is to implement a digital twin concept at selected stages of a product development. Tenneco implemented two chains of processes aimed at product development. In Tenneco internally they are called: (1) New Technology Introduction (NTI) and (2) Program Launch System (TenPLUS), as presented in Figure 3. The scope of the dissertation is engineering knowledge gathered during design and validation stages of the TenPLUS process. The knowledge considers technical, commercial, warranty, logistics and legal requirements. The gathered knowledge shall be available as input for the following upcoming projects.

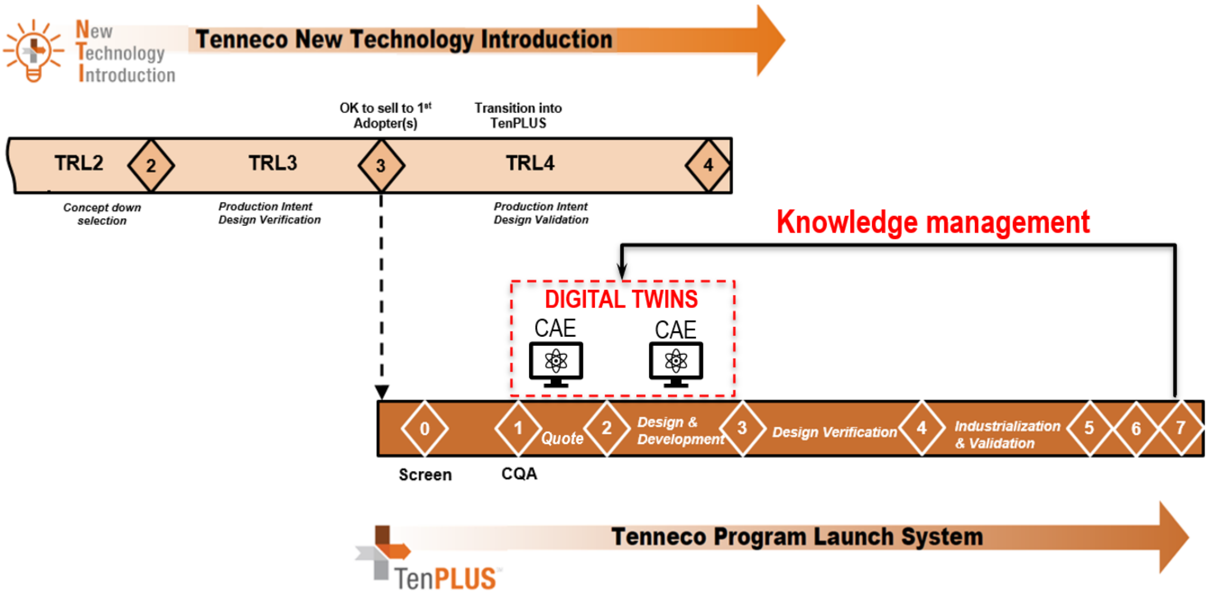


Figure 3. Tenneco processes for New Technology Introduction and Program Launch System.

Contemporary processes of product development and manufacturing, independently on a company approach, are very complex. Storage of the engineering knowledge and efficient knowledge management are strategic processes in the company. It concerns also proper data collection, information processing, as well as the knowledge management. Especially the knowledge from previous projects must be available to be reused in the similar projects. It speeds up the whole process parallelly. The provided knowledge is validated and ensures the expected quality. Moreover, it also let minimise efforts for the product development, especially the prototyping phase and let define the product performance and durability boundaries. Conducting projects as isolated tasks, without considering past cases and the historical knowledge leads to wasting time and components at the prototyping phase, and finally loss of money.

It is important to state that each company defines its own knowledge management process, which is usually directly linked to product launch process. There are several specific aspects and requirements in the automotive industry that must be considered. Therefore, to understand the standards followed by automotive companies it is crucial to present some specific aspects of this industry.

A typical automotive supplier delivers its own products to several vehicle manufacturers called customers. It is important that the requirements significantly vary between the customers. However, similarities in design solutions for some families of products are visible.

Automotive companies are obligated to follow very well-developed standards and manuals to ensure required quality and achieve customer satisfaction. It should be stressed that the standards are being constantly developing by car manufacturers or organisations gathering vehicle manufacturers. The standards are requirements concerning generally understood product manufacturing and concern mainly a supplier system in the automotive industry. Currently defined manuals refer also to the program management that includes budgeting, prioritisation, ensuring resources for several projects and managing interdependencies between the projects. Considering importance of the requirements, the role of the program manager is crucial and is focused on a proper collaboration between several departments in the company. Usually, a single project is aimed at delivering a single product that fulfil well-defined requirements. The project management involves such aspects as date of product delivery, cost and resource plan (Xie, 2014). It depends on a company, but usually single projects are organized in a program structure. It is the case of Tenneco company. To understand the dependencies and differences between the program and project, an exemplary scheme was presented in Figure 4. Programs and projects are managed through process named *Tenneco Program Launch System – TenPLUS.*

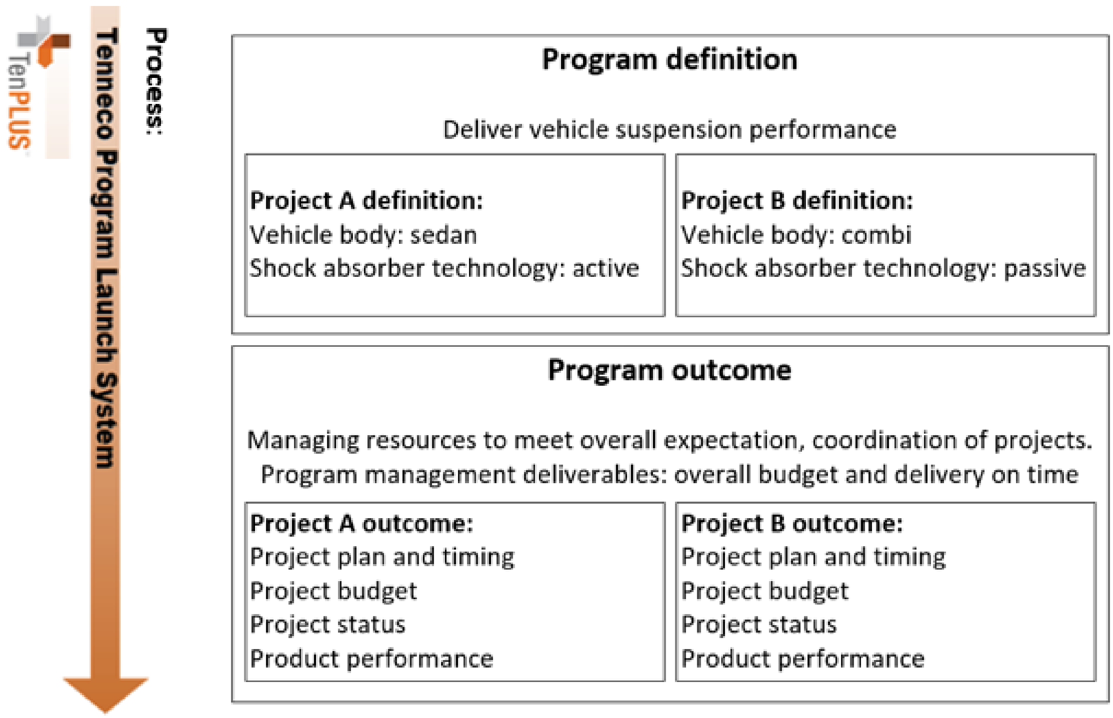


Figure 4. Program and projects dependencies and differences.

Considering the currently applicable standards and trends two key global organisations establishing standards should be mentioned. They are:

- Automotive Industry Action Group (AIAG) related to North America base car manufactures, called in further parts of the thesis the American approach
- Verband der Automobilindustrie (VDA) focusing on German car manufactures, called in further parts of the thesis the German approach.

These two documents are the basis for the review of current problems in the automotive industry. The results of the review are presented in the consecutive parts of the thesis. The standards commonly accepted in the automotive industry are different but both enumerated organisations are focused on the same key process steps:

- Achieve the required product quality
- Approve the manufactured product
- Perform the risk analysis for design and manufacturing processes
- Use statistical tools and methods to improve the quality assurance process.

To understand the problems of knowledge management as well as product design processes, specifically in the automotive industry, the specific steps of these processes should be discussed. The steps characterize launching a new product and ensuring the required quality. In case of AIAG (the American approach), the basic manual is called Advanced Product Quality Planning (APQP) (Chrysler Corporation & Chrysler Corporation, 2008). The aim of the manual is to establish common guidelines ensuring the product quality planning. It is especially important to follow the requirements at the development product phase or service. The APQP provides clearly defined steps. The timing chart related to this standard is presented in Figure 5.

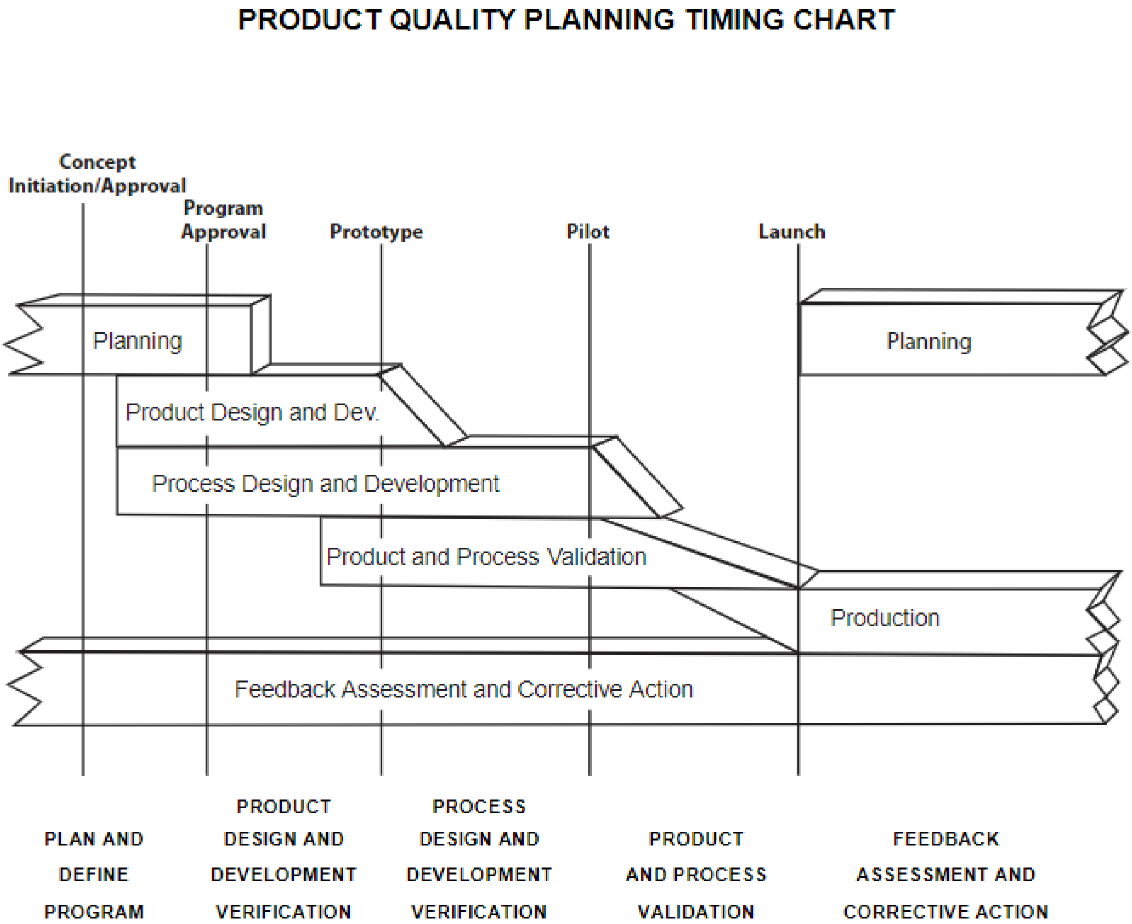


Figure 5. AIAG Product Quality Planning timing chart (the American approach) (Chrysler Corporation & Chrysler Corporation, 2008)

It is important to add that in the American approach such terms as a program and project are distinguished. According to the guidelines, the first program stage is called *Plan and define program.* The typical sequence of consecutive steps at this stage is presented in Figure 6.

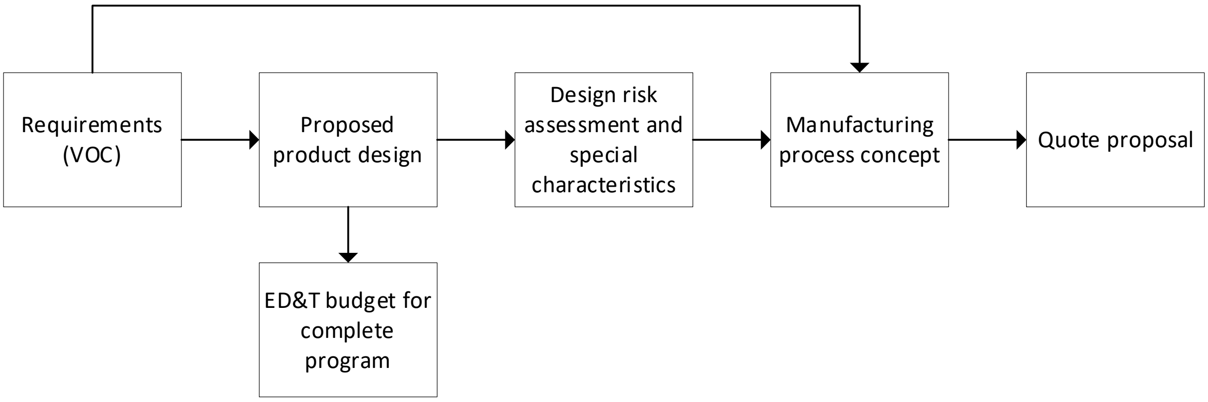


Figure 6. Steps of Plan and define program (the American approach).

The process includes a lot of commercial procedures, which start with an analysis of a commercial offer prepared on the basis of an initial design proposal. The initial design is elaborated basing on currently available design standards as well as results of simulation methods. Usual short timing of this stage is required, what does not allow to perform the reliable risk analysis followed by the design verification tests. It is important to mention that any mistake in the design proposal leads to the necessity of redesign of the product or the whole manufacturing process. It is obvious that such mistakes negatively influence the financial state of the complete program. The goal of the APQP (the American approach) is to meet the requirements of customers. Such approach is called in the automotive industry the Voice of Customer (VOC).

The next stage of the APQP is *Product Design and Development*. At this stage the product design is performed. The aim is to optimize the selected design solution, conduct the risk analysis (Automotive Industry Action Group & Verband der Automobilindustrie, 2021) and also perform the verification tests. It should be stressed that the project team at this stage is able to optimize or slightly change the design. However, it is important that from this stage the selected design solution is usually accepted basing on the results of the previous program stages and major changes of the product design or manufacturing process are not recommended. Any significant changes lead to delays or increase of the final cost. The sequence of the steps at this stage is presented in Figure 7.

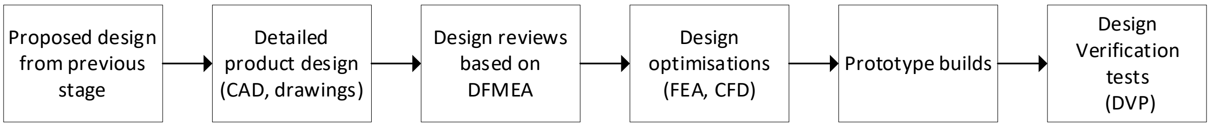


Figure 7. Steps of Product and Process and Development (the American approach).

The presented process does not include design iterations, which usually happen in case of failing the design verification tests. However, the expectations of automotive suppliers are to avoid costly design iterations and deliver design, which is the result of the first attempt. It is called in the automotive industry the first-time right approach.

The next stage in the APQP is called *Process Design and Development* and is focused on the manufacturing process. Typical elements of this stage are presented in Figure 8.

Figure 8. Steps of Process Design and Development (the American approach).

This stage includes also elements of control procedures like *Control plan and Measurement System Analysis* (*Measurement Systems Analysis*, 2010) that are crucial for quality control of the final product.

The next stage is related to *Product and Process Validation* where program activities are executed by the teams responsible for manufacturing, quality team and program management. The aim of this stage is to prepare the serial production. It should be stressed that in case of products discussed in the thesis, they are typically manufactured in conditions of serial manufacturing in large sample size batches in order to encounter all potential process variation (*Statistical Process Control (SPC)*, 2005). The manufactured products are used to perform the predefined validation tests of finished goods. The steps of this stage are presented in Figure 9.

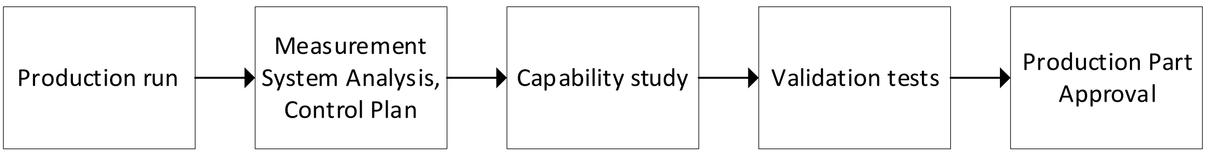


Figure 9. Steps of Product and Process Validation (the American approach).

The *Advanced Product Quality Planning* is not finished at the *Start of Production* (SOP) because the valuable data and feedback from the serial production is used for corrective actions. The stage described as *Feedback, Assessment and Corrective Action* can be analysed on the basis of the complete APQP process. It must be stressed that feedback from the serial production is highly valuable due to the data resulting from big sample size based on the stabilized production process and serial components.. The typical output elements are:

- Reduced manufacturing variation of product characteristics
- Improved overall customer satisfaction
- Improved delivery of product to customer manufacturing location
- Improved engineering service
- Lessons Learnt leading to improvement of internal standards.

Considering the German approach, enumerated above and characterized in the VDA manual, one should take into account the *Maturity level assurance* (MLA). It is defined for new products and provides different aspects of manufacturing process in the serial production. The main steps in this case are practically the same, but it is important to stress that the nomenclature is different from the American approach. The VDA MLA process is presented Figure 10.

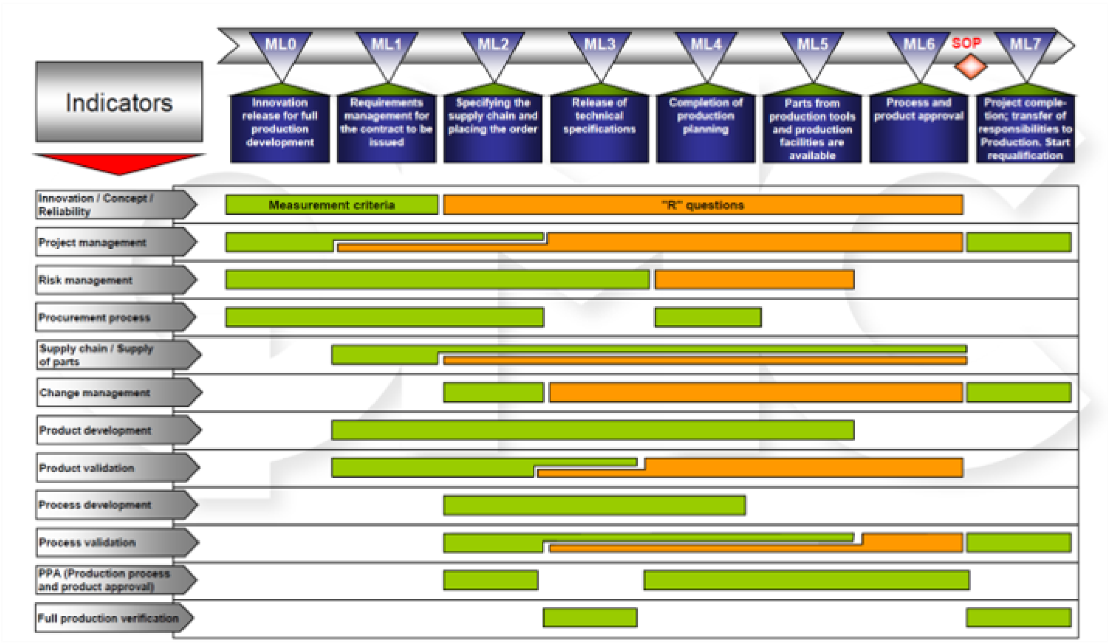


Figure 10. VDA MLA process (http://www.se2u.com/, 2023; Wspólne zarządzanie jakością w łańcuchu dostaw, *2018) (the German approach)*

The VDA MLA process consists of 8 stages (ML0 to ML7) that are defined int the following way:

- ML0 – Innovation release for the full product development
- ML1 – Requirements management for the contract to be issued
- ML2 – Specifying the supply chain and placing the order
- ML3 – Release of technical specifications
- ML4 – Completion of production planning
- ML5 – Parts from production tools and production facility are available
- ML6 – Process and Product approval
- ML7 – Project completion, transfer of responsibilities to production. Start of requalification.

One of the key aspects being considered in the PhD project and described in the thesis is related to the engineering time spent on designing and developing the product. The time to perform the design verification tests is also analysed. Due to fact, that APQP (the American approach) is not specific enough in description of the detailed engineering process. Therefore, automotive companies are defining their own project management processes, staying in line with the APQP, but aligning with internally existing departmental structures, procedures, and systems. Tenneco company defined also its own standards based on the APQP and internally developed best practices. Due to confidentiality clause, only the high-level summary of the documentation is presented in the thesis. It is concluded in the following points:

- *Plan and define program* stage known from the APQP process are split into 3 stages to analyse business benefits, prepare internal quote, and approve the offer to be presented to the customer. The last stage is usually focused on negotiations with the customer to receive a program nomination. The goal is to define the initial design fulfilling requirements and potentially perform a quick design optimisation, supported by simulations and prototype testing. Additionally, special forms are established and used to perform a technical project risk assessment.
- Customer program nomination is officially used statement determining the customer approval of the program to be launched. The start of the program includes also creating a team and allocating resources and program budget. The main department performing

next three program stages is the product engineering organisation. Discussing the Tenneco Program Launch System, it should be stressed that it follows rather APQP (the American approach) than VDA (the Germans approach). Moreover, there are a few engineering procedures that are more highlighted in details than in the APQP:

  - Defining ED&T budget specific for a given project allows proper control of resources utilization over the program stages
  - Use of standardized component design, standardized design of assemblies, finally supported by predefined BOM (Bill of Material)
  - Design optimisation loops that include CAE analysis supported by building prototypes and executing performance or durability testing. CAE includes 3D modelling in CAD, FEA analysis and even CFD analysis if required by a specific project.
  - The document control system, even for experimental purposes.
  - Use of DFMEA software that allows to start a specific project based on the template DFMEA as well as on Lessons Learnt loops from a specific program back to the template DFMEA.
  - Key engineering deliverables are results of meetings on the design review, what is supported by predefined templates created based on the received lessons learned

- Tenneco clearly defines roles and responsibilities of the launch program by establishing a standard team and creating a detailed process map, presenting all actions split over all involved functions. It must be noted that the company defines program launch deliverables and considering some of them as key deliverables.
- The launch program also includes a standardized review form that verifies completeness and content of key activities across all involved functions. The form is designed to cover three stage reviews throughout the complete process. Regular practise is the feedback from function leaders and review of checklists. It is performed for all active programs and is the basis for a decision to accept program to be advanced to the next stage, of a program performance. The results of the characterized reviews are represented as traffic lights. They are aimed at checking the following principles:
  - Red – at least one key deliverable is not fulfilled, and no plan exists to overcome. Red programs are regularly revied at the Director and Manager level and get highest priority in the company, allowing faster execution of required actions.

    - Yellow – at least one key deliverable is not achieved, but the plan to improve the current situation is existing and being approved by all leaders involved in stage gate review. The yellow status is not approved, even in case of disagreement of one department leader. The approved action plan leads to yellow program status, being also reviewed during regular calls and getting the secondary priority withing involved departments.
    - Green – no obstacles are observed in the program status, all key activities for given stage of the program are executed and content of deliverables is approved by all interested parties within the review team.
- Tenneco uses professional software to manage all programs on global level. The software was adapted to the company processes and tools, including names of the stages, approval of stage gate reviews, providing standardize project timing and finally reporting overall program status. Red, yellow, and green program statuses are used to control program launch progress over all global programs and create a report used in the Key Process Indicator (KPI) review.
- The company supports the project teams by providing detailed training related to the process and software package. The procedures are described in the official, controlled documents. All templates and supporting documentation are stored on SharePoint accessible in the Intranet.

This example of the project launch system is significantly more detailed and focused on activities and reviews embedded in supplier processes and systems. The key activities are presented in the **Error! Reference source not found.**Table 1.

Table 1. Stages of Tenneco Program Launch system.

Stages of Tenneco Program Launch system	**Key activities**
Qualify	Screening business opportunities based on the market research and customer Requests for Information (RFI), proposing an initial design concept, calculating engineering budget (ED&T) for Quote stage

Propose	Design proposal and Bill of Material (BOM), technical presentation, Quote Business Case and Legal Review, Preliminary manufacturing location selection, preliminary manufacturing process flow, Engineering budget (ED&T) for a full program, lunch cost budget, Quote Design and Manufacturing Sign Off (Quote DMSO)
Quote	The customer negotiations, Program team definition, Project timing preparation, Program risk assessment, customer award
Design and Development	Product design activities, design optimisations including simulations, experiments, initial prototypes, and testing. Design risk analysis (DFMEA), DVP&R, BOM, design Verification release DMSO, Plant layout, process flow, PFMEA, supplier sourcing matrix
Design Verification	Design Verification (DV) tools, parts, DV prototypes builds, DV testing, DFMEA updates, Process Validation (PV) documentation release, PV Test plan, supplier nomination letters, manufacturing process development updates, PFMEA updates, manufacturing equipment specification, Pre-production Control Plan, MSA plan
Industrialization & Validation	Manufacturing equipment and tooling fixtures availability, Process Sign off, Run at Rate, PV protypes builds, PV testing and reporting (PVP&R), BOM release, Supplier PPAP, Production Quality Controls, Gage R&R studies and equipment certifications, customer PPAP
Pre-Production	Process Sign-off, Run at Rate approved by customer, Process capability available, Final Customer PPAP approval, recoveries invoiced, sealable pre-production builds
Production	Series production of product per customer orders, long term capability, Lessons learned and Risk assessment, recoveries paid

The research described in the thesis is directly linked to the *Product Launch System* presented above. The topic concerns especially the activity of the product engineering team. Aspects and problems characterized above are crucial to understand how the digital twin concept can be implemented to capture and use knowledge within design and development processes. The documentation of the Tenneco *Program Launch System* is categorized as confidential, therefore following summary is presented:

- The three first stages of the Tenneco *Program Launch System* are targeting at the customer project award. The successful nomination depends on commercial aspects of the quotation and on fulfilment of technical project requirements. The design proposal is prepared basing on the analyses of the provided technical documentation, using as much as possible standard solutions. However, due to different customer requirements and increasing vehicle weight, the results are often based on optimisation of existing standards or even development of especially tailored design solutions. Due to limited time at quoting stage, design optimisation is limited and regularly replaced by different simulation methods. Another task for the *Product Engineering* organisation is estimation of the engineering budget to prepare a design package for quoting purposes. This budget is called ED&T and covers cost of engineering design and testing. The stage of the project also requires program risk assessment related to design, manufacturing, supplier base and commercials.
- *Design and Development* stage is focused on a detailed design of a product basing on the proposal offered in quotation. This stage includes the complete portfolio of engineering tools, starting from CAD and simulations, using proven design standards, analysis of design risks through the DFMEA, and finally manufacturing initial prototypes and performing functional and durability tests. As the outcome of DFMEA and customer input, *Design Verification Plan* (DVP) can be consolidated, and the test plan is prepared. Finally, the optimal design with manufacturing processes is done by *Design for Manufacturing and Assembly* workshops and consensus achieved during the *Design Manufacturing Sign Off* meeting is established. The critical deliverable is the *Design Freeze*, which is an agreement between the customer and supplier on proposed design and allowance to progress with the DVP testing. It must be stressed that some

customers are very strict and formal on the *Design Freeze*, but for some customers, drawing approval or e-mail confirmation is a standard method.

Each of presented approaches to Program Launch is characterized by the same target of achieving product quality of program launched on serial production line. The analysis of all process descriptions was conducted and presented in the following Table 2.

Table 2. Comparison of Program Launch Systems

AIAG APQP Process (the American approach)	**VDA MLE Process (the German approach)**	**Tenneco process**	**Additional comments related to Tenneco process**
	ML0 Innovation release for full production development	New Technology Introduction (NTI) Process	Stand-alone process focused on new technology development
Plan and define program	ML1 Requirements management for the contract to be issued	Qualify	Business opportunities defined
	ML2 Specifying the supply chain and placing the order	Propose	Quote preparation and internal Customer Quote Approval (CQA)
		Quote	Quote proposal and customer negotiations
Product Design and Development	ML3 Release of technical specification	Design and Development	Product designs and manufacturing processes developed to production intent, critical suppliers selected

Process Design and Development	ML4 Completion of production planning	Design Verification	Production intent product designs and manufacturing processes verified, remaining suppliers selected
Product and Process Validation	ML5 Parts and production tools and production facilities are available	Industrialization & Validation	Industrialization of the product tooling, equipment and gages. Production validation internally and at suppliers
	ML6 Process and product approval	Pre-Production	Run at Rate demonstrated, shipment of saleable pre-production product per customer ramp-up plan
Production	ML7 Project completion, transfer to production, start requalification	Production	Series production of product per customer ramp-up plan, completion of product launch activities
Feedback assessment and Corrective Actions			Lessons Learnt feedback implemented in two steps of Program Management and in two Lessons Learnt in FMEA process

1.4. Shock absorber and stabilizer bar functions and design

The PhD thesis concentrates on digital twins elaborated for two components of a shock absorber:

- a stabiliser bar bracket
- a piston rod.

