



Facing environmental uncertainties with the Digital twin technology: A Case Study of German Automotive OEMs

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I. Abstract

Title: Facing environmental uncertainties with the Digital twin technology: A Case Study of German Automotive OEMs

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The German automotive development and production process is vulnerable to environmental uncertainties, threatening the goal of low-cost and efficient processes for original equipment manufacturers (OEMs). Uncertainties like changing market regulations, market price volatility of materials, or product market feasibility force the OEM to adapt its processes and vehicles. Lack of technical resources, good coordination and flexibility issues across actors involved in the problem space are the main cause of adaption failure leading to production stops and market delays. Past research has shown how OEMs integrated the digital twin technology (DTT) into their ecosystem. Digital twins (DTs) are real-time virtual presentations of their physical counterparts simulating and predicting its behavior, leading to reduced planning complexity. Different DTs can be created for vehicles (parts, software, processes, technologies) or factories (production lines). Thus, this research will provide an explanatory case study comparing how OEMs adapt automotive development and production processes to environmental uncertainties without incorporating DTT versus with DTT. It consists of qualitative data only: expert interviews and literature research. Results suggest DTT provides a single source of truth by linking different DTs, actors, systems and work processes allowing for hybrid analyses instead of discrete analyses with different modules and simulators, providing fluidity of knowledge and inclusivity across actors involved. The visualized data provides simulations and predictions to evaluate business decisions digitally first and synchronizing updates across actors involved supporting coordination. Ultimately, supporting the concept of DTT to help OEMs adapt efficiently.

Keywords: Germany, Automotive Industry, Automotive development, Automotive production, Digital Twin Technology, Environmental uncertainty

II. Resumo

Título: Enfrentar as incertezas ambientais com a tecnologia de gémeos digitais:
Um estudo de caso dos OEM alemães do sector automóvel

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O processo de desenvolvimento e produção automóvel alemão é vulnerável a incertezas ambientais, ameaçando processos eficientes e de baixo custo para os fabricantes de equipamento original (OEM). Incertezas como a alteração da regulamentação, a volatilidade dos preços de mercado dos materiais, ou a viabilidade do mercado dos produtos forçam os OEM a adaptarem-se. A falta de recursos técnicos, boa coordenação e flexibilidade entre os actores envolvidos no espaço problemático são a principal causa de falhas de adaptação que levam a paragens de produção e atrasos. Pesquisas anteriores mostram como os OEMs integraram a tecnologia digital de gémeos (TDT) para os seus veículos, fábricas ou processos no seu ecossistema. Os gémeos digitais (TDT) são representações virtuais das suas contrapartidas físicas simulando e prevendo o seu comportamento. Esta investigação fornecerá um estudo de caso explicativo comparando a forma como os OEM adaptam o desenvolvimento e os processos de produção automóvel às incertezas ambientais sem incorporar TDT versus com os TDT. A investigação consiste em dados qualitativos (entrevistas a especialistas e investigação bibliográfica) mostrando como os TDT fornecem uma única fonte de verdade ao ligar diferentes TDT, actores, sistemas e processos, permitindo análises híbridas em vez de análises discretas com diferentes módulos e simuladores, proporcionando fluidez de conhecimento e inclusividade entre os actores envolvidos. Os dados visualizados fornecem simulações e previsões para avaliar primeiro digitalmente as decisões empresariais e sincronizar as actualizações entre os actores envolvidos, apoiando a coordenação. Em última análise, apoiando o conceito de TDT, ajudando os OEMs a adaptarem-se eficientemente.

Palavras-chave: Alemanha, Indústria Automóvel, Desenvolvimento Automóvel, Produção Automóvel, Tecnologia Digital Twin, Incerteza Ambi

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VI. List of Abbreviations

R&D	Research & development
GDP	Gross domestic product
OEM	Original equipment manufacturer
DTT	Digital Twin Technology
CFD	Computational fluid dynamics
CAD	Computer aided design
CAE	Computer aided engineering
AI	Automotive Industry
BMW	Bavarian Motor Works
CO2	Carbon dioxide
TCT	Transaction Cost Theory
Ex ante	before the event
VR	Virtual Reality
RQ	Research question
Q&A	Question & Answer

1. Introduction

Germany is a key country in the automotive industry (AI) deploying high-tech strategies to bring key innovation and technology alliances together (MacDougall, 2020). For original equipment manufacturers (OEMs) like BMW, Audi or Volkswagen etc. to hold a competitive edge, there is ongoing need for new technology and business models to keep costs low and efficiency high (Barthel, et al., 2015). The automotive industry is characterized by long planning horizons, intensive use of resources, and inflexibility. This is true for the most intense periods of introducing a new vehicle: the development and production phase (Krywdzinski, 2017). These periods are vulnerable to uncertainties beyond the control of the OEM. Hence, environmental uncertainties threaten the goal of low-cost and high-efficiency development and production. This includes uncertainties like changing market regulations, market price volatility of materials leading to shortages, or product market feasibility forcing the OEM to adapt the vehicle and processes to sudden changes. Although OEMs follow existing strategies for adapting to environmental uncertainties, it is always unknown whether they can do so effectively because technical resources are the main cause of adaption failure (Rothenberg & Ettl, 2011). This is supported by the concept of Transaction cost theory (TCT) and real options theory: companies are not able to foresee *ex ante* in case of changes in the environment. Their only option is to adapt as fast as possible. Challenges in such situations are information overload, inflexibility, and coordination difficulties between actors involved (Williamson O. , 1985).

OEMs began to integrate digital twin (DTT) technology across their ecosystems. Digital twins (DTs) are virtual shadows of their real-life counterparts being able to reflect attributes of the latter. Thus, DTs can reflect the temperature, functionality, movements, processes or systems and more. Providing classification, recognition, prediction, and determination services for their physical entities (Lee, et al., 2021). Connections between the virtual and physical twins are tied by their data (Grieves & Vickers, 2017). Digital twins can be created for the automotive, facilities and even work processes. Allowing for an efficient analysis for adapting the vehicle and processes in an integrated space. Additionally, DTT provides fluidity of knowledge because the data needed for an efficient analysis, is visualized and synchronized automatically allowing for better coordination between the actors involved (West, Stoll, Meierhofer, & Züst, 2021). Thus, DTT can tackle coordination and flexibility issues. It has been proven to elucidate key

cost impacts, extract improvement opportunities and develop informed technology roadmaps before the vehicle is further developed/produced (Biesinger, Kraß, & Weyrich, 2019).

1.1 Academic & Managerial Relevance

DTT is already well-established in several areas and industries ranging from healthcare, fashion, and architecture. It has become a transformative and innovative technology across multiple areas including development, production, engineering, or supply chain management (Rasheed, San, & Kvamsdal, 2020). In 2022 the automotive industry application of DTT is only at 12% and past research mostly provides insights such as benefits of DTT and its applications (Botín-Sanabria, et al., 2022). For instance, it has been proven that DTT can lower costs and risks because of its simulation and prediction capabilities (Biesinger & Benedikt Kraß, 2019). Additionally, development and production of vehicles is subject to environmental uncertainties requiring OEMs to rely on highly innovative technological resources (Krishnan, Geyskens, & Steenkamp, 2015). Despite recent interest in DTT in the AI, which is the most innovative industry in terms of R&D, there is a noticeable absence of research on how OEMs can use DTT to adapt to sudden changes due to environmental uncertainties in development and production (MacDougall, 2020). By being able to react and adapt quickly and efficiently to sudden changes, OEMs gain a competitive edge and acquire flexibility, cost savings and the ability to plan more efficiently. Therefore, this research provides insights for better managerial efficiency and additional academic knowledge.