In this part of the thesis the description of the shock absorber and stabiliser bar functionalities is provided. The vehicle suspension types vary between front and rear vehicle axles. For the front suspension typical design solutions are McPherson unit, double wishbone or multilink for more demanding vehicle requirements. There are more solutions usually available for the rear suspension. Typically, the following solutions are implemented multi-link, double wishbone, trailing arm, semi-trailing arm, five link and trapezoidal (Kline, 2018). The main functionality of shock absorber is delivering damping characteristics in both directions of suspension movements: rebound and compression. In such cases the damping characteristics need to be defined properly for specific vehicles in order to achieve a compromise between ride, handling and comfort (Jadhav et al., 2012). These characteristics are crucial for vehicle driving dynamics and also for safety of passengers (Skačkauskas et al., 2016).

A typical double tube shock absorber construction was presented in Figure 11 and typically consists of (Dixon, 2007; Kline, 2018):

- Upper and lower mounting used as connection to the vehicle suspension. There are multiple designs utilized for mounting, typically loop and bushing, rod stem end and brackets
- Dust shield, which is the outside part covering the hydraulic system protecting the upper part of shock absorber against contamination from the road
- Piston rod connected with piston and valving system, which are responsible for creating proper damping force characteristics
- Rod guide and oil seal assembly responsible for the guidance of the piston rod during movement and sealing the shock absorber from the external environment
- Relief valve used to transfer hydraulic oil from the working chamber to the reservoir chamber closed by the reservoir (also called the reserve) tube

- Nitrogen gas, which is added to create initial gas spring force and reduce the negative effect of the aeration

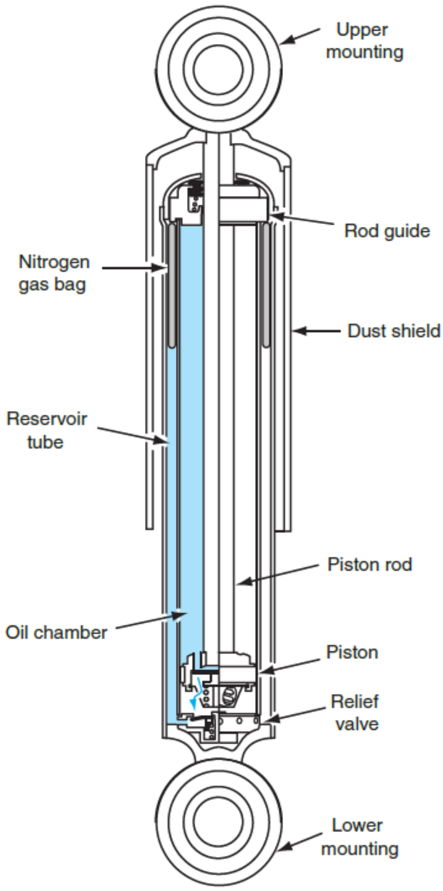


Figure 11. Double tube shock absorber. (Kline, 2018)

The shock absorber used in McPherson suspension is named *strut* and it delivers additional functionalities in comparison to the standard shock absorber, mainly related to transferring the suspension loads. The mounting points are designed to withstand loads and fit into McPherson suspension. An example of the strut design is presented in Figure 12.

Anti roll bar, also called a stabilizer bar supports the design of the vehicle suspension. The primary function of the stabilizer bar is minimizing the body roll motion during cornering manoeuvres. As the result, the vehicle handling is improved. The stabilizer bars are used mainly for front suspensions but can be also implemented as a part of the rear suspension design. The anti-roll bar is connected directly to the strut shock absorber through a dedicated bracket. Passive stabilizer bars are produced as hollow or solid tubes and are of different shapes. The key design parameter of the passive anti-roll bar is stiffness which needs to be correctly designed for a specific vehicle ride, handling and comfort requirements (Sharma et al., 2015).

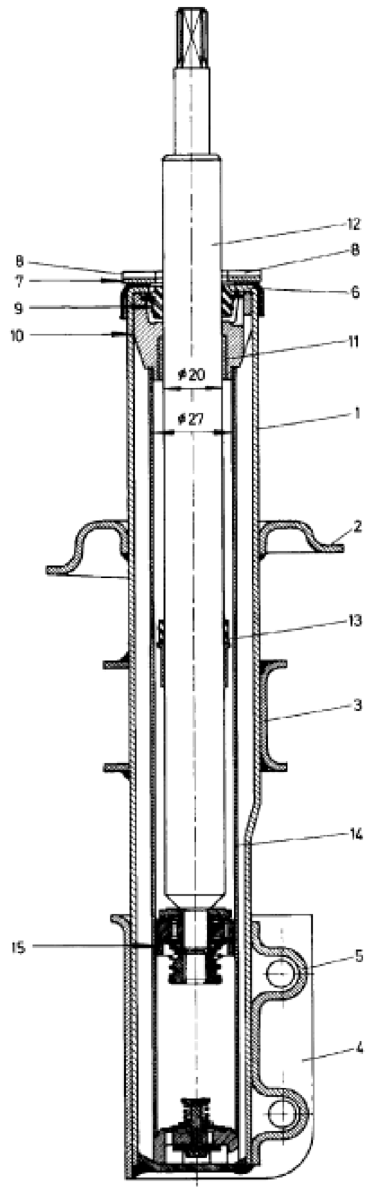


Figure 12. Strut design section.(Dixon, 2007)

The typical design of the passive stabilizer bar is presented in Figure 13. Further enhancement of the suspension performance can be achieved by the use of the active anti-roll bars equipped with hydro pneumatic or hydraulic actuators that allow change anti-roll bar characteristics actively (Zulkarnain et al., 2012).

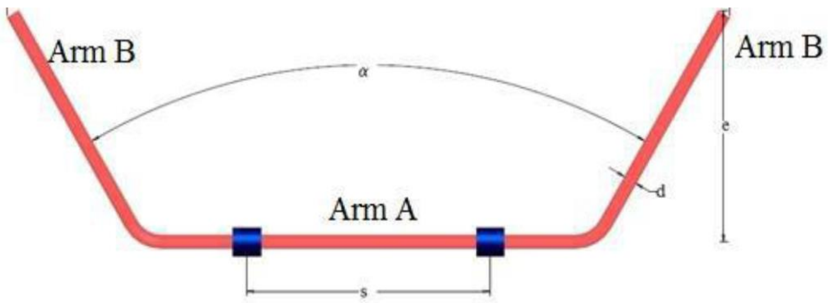


Figure 13. Design of the anti-roll bar (stabilizer bar) (Sharma et al., 2015)

As it was mentioned, within the scope of the doctoral thesis, the following two elements are investigated:

1. The stabilizer bar bracket, called *stabilizer bracket or stabi bracket.* It is presented as element 3 in Figure 12 and as a stand-alone component in Figure 14. The stabi bracket transfers load from the stabilizer bar, also called the anti-roll bar, which connects both sides of the suspension
2. The piston rod is presented as the component 12 in Figure 12. The main task of this element is allowing telescopic movement of the shock absorber, but also transferring side and axial loads.

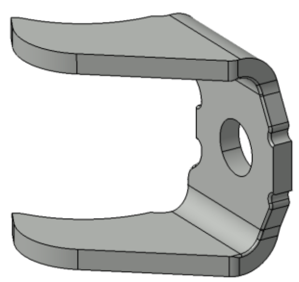


Figure 14. The stabilizer bar bracket.

2. The theory of digital twin and industrial revolutions

2.1. Industrial revolutions and technologies supporting Industry 4.0

The development of the globally understood industry is historically divided into four periods triggered by industrial revolutions (Figure 15). The First Industrial Revolution started in the 1800s with implementation of mechanisation and steam power supporting manufacturing operations (Papulová et al., 2022). The main innovation was transition from hand-made manufacturing to implementation of mechanised processes (Groumpos, 2021).

The second industrial revolution started in 1870 (Groumpos, 2021). The key element for that period is the use of electricity in manufacturing also in daily life. However, the most famous breakthrough is implementation of the assembly line introduced by Henry Ford for automobile manufacturing.

The Third Industrial Revolution started a few years later after the end of the WWII and brought first of all semiconductors and computers to manufacturing processes. The innovation that time was also automation were and robotisation of manufacturing processes (Vaidya et al., 2018).

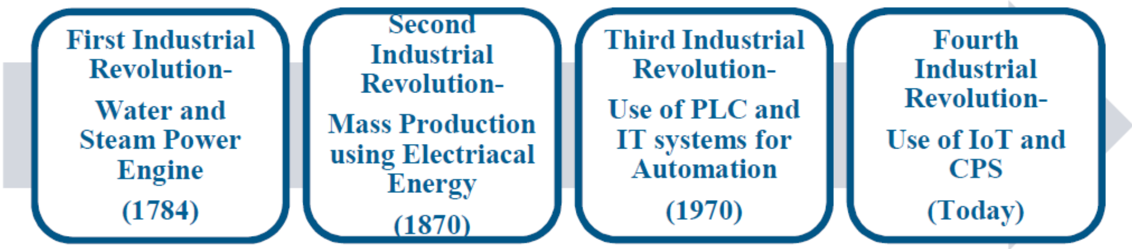


Figure 15. Four Industrial Revolutions (Vaidya et al., 2018)

Currently, the Fourth Industrial Revolution is being observed. This period started more than 20 years ago. Industrie 4.0 concept was created at Hannover MESSE in 2011, mainly based on the Bosch company presenting their ideas of new technologies integration into manufacturing processes. It was especially visible in the area of information and communication (Winter, 2022). Well known description of the Industry 4.0 can be found in book *The Fourth Industrial Revolution* by Klaus Schwab (Schwab, 2017). Professor Schwab described not only the technologies supporting the industrial revolution, but also highlighted potential challenges. Germany is considered to be the first country strategically interested in digitalization of manufacturing processes (Gudanowska, 2017). The key German trade association defined Industry 4.0 as follows (Uhlmann et al., 2017):

“The term Industrie 4.0 stands for the fourth industrial revolution, the next stage in the organisation and control of the entire value stream along the life cycle of a product. This cycle is based on increasingly individualised customer wishes and ranges from the idea, the order, development, production, and delivery to the end customer through to recycling and related services. Fundamental here is the availability of all relevant information in real-time through the networking of all instances involved in value creation as well as the ability to always derive the best possible value stream from data. Connecting people, objects and systems leads to the creation of dynamic, self-organised, cross-organisational, real-time optimised value networks, which can be optimised according to a range of criteria such as costs, availability, and consumption of resources.”

The digitalisation of manufacturing processes appeared to be interesting in other countries and even regions bringing other approaches under different names, different purposes, and different implementation scope. For example, China came up with “Made in China 2025”, the United Kingdom started in 2013 “Future of Manufacturing”, European Union proposed “Factories of the Future” in 2014, and U.S, started “Manufacturing USA” in 2014. A commonly used term in USA to describe the implementation of new technologies into manufacturing is called “Smart Manufacturing”. The Polish government established a foundation “Platforma Przemysłu Przyszłości” (https://przemyslprzyszlosci.gov.pl/, 2023), that provides training materials, support digital transformation, implementation of digital solutions and services, as well as, manages with experts base.

European Union initiative resulted in establishment of The European Factories of the Future Research Association (EFFRA), which is a non-profit, industry-driven association promoting the development of new and innovative production technologies. The standardisation aim was conducted by two well-known standards organisations, the International Organization for Standardization (ISO) and the International Electrotechnical Commission (IEC) formed a team in 2021 and proposed a definition under the new name “Smart Manufacturing”.

"Manufacturing that improves its performance aspects with integrated and intelligent use of processes and resources in cyber, physical, and human spheres to create and deliver products and services, which also collaborates with other domains within enterprises' value chains.

Note 1: Performance aspects include agility, efficiency, safety, security, sustainability, or any other performance indicators identified by the enterprise.

Note 2: In addition to manufacturing, other enterprise domains can include engineering, logistics, marketing, procurement, sales, or any other domains identified by the enterprise." (Winter, 2022)

The Fourth Industrial Revolution is a process to implement new and modern technologies into manufacturing operations, initially experts and scientists were focused only on typical manufacturing operations, but it must be stressed that all surrounding processes include marketing, sales, engineering, logistics and quality (Jiao et al., 2021; Ramezani & Jassbi, 2020). The list of high-end technologies that support Industry 4.0 varies from article to article, within professional books and professional materials. These differences are caused by the scope of implementations, technologies and personal preferences. Manufacturing-oriented engineers focus more on the technologies directly supporting production lines, while IT specialists focus more on the IT solutions and cyber security. One of the most interesting collections of the technologies involved in the Industry 4.0 was presented by Menezes as graphics shown in Figure 16. (Menezes et al., 2019)

Figure 16. Industry 4.0 elements (Menezes et al., 2019)

Another interesting representations of technologies was proposed by Uhlman, Hohwieler and Geisert as the scheme presented in Figure 17.

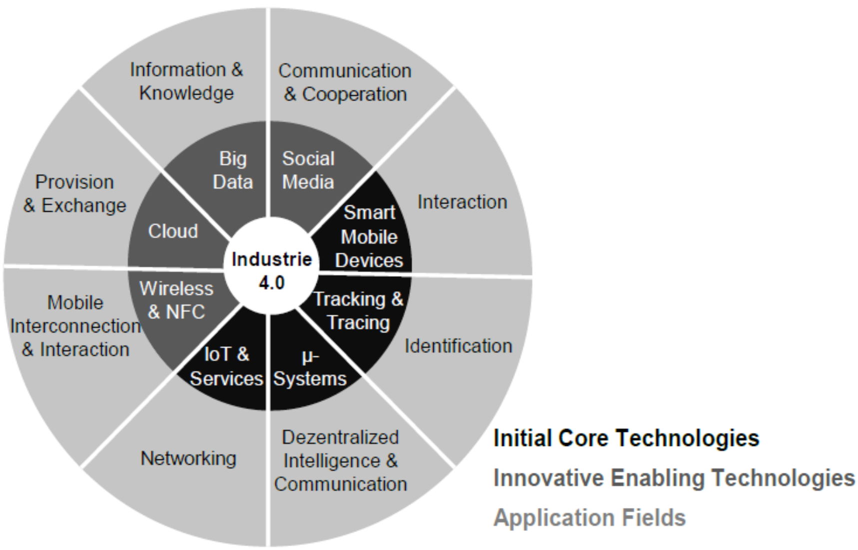


Figure 17. Technologies and their application fields of Industrie 4.0 (Uhlmann et al., 2017)

There is a large number of Industry 4.0 definitions and technologies supporting this concept therefore several sources (https://www.i-scoop.eu/industry-4-0/, 2023) have been analysed and gathered in an overview table (Figure 18, Figure 19).

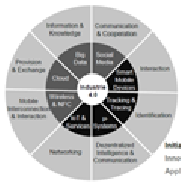
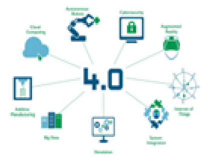
				
Categories	1	2	3	4
Simulation		Advances Analytics	Simulations	Simulations
Advanced analytics				
Cybersecurity		Cybersecurity	Cybersecurity	Cybersecurity
Cloud	Cloud	Cloud computing	Cloud computing	Cloud computing
Big Data	Big Data	Big Data	Big Data	Big Data
Autonomous Robots		Autonomous Robots	Autonomous Robots	Autonomous Robots
IoT & IoS	IoT & Services	IoT	IoT	IoT
Additive Manufacturing			Additive Manufacturing	Additive Manufacturing
Augmented Reality			Augmented Reality	Augmented Reality
Smart Devices		High-End sensing		
Smart Devices	Wireless & NFC			
Smart Devices	Smart Mobile Devices			
Smart Devices	Micro systems			
System Integration		Systems Integration	Systems Integration	Systems Integration
System Integration	Social Media			
Smart Devices	Tracking & tracing			
Cyber Physical Systems		Interaction Human-Machine		

Figure 18. Comparison of elements of Industry 4.0 – part 1.

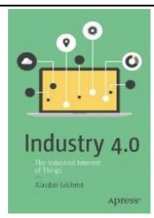
				
Categories	5	6	7	8
Simulation	Simulations	Simulations	Simulations	Simulations
Advanced analytics	AI			
Cybersecurity	Cybersecurity	Cybersecurity	Cybersecurity	
Cloud	Cloud computing	Cloud computing	The Cloud	Cloud computing
Big Data	Big Data	Big Data	Big Data & Analytics	Big Data
Autonomous Robots	Advanced Robotics	Autonomous Robots	Autonomous Robots	Autonomous Robots
IoT & IoS	IoT	IoT	IoT	IoT, IoS
Additive Manufacturing	Additive Manufacturing	Additive Manufacturing	Additive Manufacturing	Additive Manufacturing
Augmented Reality	Augmented Reality	Augmented Reality	Augmented Reality	Augmented Reality
Smart Devices				
Smart Devices				
Smart Devices				
Smart Devices				
System Integration	Integration	Systems Integration	Horizontal and Vertical System integration	
System Integration				
Smart Devices				
Cyber Physical Systems				CPS

Figure 19. Comparison of elements of Industry 4.0 – part 2.

It must be noted that there is lot of synergies between Industry 4.0 and Lean methodology. The Lean concept is widely used in manufacturing and service processes and the key approach is to improve processes by eliminating waste and simplifying manufacturing (Earley, 2016; Elafri et al., 2022; Liker, 2004; Palange & Dhatrak, 2021). The main aspects of the Industry 4.0 also strongly support waste elimination. They are usually integration of such technologies as Big Data, IoT, CPS, cloud computing and smart sensors (Elafri et al., 2022; Mahmoodi et al., 2022).

The industry 4.0 must be seen as a revolution bringing also social effects. The implications of Industry 4.0 on society have positive impact mainly related to new job opportunities, collaboration between companies and higher productivity. The negative impact is observed as unbalanced development, income polarisation and too fast growth of technology (Grybauskas et al., 2022).

The term Industry 5.0 appeared in the literature in 2018 (Barata & Kayser, 2023). Industry 5.0 is able to overcome challenges of Industry 4.0. The key aspect of the new approach is a human-centric vision of the industrial revolution, using collaborative robots, predictive and prescriptive maintenance and cyber-physical cognitive systems (Golovianko et al., 2023; Huang et al., 2022; Khan et al., 2023; Ordieres-Meré et al., 2023)

The implementation of a digital twins involves many of technologies associated with the Industry 4.0. The crucial role is played by data collection and transfer. The following technologies are crucial for the digital twins implementations:

1. Big Data technologies deal with large data structures that cannot be managed by traditional solutions like databases and stand-alone data processing methods. Typically big data includes traditional data sources like text, forms, pictures, videos but also is a result of data gathering with the use of modern technologies and applications like IM chats, blogs, data from a variety of sensors. (Gajdzik & Grabowska, 2018; Gilchrist, 2016, 2016; Khalid & Yousaf, 2021).
2. Big data analytics goal is to understand trends, and correlations in data. Big Data analytics are usually available as open-source algorithms. (Khalid & Yousaf, 2021).
3. Another technology supporting the concept of Industry 4.0 is Cyber-Physical-Systems (CPS). It is characterized as a physical system that combines physical asset

with a cyber system. (Gilchrist, 2016). CPS uses the Internet of Things for communication.

4. IoT – The Internet of Things is treated as one the core technologies of the Industry 4.0 (Bartodziej, 2016). IoT is understood as the connection of smart devices into the Internet with the ability to deliver powerful datasets for further analysis (Bartodziej, 2016; Hermann et al., 2015).
5. Cyber Security. The industry 4.0 involved a lot of new technologies connected into Internet and continuously exchanging data. In this environment, cyber security is becoming critically important for business continuity. Cloud, IoT and CPS are all based on data, data become extremely valuable asset. The safety of information resources can be described as a "process of support for confidentiality, integrity and accessibility of information"(Kapitonov et al., 2019).
6. Blockchain is a technology that was developed by Satoshi Nakamoto to ensure a mathematical foundation for Bitcoin cryptography. The technology is not only limited to cryptocurrency, but is also used for traditional e-banking transactions, as well also for securing data shared through smart applications (Di Piero, 2017).

2.2. Simulation history

Simulations became a standard tool in 21st century. Such approaches are widely used not only in scientific research but became common and mandatory methods in any kinds of research or development processes, including manufacturing. Nowadays, simulations support scientists, engineers, and experts in project development by providing decisions on design concept selection, geometry, or design parameters optimization. A few years ago, there was a long debate whether simulations became radical innovation in science (Borrelli & Wellmann, 2019). Simulations are also crucial stage of manufacturing process.

One may suppose that the simulation history started parallelly to computer development, what allowed complex mathematical modelling and calculations. However the history of simulations leads back to 1770 when Buffon's needle problem was solved by means of Monte Carlo simulation (Goldsman et al., 2010; Wang & Wang, 2014). The problem is related to geometric probability, and it became an example of implementation of Monte Carlo simulation by randomly throwing needles onto plane with parallel, equally spaced lines. Further work on this problem was done by Laplace, therefore name of Buffon-Laplace needle problem is commonly used in literature. The concept of simulation was used by William Sealy Gosset to complete his study on probability density function of t-distribution. In this case the history of simulations is connected with Six Sigma methodology, where t-distribution is frequently used for population means comparisons.

The development of numerical simulations started with the first electronic computer ENIAC (Electronic Numerical Integrator and Computer) (Borrelli & Wellmann, 2019). The computer was developed in 1943-1945 and the simulation were used for ballistic research, hydrogen bomb and weather forecast calculations. Further development and availability of computers led to define new simulation models and methods. Keith Douglas Tocher developed General Simulation Program (GSP) in 1960 as the general-purpose simulator of an industrial plant. In 1964 Tocher presented another method called activity- cycle diagram (ACD), that became standard in simulation teaching in United Kingdom.

Next years, IBM company became also involved in development of numerical simulation approaches. In early of 1960's IBM designed General Purpose Simulation System (GPSS) that supported simulation of urban traffic control, airline reservations and telephone call switching. To minimize complexity of simulation programming, the block diagram interface was introduced. The next big step in the simulation modelling was SIMSCRIPT released in 1963. Alternatively, Royal Norwegian Computing Centre developed SIMULA in 1961, becoming one of the most important and well-known programming languages in computing history. Conway, Maxwell and Johnsons divided simulation problems into model construction and model analysis. The problems related to the simulation models include files management, computer memory management, time advance mechanism, control of simulation error and modularity of simulation models. The model analysis includes determination of simulation equilibrium, estimation of precision at equilibrium, comparison of alternative system simulations. In years 1970-1982 further development of simulation methods was observed, leading to release of new software or methods, for example SIMSCRIPT II.5, or processors SIMPL/I, SIML/I, SIMPL/I X. The important aspects of these methods are a random number of generations, event graphs, verification and validation and output analysis. The key point was still focused on random data generators, delivering methodologies supporting also one-dimensional and multidimensional random processes.

Regarding output analysis several methods were evolved, supporting bias, confidence interval estimations, statistical ranking and selection methods, and variance reduction.

This simulation development was limited due to computing capabilities. The next era of simulations is related to development of several simulation packages, linked to other CAE, and CAD programs, as well as the use of artificial intelligence methods [36]. Nowadays, a significant step is democratisation trend in simulations [35], which includes such aspects as education, presenting best practices and successful projects, understanding challenges, and facilitating partnership. Simulations technics became the essential tool in science and engineering. Software providers are offering specialized software solutions dedicated to different types of simulations, some of them are described below:

- CFD – Computational Fluid Dynamics can predict fluid flow, heat and mass transfer and other related phenomena (Mrope et al., 2021).
- FEA – Finite Element Analysis is simulating behaviour of investigated element or assembly under certain conditions. FEA is based on finite element method (FEM) and is used to assess potential problems in design, such as stress or strain rates.
- MBD - Multibody Dynamics is focused on analysis of mechanical systems in given application conditions. MBD simulations allow to investigate kinematic and dynamic motion of mechanical and mechatronic systems in order to understand motion, coupling forces and stresses. One of the most popular software packages for MBD simulations is Simulia delivered by Dassault Systems. Multibody dynamics simulations are commonly used in automotive sector, especially to analyse and optimise performance of vehicle suspension systems, or single components of suspension, for example cast iron knuckle (Reza Kashyzadeh et al., 2022). Another example within automotive industry is Disc Brake System, where analysis is related to vibration of a brake disk what can influence comfort and even safety of bike or e-scooter (Joerger et al., 2021).

The next step of the simulation development is related to Industry 4.0 concept, where a digital twin idea was developed. Engineers and scientists have been already using simulations for decades and there is enormous number of interesting use-cases within different industries or science disciplines. Digital twin is not only creating a virtual copy of an existing asset, but also ensuring correct modelling based on specific characteristics. It might be observed a trend to overuse name of digital twin, but this concept gives approach for modelling trust and further democratisation of simulations (Wright & Davidson, 2020).

The consecutive industrial revolutions and simulation development over time was compared. From one side the simulations are using technologies developed as result of industrial revolutions, but from other side the simulations are supporting development of industrial revolutions. The comparison prepared by the author of the thesis is collected in Table 3.

Table 3. Industrial Revolutions and history of simulation.

Industrial revolutions	**Industry 1.0**	**Industry 2.0**	**Industry 3.0**	**Industry 4.0**	**Industry 5.0**
Year estimation	**1800**	**1900**	**2000**	**2010**	**2020**
Industry elements influencing simulations	Water and steam power, mecha-nization	Mass production, electrification, assembly line	Use of computers	Simulations, Digital twins, IoT, Cloud computing, CPS	Artificial Intelligence, human-robot collaboration
Simulation methods	Monte Carlo simulations, analytical methods, development of mathematical algorithms as base for simulations		Use of computers in simulations, development of simulation software, manual correlation of simulations	Simulations as base for Digital Twins, Simulations integration with other systems	Simulation processes supported by AI leading to proposals of solutions

2.3. Digital twin

Many researchers defined the beginning of a digital twins in 2002, when Professor Michael Grieves from the University of Michigan, presented a concept of the digital twins for the Product Lifecycle Management centre. That time, the concept was not directly implemented due to the lack of sufficient technology for data acquisition and processing (Liu et al., 2023; Shao et al., 2019), but there were other reasons to develop a new approach. The presented concept covered the following aspects: physical space, virtual space, and data exchange between physical and virtual spaces. The most known case related to the digital twin is dated for April 1970, when NASA developed a rescue mission for Apollo 13. It was based on the digital twin of a spaceship. The next case is also coming from NASA in collaboration with Air Force Research Laboratory. The goal was to create the digital twin of an aircraft to optimise its crucial parameters (Pang et al., 2021; Piromalis & Kantaros, 2022). Professor Michael Grieves published in 2012 white paper on digital twins, including characteristics of the real and virtual spaces and connection between them (Piromalis & Kantaros, 2022). Nowadays, the high interest in digital twin concept and implementations is visible. The systematic review of papers on this topic over the years was presented in the paper by (Liu et al., 2023). The following graphical summary, coming from this paper, is shown in Figure 20.

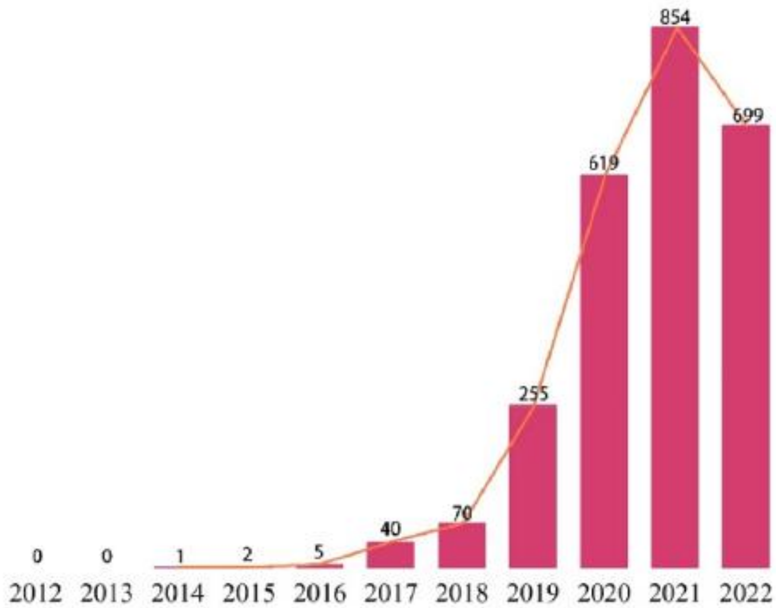


Figure 20. Number of digital twin papers over the years (Liu et al., 2023).

The approach to the digital twin concept went through evolution over the years. Starting from 2019 a significant increase of papers related to this topic is visible. From the level of 255 in 2019 to 724 annually in years 2020 – 2022. There are several definitions of digital twins presented by different scientists, experts, or companies. They are based on numerous backgrounds and implementation targets. In 2020 a Digital Twin Consortium was founded. The goal was to establish a collaboration between corporations and governmental organisations to support the development and implementation of digital twin technology. The steering committee of the consortium includes well-known companies like Dell Technologies, GE Digital, Microsoft, Northrop Grumman, and Johnson Control. They defined the digital twin as a virtual representation of real-world entities and processes. Both instances must be synchronized to provide high fidelity of the virtual representation. It is important that the Digital Twin Consortium defined key characteristics of the approach (Biller & Biller, 2023):

1. physical representation (a factory)
2. virtual representation (assets and manufacturing processes)
3. synchronization of physical and virtual representations at given frequency and fidelity
4. the ability to learn in order to improve a virtual model and physical representation

It is also important to study the regulation ISO 23247:2021 which describes *Automation systems and integration — Digital Twin framework for manufacturing*. This document provides a framework for digital twin characteristics within a manufacturing environment including processes, facilities, environment, product, and supportive documentation. As usual ISO defined also crucial terms and abbreviations. The digital twin according to ISO is specified as follows (International Organization for Standardization, 2021):

- *digital twin <manufacturing> fit for purpose digital representation of an observable manufacturing element with synchronization between the element and its digital representation,*
- additionally digital representation is defined as *data element representing a set of properties of an observable manufacturing element.*

Other papers include the following definitions of digital twins:

- *A digital model is a simplified representation of a real system and process, with the characteristics which reflect the properties and explain the behaviour of the* *real manufacturing system. It represents a partial description of the real system, because it is made for a specific purpose and therefore cannot include all the details of the real system.* (Resman et al., 2021)

- *A digital twin (DT) is a digital representation of a real-world entity or system. Usually, DT is used in the context of Internet of Things (IoT), where twins are linked to real-world objects and offer information on the state of the counterparts, their functionalities and response to environmental changes. In industry DTs are mainly responsible for virtual description of physical devices and materials, but also for monitoring and analysis of data gathered from online sensors during the process.* (Rauch & Pietrzyk, 2019)
- *A digital twin is a machine interpretable representation of a real-world entity or system. It represents the structure, behaviour, current state and historical states of a system for query-based interaction and what-if analysis.* (Barat et al., 2019)
- *A digital twin is the manifestation of the physical system in the digital world that can be used for various purposes. It can provide an environment for monitoring, testing, planning, and decision-making without real physical or time constraints. Besides the spatial representation* (Shao et al., 2019)
- *The virtual representation of the product is created and tested to validate performance under expected use conditions. Production is optimized through manufacturing process simulations where any sources of error or failure can be identified and prevented before proceeding to physical production* (Pang et al., 2021)

Analysing presented exemplary definitions of digital twins one can formulate the following conclusions:

- A digital twin is a digital representation of a physical process or asset, such as a physical entity or system
- A digital model is simplified representation of a real item, focusing on characteristics which are important for the analysis
- A virtual representation and physical asset are connected through data exchange

- A digital twin is usually equipped with other Industry 4.0 elements like IoT, sensors
- A digital twin is implemented to perform the analysis and optimisation under expected conditions on the virtual representation before implementing a determined change to the real world.
- Definitions are concentrated mainly on manufacturing systems and equipment or maintenance procedures

The digital twin exemplary applications are implemented in the different industrial sectors. It is related to different characteristics of real assets and finally different purposes of the implementation. Piromalis D. et al. present in their paper an overview of specific application domains, and split it up into the following 3 aspects (Piromalis & Kantaros, 2022):

1. Application domains:
   - Industrial production – monitoring, coordinating and control of manufacturing processes and machines
   - Healthcare – digital monitoring and modelling of a human body, supporting studies on various diseases, medicine formulas or medical devices
   - **Automotive – design of new products and control, or optimisation of a production line**
   - Smart Cities – directly connected to IoT to increase Smart Cities efficiency, by improving resources utilization or controlling financial indicators
   - Agriculture – maximizing profits and failure avoidance based on controlling tools or supplies sources through sensors and IoT.
2. Process function:
   1. **Design – supporting design verification, inspection of 3D assembly to check fit of components or assemblies**
   2. Diagnostics – simulations run to understand various signals like forces or stresses applied to the complete assembly or individual parts
   3. Prediction – forecasting system or design element behaviour based on an existing digital model, can be used also for prediction of lifetime of manufacturing equipment, as well as for product lifetime

   4. Maintenance – analysis of machinery performance to provide to personnel specific maintenance actions
3. Application category:
   1. **Product twins – design optimisation activities elaborated on the basis of a nonphysical prototype, what let us reduce cost of physical prototypes**
   2. Process twins – development of optimised manufacturing process under various condition cases. The digital twins can be created for individual production equipment or complete set of machinery
   3. System twins – virtual systems allow to optimize processes in a single system and the entire system. In this case the acquisition of a large number of system information is required.

The overview presents a variety of possibilities of digital twin implementations. The papers and commercial information review lead to the following examples of digital twin applications:

- Use of Finite Element (FE) methods as the base for a digital twin application in the area of metal forming industry (Ralph et al., 2020) or structural life prediction (Tuegel et al., 2011)
- Digital Twin used to design the manufacturing process of flat products in the form of hot and cold rolled thick and thin strips (Rauch & Pietrzyk, 2019)
- Digital twin in analysing complex business systems on the basis of an hypothetical university to improve its academic and research ranking (Barat et al., 2019)
- Developing a digital twin and digit thread framework for an Australian complex shipyard that contains an huge area with dry docks, slipways, warehouses, painting facilities and other assets (Pang et al., 2021)
- Integration of digital twins with Artificial Intelligence methods to describe, predict and optimize a supply chain (Biller & Biller, 2023)
- Digital twin application for robotic system as a target to propose solutions for real-time scheduling decisions and forecasting (Coito et al., 2022)
- Several cases of digital twin implementations in healthcare, as exemplary applications of an agent-based digital twin to manage severe traumas (Croatti et al., 2020)

The definitions of digital twins include a digital model as a crucial part of this concept. It is important to clarify a difference between virtual representations of real assets and the digital model. Typically, the digital model is understood as a digital representation of an existing real object, but there is not a clear definition of data exchange between the physical and virtual side. The digital twin is also virtual representation of the physical assets but important is that they include bi-directional data flow between both units. Moreover, in the bibliography there is also a definition of so-called a digital shadow. It is a case when an one-directional data exchange is defined (Shao et al., 2019). Such approach is not often described and tested. It should be stressed that in many cases, the name of the digital twin is used incorrectly since it means the digital model without properly defined data exchange. On the basis of the analysis of different definitions, case studies and demands requirements, as well as some characteristic for an automotive process, the following definition of the digital twin was established and accepted in the thesis:

The digital twin concept is a virtual representation of a physical asset reflecting key characteristics for a given study. A determined prediction error is known and accepted for purposes of the study. At least one-way data exchange is provided to improve the predictive ability of the model.

3. Description of the research problems in a context of an automotive market

3.1. Characteristics of the automotive market

Nowadays, the automotive industry is passing through several challenges and transformations. The trend of vehicle electrification is a key driver of changes that are influencing the design and development of the systems and components used to build the vehicles. The weight of contemporary electric vehicles, hybrid and plug-in hybrid vehicles has increased significantly. Reasons are the weight of the batteries and also the bigger number of new, additional systems. The data presented in European Vehicle Market Statistics from 2021/22 prepared by The International Council on Clean Transportation (ICCT) (The International Council on clean transportation, 2021) shows directly these trends. This report combines data from the European Union, the United Kingdom and four members of EFTA (European Free Trade Association). Figure 21 presents that both plug-in hybrid and battery electric vehicles are only around 2% of sales share in 2014-2015 in a segment of passenger cars. The period of 2017-2019 brought a increase to the level of nearly 6% in 2019. The percentage of electric vehicles increased significantly in 2020 reaching the level of nearly 14%.

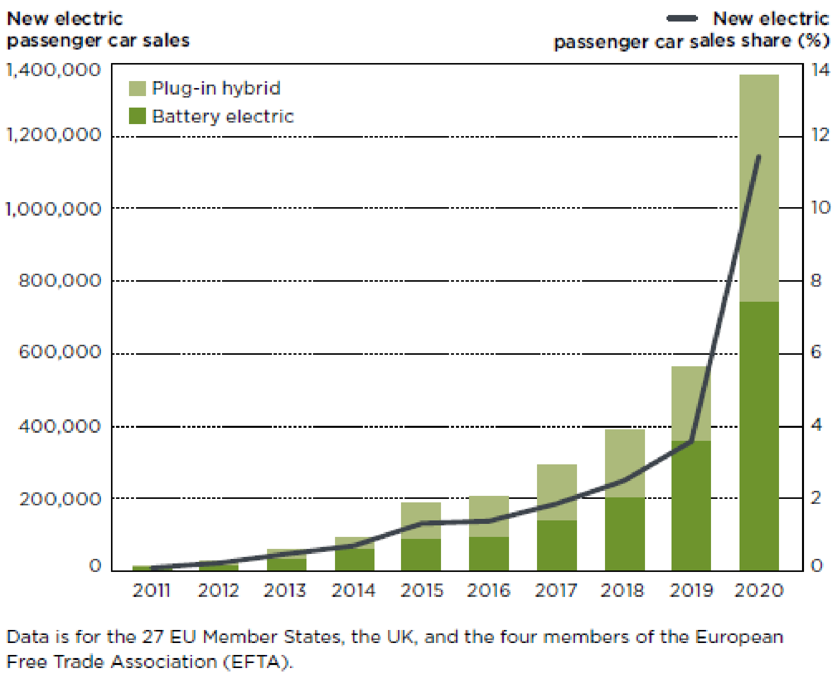


Figure 21. New electric passenger car sales over years. (The International Council on clean transportation, 2021)

Taking into account another report prepared by the European Automobile Manufacturers' Association (ACEA) for 2022/2023 (European Automobile Manufactures'Association (ACEA), 2022) that covers only European Union market, similar trends are observed.

Figure 22 presents fuel type share over 2018-2021, where total alternatively powered vehicles in 2018 took only 7.7%, with a slight increase in 2019 to 10.6%. The following two years brought also significant increases leading to 24.5% in 2020 and 40.4% in 2021, where 9.1% are battery electric and 8.9% is plug-in hybrid vehicles.

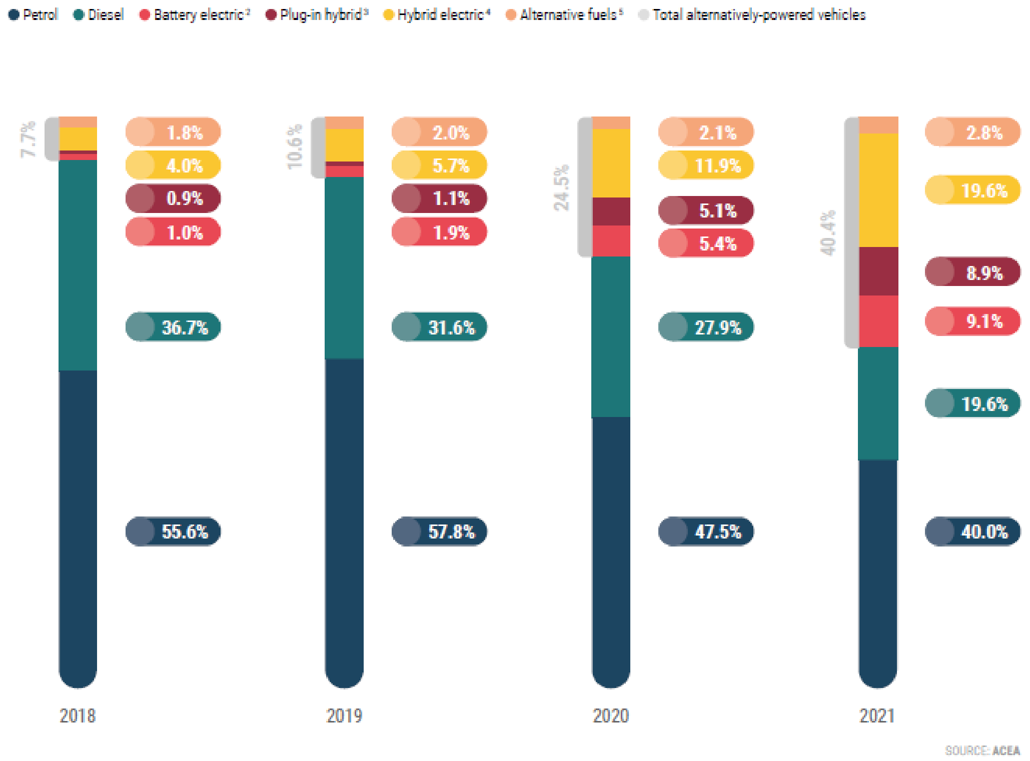


Figure 22. New cars in the EU by fuel type (European Automobile Manufactures'Association (ACEA), 2022).

As already mentioned, the battery weight is directly influencing the total vehicle weight, based on the ICCT report (The International Council on clean transportation, 2021) plug-in hybrid results also in the highest vehicle weight, and the battery electric vehicles are taking the second place. The weight increase of the hybrid vehicles having relatively small battery packages is noticeably less. Figure 23 presents vehicle mass evolution over the year from 2012 to 2020, and the following conclusions can be taken:

- One can observe the increase of weight over the years for all types of power train, except hybrid electric, which probably is related to hybrid systems efficiency improvements
- Hybrid electric is lighter around 200-300 kg than Diesel engine vehicles in 2020
- Battery electric and diesel power train are similar in weight
- Plug-in hybrid is the heaviest type of power train, being more than 200kg heavier than battery electric vehicles.
- Extreme difference of around 600 kg exists between gasoline and plug-in hybrid vehicles.

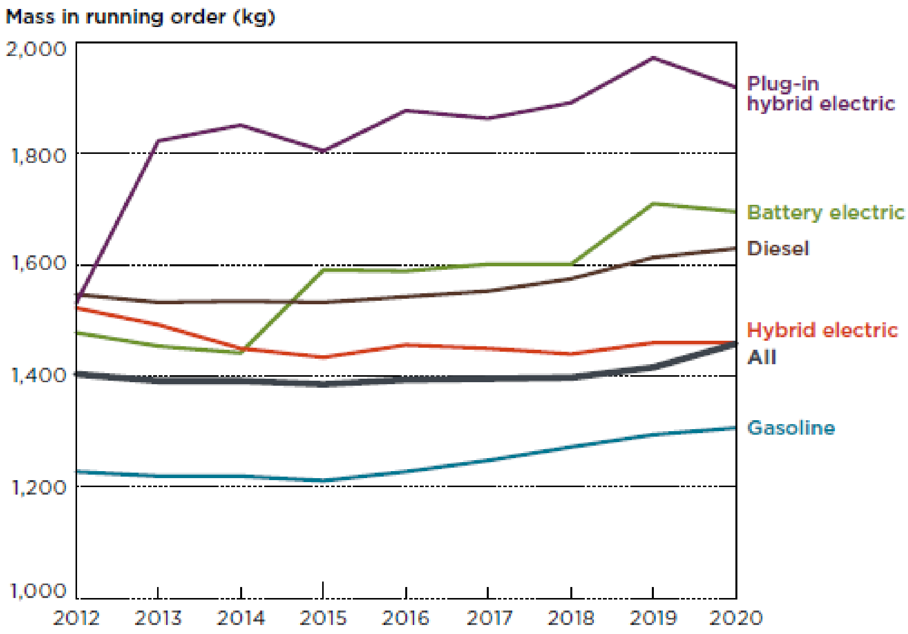


Figure 23. Average mass in running order of new cars registrations in the EU and UK by power-train type (The International Council on clean transportation, 2021).

A comparison between common cars is presented in Table 4. Both vehicles are similar in size, even battery electric Enyaq (https://ev-database.org/car/1280/Skoda-Enyaq-iV-80) is slightly smaller than Kodiaq (https://www.automobile-detail.com/skoda-kodiaq-1-5-tsi-greentech-act-style-business-car-technical-specifications-2/). The comparison of vehicle weights provide opposite conclusion as the weight of Skoda Kodiaq with petrol engine is 1507 kg, weight of Enyaq is 2090 kg, what gives difference of more than 500 kg. The vehicle weight increases of 300-500 kg what gives significantly higher load requirements for all suspension components, including the shock absorber and consequently leads to a selection of bigger tube sizes, material thicknesses and higher material grades.

Table 4. Example of vehicle weight.

Vehicle	Picture	Vehicle parameters	Weight
Skoda Kodiaq		Length 4697 mm Height 1655 mm Width 1882 mm Wheelbase 2791 mm Rear track 1576 mm Car weight 1507 kg	1507 [kg]
Skoda Enyaq		Length 4649 mm Width 1879 mm Width with mirrors 2148 mm Height 1616 mm Wheelbase 2765 mm Weight Unladen (EU) 2090 kg	2090 [kg]

The electrification trend is not the only one aspect responsible for the increase of the vehicle weight. Based on the ICCT report (Figure 24) (The International Council on clean transportation, 2021) vehicle body types registration trend over the years can be analysed. The conclusion is that SUV/Off-road vehicle registration is 10 times bigger comparing 2012 and 2022 registrations. Especially, recent decade SUV vehicles became a very popular, being selected instead of light or medium vehicles.

ACEA report (European Automobile Manufactures'Association (ACEA), 2022) provides also another interesting statistical study related to overall picture of industrial sectors. Figure 25 presents investments into Research and Development (R&D) canters in Europe across different industrial sectors. Automobile and parts sector is number 1 in this overview, having nearly 60-billion-euro investment in 2020. Therefore, the investments into automotive R&D are outstanding on the market and the conclusion can be taken that automotive market revolution is taken seriously by car manufactures on European market.

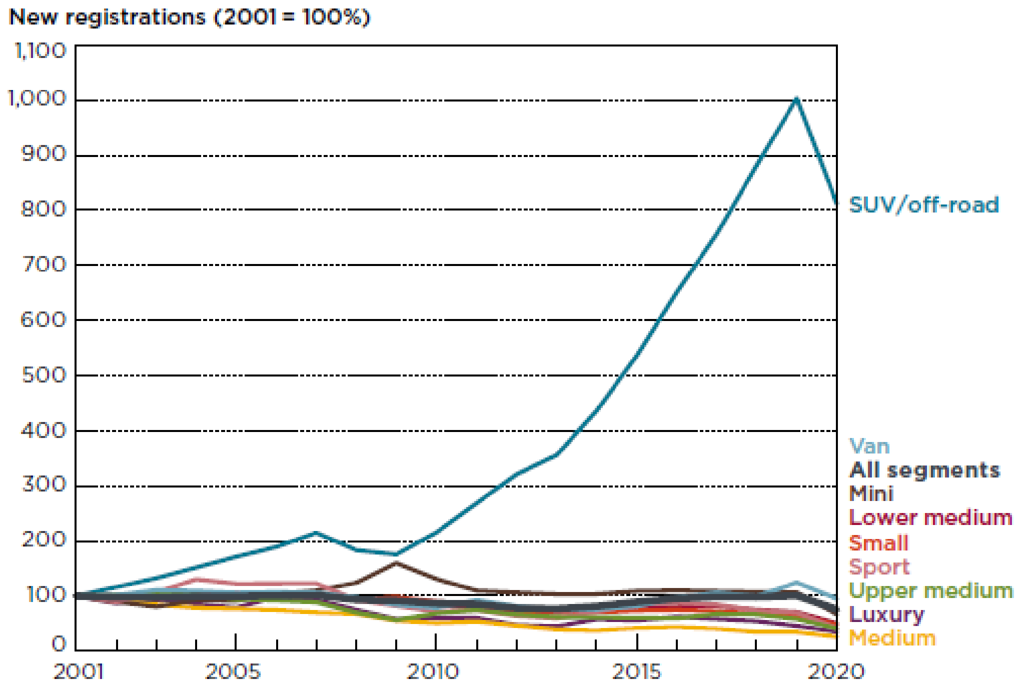


Figure 24. New registration per car segment (The International Council on clean transportation, 2021).

EU R&D INVESTMENT IN THE TOP 10 INDUSTRIAL SECTORS

In billion € / 2020

Automobiles & parts	58.8
Pharmaceuticals & biotechnology	31.4
Technology hardware & equipment	15.9
Software & computer services	10.3
Electronic & electrical equipment	9.6
Industrial engineering	8.8
Aerospace & defence	6.3
Banks	5.4
Health care equipment & services	5.3
Chemicals	5.1

Figure 25. EU R&D investment in the top 10 industrial sectors (European Automobile Manufactures'Association (ACEA), 2022).

3.2. Main research problems

The current state of the automotive industry has impacted the product development processes of component suppliers. One significant change is the increase in vehicle weight due to the trend of electrification and the growing popularity of SUVs. Another notable change is the rise in the centre of gravity for SUVs. Both inputs give greater loads on the suspension elements, including the shock absorber. As a result, new components must be developed, and prototypes must be manufactured and tested. Given these circumstances, several research problems can be identified:

Development time. Vehicle manufacturers tend to decrease complete project development time, which minimises the time required to define design solutions during the quoting stage. Project teams usually have 2-4 weeks to analyse requirements and propose design solutions. The organisation expects to utilise trustful simulation techniques to speed up development time by eliminating the need to manufacture prototypes and execute testing plan.

Simulation. The utilisation of various types of simulation techniques in the product development process is constantly increasing. Strong computation possibilities and the development of the simulation software packages result in the strengthening of simulation capabilities. However, it must be stated, that simulation results are not always correlated with test results. As a consequence, the proposed design solution might fail against customer requirements. To avoid such design issues, project teams decide to manufacture prototypes and perform verification tests. The expectation is to obtain simulation techniques that predict results in line with test results and, finally, minimizing cost of prototypes and tests.

Digital systems. Currently, available systems are not interconnected and available data is not digitised. As a result, engineers are wasting time entering data manually into subsequent systems. There is a high risk of mistakes made during manual data transfer. Another problem of currently available systems is related to limited possibilities for searching historical test results. Project teams lack easy and fast access to knowledge collected in previous projects. The company expects to obtain digital and connected systems with satisfactory data-search possibilities.

3.3. Thesis

Understanding described research problems and being aware of digital twin possibilities following thesis can be stated:

Digital twin concept can be implemented into Product Design and Development process, resulting in improvements in areas of engineering knowledge management, reducing development and testing time.

The targeted scope of digital twin implementation is presented in Figure 26.

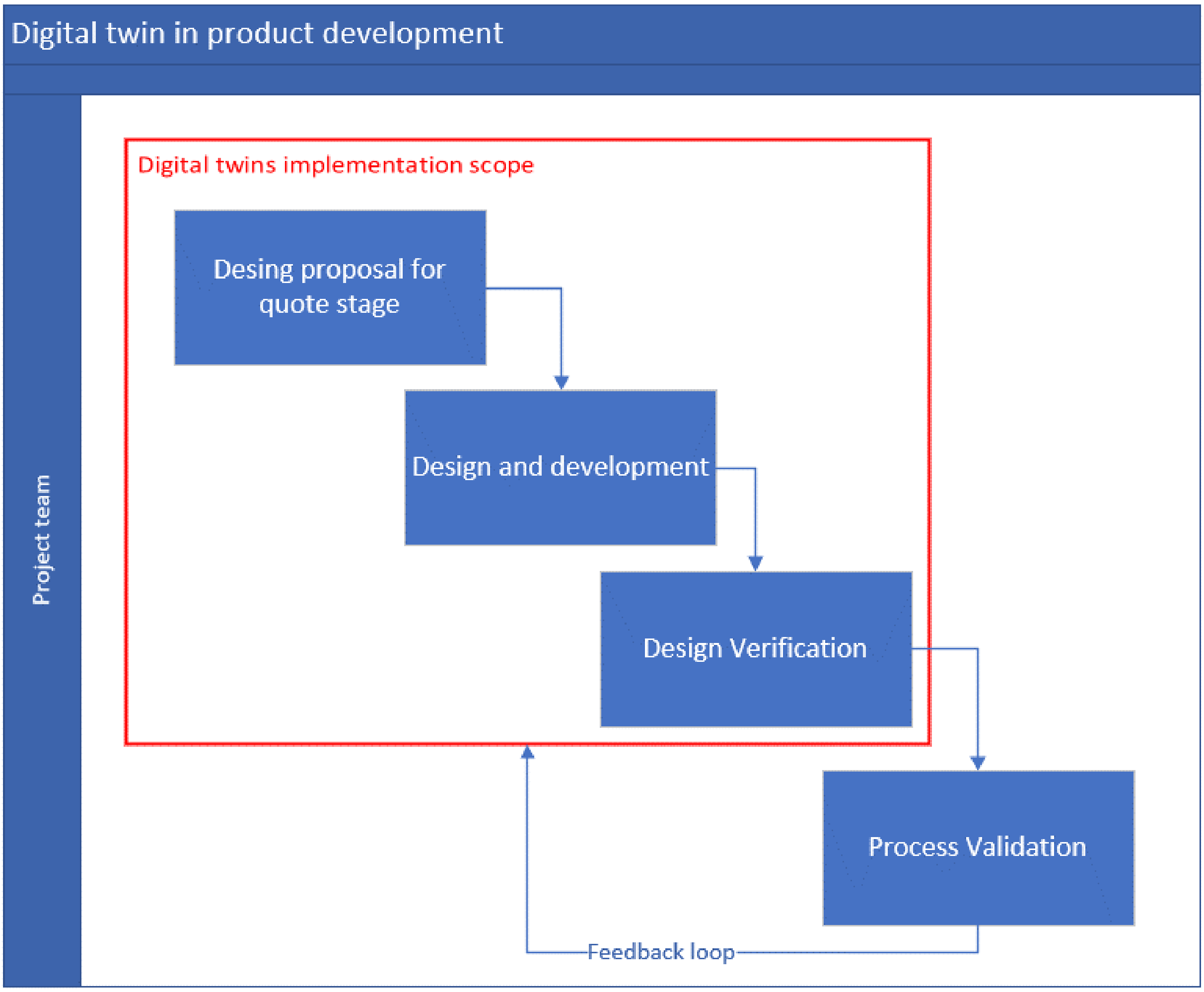


Figure 26. Digital twin implementation scope

4. Analysis of the design process and engineering knowledge

4.1. Process mapping

The best practice in a current stage analysis related to business processes is to start with a high-level process map. It allows to understand the process and achieve an agreement on process steps. The high-level process mapping includes several procedures conducted in a company. It starts from a discussion on crucial departments or company activities involved in a given process. Next procedure is an identification of key steps or even categories of the process steps. To achieve a desired target of the process mapping, the following rules need to be considered:

- Identification of an **initial team**, including representatives of main departments or functions. According to commonly accepted rules, the proposed team size is of 4-5 team members including the leader. It was proven that a bigger team is usually inefficient
- Clearly specified **subject** of the process mapping. Usually in companies there is a special pattern of the subject specification
- Organizing the **teamwork** including standardized way of invitations for meetings, agendas, form of discussions and reports from the meetings
- Standardized way of **information collecting**. It is important to collect not only data resulting from queries, effects of discussions but also consider historical knowledge and state-of-the-art (e.g. current and valid patents, results of projects realized at universities).

To understand a complete product design process the representatives of the following departments are involved in the process mapping:

- Application team – covering application engineering processes and issues related to internal design standards
- CAD team – knowledgeable about 3D modelling, design standards and documentation release procedure
- CAE team – responsible for various simulation analysis methods e.g. for Finite Element Analysis

- Testing and Workshop – responsible for the complete process of prototyping and performing validation tests, including logistics and warehouse processes
- Manufacturing team – delivering serial components and prototypes manufactured on serial production lines

The result of the high-level process mapping was presented in Figure 27, where on the left side all business processes were presented. The process map presents sequential steps over all functions and it is based on a typical customer program. The overall process including bottle necks and hazards can be summarised in the following way:

- The RFQ (Request for Quotation) process includes a design proposal prepared by the application team based on the customer requirements. The CAD department is responsible for preparation of a technical documentation using the internal developed design standards. Design optimisation is performed with the use of various simulations. The optimisation outcome is included in the technical documentation. Due to fact that results of simulations are usually not correlated with the tests results, there is a risk of proposing the design solution that finally does not meet the customer requirements. As a consequence additional time and resources are needed at the *Design and Development* stage to correct the proposed design, what is negatively impacting the program budget.
- *The design and development* stage includes preparation of the detailed shock absorber design, update of the technical documentation, design optimisation using simulations and verification tests based on initial prototypes. Similarly, as in the previous stage, the problem of non-correlated simulation is negatively impacting this stage, as the design proposal given by simulation needs to be verified by the test. The test results need to be evaluated by the application team. In case of negative results, another iteration of the design optimisation is required. Positive test results are leading to update of the technical documentation and start to manufacture a large number of prototypes and perform the complete verification test plan. At this stage the term *Design freeze* is used to indicate, that design changes are not allowed till end of the *Design Verification* tests.
- *Design Verification* stage includes two steps: manufacturing of prototypes and performing the complete Design Verification Plan (DVP). The purpose of this stage is

to verify the optimised, detailed design through a complex set of testing procedures. Typical the DVP consists of 60-80 tests covering different product characteristics. This stage consumes significant program budget due to the cost of prototypes and testing. As the complete test a program from the DVP is repeated in the next stage based on prototypes manufactured on a production line, the design verification is a potential source of cost reduction.

The review of consecutive processes, performed within scope of the PhD project was aimed at the identification of process bottlenecks, hazards, or technical project risks. They were analysed in order to calculate potential engineering hours and budget available for reduction. The results of the analysis are compared to the implementation of the digital twin. The summary of potential savings of labour and machine hours are presented in Table 5.

4.2. Current data flow.

The next step was to perform a detailed process mapping based on the process scope defined in the first step as the high-level process mapping. It should be stressed that the detailed process mapping is taking significantly more time that the high-level process mapping. This task was divided into several procedures. The complete overview of the final process map is visualised in Figure 28.

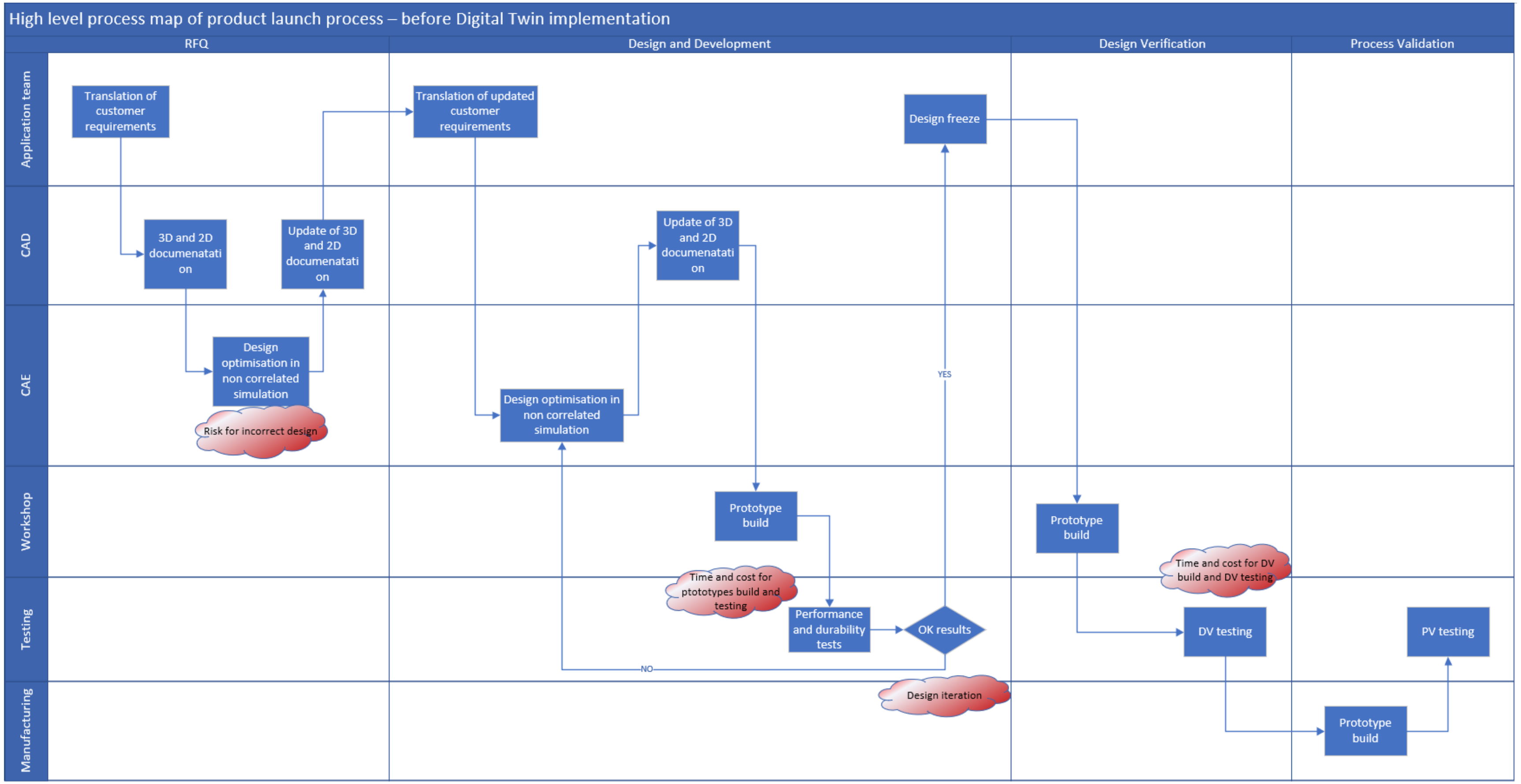


Figure 27. The high-level process map of a product launch process before the digital twin implementation.