1.2 Research objective

There are five main objectives which are crucial to answer the research question. First, the researcher seeks to explain the development and production process of automotives and what environmental uncertainties faced within these processes. Second, to explore the potential damages caused by uncertainties. Third, to explore how OEMs currently adapt to those environmental uncertainties and the problems of those tactics. Fourth, to elaborate DTT in development and production processes and its potential to mitigate and promote adapting to environmental uncertainties. Ultimately, the goal is to compare how OEMs adapt automotive development and production processes to environmental uncertainties without incorporating DTT versus when using it.

1.3 Research method

For this research, a multi-method research design was selected focusing on qualitative data collection. Semi-structured expert interviews were conducted to generate insights about development and production processes, concepts of DTT, and its potential to adapt to environmental uncertainties. Second, an explanatory case study will be presented to explain how OEMs adapt automotive development and production processes to environmental uncertainties without incorporating DTT versus with DTT. This is combined with expert interviews.

With six experts working in the field of automotive development, production, and two experts working in the field DTT. Secondary data has been collected in the form of literature research.

2. Literature Review

2.1 Overview of the Automotive Industry in Germany

A vital element of Germany's economic structure and a major driver of innovation is the automotive industry. Automotive development and production is one of the most complex and technology-intensive processes. In 2020, the German automotive industry accounted for 435.3 billion euros of GDP with 16 million vehicles produced in 2019 (MacDougall, 2020). The top of the industry pyramid is represented by original equipment manufacturers: OEMs are responsible for vehicle design and development, system integration and component production. With 43 OEM factories in Germany, these are companies that sell their products in global markets and have production facilities including for instance BMW, Mercedes-Benz Vehicles (Daimler Group), Porsche, Audi or Volkswagen (Barthel, et al., 2015).

Germany's automotive industry is characterized by the ability to innovate and in 2019 was held to have an innovation rate of 9.7%. It produced more than one third of the nation's industrial R&D expenditures resulting in EUR 72bn in 2018 (MacDougall, 2020). Having a competitive and successful automotive industry in Germany requires continuous new vehicles, new driving technology, new business models and low costs (Barthel, et al., 2015).

However, this comes with notable challenges. The automotive industry is characterized by long planning horizons and extremely high fixed and variable costs, especially associated with introducing new models or adapting current models. This requires utilization of facility and equipment. As seen in *Figure 1*, a new automobile has to undergo a lengthy process including (1) development phase (2) the production and purchase of equipment and materials

needed (3) testing of production technologies and processes, and (4) mass-production, which takes place once the facility reaches full capacity and quality and productivity requirements are met. Further, this process is prone to coordination issues (Krywdzinski, 2017).

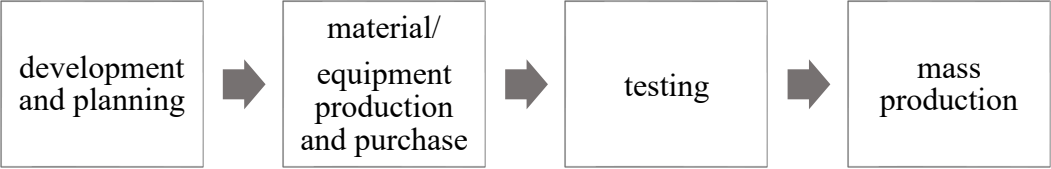


Figure 1. Example procedure of introducing a new vehicle (Krywdzinski, 2017)

2.1.1 Automotive development process

Since this research will focus on development and production processes, the researcher will look at both of these areas.

The most intense period can be the development phase. Introducing for instance a new front-wheel drive automotive, can take up to 5 years of planning, requires large amount of capital and efficient coordination. Based on an example of Porsche, the development process starts with (1) a pre-development phase for a rough estimate of feasibility and product ideas, (2) definition phase, (3) design development and assurance including simulations and initial testing, (4) mass development, (5) mass preparation, (6) production startup and (7) ready for mass production - The product's development phase is now concluded (Rudert & Trumpfheller, 2015).

These long lead times and immense investments are also subject to a large degree of risk since such long planning horizons are influenced by uncertainties outside of the control of the company (Friedlaender, Winston, & Wang, 1983).

2.1.2 Automotive production process

Also based on an example of Porsche, the production process of the automotive in the facility starts with pressing the materials into forms such as vehicle doors etc. These are forwarded to the body shop line where the vehicle parts are assembled. After the vehicle is passed on to painting and interior alignment. In the last step the body is joined (engine, gearbox, shafts, joints). The materials used for vehicle parts include importantly steel, plastics, aluminum, rubber, glass, titanium, or magnesium and are deliver on-time (Bergmann, 2020).

As one of the most resource-intensive industries in Germany and many steps in

development and production, the AI presents challenges. Because of sudden changes in the automotive environment, following a straight path is unlikely (Mildenberger & Khare, 2000).

2.2 The automotive Industry in Germany and environmental uncertainty

The importance of this industry and the intensity of development and production processes, make it vulnerable to uncertainties beyond the control of the OEM. For the purposes of this research, we focus on the most common environmental uncertainties: changes in market regulations, market price volatility of materials leading to shortages and product market feasibility. Although companies have a time frame to adapt their strategies, it is unknown whether OEMs will be able to do so effectively given the specificity and intricacy of their competencies (Rothenberg & Ettl, 2011).

2.2.1 Market regulations

The OEMs regulatory environment is complex with ever changing regulations. There are long planning horizons, high fixed costs and coordination needed for an automotive – where unknown future regulations must be considered when making decisions (Reid & Toffel, 2009). Science, climate, public policy, and new technologies depend on government support of infrastructure development, contributing to uncertainty (Rothenberg & Ettl, 2011). Recent examples of changing regulations in Germany include stricter norms forcing OEMs to lower CO2 emissions by 15% by 2025. But OEMs are still producing units with higher emissions level since it takes years to adapt to new regulations. Additionally, as seen in *Figure 2* due to the start of the pandemic, which resulted in a crisis for the automotive industry, production has dropped from -8% to -14% over the past two years due to changing regulations. Such rules will lead to extreme bottleneck situations, and it has been shown that testing and approvals for implementing new solutions to address these issues take indefinitely and will flood testing stations (Ait-Yahia, 2019).



Figure 2. Automotive production in Germany 2016-2021 (Koptuyug, 2022)

2.2.2 Market price volatility of materials and product market feasibility

Whether its price changes due to political events, world crisis, or natural disasters these affect the input costs of automotive parts and sudden shortage of materials and can force OEMs to look for options. Due to political events in 2022, iron ore prices rose over 101% and with over 900kg of steel for one passenger vehicle, this has serious consequences. Also, shortages due to 25% tariffs on imports leads OEMs like Volvo and BMW to develop cheaper options such as fossil free high-quality steel which is expected to go into production after 2026 and 2030 for each OEM (Chow, 2021). Thus, rethinking how materials can be reused or switched to other types of materials require production and testing. Additionally, companies invest heavily in consumer research; however, they admit that it is complicated to predict consumer preferences when these are untested. Technology within the vehicle is an uncertainty as well. For example, if a company decides to focus on drive-train technology, they cannot predict commercial viability. Moreover, with more and more electric vehicles are more and more on the roads, there are still performance uncertainties and range adaptations such as driving with fuel cells, alternative fuels like hydrogen or clean diesel, all leading to commercial further feasibility questions (Rothenberg & Ettl, 2011).