Table 5. Potential savings of labour and machine hours.

Stage	Bottleneck, hazard	Activity	Hours	Comment
RFQ	Risk for incorrect design	Redesign - red project flag	-	not included in saving due to multiple reasons of red program status - estimation not possible
Design and Development	Time spent for prototype builds and testing	Prototype builds	24 h	cost includes the cost of hours and the cost of prototype components and manufacturing cost
		Testing	10 h	cost includes cost of hours and testing machines cost
	Design Iterations	Engineering hours	159.5 h	assumed single design iteration
Design Verification	Time spent for DV build and DV testing	Prototype builds	576 h	Prototype build cost includes hours, material and supplies cost
		DVP testing	496 h	cost includes cost of hours and testing machines cost

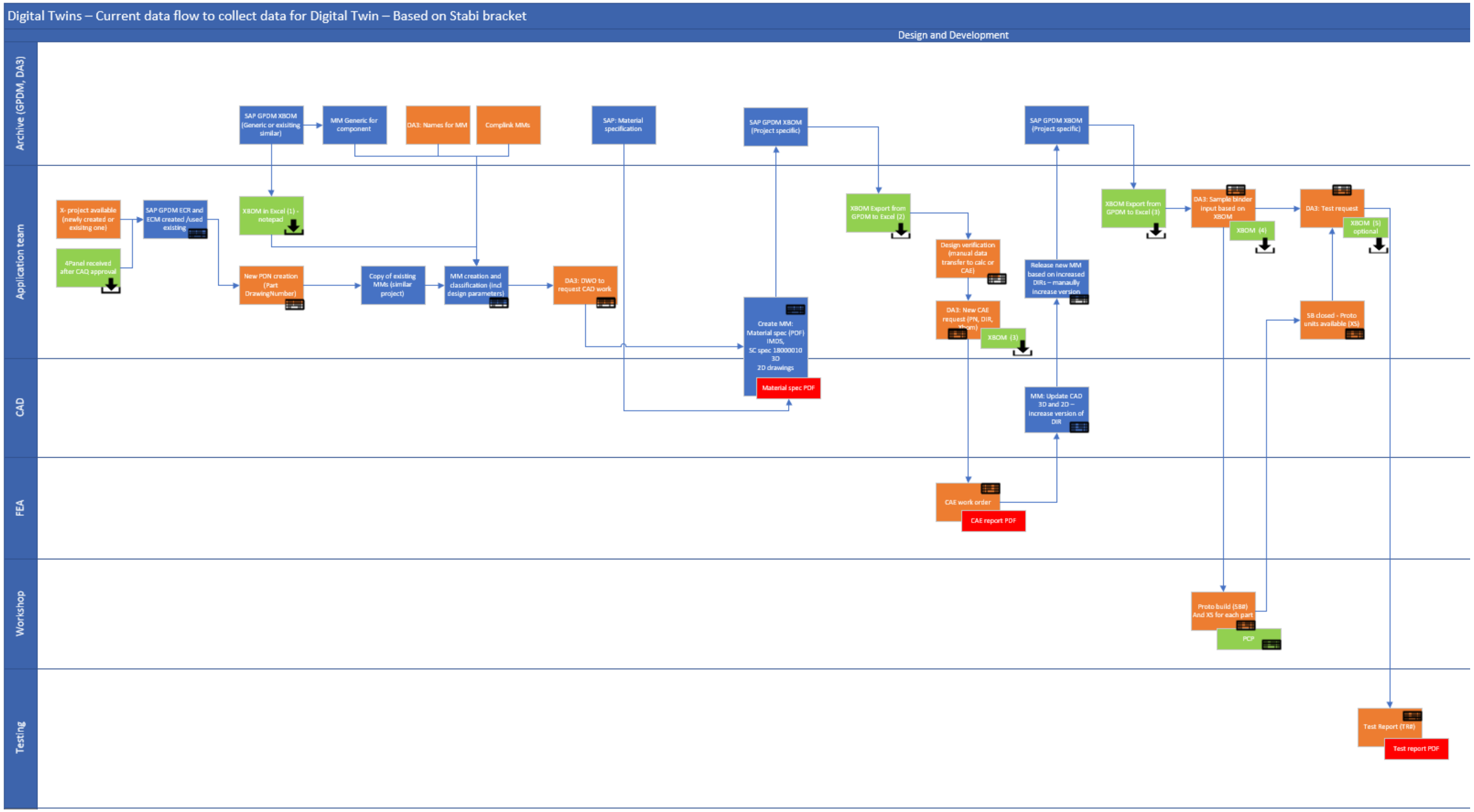


Figure 28. The high-level process map of a product launch process after the digital twin implementation.

During the process mapping a type of systems within this process was considered. As the result the process steps are indicated in different colours (Figure 29). The orange colour indicates an internally developed system called DA3, which is used to navigate through design standards and manage engineering business data including ticketing of job into different departments like CAD, CAE, Testing and Workshop. Other colours represent commonly known systems.

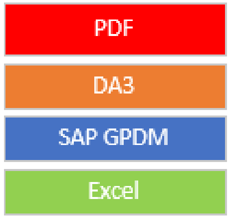


Figure 29. Type of systems included in process mapping.

Due to relatively huge complexity the analysis of the detailed process map is delivered in 3 consecutive steps:

1. The component design and development presented in Figure 30 covers the initial process starts from labelling (giving a project number) in order to identify the documentation, allocate necessary engineering time and also expenses foreseen in the related project budget. Technical input is given in a 4Panel form summarizing the design solution quoted to the customer. The solution also includes a risk assessment of the project and design. The symbol of an arrow pointing down presents download operations. Data transfer is provided by sending emails with attachments. The symbol of a keyboard entitles a manual data entry in respective process steps. It is visible that nearly 50% of engineer activities at this initial stage is based on manual operations. The specific project documentation is created basing on the similar project. It is also manually verified according to existing standards. It should be stressed that it is also an inefficient process. However, the solution to this problem is out of the scope of this doctorial project. As the outcome of this part of the process, an initial experimental Bill of Materials (XBOM) is created, and the manual entry is given into the

ticketing system related to the CAD department. The goal is to create 3D and 2D documentation.

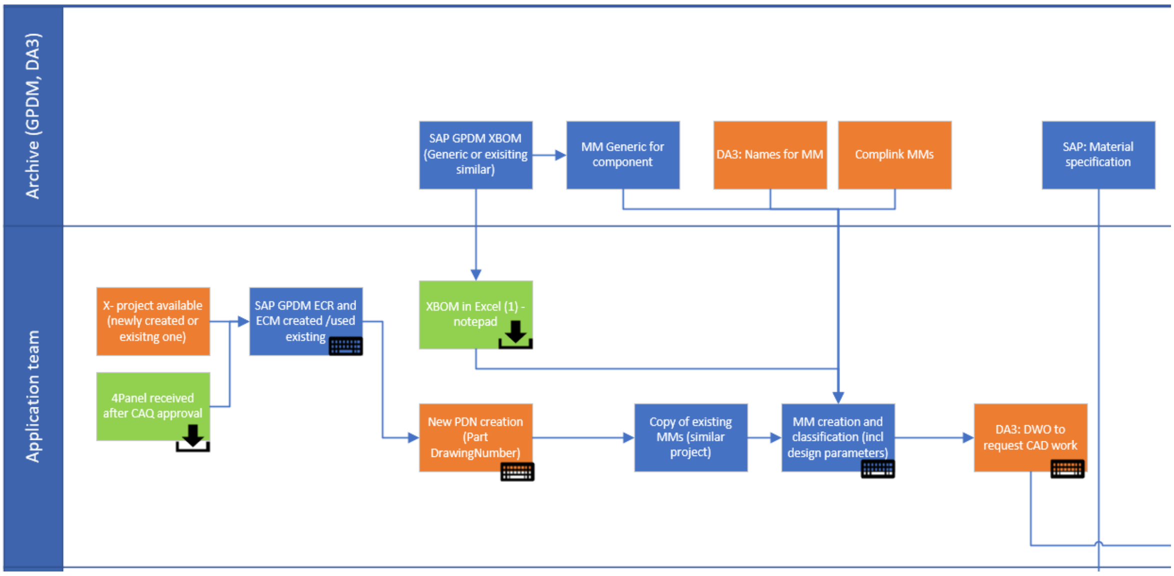


Figure 30. Current data flow and engineering knowledge - part 1.

2. The next part of the detailed process map is presented in Figure 31. It is a single design optimisation loop. It must be mentioned that in case of more complex projects this kind of design loop takes place several times to complete the assembly level, as well as for the design optimisation. The documentation for each component and assembly is manage in the SAP GPDM system and is gathered in dedicated folders called material masters (MM). The material master of an exemplary component is enriched with the material specification including characteristics of chemical and mechanical properties of the required material. Unfortunately, currently due to .pdf format the data is not available in the digital form and requires human activity to read out the material properties. This data is used during the CAE analysis, during components procurement process as well as for proper calculation of component weight. The next step is to download manually to Excel the XBOM. As in previous cases this document is not connected with the system and content wise, and versioning is not controlled. The data introduction is manual to the CAE subprocess. Additionally, all business and technical data is provided into the work order system. Such unconnected systems are leading to process inefficiency and also to mistakes during repeated several times manual data inputs. As the outcome of the CAE work order, a CAE report is created .pdf file, following the same problems of digitally non-readable values. The application

engineers are manually reviewing the CAE report and requesting the design updates and documentation release. The final step of this part of the process is to upload the updated version of the XBOM in Excel format already at third time. The XBOM versioning must be also kept manually so data inaccuracy is also related to potential human mistake.

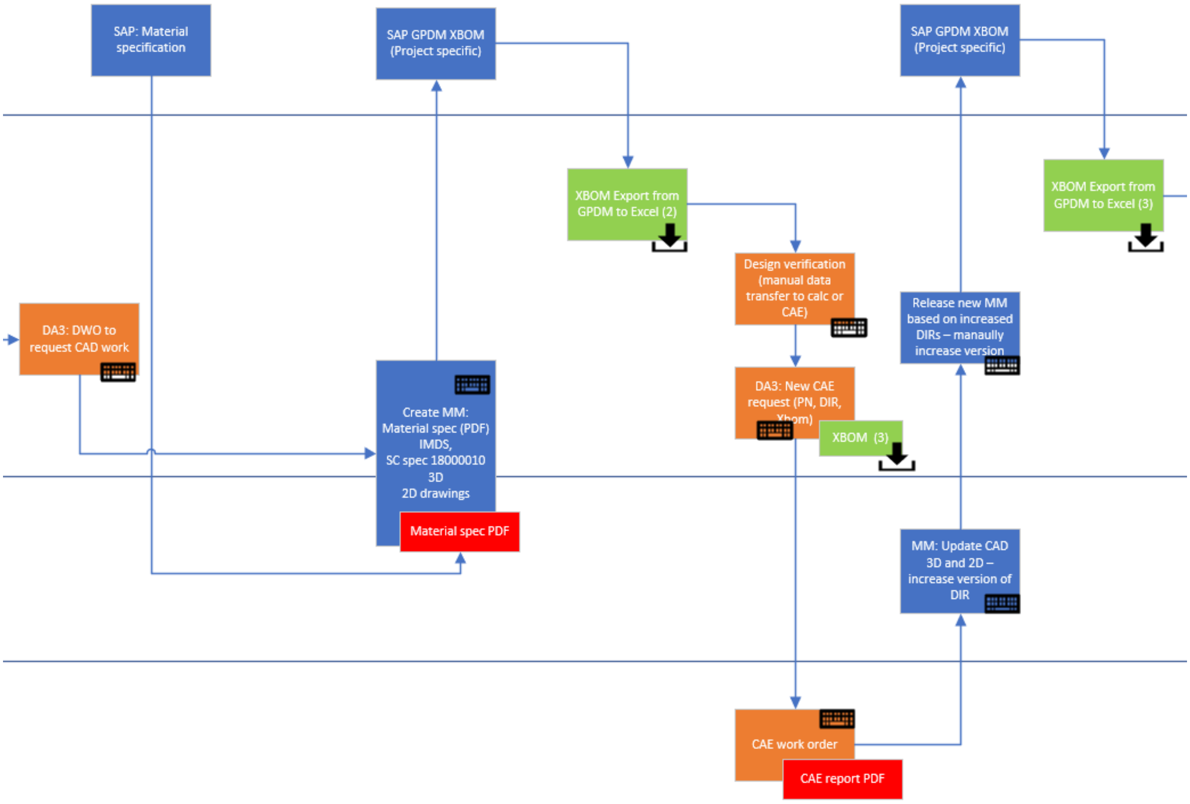


Figure 31. Current data flow - part 2.

3. The last part of the process being analysed is related to a subprocesses of the protype building and testing (Figure 32). Both subprocesses are managed by the same type of the ticketing systems, but they are not connected and not synchronized. Therefore, the manual input data is repeated into the prototyping and testing processes and an uncontrolled copy of XBOM is created at least two times in this part of the process. The process includes a lot of other manual entries potentially leading to mistakes, and also leading to the inefficiency of the process. The outcome of the complete Design and Development process is a report of testing results. The testing report is stored in a internally developed database in the testing ticketing system. The format of the report is following company standard, thus the .pdf format is used. Similarly, to the

previous reports, automatic search algorithms are not able to process the test results or final conclusions. It must be noted that all test reports even these that are stored in the same database, must be treated as individual datasets, without any possibilities of common and overall analysis. Even when additional statistical analysis is required to be performed, the data from a single report needs to be manually transferred to the statistical software.

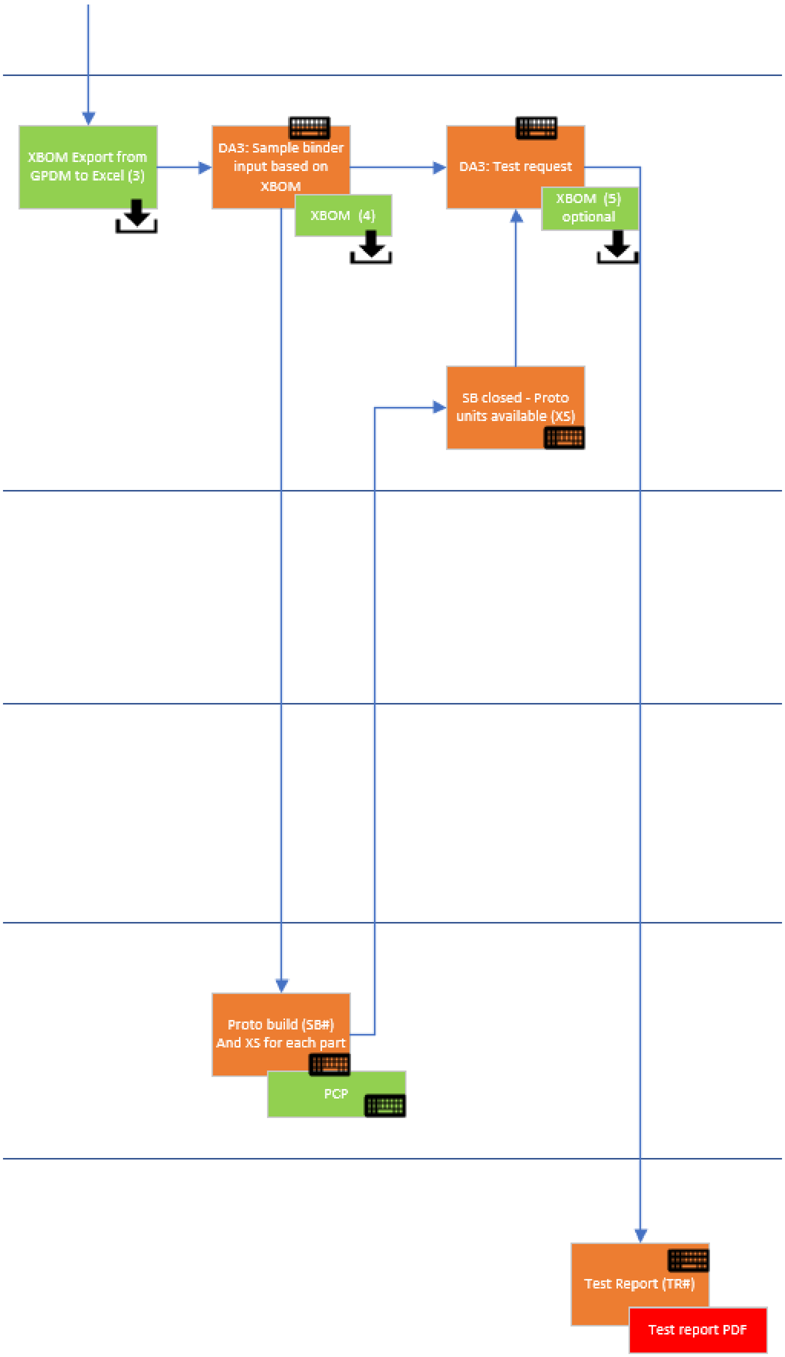


Figure 32. Current data flow - part 3.

4.3. Design element classification

To understand the process at the level of a single activity and analyse the sequence and connections between process steps, the detailed process mapping is necessary to be provided. A typical process mapping gathers information regarding a system used during each process steps. However, the data structure and data identification are typically not captured during the process mapping. To clarify the problem related to digitalization of the processes within the company, datasets were identified for data transfer involved in each process step. In order to keep the process map understandable for the review and analysis, a specially predefined table was proposed to collect datasets. These datasets which are introduced manually several times are marked in red colour. The data presented in black colour are initial entries. The first part of the table (Table 6. Stabi bracket data set - part 1.Table 6) shows the design identification of 2 components and 1 subassembly and the same data is taken from the SAPGPDM as the source. It made it available in the DA3/ Complink and finally exported to Excel as an uncontrolled document.

Table 6. Stabi bracket data set - part 1.

Dataset	Generic XBOM	Generic XBOM	Generic XBOM
Database	GPDM	DA3 / Complink	Excel
Stabi Bracket			
Stabi Bracket	Material	Material	Material
Stabi Bracket	Type	Type	Type
Stabi Bracket	Material Specification	Material Specification	Material Specification
Stabi Bracket	Thickness [mm]	Thickness [mm]	Thickness [mm]
Reserve Tube			
Reserve Tube	Material Specification	Material Specification	Material Specification
Reserve Tube	RT thickness under Stabi Bracket [mm]	RT thickness under Stabi Bracket [mm]	RT thickness under Stabi Bracket [mm]
Reserve Tube	RT OD under Stabi Bracker [mm]	RT OD under Stabi Bracker [mm]	RT OD under Stabi Bracker [mm]
Base Assy			
Base Assy	Number of welds	Number of welds	Number of welds
Base Assy	Weld Run Out	Weld Run Out	Weld Run Out
Base Assy	Weld Configuration	Weld Configuration	Weld Configuration

The second part of the table (Table 7) includes details on the process steps related to adding the application project specific part numbers and uploading the defined XBOM to SAP GPDM as data-controlled system. This non-efficient way of working is caused by the complicated, time-consuming, and difficult process of the new XBOM in SAP GPDM. The result potentially lead to data inconsistency. The company developed a set of workarounds based on standardized templates of the XBOM for a typical product, what gave as drawback the risk for uncontrolled XBOM in form of Excel tables. The last 4 columns in Table 7 provide a view on dataset for CAD documents. In the next steps, it is used to the request a prototype building and identify each physical prototype with an unique XS number.

Table 7. Stabi bracket data set - part 2.

Dataset	Specific XBOM	Specific XBOM	3D models	2D drawings	Proto request	Prototyping
Database	Excel	GPDM	CATIA	CATIA	DA3	DA3
Stabi Bracket	Part Number	Part Number			XBOM	
Stabi Bracket		Material				
Stabi Bracket		Type				
Stabi Bracket		Material Specification				
Stabi Bracket		Thickness [mm]				
Reserve Tube	Part Number	Part Number				
Reserve Tube		Material Specification				
Reserve Tube		RT thickness under Stabi Bracket [mm]				
Reserve Tube		RT OD under Stabi Bracker [mm]				
Base Assy	Part Number	Part Number				
Base Assy		Number of welds				
Base Assy		Weld Run Out				
Base Assy		Weld Configuration				
			DIR 3D	DIR 2D		
					SB number	
					SB entity	
						XS

The last part of the process and the related datasets were presented in Table 8. It starts with the test request (TR), where the individual TR number is defined and the entry form allows to provide the test specification details. As example is the test input signal defined by means of cycles and loads and also test acceptance criteria. As the result of this test a report is prepared. The report is created manually based on a predefined template for a test type. The next process step is related to the CAE request which is separated from the ticketing. The same system is used for testing and CAE procedures. The reason is mentioned before a silo effect and limitations in IT tool development. As the consequence 3 parameters need to be provided to the CAE request.

Table 8. Stabi bracket data set - part 3.

Test Request	Test Report	FEA request	FEA report
DA3	DA3/pdf	DA3	DA3/pdf
TR		CAE request	
cycles		cycles	
loads		loads	
criteria		criteria	
	test: cycles @ damage		FEA: cycles @ damage
	XS		

Material specifications. During the review of an initial design dataset, the material specification was identified as another potential problem that requires improvement. The material specifications include mainly the limitations and requirements of chemical and physical parameters. They are created by the company for typical steel materials used during development of components. In the PhD project, the scope of the material specification was limited to the steal materials for tubes and stamping components. The review of documentation let to identify 10 materials characteristics.

During analysis of the material specifications the following gaps were characterized:

- Lack of a standard template for the material specification document
- Material specification is released in .pdf format and automated data reading algorithms are failing to obtain the material specification parameters
- Lack of standardized nomenclature of material specification parameters, typically due to specification development performed in various regions
- Lack of standardized material parametrisation

- Lack of standardized units of measure
- Conflicting and incorrect data.

The example of the current material specification format is presented in Figure 33, where a part of physical parameters was highlighter in red frames. These parameters are the most important for the strength of the component under development.

Raw material specification for shock absorber tubes

1. General description

This specification covers a cold or hot rolled, electric welded, annealed and redrawn steel tubing used for Mac-Pherson reserve tubing.

1.1. Norm reference

Except as otherwise noted in this specification or the purchase order, this material shall be conform to EN 10305-2, quality E 275 +C or higher.

1.2. Chemical analysis

Carbon (C)	: 0,20 % max.
Manganese (Mn)	: 1,50 % max.
Phosphorous (P)	: 0,025 % max.
Sulphur (S)	: 0,025 % max.
Aluminium (Al)	: 0,02 - 0,08 %

2. Mechanical properties

2.1. Yield strength	: 550 - 620 N/mm^2
2.2. Tensile strength	: 600 - 670 N/mm^2
Ref.: hardness	: Rockwell B 88 - 92
2.3. Elongation	: 10 % min.

Figure 33. Example of material specification.

Stabilizer bracket design classification. The next identified problem within the analysed documentation is related to categorisation of the stabilizer bar bracket designs and standardization of the design parameters. Initially several types of the components were existing as listed below:

- C-shape
- T-shape
- Butterfly
- Butterfly – 1-sided

For each type of the design parameters they are described differently, having different nomenclature and different dimensioning. The existing design types of the components and dimensioning were standardised.

FEA report preparation. Another bottleneck in the process was identified in the method of the FEA results reporting. Currently, the FEA engineer needs to insert all items required in the FEA report manually. Usually, these elements are the following issues:

- request an input detail
- product and fixture geometry
- simulation boundaries and assumptions
- FEA results
- conclusions

This process requires a large amount of editing time. Additionally, all graphical representations are provided as pictures. As a result, readers of the report do not have any possibility to review the 3D geometry of the analysed design. The example of the current FEA representation in the report is presented in Figure 34. The report needs to include pictures of all necessary 3D views to present all key aspects of the results. It must be stressed that the FEA engineer needs to develop the report in Word application and then transfer the document to the non-editable .pdf format. In case the FEA report should be modified, both files need to be also updated and stored in the database. The described method is not time efficient and potentially leads to inconsistency between the Word reports and PDF export.

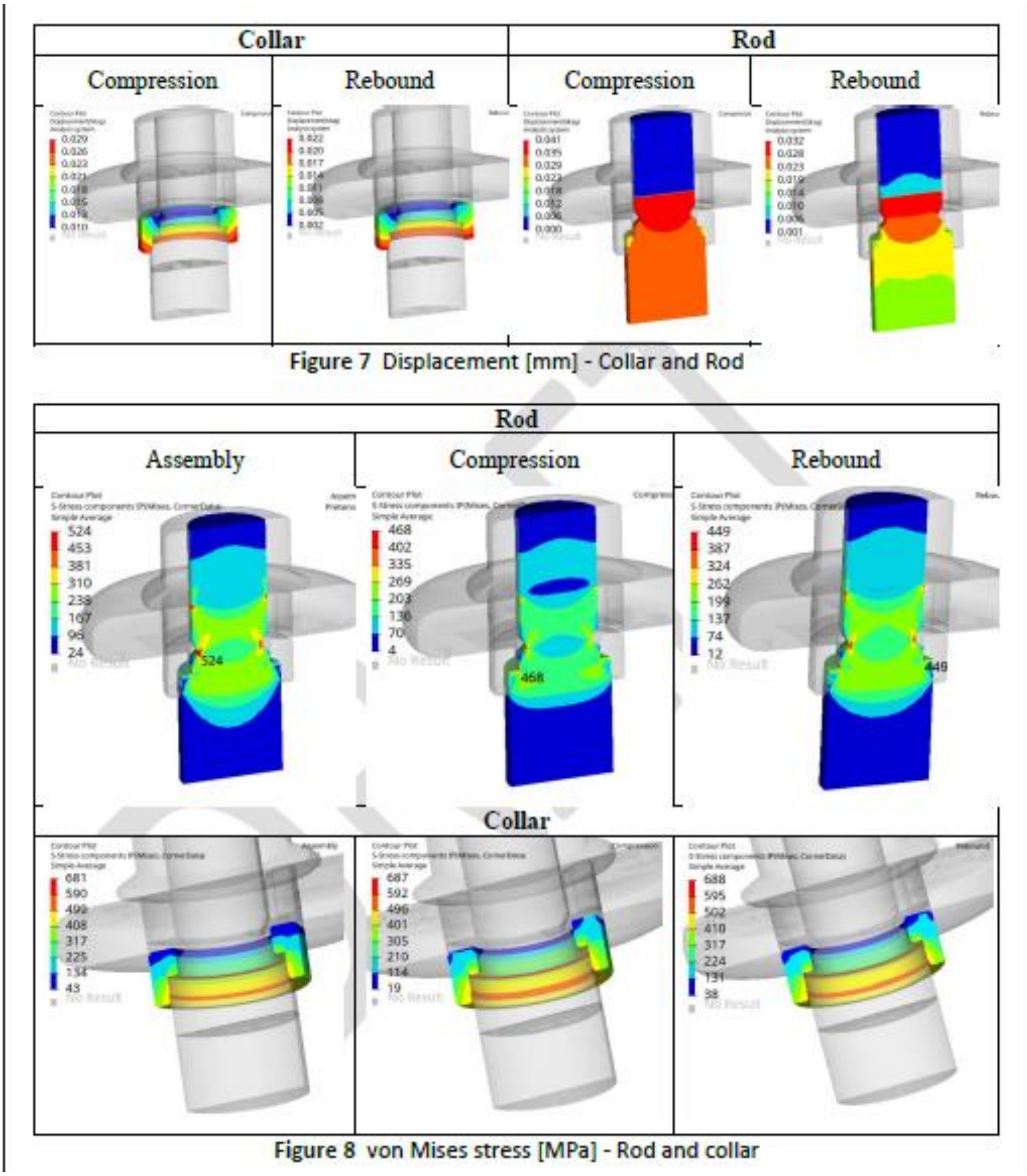


Figure 34. Current FEA results reporting possibilities.

5. Digital twin implementation

The main aspect of the PhD project performed by the author is to implement the digital twin into the project development process. It requires several steps to be taken. Moreover, the correct sequence of the steps should be considered. It is presented in Figure 35. The initial steps are related to the standardisation of geometrical shapes of the stabilizer bar bracket. The standard also includes a clear definition of the component parameters including nomenclature and units of measure. The similar standardization approach is conducted in case the material specification. All parameters were digitised and recorded in the SAP system what allows automated transfer from the SAP system to a test or FEA management platform supporting creation of the digital reports. The next key step was development of a data analysis platform where the simulation results can be compared to physical results. In case of a non-acceptable difference, the simulation adjustment procedure is performed based on the optimisation algorithm in order to minimize the difference between the simulation and test results. This procedure requires an accurate replication of test conditions by the simulation. The adjusted simulation is considered as the digital twin and can be used to predict physical performance of the simulated component. The adjustment algorithm uses the result of validation tests performed on prototypes manufactured on a standard manufacturing line. The concept assumes the continuous simulation parameters adjustment in order to achieve the simulation prediction being in line with new test results.

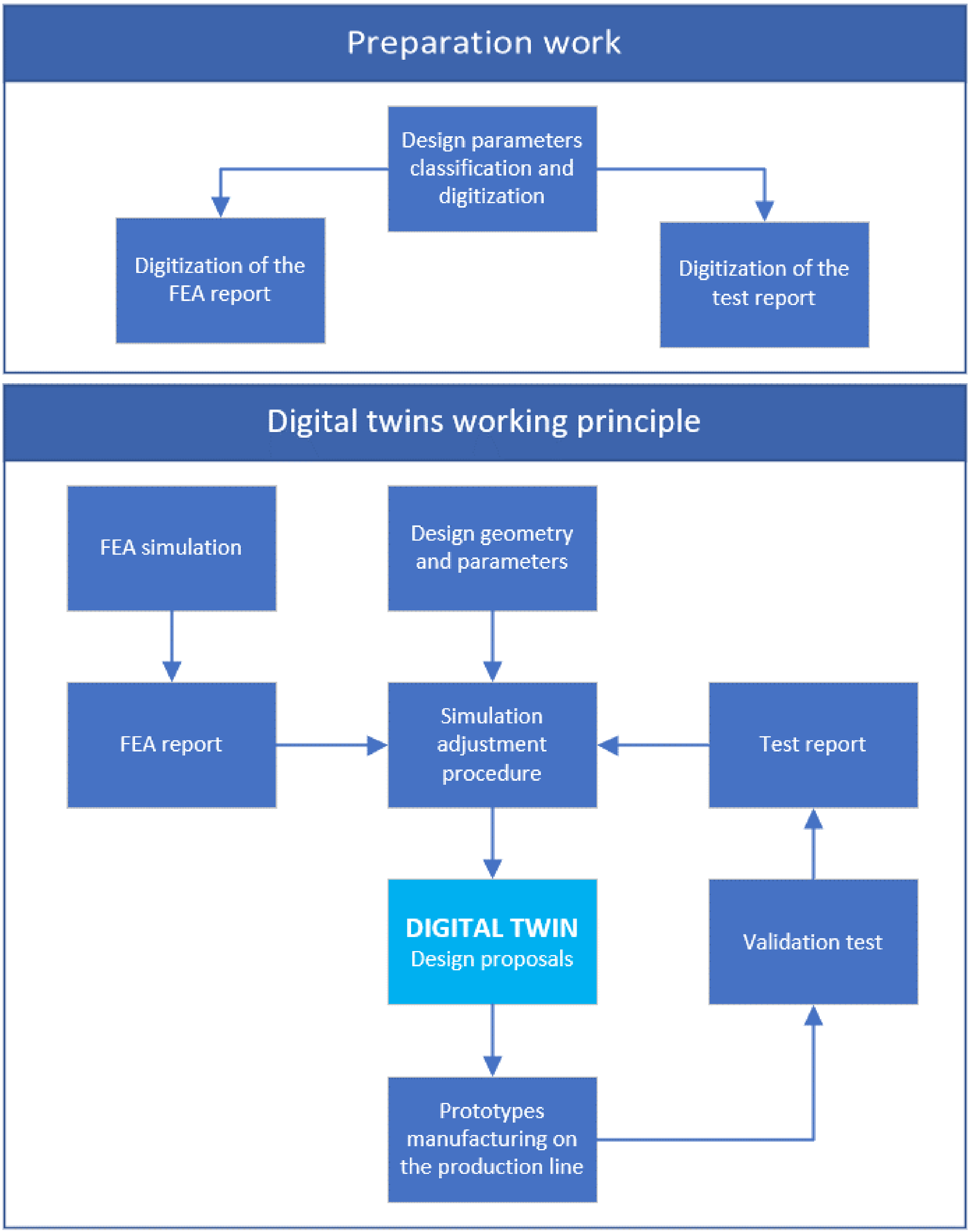


Figure 35. Digital twin implementation steps.

5.1. Design element digitization

Stabilizer bracket classification. As a pilot project for verification of implementation the digital twin. The project concerning a stabilizer bracket was selected. It is a part of a shock absorber. During the process mapping a lack of design standardization and not unified nomenclature of the component design parameters were identified. Finally, the variety of components was reduced to two types, and their dimensions were standardized. The design parameters were also properly sequenced, and the outcome of the work was presented in Figure 36 showing a type of the bracket, design parameters, and 3D geometry. This procedure let us deliver the standardized component parameters, available in the digital form that can be used for filtering and clustering tests and simulation results.

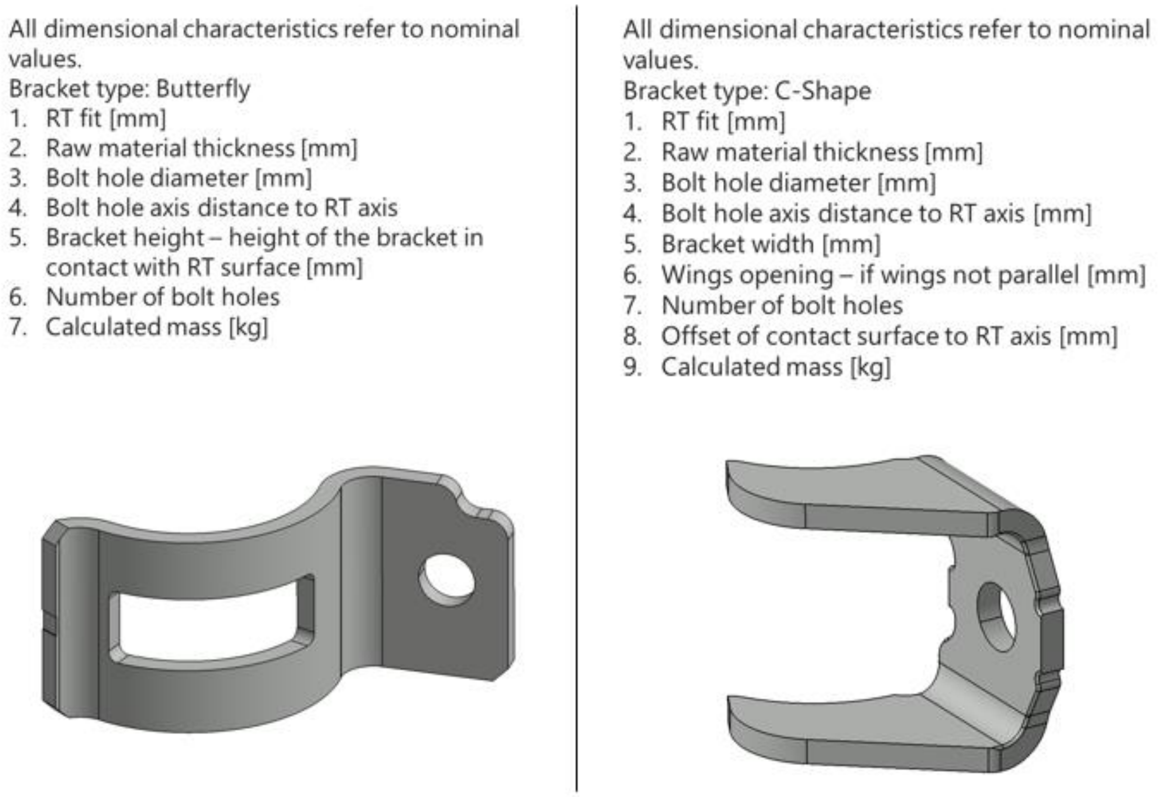


Figure 36. Stabilizer bar bracket classification.

Material specification classification. The first step of improvement of the material specifications management was to establish the mechanical properties common for all used steel materials within the company. The author prepared the review of existing material specifications and as the result, the following standards of mechanical properties were proposed:

- Material Specification Type
- Yield Strength MIN [MPa]
- Yield Strength MAX [MPa]
- Tensile Strength MIN [MPa]
- Tensile Strength MAX [MPa]
- Elongation [%]

The second key agreement was that the SAP system continues to serve as the master database for all product data, including the material specifications. To implement the newly defined material specification standard, a special IT project was requested by the author. This project involved embedding material parameters as product classifications within the SAP system. Since this improvement activity was related to the existing data, the upload of the material specification was performed for already existing records in the SAP system for currently available 10 material specifications.

The outcome of this improvement can be summarised as follows:

- All steel material specifications are described through the standardize mechanical properties and standardized units of measure
- Mechanical properties of the material are digitized and can be directly read out of the SAP system in order to use it in any of CAD or CAE software
- Furthermore, a similar approach can be performed at the component or assembly level to achieve digitization of design parameters

The example of a material specification entry window was presented in Figure 37, where the standards of mechanical properties are implemented. As the result of this improvement, material properties are available in the digital form and can be read out from the database and fit into the simulation models.

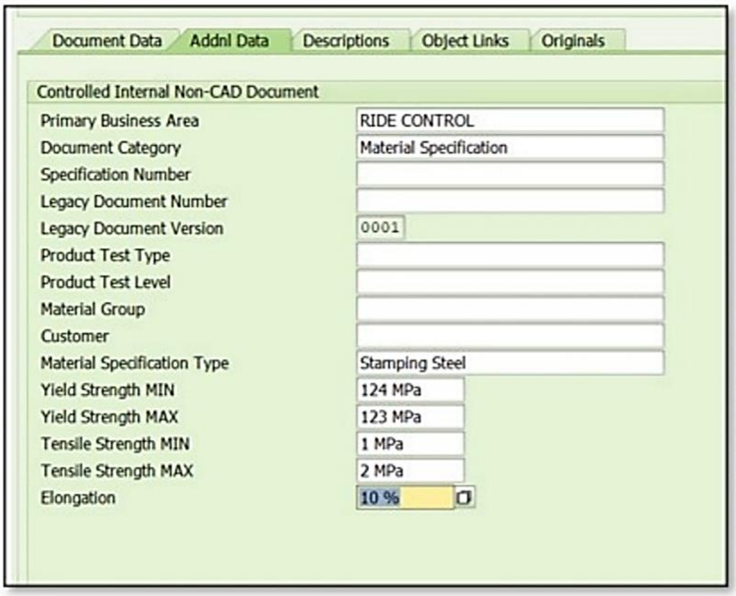


Figure 37. Material specification SAP entry window.

FEA report improvement. The approach and method for the FEA report was modified following the implementation of html format replacing the Word template. The html format allows to digitize and identify the content as well as connect objects into a template, including 3D objects, pictures, videos, data tables and graphs. The example of the FEA report is presented in Figure 38. The presented Wöhler graphs are directly taken from the durability data analyser application, pictures are added from the test results folder and FEA simulation results are presented by the FEA 3D models with characteristics of stress analysis.

The 3D models can be rotated and zoomed in. It facilities understanding and interpretation of stress allocation as well as identification of the best representation of the design analysis. The FEA report including the optimized view of 3D models can be exported to the .pdf as a summary version to be shared with a customer. The example of 3D rotation steps was presented in Figure 39.

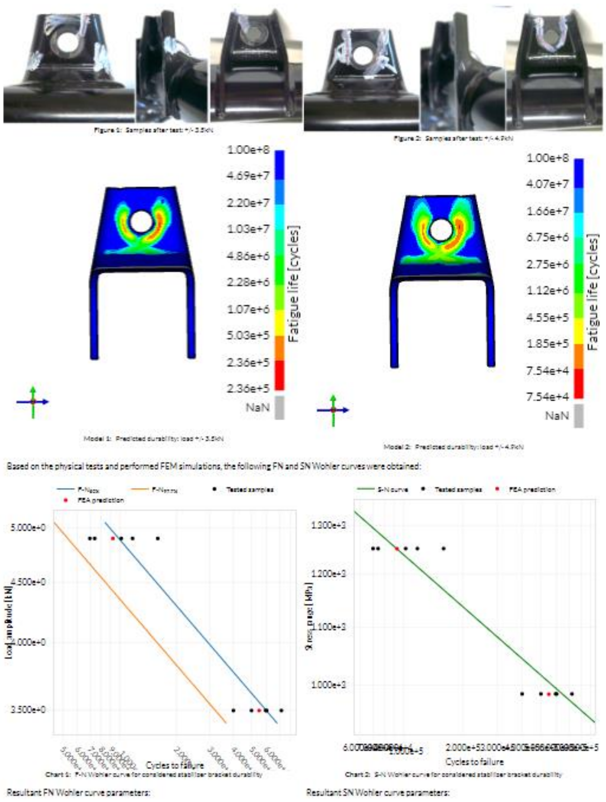


Figure 38. The FEA report example.

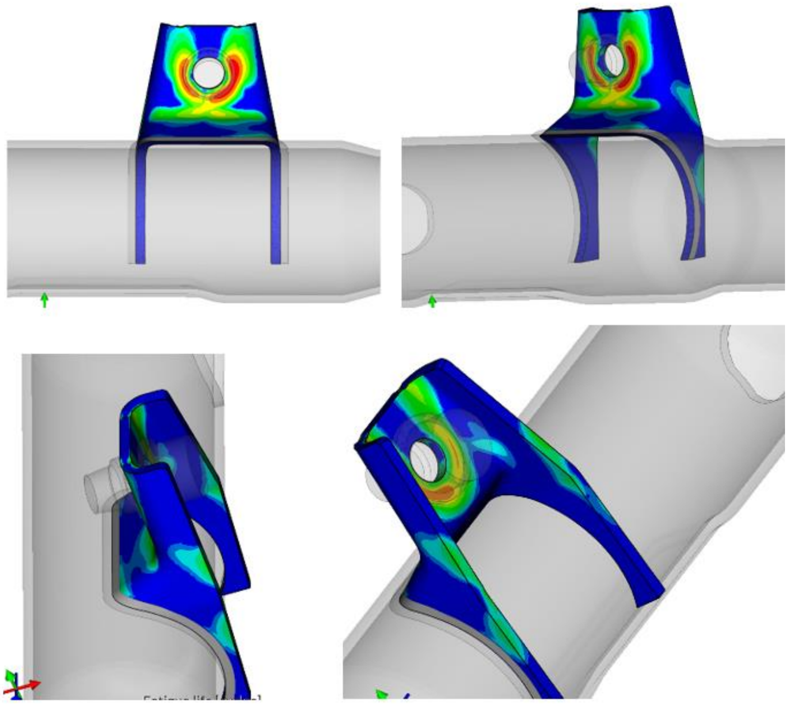


Figure 39. Example of 3D rotation steps.

5.2. Simulations and optimisation procedure

The first step of the simulation optimisation is based on the test set-up described in the test procedure. The goal is to verify if the test was done following to a given procedure. The key aspect of the simulation is to replicate actual test conditions including geometry material properties of investigated part and geometry of a test fixture. The last step is to optimise simulation parameters in order to minimize differences between results obtained from the simulations and the tests.

Test procedure. One of the best methods of assessment of the product lifetime is durability tests. The test results are usually analysed with the use of statistical methods. In the Tenneco company the standard Weibull distribution is used for such estimation. However, depending on a company, there are also defined other standards in the automotive industry. Tests should be performed for at least 5 components of the same types. Moreover, the test is always run till the complete failure and it is required that failure modes must be of the same type. An example is a crack of the bracket at the hole position. An exemplary test set-up of the test bench is presented in Figure 40. The mounting tool set-up ensures correct geometry and angles between the shock absorber body and the force vector applied by the actuator with a given displacement signal. The loading conditions are presented in Figure 41. The load cell measures the force that should be applied according to the customer specification that can be different and is related to company standards. In case of breakage of the shock absorber body, the test bench is automatically detecting an increased displacement or required force is not achieved. In case of a failure, a number of cycles is automatically recorded for the tested component. The test procedure is performed two specified load levels, where exemplary load values for the stabilizer bar bracket test are 3.5kN and 4.9kN.

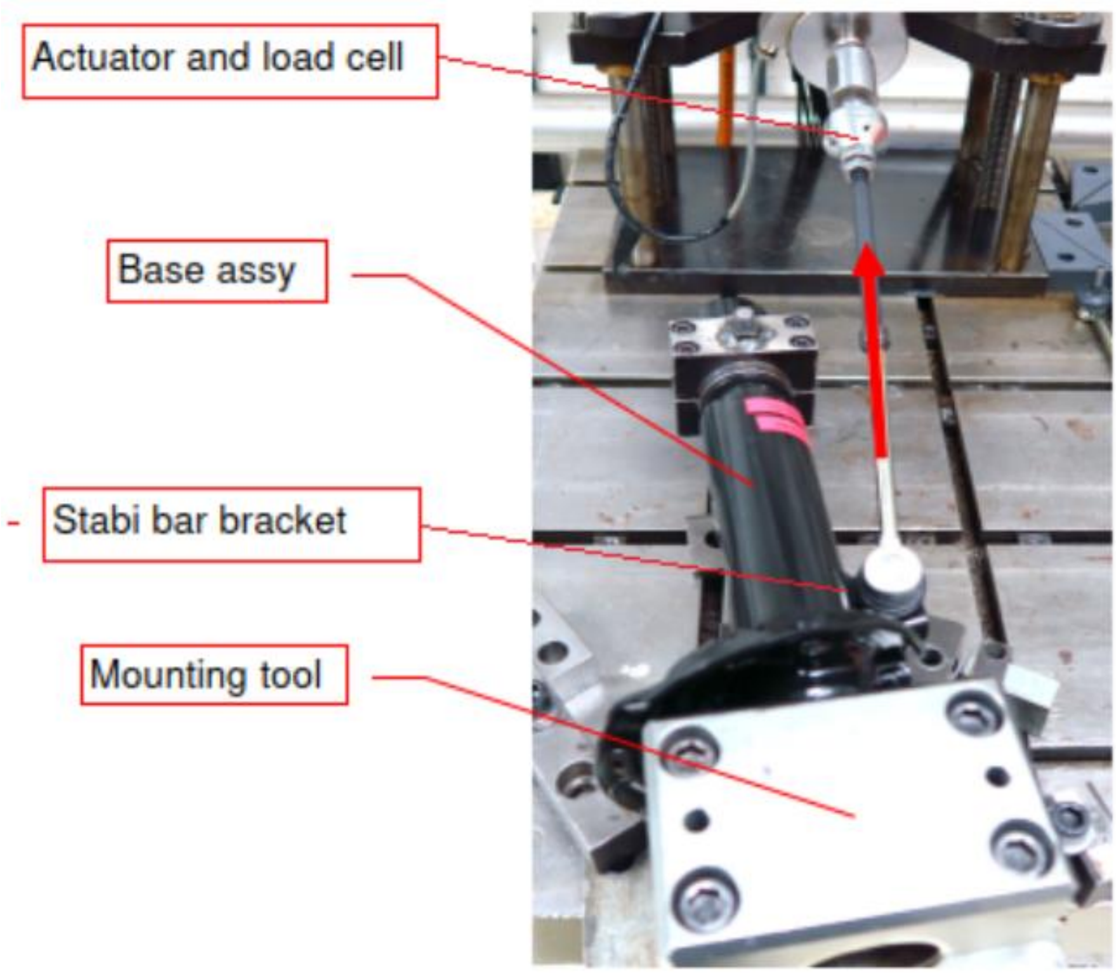


Figure 40. Stabilizer bar bracket test setup.

Load property	Value
Angle α [°]	16.0
Angle β [°]	9.0
Torque [Nm]	120Nm (45Nm + 45deg)
Eq. Clamping Force [kN]	50.0

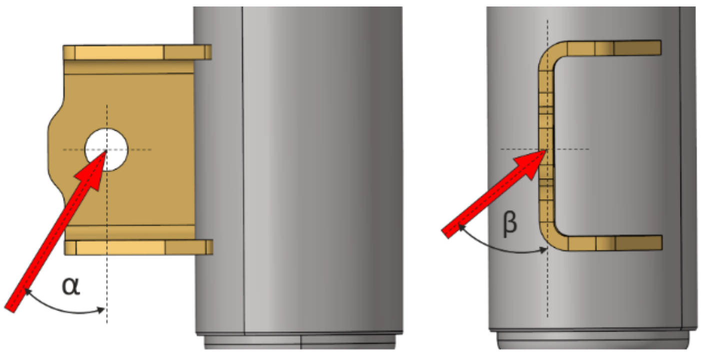


Figure 41. Load conditions.

The simulation model. The numerical FEA model is used as a simulation of component lifetime, presented in Figure 42.

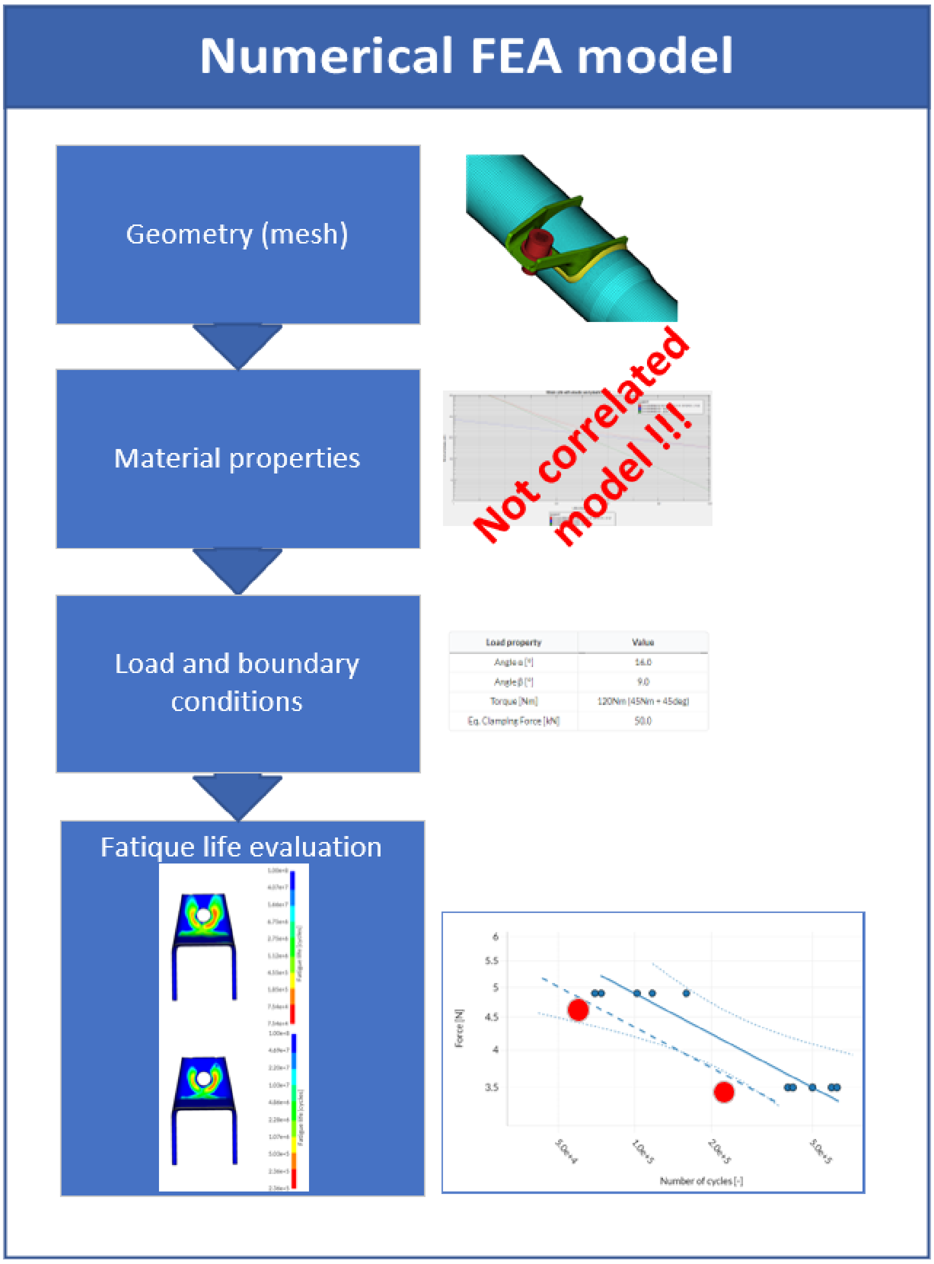


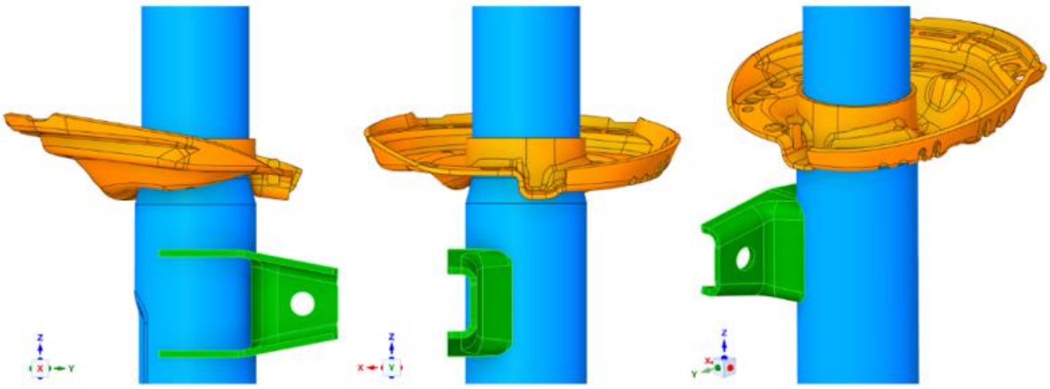
Figure 42. Lifetime simulation model.

The numerical model consists of:

- discretized 3D geometry
- material properties
- set of load and boundary conditions
- fatigue life evaluation algorithm.

The initial material properties are not optimised and as the consequence, the simulation results are presenting the shorten lifetime results comparison to the test results.

For the FEA model the key aspect is to correctly replicate the geometry of the part or complete the assembly being investigated. Therefore, the correct model geometry needs to be available for the FEA. The exemplary 3D geometry and the design parameters are presented in Figure 43. The values of dimensions are set to nominal values. The meshing shall be performed according to the internally standardised and optimised method dedicated to the specific failure mode. For example, there is different method used to predict failures of the base material than to predict failures at weld joints. It must be stressed that all presented standards are accepted by the company. The FEA model shall also replicate the test conditions such as angles of loads applied on the stabilizer bar bracket. The company performs Finite Element Analysis with the use of Abaqus software. The example of the FEA model is presented in Figure 44.



Parameter	Unit	Value
Part number	-	2071514
Type	-	C-Shape
RT fit	mm	62
Bolt hole diameter	mm	12.3
Bolt hole axis distance to RT axis	mm	54.5
Number of bolt holes	-	1
Raw material thickness	mm	3.5
Bracket width	mm	48
Wings opening	mm	48
Offset of contact surface o RT axis	mm	25
Calculated mass	kg	0.115

Reserve tube parameter	Value
Part Number	68485812
Outer diameter [mm]	62.0
Thickness under [mm]	3.0

Figure 43. Example of 3D geometry and design parameters.

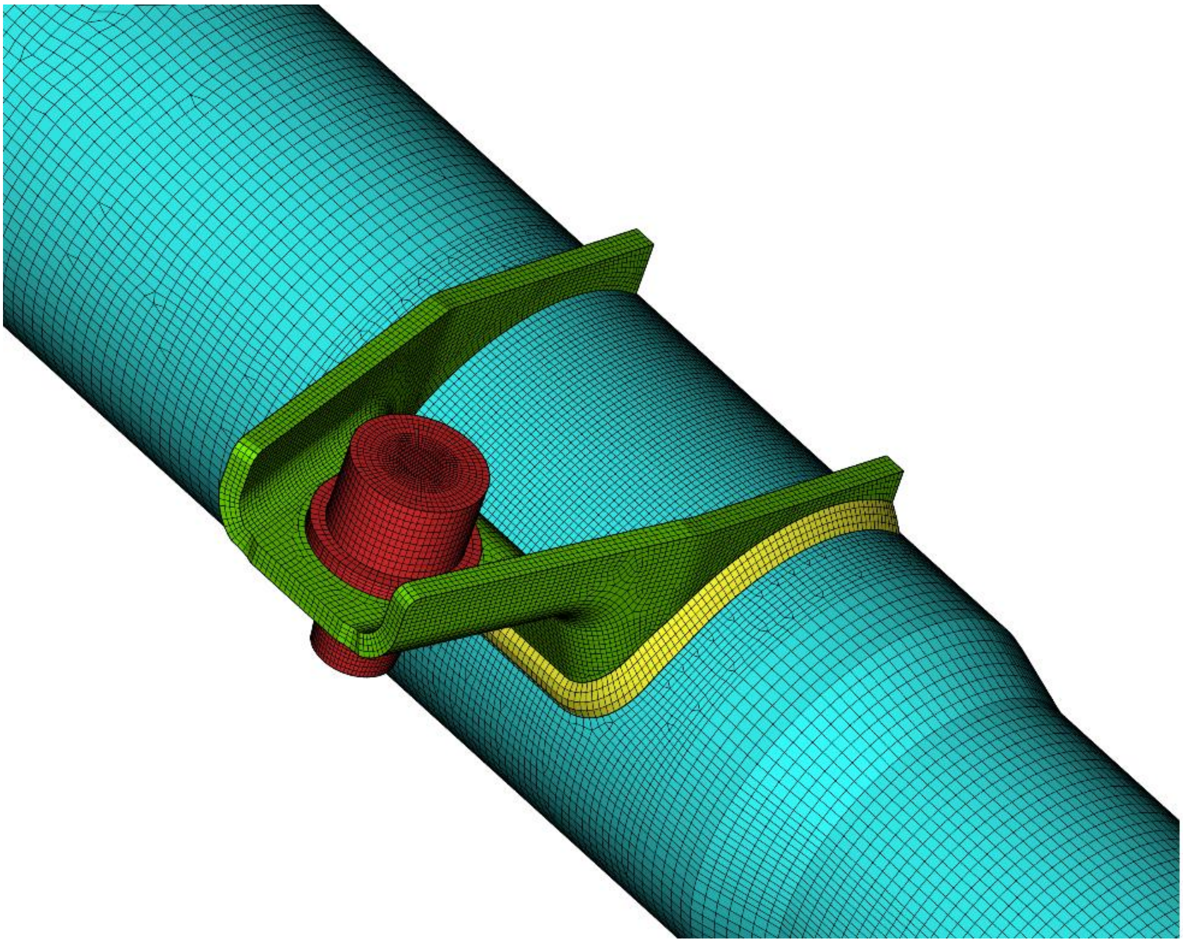


Figure 44. FEA model of stabilizer bar bracket welded to reserve tube.