2.2.3 Responds to environmental uncertainties

Technical resources and coordination difficulties are said to be the main cause for failure in the face of environmental uncertainties. These resources, such as predictors, models for analysis or simulators must run as efficiently as possible. If OEMs adapted to sudden changes in the past, they lowered production volumes, made small adaptations to physical car parts like exchanging materials, or repeated testing (Norberg-Bohm & Rossi, 2010). OEMs tend to follow a familiar route for analyzing such situations because it is more economical to use an existing skill base and equipment rather than dealing with potential failure of new technologies. But car makers need innovative technologies to capture various data points for instance to simulate the impact of exchanged materials (Dyerson & Pilkington, 2005).

2.3 Digital Twin Technology in the Automotive Industry in Germany

In order for OEMs to adapt better to environmental uncertainties, highly innovative technological resources are needed: The digital twin technology (Kuhnert, Stürmer, & Koster, 2018). In 2022 the industry application of DTT is only at 12% (Botín-Sanabria, et al., 2022). But there is enormous potential: This large-scale and high-fidelity technology provides OEMs

with a digital twin of its physical assets - via for instance information flow of physical models, fleet history or sensors (Shafto, 2010). If conditions such as objects motions, function, temperature, performance, materials, processes etc. of the physical counterparts in the real-world changes, so do digital twins (Biesinger, Kraß, & Weyrich, 2019). In *Figure 3* Lee et. al (2019) provide a visualization (Lee, et al., 2021).

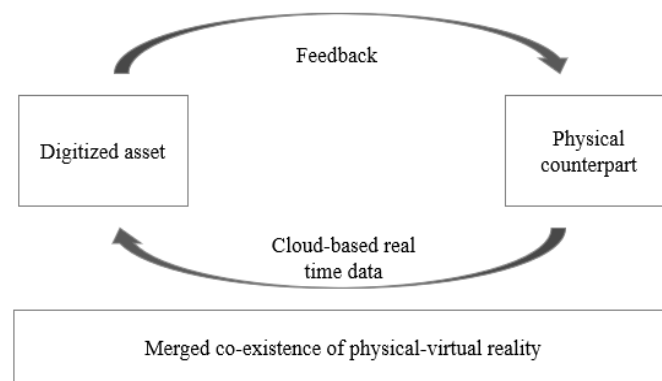


Figure 3. Relationship between digital asset and physical counterpart (Source: Author)

This ecosystem is not only able to link development or production equipment and materials needed to produce the vehicle, but it is analogous to the real-world (S.Voljoen, 2020). Hence, as Heber et al. (2018) stated, one can “... understand, predict, and optimize performance in order to achieve improved business outcomes” and changes in the development or production processes (Heber, et al., 2018). The ability to change the operating parameters of physical assets leads to benefits such as reduced risk, lower costs, increased productivity, and quality (Biesinger, Kraß, & Weyrich, 2019).

Now that there is an understanding of DTT, it needs to be assessed how this technology works through the development and production cycle of an automotive. First, according to planners and producers, when a new automotive gets produced within an operating production system, there is need for instance information about (1) availability of materials and resources. Thus, checking technologies, robot modules and resources contained in production, (2) layout of the production system to check when it can be expanded in case of changes, (3) duration of process times to see if and where robots are available and how long they need to adapt the vehicle within the entire production process and (4) the relationship between predecessor and successor production stations. This information is provided by the digital twin and has proven its benefits such as 50% lower complexity, 72% increase in production planning quality and enables for early and quick product adaption (Biesinger, Kraß, & Weyrich, 2019). This not only provides benefits when developing a new automotive but shows when it needs to be adapted

during the development or production process due to sudden changes.

There are also different versions of a digital twin in development and production.

2.3.1 Digital twins in automotive development

In the case of development, there are three main areas of the digital twin. First, the prototype twin helps foresee various scenarios such as shortage or use of different raw materials, climate adoptions or anything the OEM wishes to simulate. Since vehicles are complex due to multiple parts and materials and complicated structures, this reduces effort and costs of traditional prototyping and testing in physical test stations (Singh, et al., 2021). Second, the geometric twin shows the relationship between vehicle parts and the process and technologies needed to bring them to life. Lastly, the simulation twin is used for modeling e.g., changes in the vehicles software or joined parts (Heber, et al., 2018).

2.3.2 Digital twins in automotive production

Again, there are main areas of use for the digital twin in production: The reconfiguration twin can show the retooling needed for the production lines in the facility in case of changes and shows additionally required changes and the vehicles performance based on these changes. It speeds up changeover times (Ashtari, Jazdi, Schloegl, & Weyrich, 2018). Further, the integration twin helps to gather up to date information from the production facility and shows the status and connections between different stations in production and joining parts. (Biesinger, Kraß, & Weyrich, 2019).

Figure 4 provides a better visualization.

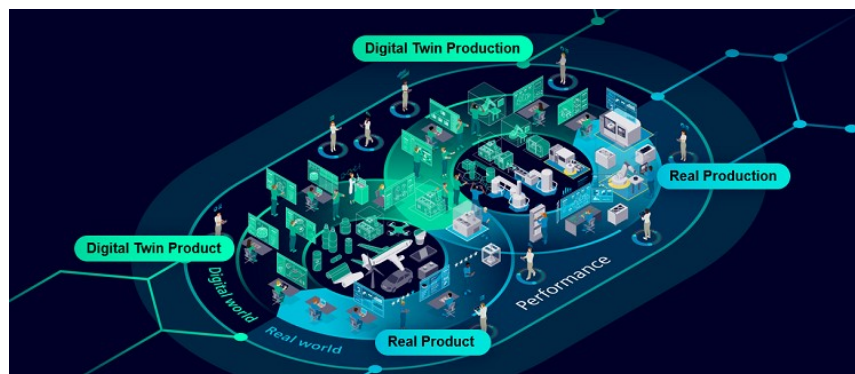


Figure 4. Visualization of DTT in production (Saracco, 2020)

DTT is clearly able to support sudden changes within development and production processes which are outside of the control of the OEM. Prediction of the vehicle's performance

becomes possible e.g., when different materials are needed, and there is faster adaption while production is already in place. Next, the researcher will explain the management theory behind environmental uncertainty and thus its importance.

2.4 Environmental uncertainty by Transaction cost theory and Real option theory

Williamson (1991) emphasized environmental uncertainty as primary uncertainty in his Transaction cost theory (TCT): Changes in the environment happen rapidly that companies are not able to foresee *ex ante*. As a result, the market value of the product can change and this creates a necessity for frequently coordinated adaptations (Williamson O. , 1991). Further, the phenomenon does not happen independently. Humans bounded rationality and are not able to make perfect decisions. According to Williamson (1985) the pairing of bounded rationality and uncertainty creates coordination difficulties within the firm. These are seen as “non-strategic” since they are caused by other actors (Williamson O. , 1985). Many scholars supported this theory in the past and stressed that prediction problems are due to changes in the environment, such as regulatory changes or volatility in the product market (Wholey & Brittain, 1989). Due to a rise in information flow about sudden changes among alliance partners, inter-organizational relationships deal with information overload and unfamiliarity. Hence, there are significant changes of inappropriate and slow responses that may damage performance (Mintzberg, 1978).