The simulation optimisation method. The FEA model optimisation cannot be currently performed with the use of automatic algorithms, due to the high complexity. To verify the approach elaborated as the result of the PhD project, these comparisons were done manually. The optimisation element of the simulation is a fatigue material model assumed as the relationship between total strain and endurance proposed by Coffin and Mansion (Öztürk, 2016; Xu et al., 2021) (Figure 45). The applied adjustment methods were based on the reverse engineering and optimizations algorithms to minimize the difference between the obtained fatigue lifetime results in the physical test and simulation.

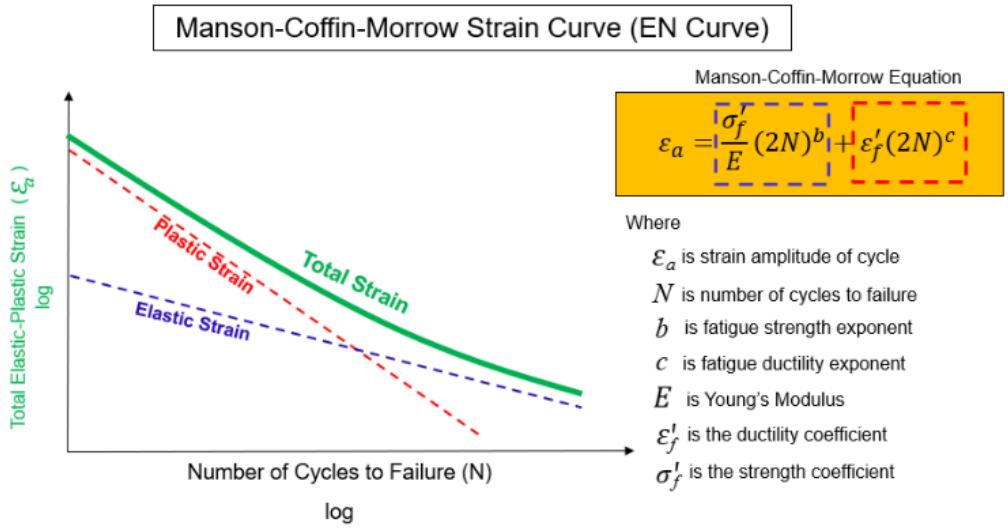


Figure 45. Relationship between total strain and endurance (Siemens.com, 2023).

The optimisation procedure, presented in Figure 46, is accepted as the company standard and consists of the following steps:

- Define a DOE matrix for material properties
- Setup an nCode to execute the prepared DOE matrix
- Calculate durability in the nCode
- Calculate an error
- Provide the error feedback to the DOE procedure
- Run an optimisation algorithm to minimise the error, the error is a difference between the simulation result and test result.

The optimisation was done with use of Isight software on the basis of the fatigue engine with parametrized fatigue properties showed in Figure 45.

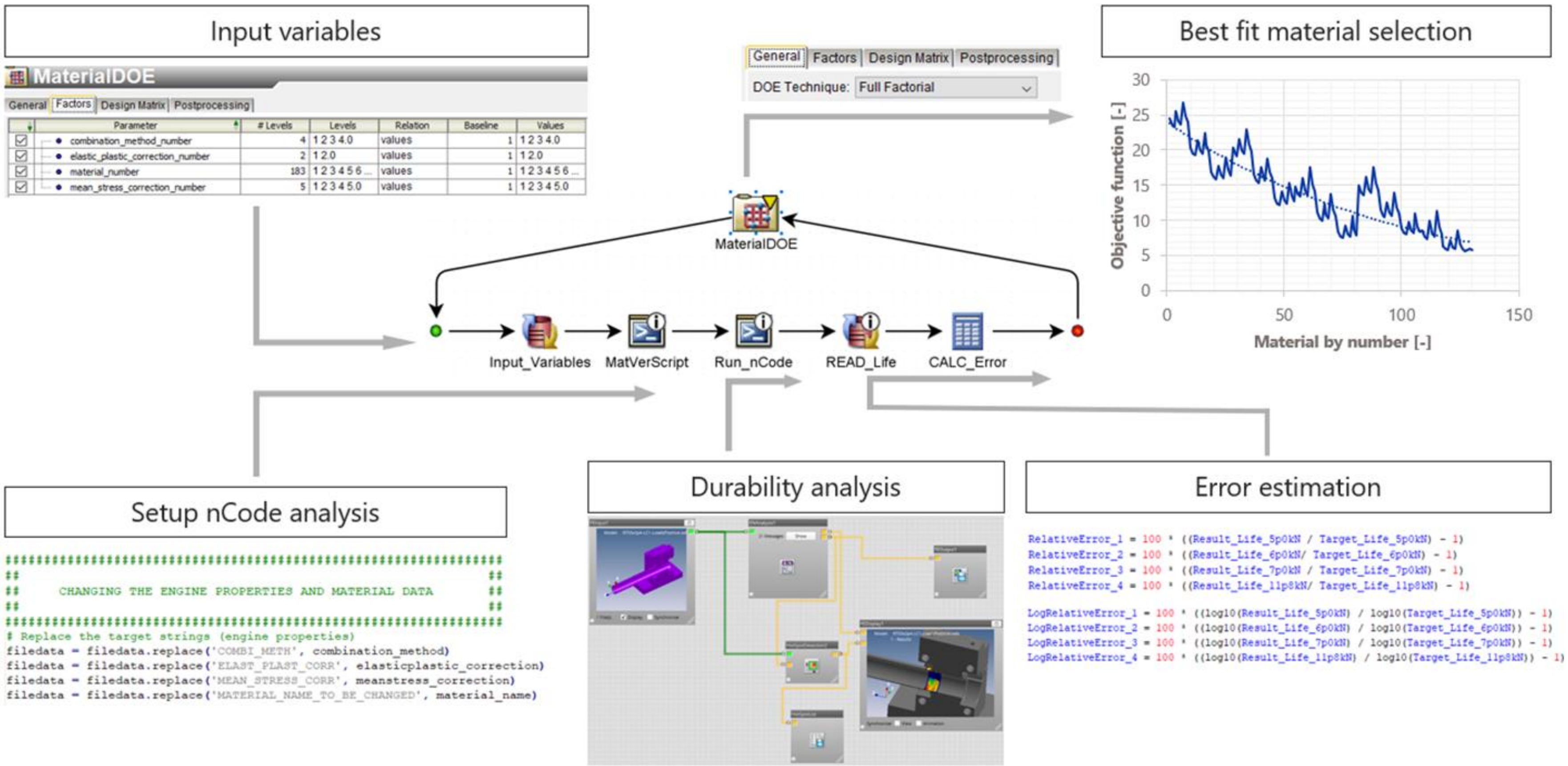


Figure 46. Simulation optimisation procedure.

The simulation optimisation procedure based on available data. The described optimisation method was used to improve prediction resulting from the simulation of the stabilizer bar bracket. Results of ten tests were reviewed according to completeness and correctness of data and fixture parameters. The product and test signal classifications were available and correctly defined, but it was discovered that fixture parameters were missing in eight tests. Taking it into account, results of two remaining tests were only used for the optimisation procedure. To prevent such cases and to avoid missing data in the future, the input data for the fixture design parameters was set as to be mandatory fields. The summary of the test results of two correct tests is presented in the Force vs number of cycles graph in Figure 47.

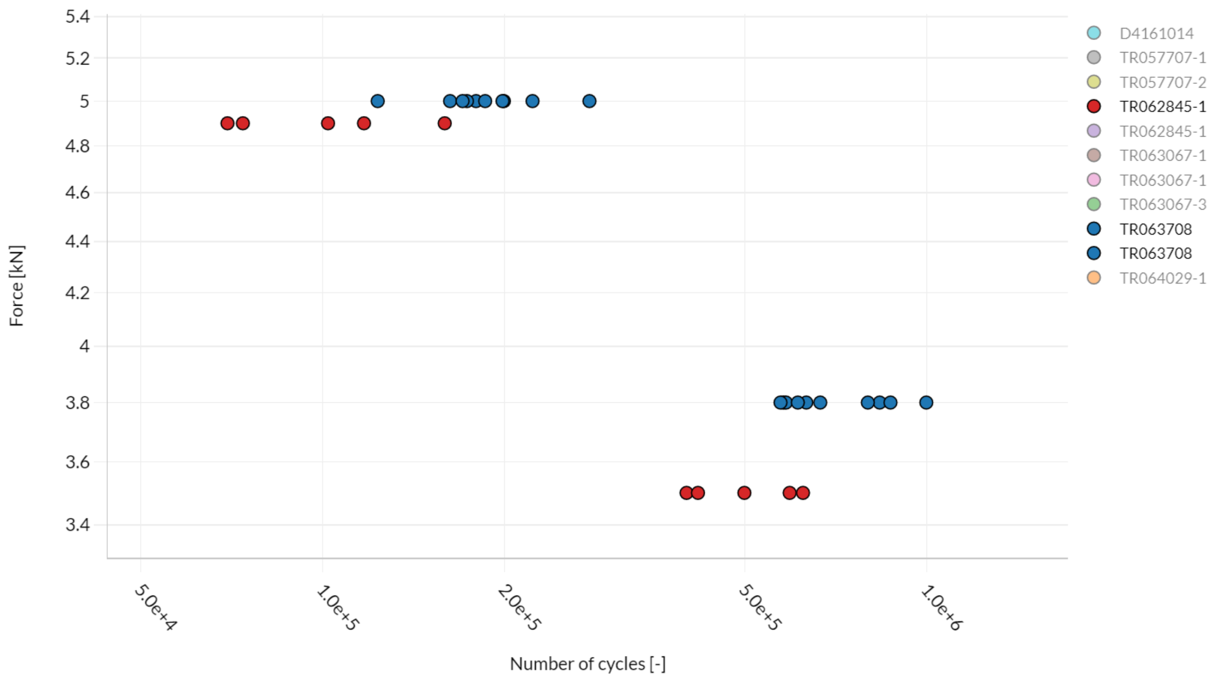


Figure 47. Force - number of cycles graph.

The test parameters of the selected test are presented in Table 9. The key parameters are collected to explain the differences between the tests and total number of test results. There are two different geometries of the stabilizer bar bracket tested, distinguished by the test result ID. The load levels differ between the test results ID, due to different project requirements. The test request identified as TR063708 was performed for two different angles, but the remaining parameters of this test are exactly the same. According to the requirement, all tests were conducted till the complete failure of the same mode. The term failure mode is a standard nomenclature within automotive industry as per Failure Mode Effect Analysis handbooks and refers to the manner in which product could fail to fulfil requirements. (Automotive Industry Action Group & Verband der Automobilindustrie, 2021; Chrysler Corporation, 2008). For each load five samples were tested, therefore total number of test results is equal to ten.

Table 9. Test parameters overview.

Test result ID	Stabi bracket type	Stabi bracket part number	Load level 1 [kN]	Load level 2 [kN]	Angle α [°]	Angle β [°]	total number of test results
TR062845-1	C-shape	02071514	3.5	4.9	16	19	10
TR063708	C-shape	02070817	3.8	5.7	10	10	10
TR063708	C-shape	02070817	3.8	5.7	-10	10	10

The 3D geometry of both components is presented in Figure 48. The stabilizer bar brackets (indicated in green colour) is characterized by different geometry but it still represents the same C-bracket type.

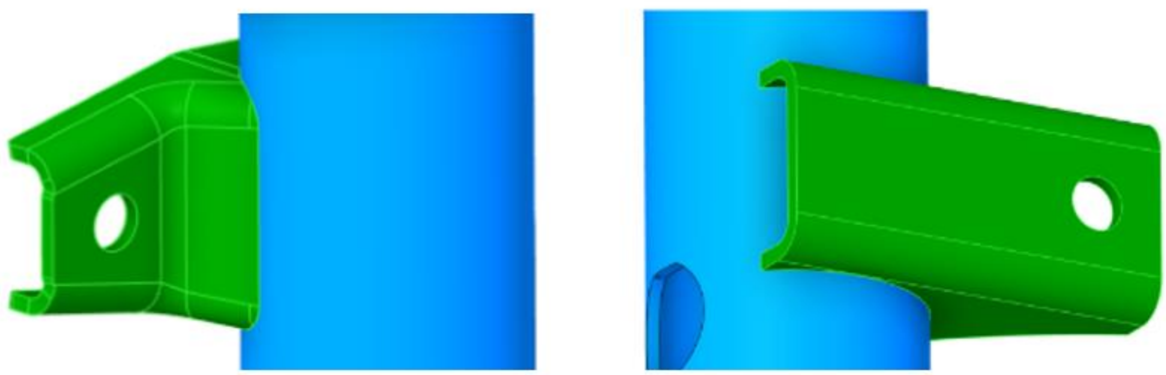


Figure 48. The 3D geometry of the stabilizer bar bracket (left: TR062845-1; right:TR063708).

The overview of the test and FEM results for TR062845-1 is presented in Table 10. The column *Durability cycles* presents test results for each tested sample. The life prediction based on FEA is provided for both loads and values are presented in column *Life prediction – FEA N50%.*

Table 10. Example of the test and FEM results for TR062845-1.

Sample	Load amplitude (+/-)	Durability	N50%	N97.7%	Stress Range	Mean Stress	Life prediction - FEA N50%	Failure
XS Number	kN	cycles	cycles	cycles	MPa	MPa	cycles	location
XS529884	4.9	102 135	91 590	53 160	1 251	-140	92 200	bolt hole
XS529885	4.9	73 839	91 590	53 160	1 251	-140	92 200	bolt hole
XS529886	4.9	69 637	91 590	53 160	1 251	-140	92 200	bolt hole
XS529887	4.9	117 133	91 590	53 160	1 251	-140	92 200	bolt hole
XS529888	4.9	159 305	91 590	53 160	1 251	-140	92 200	bolt hole
XS529889	3.5	592 874	640 900	338 200	986	-103	547 400	bolt hole
XS529890	3.5	400 270	640 900	338 200	986	-103	547 400	bolt hole
XS529891	3.5	418 060	640 900	338 200	986	-103	547 400	bolt hole
XS529892	3.5	623805	640 900	338 200	986	-103	547 400	bolt hole
XS529893	3.5	498944	640 900	338 200	986	-103	547 400	bolt hole

The elaborated data is presented in Figure 49 as the force versus the number of cycles, called by the F/N curve. The graphs present Wöhler curves based on the results achieved for two load cases for the same component. The black dots represent the test result, red dot presents the FEA calculation result for a given force level.

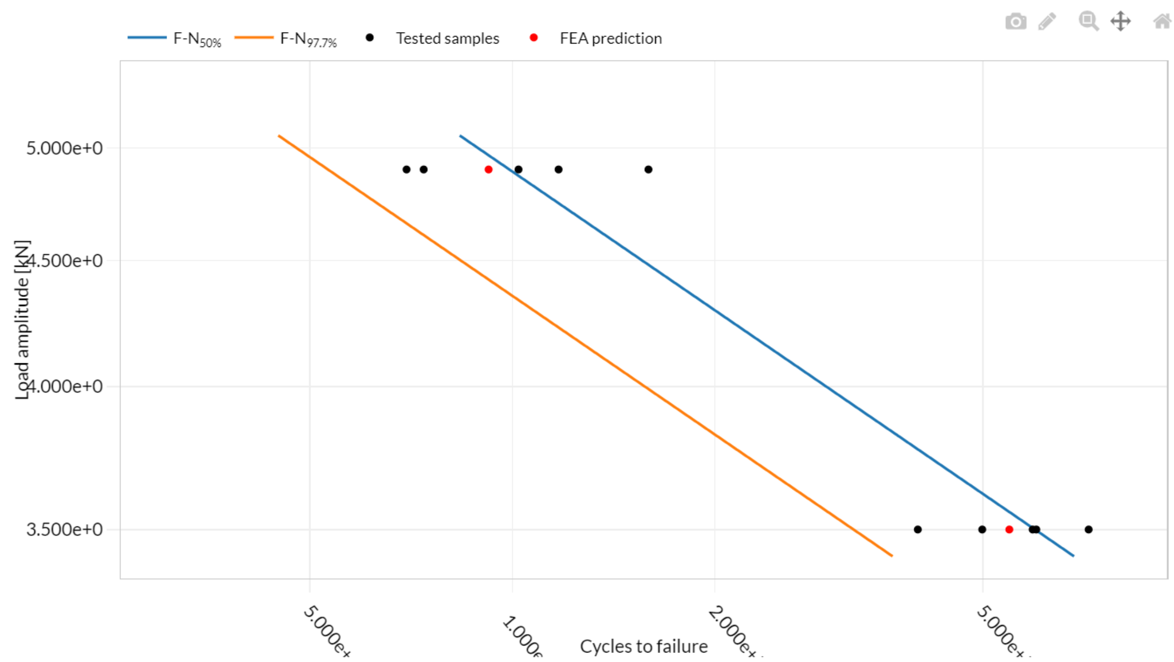


Figure 49. F-N Wohler curve for the stabilizer bar bracket durability (TR062845-1)

The statistical analysis was conducted for each dataset consisting of results of 5 tests and 1 simulation result based on 1-sample T test. The FEA result was used as the target of the hypothesis testing in statistical software minitab. The exemplary results are presented in Figure 50. The statistical output confirms that the population mean of the test result is not statistically different than FEA simulation result.

Descriptive Statistics

N	Mean	StDev	SE Mean	95% CI for μ
5	192185	19588	8760	(167864, 216507)

μ: population mean of Durability cycles at 5kN_B

Test

Null hypothesis	H_0: μ = 173328
Alternative hypothesis	H_1: μ ≠ 173328

T-Value	P-Value
2.15	0.098

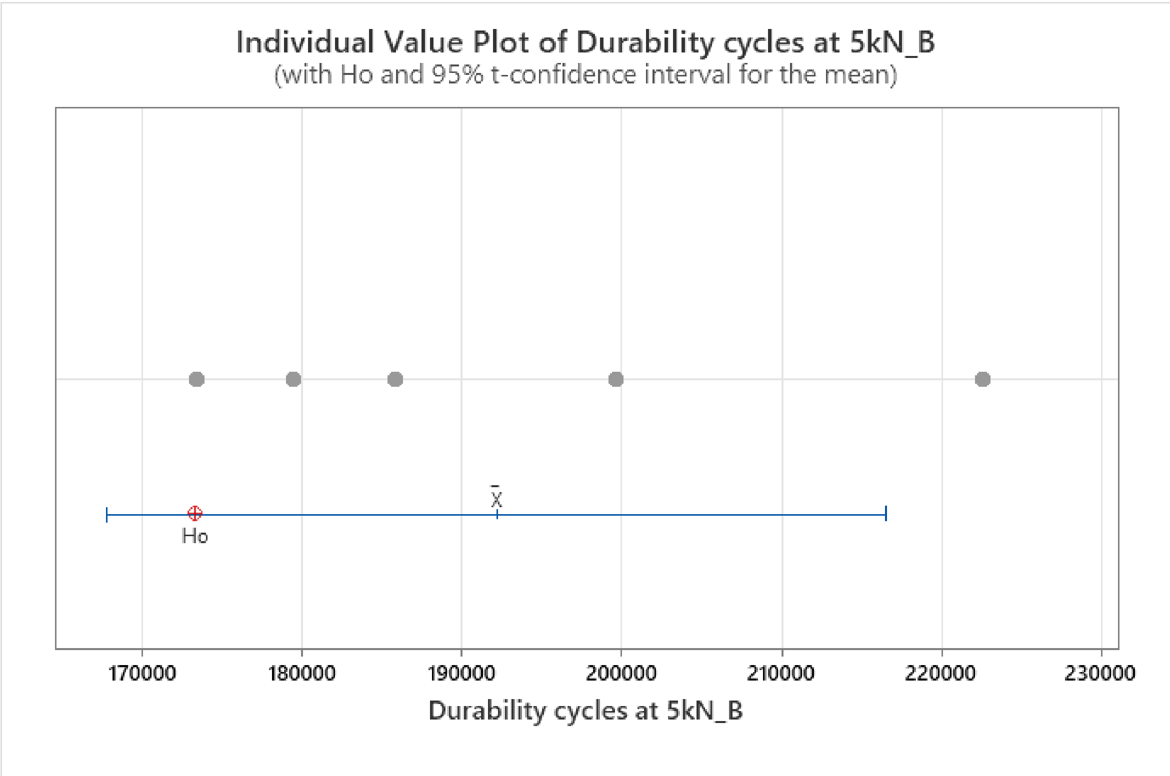


Figure 50. 1-sample T test analysis result.

Finally, based on the executed optimisation procedure, the numerical model is treated as the digital twin not only of the element and also but as the digital twin of the prototyping and simulation stage. The automotive nomenclature as described in the design detection ranking table (Chrysler Corporation, 2008) is providing term of virtual analysis highly correlated with actual or expected operating conditions. Therefore, later on in the thesis, correlated simulation is described. The complete concept of the digital twin is presented in Figure 51.

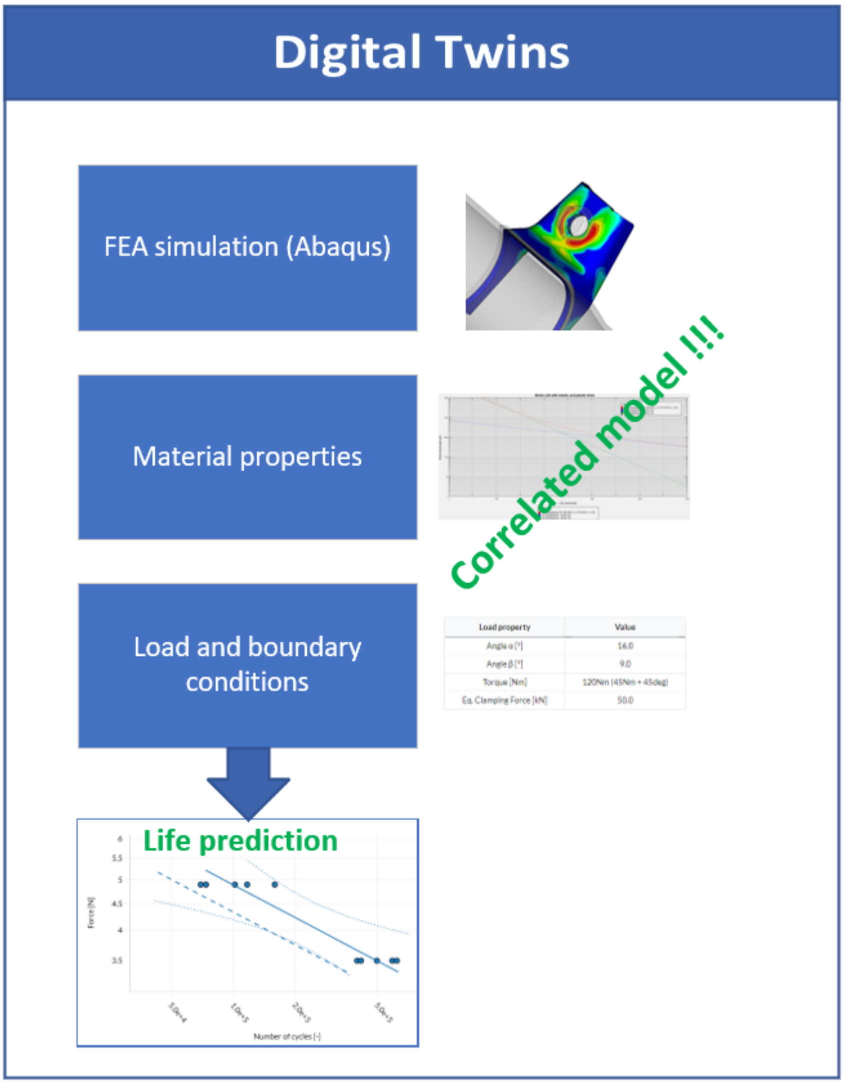


Figure 51. Digital twin implemented in the product development process.

Failure type prediction. The stress concentration presented in the FEA was compared to the failure type achieved during the durability test. The exemplary visual comparison was presented in Figure 52. The location of the crack on the physical element after the test is perfectly matching with the stress concentration presented by the FEA simulation. It must be stressed that FEA experts together with testing experts judge the correlation on very high level and the FEA results can be trusted and used as the final design decision.

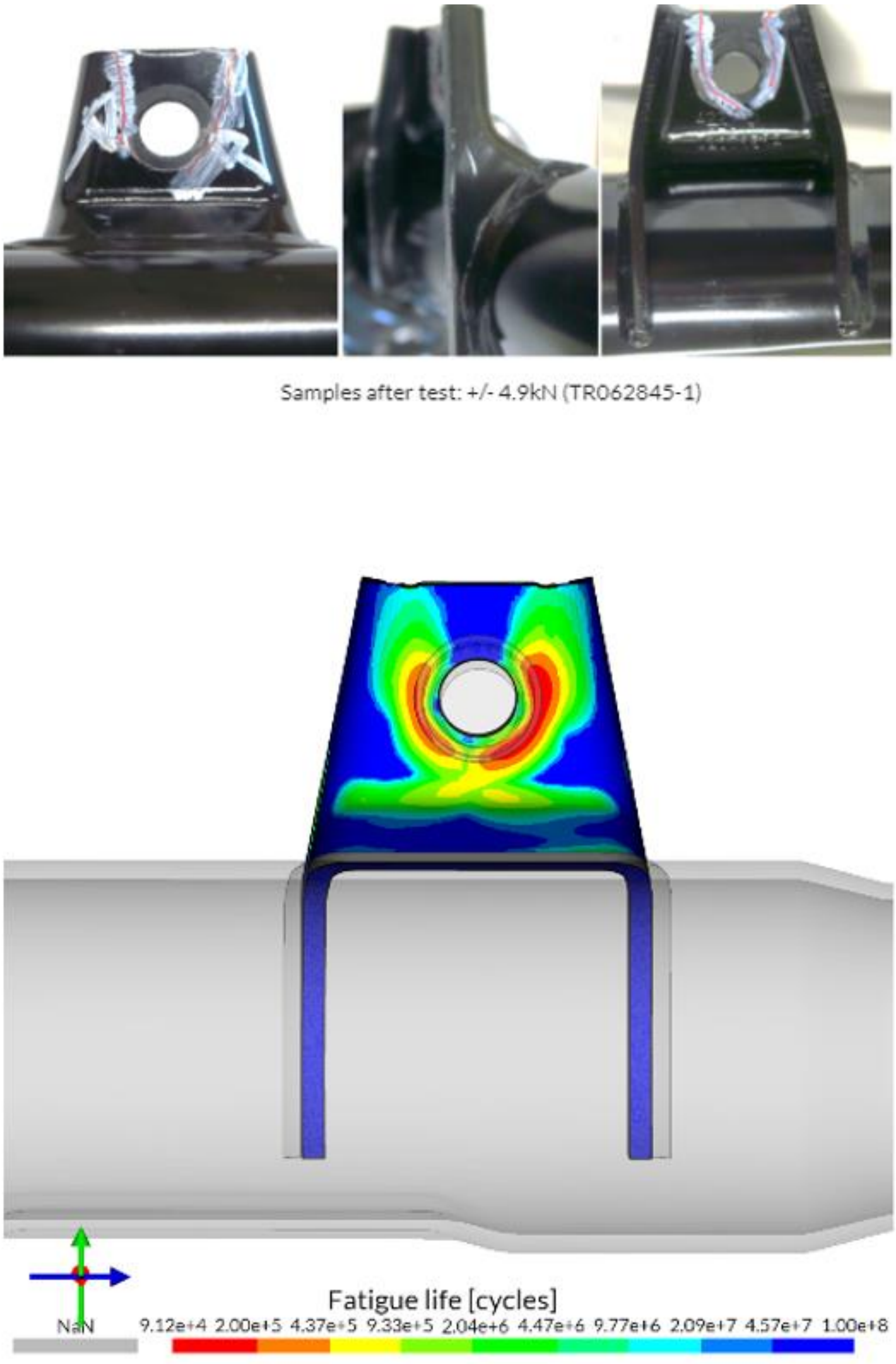


Figure 52. Failure mode and stress concentration comparison (TR062845-1)

Digital Twin input and analysis applications. It should be stressed that the pilot project, selected as the verification of the digital twin implementation required some additional specific decisions and tasks undertaken by the company. On the basis of the results obtained from the presented PhD project, the management of Tenneco company decided to develop two applications related to the CAE department. The requirements were formulated on the basis of data collected by experts during sessions managed by the author.

To collect the data and requirements for two pilot projects, a special application was developed by the company. The application was located on the internal website dedicated for several CAE tools (Figure 53).

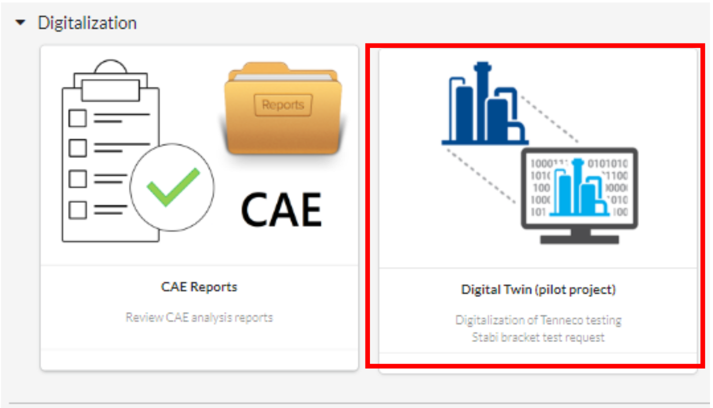


Figure 53. Digital twin data collection application icon.