Second, the real option theory states that dynamic political and economic forces and or competition threaten profitability due to unpredictability. Thus, influencing the demand and related input costs of a company producing a product (Kogut B. , 1991). If a company wants to compete successfully, resources and capabilities are needed. Moreover, scholars mention flexibility, which can allow a company to redistribute its resources smoothly in reaction to change. The ability to do so can be strengthened by investments in technology which allow firms to take different route of actions instead of focusing on one strategy (Sanchez, 1993). Lee and Makhija (2009) stated:

“Investments structured for such flexibility allow the firm to more easily adapt its strategies in line with any unforeseen circumstances in which it finds itself, rather than lock it into a single deleterious direction that no longer fits new environmental conditions. Consequently, the greater the uncertainty faced by the firm, the higher will be the value associated with investments that confer such options” (Lee & Makhija, 2009).

2.5 Research Gap

Research shows the significance of the AI in Germany and its innovation, turnover, and contribution to the economy. But environmental uncertainties disrupt long term planning and increase the already large amounts of capital needed to produce a vehicle. However, thanks to modern technologies such as DTT, OEMs can adapt to environmental uncertainties more efficiently. However, past research has only dealt limitedly with DTT. DTT has not become so prevalent that firms have all the knowledge they need (Moyné J. , 2019). Additionally, research based on Williamson's TCT, and real option theory suggests investigating how most recent technological advances influence coordination of environmental uncertainties (Cuypers, Hennart, Silverman, & Ertug, 2020).

The following research question has been formulated:

RQ. How does DTT mitigate and promote adapting automotive development and production processes to environmental uncertainties?

3. Methodology

This Chapter describes steps for answering the RQ. Based on Saunders, Lewis and Thornhill (2009), the methodology will be divided into the following (Saunders, Lewis, & Thornhill, 2009):

1. Research Design
2. Data collection

3.1 Research Design

A multi-method research design was selected which allows for use of more than one qualitative data collection technique (Saunders, Lewis, & Thornhill, 2007). Also, a cross-sectional study works best for this research, since it takes place within time constraints (Easterby-Smith, Thorpe, Jackson, & Lowe, 2009).

First, the researcher conducted semi-structured expert interviews to gain industry-specific insights as well as knowledge about DTT and potential to adapt to environmental uncertainties. Additionally, to back up the knowledge and opinion of experts working for OEMs in development and production, sellers of DTT were interviewed as well. Since production and development are two different areas, questions were asked to fit individual processes. There

were no pre-determined questions except a clear concept about what the researcher sought to explore. This allowed for uncovering behaviours, events, beliefs, and opinions in different areas and enabled switching topics to find new insights (Saunders, Lewis, & Thornhill, 2007).

Second, case studies were widely used to collect qualitative data (Baskarada, 2014). The subject of this explanatory case study was OEMs: How they adapt automotive development and production processes to environmental uncertainties without incorporating DTT versus with DTT. The intention was to use qualitative data based on expert interviews and academic research. Further, answering the research question sought to reveal different views of DTT in development and production processes. More knowledge will emerge throughout the process (Denzin & Lincoln, 1998).

The case study consisted of a pre-field phase, field phase, and reporting phase. The pre-field phase was used to describe the objective and reason for choosing a case study. The field phase will present the motives behind the chosen data gathering techniques; expert interviews and academic research. Lastly, the reporting phase will present two cases in a detailed manner to answer the research question.

3.3 Data collection

3.3.1 Primary data collection

To collect qualitative data, the researcher interviewed eight experts in the field of automotive development, production, and DTT. In total 59 experts were contacted via LinkedIn and through acquaintances. However, eight experts accepted the interview request: two DTT experts selling DTT to OEMs, two experts working in development, and four experts working in production for automotive OEMs. One interview was face-to-face, and the other were conducted online via Zoom. Every interview started with an introduction to the topic and a short explanation of DTT, market regulations, market price volatility leading to material shortages, product market feasibility, and other main concepts of this research. Additionally, since the automotive industry is a sensitive data-regulated industry, it has been agreed to not name names and brand names. The interview lasted between 60 and 90 minutes and ended with a Q&A for the candidates.

The experts began by explaining the typical development or production processes of a vehicle and what environmental uncertainties they deal with, how they adapt and the problems they face. Experts were then asked to provide their knowledge about DTT and whether they have experience working with it. Lastly, they needed to assess the potential of DTT in their

field and how it would mitigate and promote adapting automotive development and production to environmental uncertainties. The same pattern has been followed with experts selling DTT to OEMs providing a different point of view.

An overview of the interview scripts and the summary of the interviewee’s objectives, work backgrounds, and reason for being chosen, can be found in *Appendix 1 – 9*.

3.3.2 Secondary data collection

Secondary data is summarized in Chapter 2 in the form of literature research focusing on studies from renowned management journals such as IEEE, studies from well-known consulting firms, industry-specific reports, and peer-reviewed graded papers by other scholars.

4. Analysis & Discussion

The key findings are summarized and discussed in this Chapter. Management implications, as well as research limitations and recommendations for further research, are then examined. Finally, there are our conclusions. The points of view of experts working in automotive development and production for OEMs will be presented first followed by experts who sell DTT solutions. After, the case study will be presented.

Experts knowledge was weighted based upon ‘working experience with DTT’ and ‘level of knowledge about DTT’.

	Working experience with DTT	Level of knowledge about DTT
1	0-1 years	Beginner
2	2-3 years	Competent
3	4-5 years	Proficient
4	6-7 years	Expert

Table 1. Points for expert experience and knowledge

Then, the points were allocated based on the experts input as follows:

Interview ID	Working experience with DTT	Level of knowledge about DTT	Degree of credibility
Interview A	1	2	2
Interview B	1	4	5
Interview C	3	4	7
Interview D	1	3	4
Interview E	2	4	6
Interview F	2	3	5
Interview G	3	4	7
Interview H	1	2	3

Table 2. Expert degree of credibility

4.1 Interviews: The potential of DTT in automotive development and production to address environmental uncertainties - OEM point of view

Question	Key findings	Interview ID
What can you tell me about the development/production process of a vehicle? / <i>What step is most vulnerable to environmental uncertainties?</i>	Development	
	<ul style="list-style-type: none"> • Employees needed → Designer, component engineers, legal team, departments from testing, safety, production, after-sales, durability, analysts • Pre-development phase, prototypes, concept development and validation, mass production development • Development process takes between 4-5 years • Most vulnerable to environmental uncertainties → between concept development and mass production development 	B, F B, F B, F B, F
	Production	
	<ul style="list-style-type: none"> • Buy and collect raw materials → these delivered to machine center → press process → welding process → painting process → assembly process (engine, gearbox, shafts, joints) and inspection • It is a just-in time business → materials are delivered when they are needed • A vehicle can be fully assembled within a day → produce between 50 and 110 vehicles a day • 75% of the production is done by robots with human assistance • Coordinated between machine operators, test engineers, service technicians, painters, inspectors, logistics, warehousemen, dispatchers etc. • The whole production process is vulnerable to environmental uncertainties 	A, D, E, H A, D, E, H A, D, E, H A, E A, D, E, H A, D, E, H
(A) Co-facility leader production, (B) Product developer, (D) Vehicle Integration, (E) Analyst series production, (F) Overall vehicle development, (H) Production digitalization		