The purpose of the data collection is to standardise the input data and ensure that the digital data is available for consecutive steps in the system. The input data window for the stabilizer bar bracket is presented in Figure 54, where the following data sections are visible:

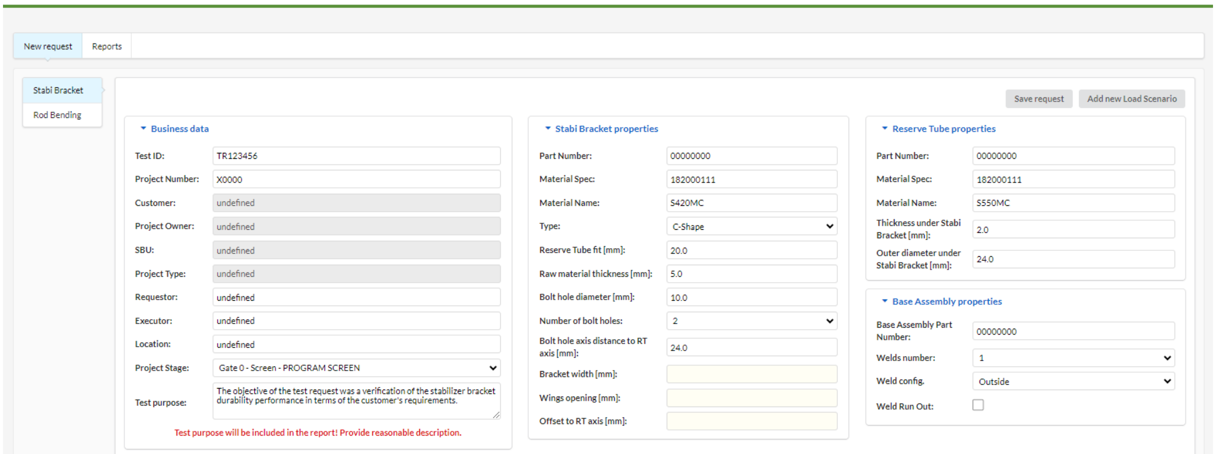


Figure 54. Stabilizer bar bracket input data window – part 1.

- Business data section collects the information on the request, including the test ID, project identification number and a requestor name as a reference to the ticketing system. Visible grey cells are automatically filled in based on the provided project number. The remaining fields must be completed manually.
- Other two data windows are related to the design parameters. In the case of the stabilizer bar bracket the durability depends on the design parameters of the stabilizer bar bracket, reserve tube and weld joint parameters. This data shall be provided manually since the current digitization level in the company does not allow to upload this data automatically.
- The second part of the input window (Figure 55) is related to details of the test method and geometry of test fixtures. The input sections are related to a test load scenario, as well as acceptance criteria and test results.

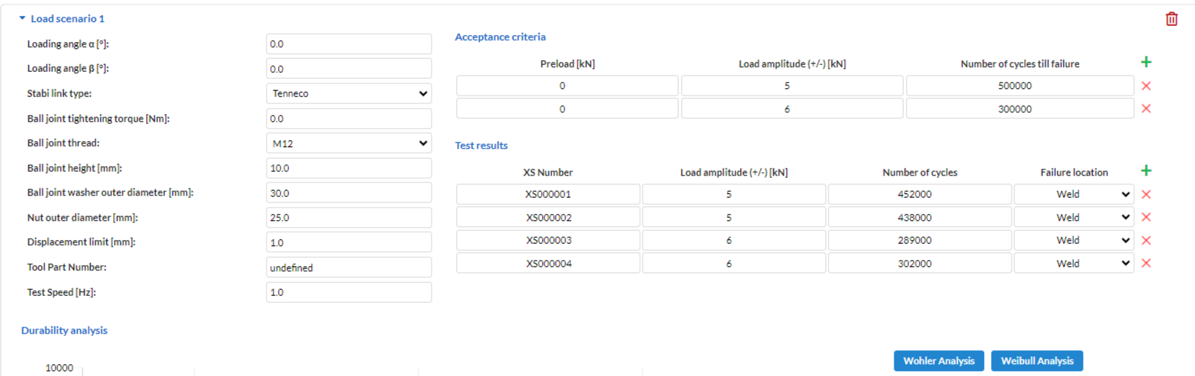


Figure 55. Stabilizer bar bracket input data window – part 2.

The second application developed to support the implementation of the digital twin is a durability processing tool (Figure 56). The aim of this application is to perform the statistical analysis of durability test and present it in a graphical form that can be directly used for the test or FEA report.

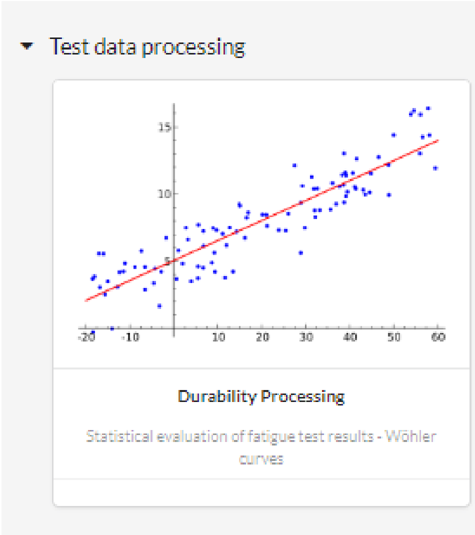


Figure 56. Durability processing tool.

The analysis tool offers two statistical methods that are commonly used in the automotive industry to analyse durability data. The first method is based on the Weibull distribution and is suitable for analysing results obtained at a single load applied to specific components or assemblies. In case of multiple load levels, the Wöhler curve method is commonly used. Additionally, this tool allows to analyse the data following the internal company standards resulting from the Volkswagen method. As the effect, the results of this tool can be directly used as an input to the FEA reports, without need to perform any additional statistical analysis. Furthermore, the tool offers a graphical representation of durability data including confidence intervals. The example of the described tool and its options are presented in Figure 57.

In order improve overall business processes, the statistical analysis of the durability data was implemented directly in the system elaborated within PhD project. As results, the additional workload related to the manual entry of a product and test data is compensated by time gained on the automatic reliability analysis. Previously, testing engineers were responsible to copy the data into the statistical software and then execute the reliability study according to the company standards. The solution elaborated as the result of PhD project, characterized in the thesis, is not only improving the process efficiency, but also eliminate the risk of incorrect statistical analysis. Moreover, the available software allows a number of other options required to follow strictly the analyses accepted by the company. The implemented statistical analysis covers the Weibull analysis used for single load cases and the Wöhler analysis used for multiply load cases. The validation of the embedded statistical analysis was performed for several test results. An example of the analysis comparison is presented in Table 11Table 11. Comparison of statistical analysis.. Both statistical methods delivered the same results for key statistical distribution parameters. The statistical analysis performed with the use of the developed tool is presented in Figure 58. It was compared to the analysis performed with the use of statistical software minitab and was presented in Figure 59.

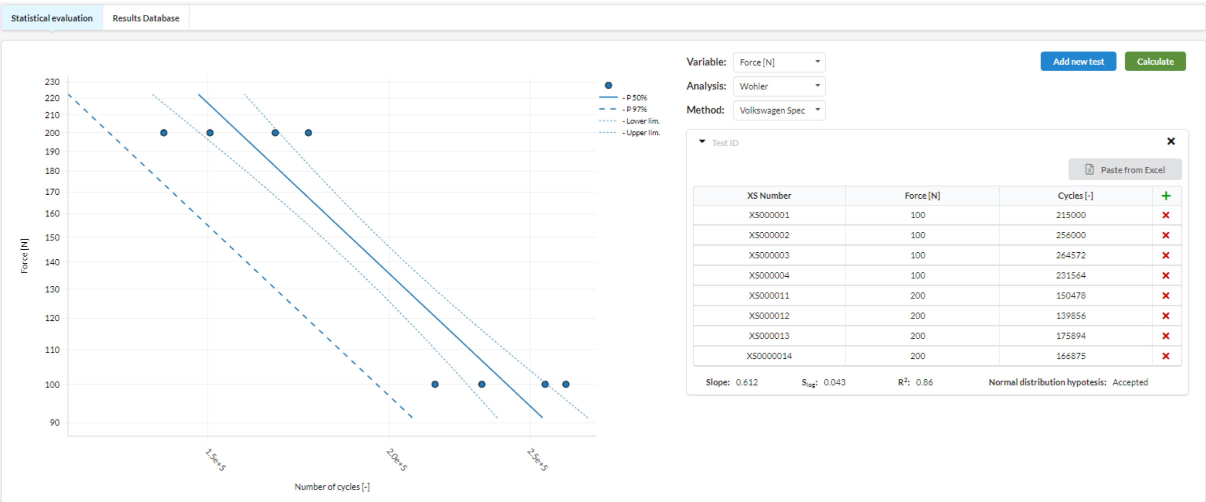


Figure 57. Wöhler curve analysis

Table 11. Comparison of statistical analysis.

Parameter	Developed tool (PhD thesis)	Minitab
Shape	8.315	8.31454
Scale	412157	412157
Anderson Darling (AD)	2.58	2.579

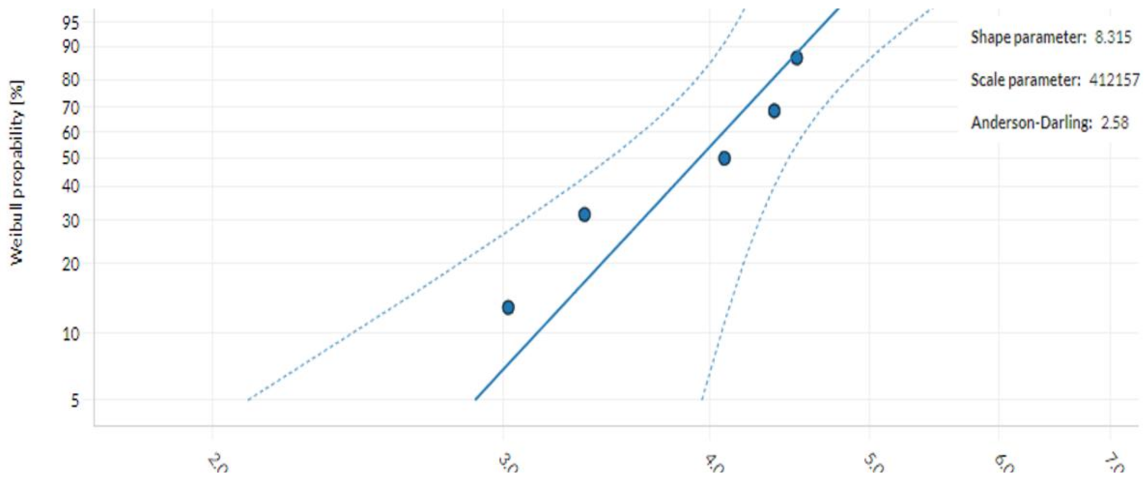


Figure 58. Weibull analysis in developed tool.

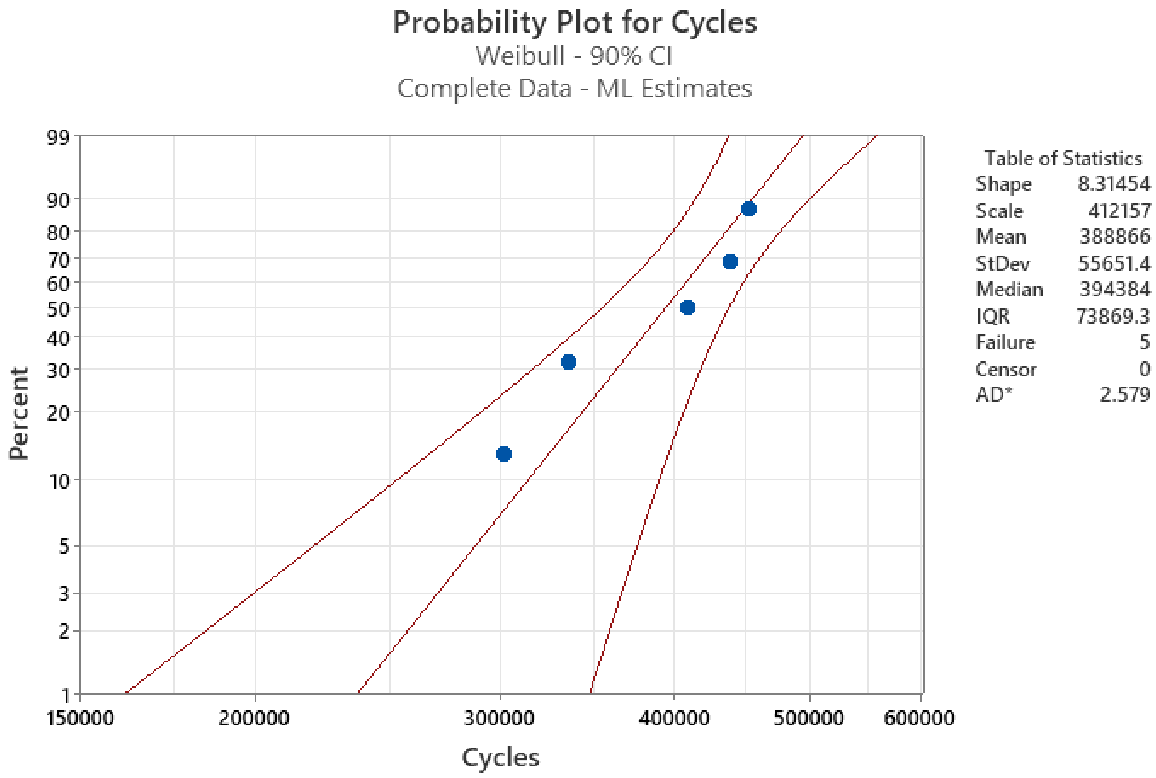


Figure 59. Weibull analysis performed in minitab.

Additionally, the same internal standard to display 90% Confidence Intervals was applied in each tool. They delivered the same results, what is visible in the presented graphs.

Another section of the elaborated tool was prepared to present currently available historical durability data (Figure 60). Several results are presented and distinguished by different colours. Collected data was gathered from 2022 to 2023 as the historical data. New test results are going to be added directly through the new data input application. Filtering options are presented in Figure 61.

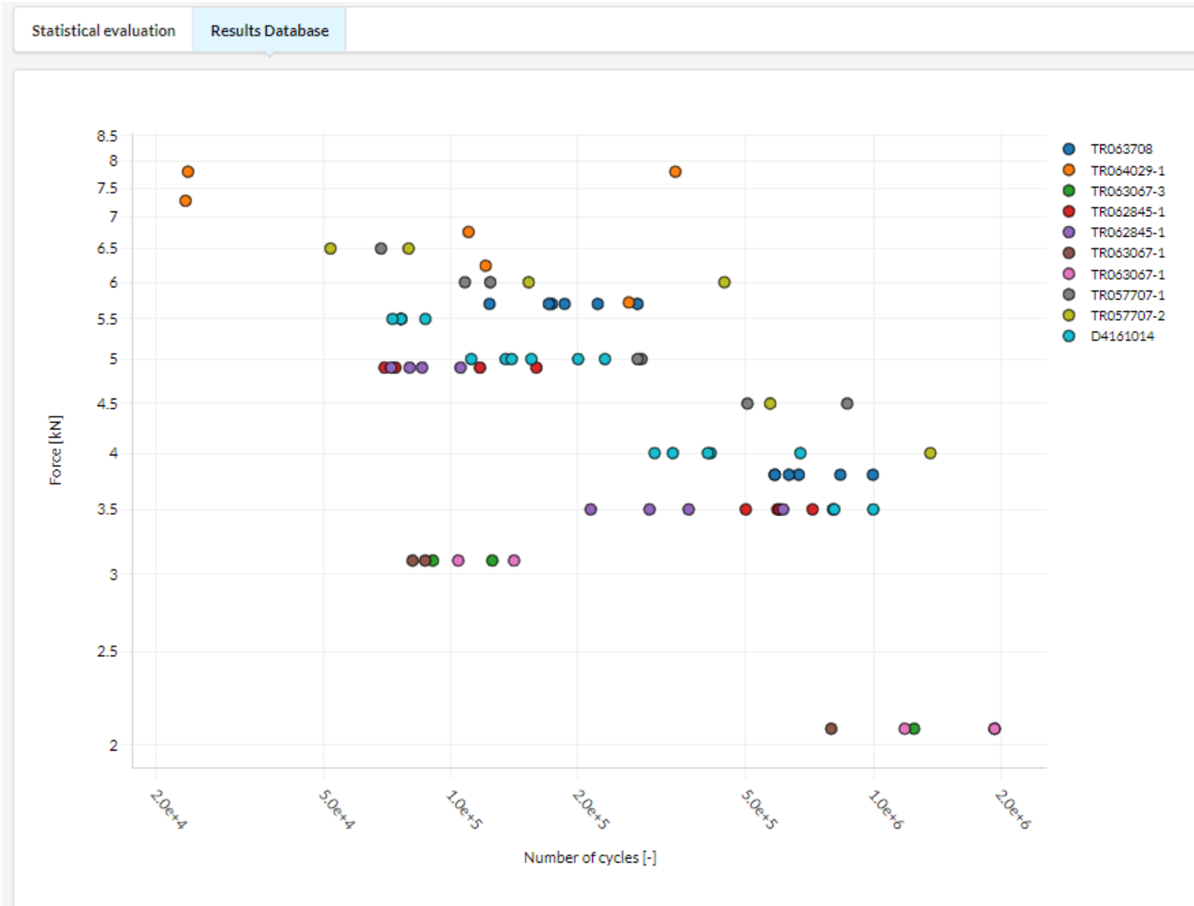


Figure 60. Durability results.

The results are presented in the graph as the Force vs Cycles or Stress vs Cycles. This selection is performed by the user by means of a drop-down menu, presented in Figure 65. It must be clarified that the force vs cycles graphs present the test results and stress vs cycles graphs consist of the simulation results.

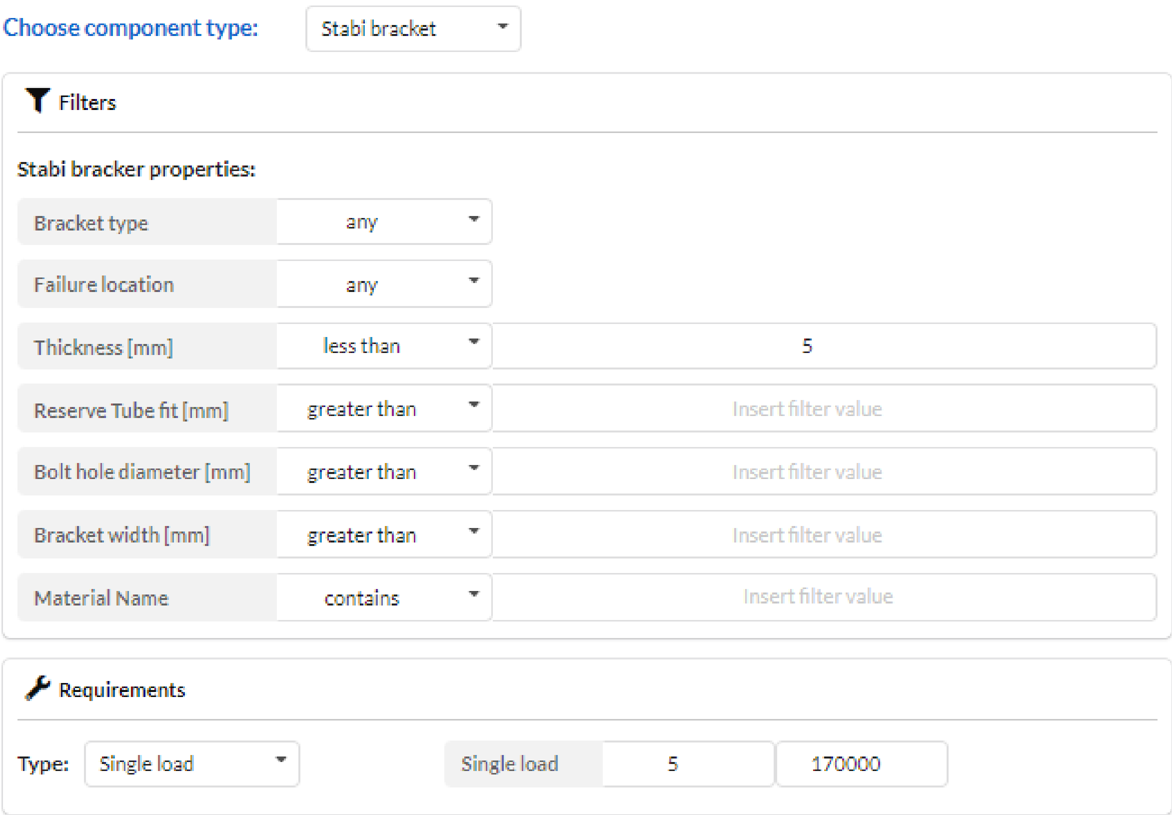


Figure 61. Filtering options.

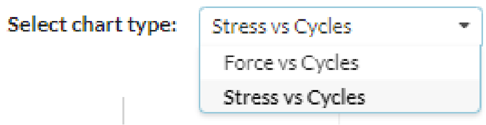


Figure 62. Chart type selection.

Force vs Cycles data representation. To understand the large amount of data available in the database a special filtering and analysis options were elaborated. An engineer reviewing the existing data is able to filter data with the use of selected design parameters such as material or geometrical characteristics. It should be stressed that customer requirements for the load and number of cycles are also considered. In the example presented in Figure 63 the bracket thickness was set to be lower than 5 [mm] and results minimum acceptance criteria were setup to 5 kN of load and 170 000 cycles. The possibility of filtering is crucial for the product development engineering, searching for existing design solutions that potentially can meet customer requirements given for a specific project. This allows us to utilize already gathered knowledge, implement it for other upcoming projects and as the result eliminate or minimize the development and testing time.

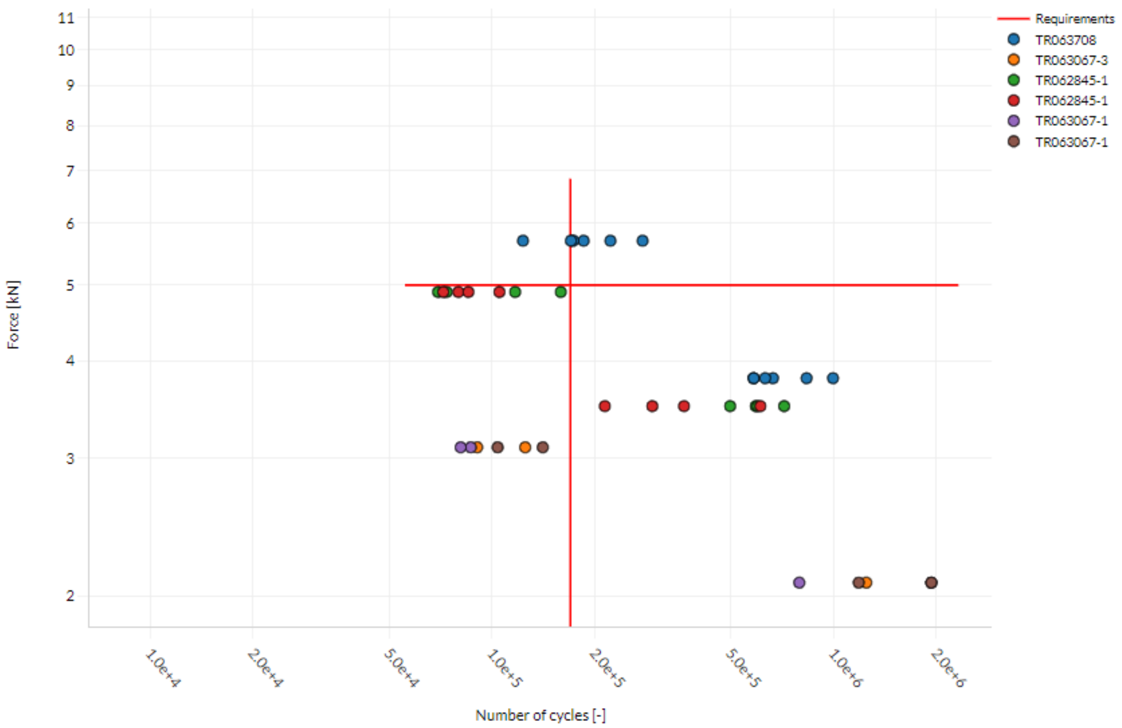


Figure 63. Durability data filtering example.

Stress vs Cycles data representation. During the analysis of gathered data, it became important to understand the stress level characteristic for a given design. Therefore, three selected test results that were used for the simulation adjustment, were used also to calculate the stress range values (Figure 65). The values were used for each tested element. One can observe that the test results presented in the force vs cycles graph (Figure 64) clearly indicate that the tested element identified as TR063708 (blue dots) have longer lifetime than the parts identified as TR062845-1 (red dots). Additionally, it must be noted that the parts identified by blues dots were tested at higher load values than the parts marked with red colour. The preferable method to understand the test results of several different elements is the analysis of stress ranges that need to be calculated by the FEA simulation. The result of this recalculation is presented as stress vs number of cycles, known as the S-N curve (Figure 65). The graph presents the lower stress range values for the parts identified by blue dots. Therefore, the design of the element is characterized by longer lifetime then the elements identified with the red colour.

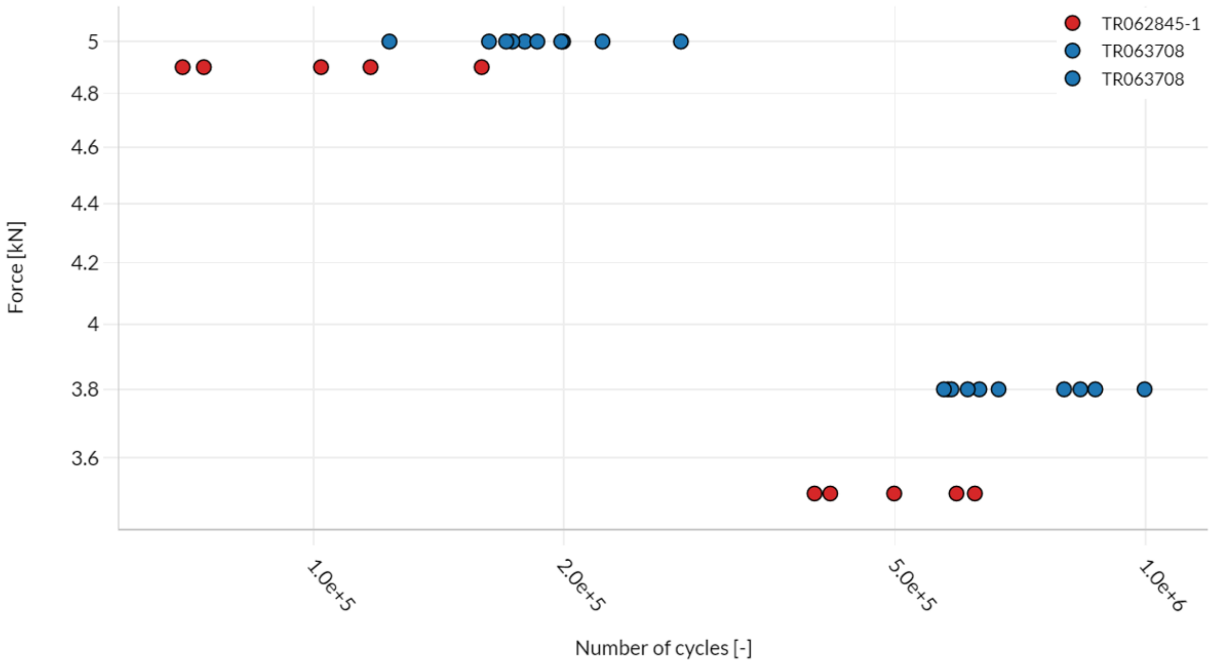


Figure 64. Force vs cycles graph for selected tests.

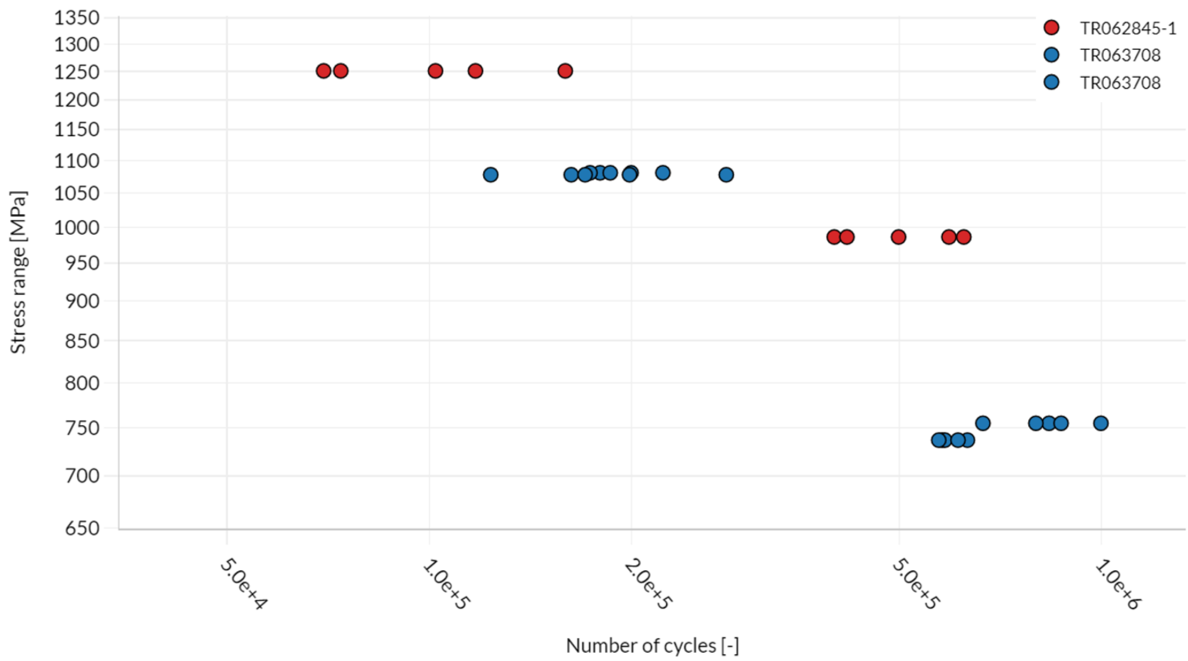


Figure 65. S-N graph for selected tests.

The stress level depends on:

- the material types
- geometry of the stabilizer bar bracket
- angles of the applied forces
- the force levels
- the bolt join geometry

- the nut torque.