Table 3. Expert Interview Question 1 – automotive development and production

First, the development process: Experts B and F discussed the pre-development phase in which first designs are created. This is followed by concept development and validation to integrate development partners and system suppliers, analyze feasibility and specification requirements, evaluate against the competition, resourcing, and budget planning. After, digital prototypes and clay models are produced to test dimensions, geometry, and the vehicles performance. These processes are refined until mass production development can start (Interview ID B, F). Lastly, mass production development. Physical prototypes are used to run tests for functional safety, failures, etc. In this phase, all suppliers will be selected and checked for materials needed (Interview ID B, F). When mass production preparation is fulfilled, the development activity of the product is complete. Further, development processes include

designers, component engineers, legal team, departments from testing, safety, production, after-sales, technicians, analysts etc. Both experts stated the development process of a new vehicle can take up to five years (Interview ID B, F). Lastly, both experts confirmed, the processes between concept development and mass production development are most vulnerable to environmental uncertainties because OEMs are two to three years through development and defined their product concept (Interview ID B, F).

Second, the production process was described similarly by all experts: buying and collecting raw parts which are delivered to machine centres where they are pressed into forms such as doors, heck, roofs, etc. These vehicle parts are assembled and processed for painting to avoid corrosion. After the vehicle is processed to the assembly line for the engine, gearbox, shafts, joints, tires, and more. Lastly the final inspection and test drive. After each step inspections and tests of behaviour are performed. Further, the whole process involves machine operators, engineers, painters, inspectors, logistics, dispatchers, and analysts. The vehicle can be fully assembled within a day and ranges from 50 to 110 vehicles a day based on the model and its complexity (Interview ID A, D, E, H). All experts confirmed that the production of a vehicle is a just-in-time business and the materials are delivered when they are needed at any stage of production. Hence, “the reason all processes within production are vulnerable to environmental uncertainties, especially market price volatility of materials” (Interview ID E).

Question	Key findings	Interview ID
Based on research, the development/production process of a vehicle is vulnerable to environmental uncertainties such as market regulations, market price volatility of materials and product feasibility. Tell me about a time when you had to deal with such uncertainties /What was the damage?	Development	
	Main environmental uncertainty <ul style="list-style-type: none"> Changes in market regulations (Emission laws, safety laws) Damages <ul style="list-style-type: none"> Overtime, temporary shutdown of development process → longer time to market, project rejections 	B, F
	Production	
	Main environmental uncertainty <ul style="list-style-type: none"> Market price volatility of materials leading to shortages (political conflicts, pandemic) Damages <ul style="list-style-type: none"> When products cannot be finished and stored in the facility corrosion can happen 6-12 months additional production process → Conventional punishment for late deliveries Cutting production of up to 50% Closing factories → loss in units produced 	A, D, E, H A A, D D, E E, H
(A) Co-facility leader production, (B) Product developer, (D) Vehicle Integration, (E) Analyst series production, (F) Overall vehicle development, (H) Production digitalization		

Table 4. Expert Interview Question 2 - automotive development and production

Within development, experts B and F stated the processes are mostly affected by uncertainties such as market regulations. The biggest issues are “emission laws, fuel efficiency requirements or additional taxation of fuels. These factors affect how we develop for instance the engine.” (Interview ID B, F). Further, expert B described how in 2017 the European commission released new emission rules lowering pollutants such as ultrafine particles. Within 2 years for new vehicles, they need to bring down the factor to maximum 2.1 and will be under annual reviews. Also, in 2018 the regulation of the European parliament required to add new mandatory safety features such as intelligent speed assistance. Equipment such as tires, wheels, lightning, brakes, and gears are subject to such changes. These situations result in overtime, temporary shutdowns of the development process, strategic changes, and changes in the vehicle’s performance (Expert Interview B).

Regarding production, shortages due to market price volatility of materials has been prominently stated as environmental uncertainty by expert A, D, E, and H. Especially in tough political situations, the pandemic, shipping accidents or natural disasters leading to situations the OEM cannot control (Interview ID A, D, E, H). Expert A presented several examples: They experienced delivery bottlenecks of cooling lubricants, couplings, and rings at the step of assembly. Thus, as we can recall from question one, at that step they are almost done with production. This situation led to a stop for five months. They needed to switch to other materials and re-tested the vehicle because performance and development of the product will change, which is detrimental to its longevity. Thus, costs increase for retesting different materials in test stations. Additional damages included conventional punishments for late deliveries resulting in millions of euros (Interview ID A). Expert E provided an example of semiconductor chip shortage due to the pandemic. This resulted in shutting down two factories, 2M euro lost revenue continuing to increase in 2022. Further, an expected loss of 500k units produced. Lastly, all experts confirmed the sanctions and trade impacts due to war between Russia and Ukraine play a huge role in market prices and the availability of materials needed. This creates huge supply problems and is very difficult when vehicles are within production and cannot be finished because it is a just-in-time business. For instance, after the invasion of Russia prices of Nickel rose from 16k per to 101k per ton also resulting in a shut-down of production for five months, loosing 250k units in Germany for the OEM of expert H (Interview ID H). Thus, all experts agreed that the faster they are able to make accurate business decision and adapt, the lower the damages (Interview ID A, D, E, F, H).

Question	Key findings	Interview ID
	Development	

What do you do to adapt to sudden changes due to environmental uncertainties? /Are there any problems?	<ul style="list-style-type: none"> Analyse the situation with CFD, CAE programs → adapt vehicles performance Simulations and configurations Coordination issues, inflexibility, independent analyses 	B, F B, F B, F
	<p>Production</p> <ul style="list-style-type: none"> Use stockpiled material and recalled vehicles Switch to different materials → Retesting Slow down factories Run vehicles down the line and leave products unfinished Skipping components → deliver vehicles without certain features Take another strategic route → switch focus to high-value vehicles Move models to another facility to increase capacity Coordination difficulties, no single source of truth, inflexibility 	A, D, E A, D, E, H A, E D, E E A, E A, D, E A, D, E, H
(A) Co-facility leader production, (B) Product developer, (D) Vehicle Integration, (E) Analyst series production, (F) Overall vehicle development, (H) Production digitalization		

Table 5. Expert Interview Question 3 - automotive development and production

Within development, experts B and F stated that if changes happen, they use CFD and CAE analysis and three-dimensional modelling to analyse and optimise the vehicles performance as a first step. Further, they use these models to change the vehicles design, analyse suppliers needed, mass-development planning and investments. Problems include weeks of coordination between different teams and if several physical prototypes exist, they need to be adapted by hand. Further, these analyses happen independently and require expert input in-between which results in coordination difficulties. Expert B explained the issue in development as design and engineering teams increasingly use three-dimensional technologies to build in more immersive and engaging ways. However, after the project is finished, these teams lose visibility into how their inventions are being used and if they are behaving in accordance with the original goal. Thus, if changes need to be made, they are not up to date (Interview ID B).