The stress range graphs shall be created for a single material type. The stress ranges represent remaining parameters listed above. The stress range vs cycles graph can be used in two following cases:

1. Verification of new test results in the domain of stresses. The new test results can be presented by the FEA simulation as stress ranges and added to existing simulation results. Engineers can compare recently achieved results with the existing data. It is fundamental for verifying whether the recent test was performed correctly.
2. The geometry of a new component can be used to calculate the stress range level and then these values can be compared to the currently available simulation results. The goal is to understand the achieved stresses and perform the geometry optimisation in order to meet customer requirements.

Rod bending test – the second digital twin pilot project. The second pilot project aimed at verification of the digital twin implementation was related to a rod bending test. A rod is one of the key components of a shock absorber. Therefore, the force transfer is a key functionality of the rod. The rod bending test is typical verification selected as the developed element. The FEA simulation related to this case was elaborated and is commonly used in the company. The goal of the simulation is to estimate the bending force at specified displacements. However, currently the accuracy of the simulation is not acceptable. The results of the rod bending test depend on the element geometry, material properties and hardening depth. The scheme of the rod bending simulation adjustment was presented in Figure 66 . The solution developed as the result of the PhD project let us to collect and display specific data. The database created for collecting the results from the rod bending test is presented in Figure 67. The load deflection data and hardening profile data are used to adjust the FEA simulation and to reflect results of the physical test. A request for the FEA simulation can be submitted completing in the data in the input window characterizing the digital twin of the rod (Figure 68).

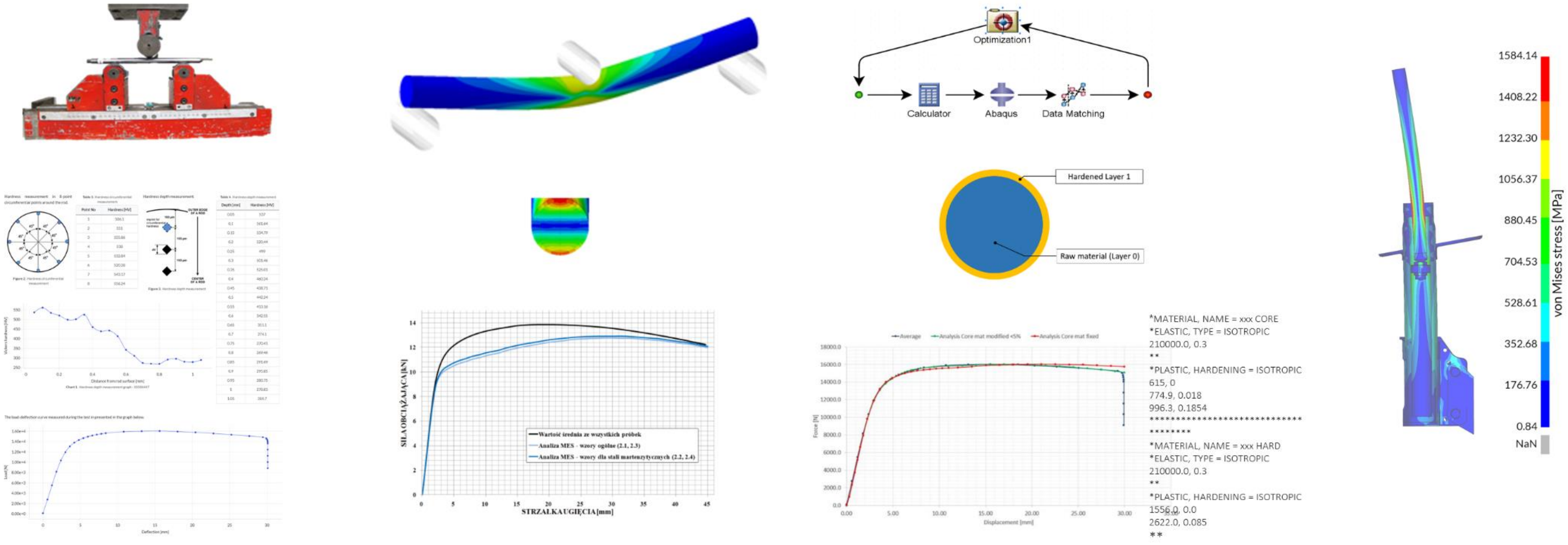


Figure 66. Rod bending simulation optimisation.

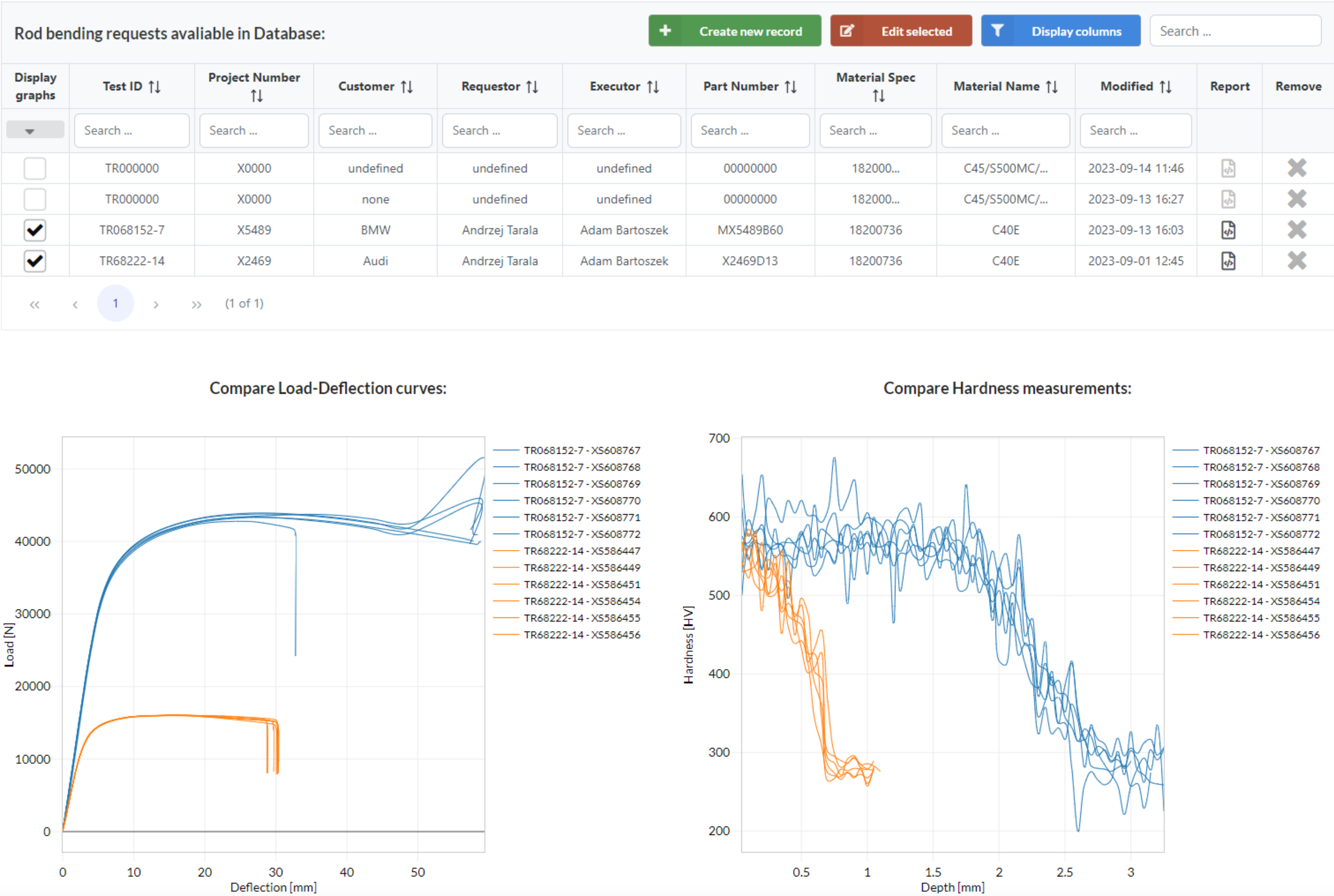


Figure 67. Rod bending digital twin data input database.

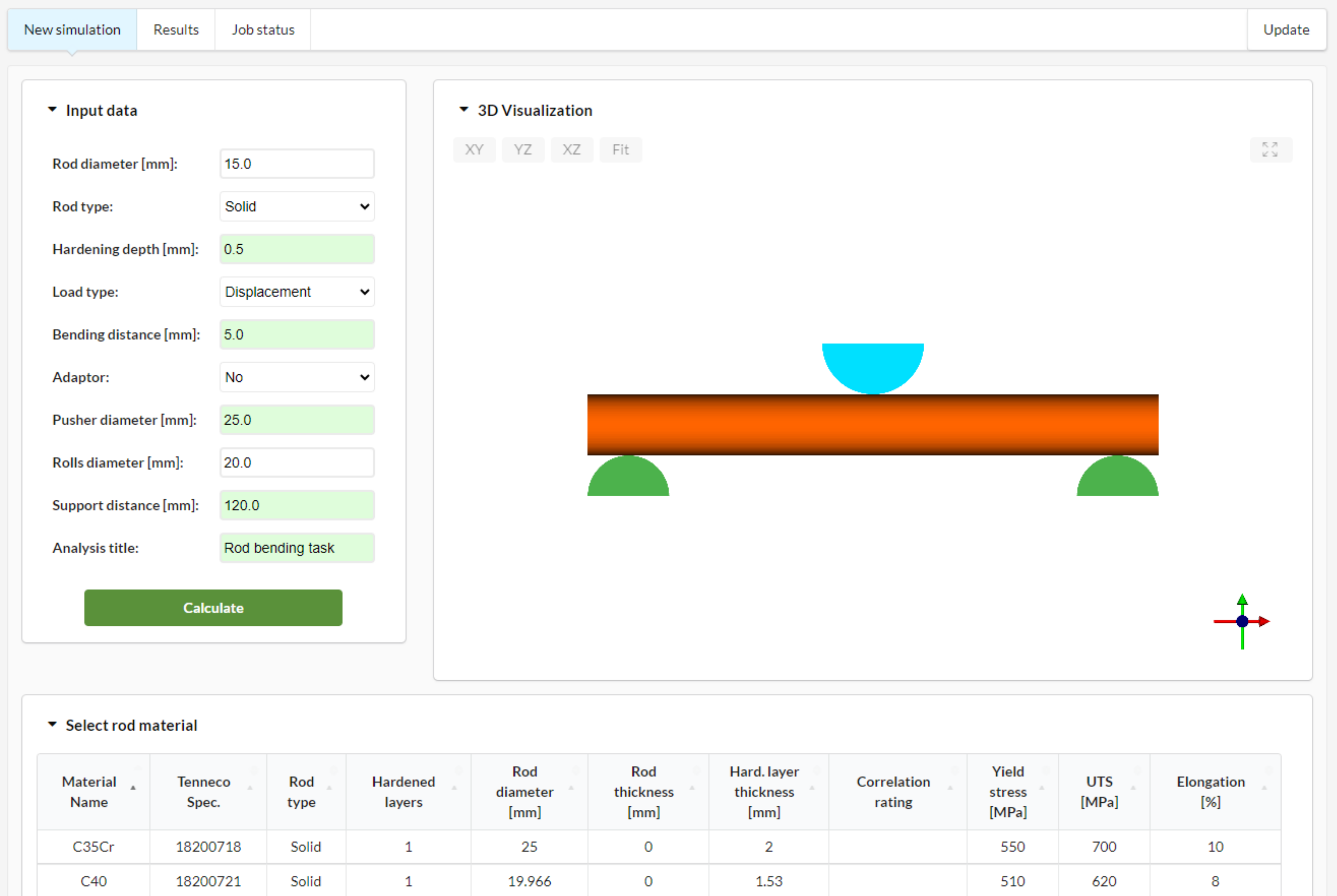


Figure 68. Rod bending digital twin.

Future process map. The simulation that is the digital twin, supported by the data classification and digitization allows to optimise processes and define the process map, presented in Figure 69. There are three key improvement areas:

- Limited risk for an incorrect design definition at the RFQ stage. The digital twin ensures that the optimized design is the simulation which is following the test results. Alternatively, the existing tests results can be easily reviewed to find already existing solution meeting customer requirements
- In the design and development stage, some trusted design proposals obtain as the results of the digital twin implementation are going to reduce the amount of test iterations. It can be replaced by the implementation of correlated simulations, reducing engineering work and test time.
- Digital Twin is also expected to support the *Design Verification stage* by eliminating a part of the physical tests. The digital twin is correlated with physical test results.

Digital Twin supporting knowledge management. The correlation of the test results with the simulation model allows to achieve the digital twin that also includes an element responsible for a fatigue lifetime prediction. The collected data, correctly identified and available for the digital twin ensures that knowledge gained from the previous projects can be used to propose a design solution for new projects. There are two potential scenarios of utilizing the gathered knowledge that are presented in the flow diagram in Figure 70. The load and cycles requirements for a given component received for a new project entering into the durability tool. An application engineer is able to determine if any already existing design is meeting the new requirements. In case of finding a similar example, the details of the test results and geometry can be revisited as they are available in the FEA report accessible directly in the durability tool. In case there is no any similar example fulfilling the requirement, a new design needs to be proposed based on the digital twin. FEA experts use the stress – cycle curve of digital twin to propose the component geometry that is optimised for the stresses in order to meet fatigue lifetime requirements for a given number of cycles.

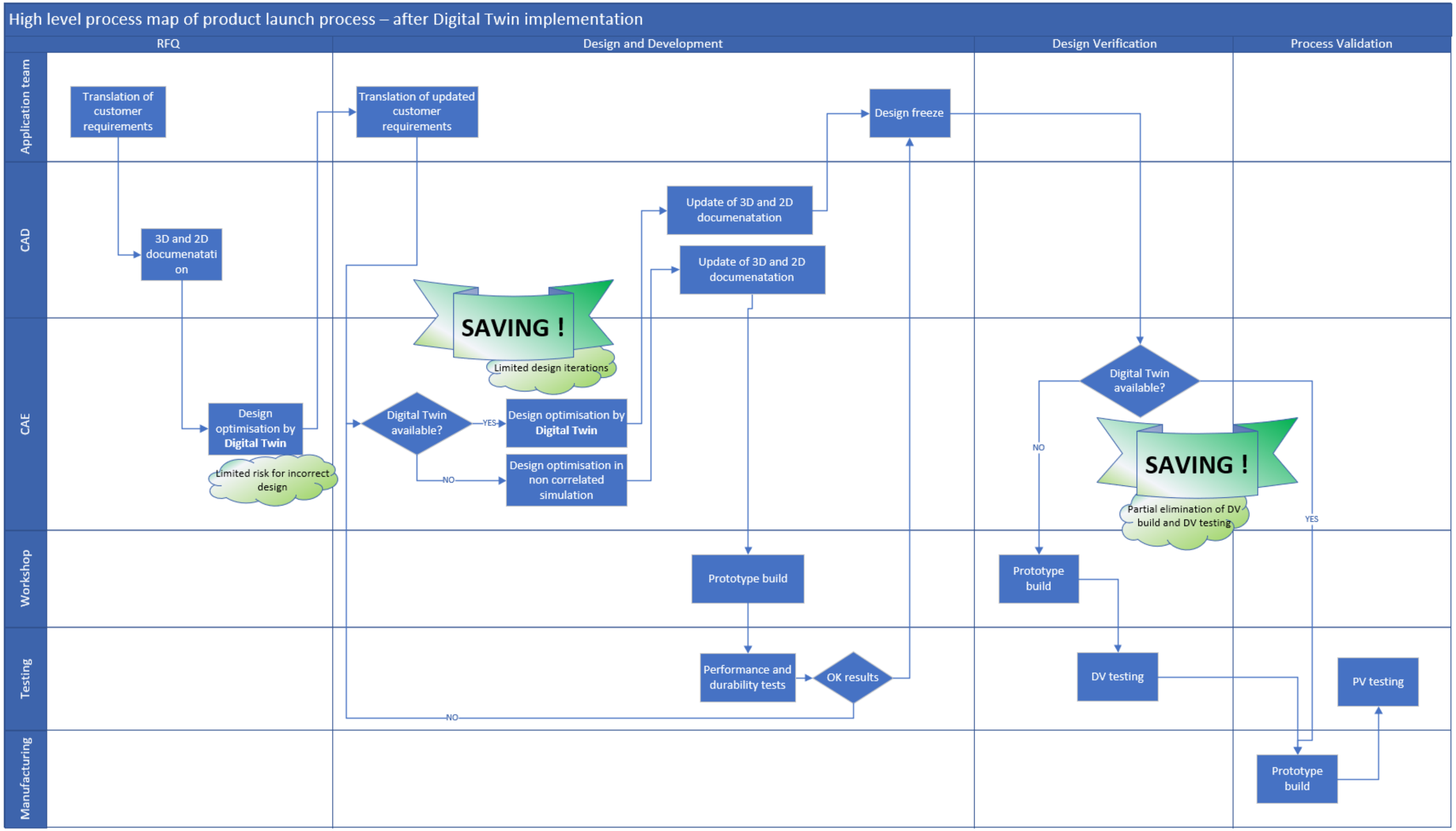


Figure 69. Future product launch process.

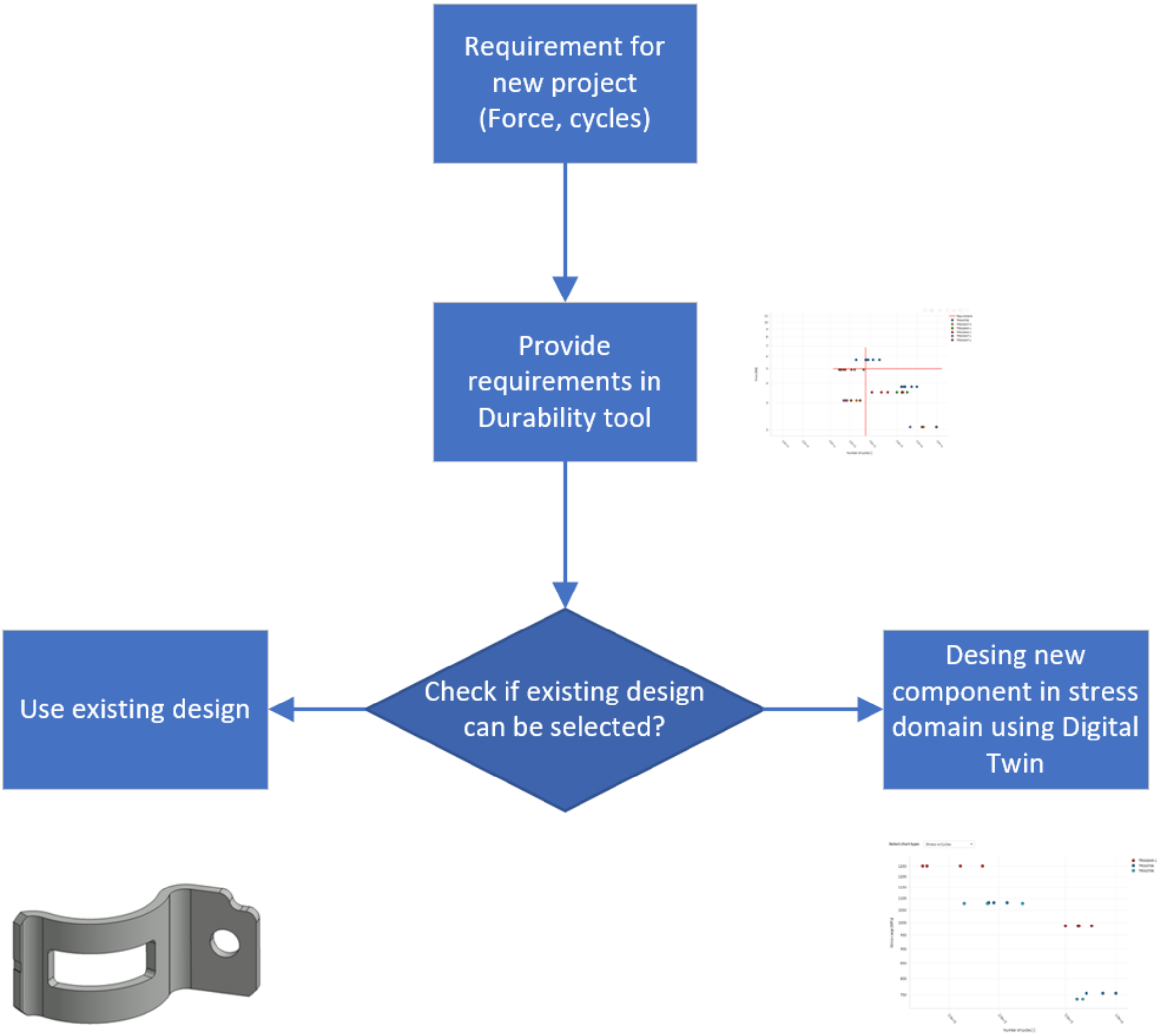


Figure 70. Knowledge management based on the digital twin.

6. Conclusions and further steps

6.1. Conclusions

Importance of process mapping and product classification. The main goal of the doctoral thesis was to improve the knowledge management in the product design and development process in the Tenneco company. However, it must be stressed that focusing solely on IT tools supporting the knowledge management one is not able to achieve the required improvement. The crucial step is to understand current processes and tools as well as activities conducted in the company. The best practice used in Tenneco is a procedure based on the process mapping presented as a swim lane. The task related to the process mapping must include the identification of tools and functions involved in the process as well as capturing all process steps on the basis of a real performance of the process. Additionally, during the process mapping, the information regarding implemented tools, systems and databases should be collected. The next key step is to understand a classification of the components and materials. There should be a clear and standardize way of the classification, what allows to transfer digital values of key design parameters such as material thickness or hole diameter to another system and tool for further processing. The identified lack of standardization and digitization of the design parameters is the cause for manual entries of the same data to the system.

During performing, the correlation between the simulation results and test results, it was noticed that the majority of historical data is incomplete. It was especially remarkable in the case of fixture geometry characteristics which are often missing. The optimisation procedure, performed in the PhD project was successfully conducted. However, only a sample of a minimum size was included. Next steps of the first pilot project was to collect new test results as the effect of the elaborated digital twin application. The results ensure that all required parameters are collected. As the consequence, the optimisation process is repeated to complete the datasets. The presented approach lets us to obtain higher fidelity of the digital twin.

The digital twin implementation is not obvious and requires a rigid process, supported by the best practice approach. The Tenneco company is going to implement the elaborated solution based on the digital twin also for other components.

Knowledge management. The complex Program Launch process, presented in the thesis, involves long time spent on a design and process of product development. The majority of expenses is spent on manufacturing and testing of prototypes. At present, each program requires prototype manufacturing and performing the complete test plan. Due to currently established processes and systems, there is no process nor system to collect the knowledge and then transfer it to design standards for future programs. Even an easy access to the historical test results is limited to the defined time. As the result one observes excessive time of prototypes manufacturing and testing. In current economic situation, especially related to power cost, reduction of prototypes manufacturing and tests is one of the key aspects of company operation. The implementation of pilot projects based on the digital twin presents how the product knowledge from one program can be implemented in other programs. As it was presented, the implementations of the results obtained from the PhD project required introductions of some additional procedures and tools in the company. Firstly, the test results are collected in the digital form and identified according to product classification. It allows dealing with the historical test results and reusing the existing and validated design. Secondly, the improved data flow and data identification allow to perform complex correlation analysis regarding the simulation and test results. It is provided by the digital twin elaborated for a specific component or assembly of complete shock absorber. In this way, the digital twin is not only representing physical product characteristics, but also it is becoming the database on the product.

Savings. The digital twin implementation is not only improving the knowledge management but is also significantly reducing the costs of the whole process. The reduction of the engineering cost is crucial for the company due to increasing energy, material, and supplies costs. Moreover, the vehicle manufacturers tend to decrease the development budget for the components suppliers or include development cost into the price of serial production. It should be stressed that the digital twin has a big potential in reducing design and development cost. The total time savings were presented as labour and machine time in Table 12. The percentage of the time reduction is **5% already in 2026, reaching 8% in 2028**. The saved time can be used to execute respectively 1 or 2 projects to develop new technologies supporting company product strategy.

6.2. Topics for further research

The further steps related to knowledge management supported by the use of the digital twin concept. The digital twin concept was implemented for two test procedures related to stabilizer bar bracket durability and rod bending. The implementation solved significant amount of identified problems, mainly related to the digitization of classifications, integration of the systems and gathering of the test results into database with possibility for data analysis and clustering. As the consequence the concept of the digital twins was widely accepted and resulted in definition of next steps:

1. Digital twin of stabilizer bar bracket durability:
    - Further collection of test results from new projects
    - Simulation optimisation to be repeated when sufficient amount of the complete test results is available. The aim is to increase simulation accuracy
    - New simulation and test results to be reported only using new reporting tool
2. Digital twin of rod bending test:
    - Execute additional test planned to capture multiply design and process characteristics with the target to increase fidelity of the digital twin
    - Review achieved results in aspect of the spread of the test results
    - Optimise simulation based on new data in order to minimize confidence interval of the estimation delivered by the digital twin
3. Digitalization of other test procedures:
    - Discuss possibilities and plan implementation of the solution from pilot projects to potential next test procedures
4. Digital twin of development test procedure:
    - Ongoing discussion to implement digital twin of the flow bench. This equipment is capable to measure hydraulic performance of the valving system. The aim is to collect data and use it to optimise available simulation, resulting in another digital twin. This case requires to use Industry 4.0 technologies related to sensors, data collection and analysis in the cloud.

Table 12. Total time savings.

	YEARS						
Time elements	2020-2023	2024	2025	2026	2027	2028	2029
number of programs (front and rear units)	10	10	10	10	10	10	10
Testing time [h]	15789	15789	15789	15789	15789	15789	15789
Prototyping time [h]	70158	70158	70158	70158	70158	70158	70158
Engineering time [h]	5385	5385	5385	5385	5385	5385	5385
TOTAL TIME	**913320**	**913320**	**913320**	**913320**	**913320**	**913320**	**913320**
Testing time potential for reduction		11053	11053	11053	11053	11053	11053
Prototyping time reduction per project		1245	1245	1245	1245	1245	1245
Design iteration reduction (CAE,Appl CAD)		143	143	143	143	143	143
Digital Twin implementation efficiency	-	20%	20%	40%	40%	60%	60%
Digital Twin development time		5160	5160	5160			
SAVINGS	0	19721	19721	44602	49762	74643	74643
TOTAL TIME AFTER REDUCTION	**913320**	**893599**	**893599**	**868718**	**863558**	**838677**	**838677**
TIME REDUCTION %	0%	2%	2%	5%	5%	8%	8%

Digitalization concept for the engineering organisation. Medium and top-level management of Tenneco company was involved in the implementation of the digital twin into the process of product development. Moreover, the elaborated approach triggered a discussion regarding future business processes in the engineering department of the company as well as the need to introduce a new system architecture. *Digitalization calls* started in the company in 2021, currently result in two global workshops related to Digitalization strategy and IT systems architecture. Both directions are planned to be realized in October 2023. The current high-level process map covering the complete engineering structure was prepared. It is presented in Figure 71.

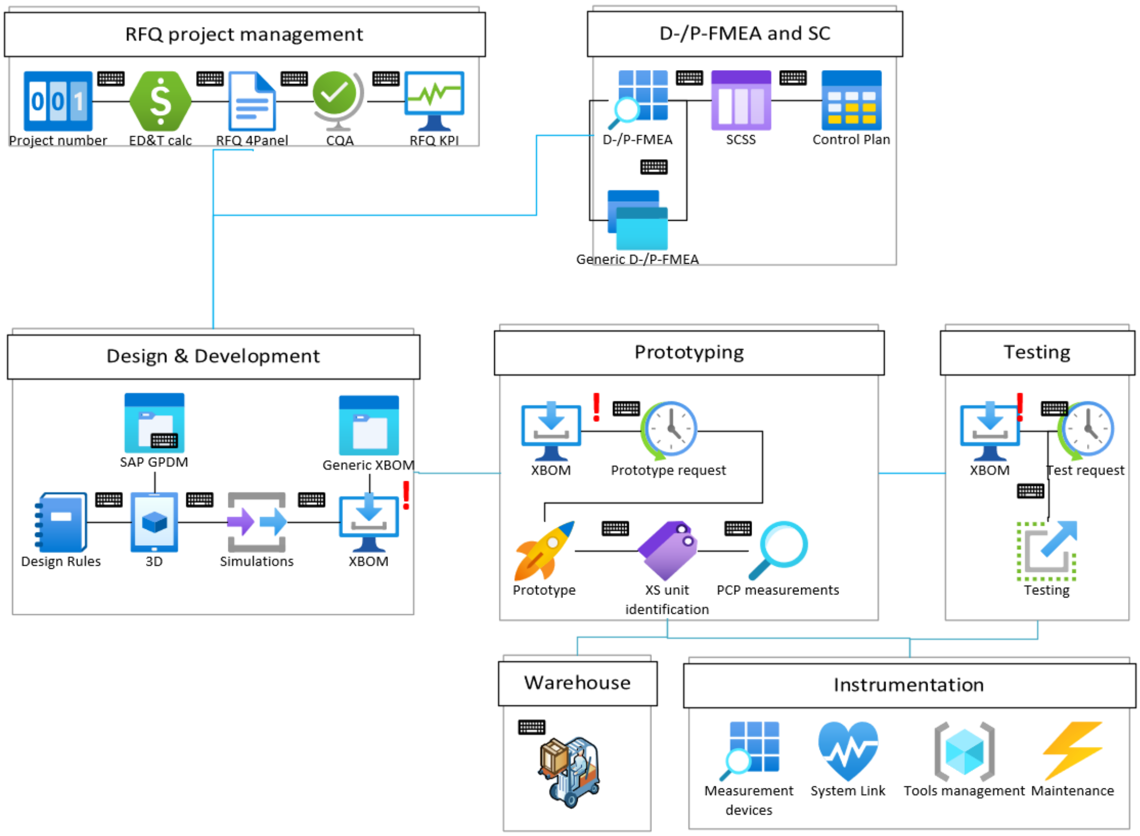


Figure 71. Digitalization map - current state.

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