For production, if OEMs experience shortages due to market price volatility, all experts said production will be stopped or slowed down to make further business decisions (Interview ID A, D, E, H). Expert A, D and H explained how they currently work with CAD, CFD and CAE programs to analyse the status of units of materials missing, how fast the machines are running to check how much time they will generate by slowing down the process and other materials for possible usage (Interview ID A, D, H). Meanwhile, expert D and E explained additional tactics. Often, they continue to run the vehicle down the production line until it cannot be further assembled. Additionally, they might skip components and hope more material will be delivered down the road or use recalled vehicles. By removing features from the vehicle,

they can ration the supply of the material needed. In cases like this, they give the buyer the option to purchase the vehicle either for a lower price or wait up to 12 months until the product can be fully assembled. However, expert E explained if the shortage has a heavy impact and cannot be resolved within the next two years, they consider taking another strategic route by shifting their attention and resources to high-value vehicles. They enhanced performance of other models which they were able to fully produce, and despite substantial market losses of up to 1,5 million euros in 2020 for the vehicle they had to stop producing, they succeeded with the other model (Interview ID E). All experts explained if production stops in one facility, they are trying to increase capacity by moving a model to another facility which produces similar models. This will provide them additional six months in which they hope to receive materials. However, to do so they need to run different types of analysis and simulations first (Interview ID A, D, H). Lastly, all experts agreed that all these options are time consuming and costly processes with no great flexibility due to coordination and complexity issues between different departments. This results in no single source of truth (Interview ID A, B, D, E, H).

Question	Key findings	Interview ID
What do you know about the digital twin technology for the development/production process of a vehicle? <i>/Do you work with it?</i>	Development	
	<ul style="list-style-type: none"> I work with DTT I do not work with DTT DTT collects real time data based on for instance sensors and it's all available in the cloud so everyone with access can work on it and collaborate 	F B B, F
	Production	
	<ul style="list-style-type: none"> I work with DTT I do not work with DTT Producing the vehicle in a virtual and real world at the same time and if changes need to be made, we can test it first in the virtual world 	E A, D, H A, D, E, H
Co-facility leader production, (B) Product developer, (D) Vehicle Integration, (E) Analyst series production, (F) Overall vehicle development, (H) Production digitalization		

Table 6. Expert Interview Question 4 – automotive development and production

The intention of this question was to discover whether the OEM works with DTT. Experts A, B, D and H do not work with DTT yet. However, experts E from production and F from development are familiar working with DTT (Interview ID E, F). All experts had a similar view of what DTT is: A digital copy of E.g., a vehicle, facility, or assembly process interacting with the physical counterpart where information about the physical product is transferred to its digital twin. One can change the digital model without changing its physical counterpart (Interview ID A, B, D, E, F, H).

Question	Key findings	Interview ID	
What is DTTs potential for better adaption to environmental uncertainties?	Development		
	<ul style="list-style-type: none"> • Synchronization across every department • Shows how workflows will change → workstations are updated, automatically adapts suppliers, investment strategy based on data • Faster validation of physical behaviour of the vehicle, software. Mechanics etc. • Reduction of physical prototypes • Combination with VR allows for virtual test phase • Single source of truth 	B, F B, F B, F B, F B B, F	
	Production		
	<ul style="list-style-type: none"> • Re-testing models with different types of materials virtually instead of physically → less usage of test stations → more flexibility and production options • Internal efficiency → one can recognize optimization options faster since DTT gives you automatically recommendations • Coordination → everyone can work with the digital twin in the cloud and does not need to be physically at the facility • Faster movement of models into other factories • Reduction of physical prototypes • Quicker adaption of production process → production layout, workstations, tools needed, robot availability and adaption, build dates • Avoiding further mistakes → combination with VR lets technicians assemble digital prototypes first • Faster validation process • Single source of truth 	A, D, E, H A, D A, D, H A, D, H A, E, H A, D, E, H E A, D A, D, E, H	
	(A) Co-facility leader production, (B) Product developer, (D) Vehicle Integration, (E) Analyst series production, (F) Overall vehicle development, (H) Production digitalization		

Table 7. Expert Interview Question 5 - automotive development and production

Even though only experts E and F work with DTT, and experts A, B, D and H do not, all experts confirmed DTT has immense potential for adapting to environmental uncertainties during development and production processes. All experts emphasized better coordination: the DT synchronizes immediately across every department (Interview ID A, B, D, E, F, H). Especially, since expert B described how design employees and engineers are cut off after they finished their tasks and have no further insights.

Expert A from the production team explained that whenever they need to use different types of steel (which exists in different strengths and affects the vehicles emissions, speed, weight and more). Instead of physical testing in test stations, DTT can test the vehicles performance with different types of materials digitally first to show how it is interacting with other materials (Interview ID A, D, H). For instance, if the OEM decides to switch to different materials, the DT can reveal how the performance of the vehicle changes along with adapting

workflows, facility layout, assembly steps, workers needed etc. Also, experts A, D and H stated if they need to relocate models from one facility to another, they can use DTT to see how the vehicle model would fit into another production line; employees needed, workstations and tools. As a result, it allows for efficient and early parallelization of the production process. It can save up to 25% on costs. Next, expert E explained how DTT can analyse where it is most cost-efficient to remove materials from the vehicle and delayed time to market by only two months instead of six. The DTT suggested how the production layout would change and because it is linked with the physical twin of the facility, the production process would be automatically updated. Thus, they were able to see immediately changes made within robots and build dates (Interview ID E). Further, expert E from production and expert B from development provided insights how they combine DTT with virtual reality (VR). In production they use it for their service technicians in cases the production process changes. Doing so, they can train via virtual assembly on the prototype before going into series-production. This has helped to avoid mistakes and fasten physical assembly (Interview ID E). For development, DTT allows designers to see and touch the vehicle in life size and experiment with it instead of producing for instance clay models. Engineers can thus validate the physical behaviour of the vehicle, the software, mechanics etc. faster and better (Interview ID B). Overall, all experts confirmed that DTT allows for faster coordination and more flexibility because it is a single source of truth (Interview ID A, B, D, E, F, H).

4.2 Interviews: The potential of DTT in automotive development and production to address environmental uncertainties - DTT sellers point of view

Question	Key findings	Interview ID
What can you tell me about DTT in the AI? <i>In which areas are they used?</i>	<ul style="list-style-type: none"> • Manufacturing for predictive maintenance, supply chain, production planning and execution, development design and prototyping 	C, G
	<ul style="list-style-type: none"> • DTT includes data like functions, aesthetics, competition, model building, customer data, performance, material properties, technological systems and more 	C, G
	<ul style="list-style-type: none"> • Prototype, simulation, engineering, geometric and comprehensive twin 	C, G
	<ul style="list-style-type: none"> • 35% of DTT applications focus on production 	G
(C) Scientist for action engineering, (G) DTT engineer		

Table 8. Expert Interview Question 1 - DTT sellers

OEMs approached experts C and G to construct DTTs of their factories, automotives, assembly processes, training, workflows, layouts and more. They need to use DTT in mass

production for predictive maintenance, supply chain improvement, production planning and execution, and development for design and prototyping (Interview ID C, G). Expert G said around 35% of the DTT applications focus on production: The geometric twin visualizes vehicle assembly, how individual vehicle parts are connected, and which robots are required in the facility. Additionally, how well vehicle components fit in a production cell, coding robots for wiring, welding, or handling, and improving production cycles for increased production. Engineering applications of the digital twin predict future behaviour and performance (Interview ID C, G). Within the development of automotives, DTT provides data for functions, aesthetics, competition, model building, customer data, performance, material properties, and technological systems. Further, DTT prototypes and simulations can create different scenarios, for testing and evaluation before the production process begins by gathering information from the physical counterpart and making product performance predictions or design optimizations. This is less time and cost-consuming than physical tests. Expert C stated, “it helps to adapt to changing requirements 3x faster.” (Interview ID C).

Question	Key findings	Interview ID
You said companies approach you from areas such as production and development. Since this is the focus of this research, can you tell me what challenges they want to resolve?	<ul style="list-style-type: none"> • Minimizing costs and optimizing processes • Making better business decisions → by having a robust ecosystem providing great coordination • Uncertainties → risk and change management • Stable environment for production → production is more vulnerable to environmental uncertainties than development 	<p>C, G C, G C, G C, G</p>
(C) Scientist for action engineering, (G) DTT engineer		

Table 9. Expert Interview Question 2 - DTT sellers

Experts C and G emphasized OEMs' goals of reducing costs, optimizing processes, and creating a stable ecosystem. This included the argument that OEMs must be more efficient when dealing with situations beyond their control. They cannot rely on materials, especially since the pandemic. In such cases, OEMs must make better business decisions. (Interview ID C, G). "Clients approach us saying last year we made a loss of millions of euros, full production stop, and vehicle parts they can't use anymore because they weren't able to adapt quickly enough," Expert G explained. (Interview ID G). To do so, they require adaptable solutions for producing more complex products, and better coordination for different automotive models on the same facility line. As well as creating workstations, and digitally building the facility and the automotive before investing in real-time production. Further, they are challenged to analyze

big data quickly and coordinate between various processes and departments. (Interview ID C, G).

Question	Key findings	Interview ID
Based on research, the automotive industry is vulnerable to environmental uncertainties such market regulations, market price volatility of materials and feasibility. How do OEMs adapt to these environmental uncertainties before they approached you?	<ul style="list-style-type: none"> • Downtime, 4-6 month production stop, shutting down factories, project rejection 	C, G
	<ul style="list-style-type: none"> • Material shortage → keep producing the vehicle as far as possible, leave out components 	C, G
	<ul style="list-style-type: none"> • Shifting models to different factories 	C, G
	<ul style="list-style-type: none"> • Use different suppliers 	C, G
	<ul style="list-style-type: none"> • Switch to different material's 	C, G
	<ul style="list-style-type: none"> • Physical retesting → increases time to market by 6 months 	C, G
	<ul style="list-style-type: none"> • CFD, CAD or CAE analysis 	C, G
(C) Scientist for action engineering, (G) DTT engineer		

Table 10. Expert Interview Question 3 - DTT sellers

Both experts confirmed whether it is for development or production processes, they will stop for at least six months, and slow down or reject the projects (Interview ID C, G). It all depends on at what stage they currently are and thus the complexity of adaption. For development, if they need to make changes to the vehicle due to new market regulations or feasibility, they currently rely on CFD or CAE models for simulation purposes, analyzing the vehicle's dynamics and performance. They run these models again with different versions of the vehicle. This includes several validation processes, affecting different teams and departments. Production is mostly affected by material shortages and they will oftentimes shift models to different facilities for greater flexibility, using different strategic routes, and trying to find different suppliers. Therefore, they also rely on CAD, CFD, or CAE models. CAD models are a great way of showing the status of materials, facility layout, etc. However, the problem is that they need to run these analyses independently. Also, they use these models to analyze other materials they can use if one is not available. However, they also need to perform physical retesting to approve the material. This is costly and take up to two months since test stations are flooded with vehicles. Another tactic is to adapt the vehicle by for instance removing vehicle parts and again they need to perform an analysis first and then perform physical tests. The problem is, most of the times physical testing is not accurate because the longer time to market, the higher the costs for the OEM. They include risks of performance failures (Interview ID C, G).

Question	Key findings	Interview ID
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How can DTT in development and production processes help OEMs to adapt to environmental uncertainties?	<ul style="list-style-type: none"> • Provides recommendations for development and production processes in case of changes. 	C, G
	<ul style="list-style-type: none"> • DTT visualizes digital workflows 	C, G
	<ul style="list-style-type: none"> • Reduces physical prototyping → reduces costs by 25% 	C, G
	<ul style="list-style-type: none"> • In case of material changes DTT shows you retooling needed, changeover times, robots needed, facility changes, workflows etc. 	C, G
	<ul style="list-style-type: none"> • DTT integrates product lifecycle and facility lifecycle. 	C, G
	<ul style="list-style-type: none"> • Synchronization between all departments 	C, G
	<ul style="list-style-type: none"> • Single source of truth → faster time to market by 20% 	C, G
(C) Scientist for action engineering, (G) DTT engineer		

Table 11. Expert Interview Question 4 - DTT sellers

The intention here was to cross check knowledge of experts who work in development and production, with knowledge of experts who sell DTT solutions. First, within development, DTT reduces the time, effort, and costs of prototyping and testing in physical test stations, decreasing costs by around 25% (depending on OEM, vehicle model). As expert G said, DTT incorporates data mining to provide valuable data such as client input, existing performance, expectations or potential scenarios etc. (Interview ID G). DTT also removes the need to perform independent analyses and creates a single source of truth: All types of DTTs are linked and if for instance the design of the vehicle has been changed it automatically adapts performance, material changes, costs and later on workflows etc., depending on the types of DTTs created. Expert C stated, that in production, DTT shows how to adapt your production process: retooling, changeover times, which robots are suited, and automatically shows recommendations on how the facility layout would change leading to faster time to market by 20%. For instance, in case of material changes, DTT gives recommendations if you exchange material x with y how does it affect assembly, energy flow, emissions produced, safety and requirements. Beyond that, expert C said “there are more innovations coming such as digital threads which is a digital form of activities and tasks, integrated into DTT. These processes also support automation, traceability, and standardizing efforts.” (Interview ID C). Thus, experts C and G emphasized how flexibility and a single source of truth lead to better and faster adaptation (Interview ID C, G).

4.3 Case study

4.3.1 Pre-field phase

The main objective was to understand how integrating DTT into automotive development and production processes help mitigate and cause better adaptations to

environmental uncertainties, especially when unexpected events happen outside of the control of the OEM such as changes in market regulations or material shortages due to market price volatility. Hence, OEMs need to adapt their processes and make appropriate business decisions. As a result, the research question evolved: How does DTT mitigate and promote adapting automotive development and production to environmental uncertainties?

The researcher looked at two cases, one for development and one for production in which real-time events compare the integration of DTT versus the negative case. Experts' work experience with DTT and level of knowledge were then combined with the literature research to add detail to the case examples and ultimately draw a conclusion. Based on the literature, the researcher discovered that regulations, price volatility of materials leading to shortages, and product market feasibility are the main environmental uncertainties for OEMs. However, based on the experts' input, it became clear that the development process is mainly affected by uncertainties such as market regulations and the production process by material shortages due to market price volatility. Due to time constraints and a clearer focus for this research, the researcher will focus on the following environmental uncertainties for development and production:

First case: How can DTT in automotive development help mitigate and promote adapting to environmental uncertainties (Market regulations).

Second case: How can DTT in automotive production help mitigate and promote adapting to environmental uncertainties (Material shortages).

Additionally, these environmental uncertainties affect OEMs the most according to how far they are within the development/production process they are lodged. For example, if market regulations change, this does not put the development process in danger if it occurs at the start of the development phase. It becomes a hazard if the concept development and validation have already transpired and modifications need to be made to conform to a new regulatory regime. Hence, for the sake of this research, the researcher will provide cases focusing on the most vulnerable parts of development/production processes.

4.3.2 Field phase

The researcher was able to collect knowledge from experts working for automotive OEMs who either use or do not use DTT solutions for their development and production processes. The researcher also collected insights from experts who sell DTT solutions to

automotive OEMs based on their needs. This considered different point of views, strengthening arguments about DTT’s potential. *Table 12* provides an overview of the main discussion topics for the semi-structured interviews from the point of view of OEMs:

Research Question	Discussion topic
Q1. Development/production process of a vehicle	<ul style="list-style-type: none"> • Overview of a typical development/production process • What steps within the processes are most vulnerable to environmental uncertainties? • Current process of collaboration between teams • Who is involved? • What is the duration?
Q2. How environmental uncertainties affect OEMs	<ul style="list-style-type: none"> • Providing a real-time event • Main environmental uncertainties • What was the damage?
Q3. Adaption to sudden changes due to environmental uncertainties	<ul style="list-style-type: none"> • Examples of adaption without DTT • What is the procedure • What are the problems with these procedures
Q4. Knowledge of DTT in development/production process of a vehicle	<ul style="list-style-type: none"> • DTT definition from OEM point of view • Status of knowledge and work experience with DTT from OEM point of view
Q5. Potential of DTT for adaption to environmental uncertainties	<ul style="list-style-type: none"> • Process of adaption with DTT • The benefits of using DTT for better adaption • How DTT is integrated

Table 12. Discussion topics for semi-structured interview – automotive development and production

The same table is provided from the point of view of experts selling DTT to OEMs:

Research Question	Discussion topic
Q1. DTT in the AI	<ul style="list-style-type: none"> • In which areas are they used • What are the functions of DTT
Q2. OEMs reasons for approaching DTT sellers	<ul style="list-style-type: none"> • Example of processes they want to optimize • Example of current challenges for development/production processes
Q3. How can DTT in development/production help OEMs to adapt to environmental uncertainties	<ul style="list-style-type: none"> • Process of adaption with DTT • The benefits of using DTT for better adaption • How DTT is integrated
Q4. Adaption without DTT	<ul style="list-style-type: none"> • Process of adaption without DTT • What are the problems

Table 13. Discussion topics for semi-structured interview - DTT sellers

4.3.3 Reporting phase

First Case: How can DTT in automotive development help mitigate and promote adapting to environmental uncertainties.

The European Commission has announced new emission rules that will require OEMs to reduce pollutants such as ultrafine particles. Within two years, the OEM must bring the factor pollutants down to 2.1 and is granted another 2 years to lower it to 1.5. Additionally, those

processes will be under annual review by the European commission and result in penalty fees if not committed. Employees from the development team were currently at the stage of concept development and validation. At this stage, product market feasibility, vehicle requirements, product evaluation, resource, and budget planning have been completed and physical and digital prototypes have been produced. Thus, being 2 years within the development phase. This project includes employees from the design team, component engineers, testing, safety, and legal team. The location is in Germany. Now, the OEM needs to make business decisions on how to adapt to such changes.

Adaption without versus with DTT:

First, academic research and expert interviews have shown that this situation will firstly result in a temporary shutdown of further development processes or complete project rejections (Interview ID B, F). Second, if they decide to continue with the project, the OEM needs to analyze the vehicles performance and check where materials can be exchanged and chips/systems can be adapted to achieve higher efficiency of fuel performance. Further, how the design of the vehicle can be changed to adapt to wind flow to decrease emissions. Without the usage of DTT the design team would start to use three-dimensional modelling, clay models and models such as CFD or CAE to analyze the situation. CFD models are used in this case to analyze the vehicles dynamics, combustion, heat, or flow distribution when different types of materials are used since they affect the vehicles performance. The CAE program is an engineering computer software helping to analyze the vehicle's engine and systems. Thus, several independent analyses are created with different models and this process is described as inflexible (Interview ID B, F, C, G). Additionally, expert knowledge is required from engineers and designers. Experts explained the issue in development as design and engineering teams increasingly use three-dimensional technologies to build in more immersive and engaging ways. However, after the project is finished, these teams lose visibility into how their inventions are being used and if they are behaving in accordance with the original goal. Thus, if changes need to be made, they are not up to date (Interview ID F). This has been confirmed by past literature review that the biggest flaw is coordination difficulties and communication between different teams which result in months of making decisions when trying to adapt (Krywdzinski, 2017). At the same time, digital prototypes and clay models are produced to test dimensions, geometry and performance of the vehicle. After, the OEM decided to insert higher quality steel and how to change the design of the vehicle. Designers adapted the clay models and test engineers went into physical testing which is very expensive. If physical prototypes exist, they

need to be adapted by hand. This process can take between 2 to 4 months (Interview ID B, F, C, G). After they went through several verification processes to meet requirements, adapt suppliers needed for their change of materials and redistribute their budget. This process has been described as non-flexible and inefficient.

Now, the process will be explained with the help of DTT. Based on expert interviews and literature research, the prototype twin, geometric twin, and simulation twin are widely used in development processes of automotives (Singh, et al., 2021). The prototype and simulation twin will help the OEM to find options faster where materials can be exchanged and how the design of the vehicle needs to be adapted to reduce emissions. At the same time engineers can work with the geometric twin which shows the relationship between vehicle parts and processes to check how the engine can be adapted. According to past research and expert interviews, using DTT decreased complexity by 50% and led to faster business decisions. Hence, the OEM was able to decide to use higher quality steel and where to change the vehicles design faster because different types of twins were linked (Biesinger, Kraß, & Weyrich, 2019). If one changes a feature of the vehicle or changes the design, the DT automatically analyses and updates vehicles performance and where emissions are reduced. Experts described how this process reduces the need for physical testing since engineers can test the vehicles performance based on a single source of truth. Thus, by exchanging materials and changing the design of the vehicle, the OEM does not need to run a separate analysis with CAE or CFD models etc. Additionally, DTT provides data for the vehicles functions, aesthetics, competition, model building, customer data, performance, material properties and technological systems showing additionally changes in cost structure and providing recommendations on pricing, suppliers needed etc. The verification processes becomes faster and more efficient. (Interview ID B, C, F, G). While working with DTT, all experts and the literature emphasized better coordination: the DT synchronizes across every department. Therefore, DTT has been described as an efficient way to coordinate and communicate the development process between the design team and engineers. Lastly, another way to avoid the costs for physical testing, an incredible feature has been provided by experts: OEMs are also able to connect DTs to VR. Engineers and designers can see the vehicle in front of them and enter the virtual space as avatars. With this feature they can change the design of the vehicle, work with high quality steel and check in a virtual space how a different type of steel changes the vehicles performance. Experts emphasized this as cost and time efficient since mistakes can be avoided (Interview ID G). Based on primary and secondary data gathered, DTT helps speed up adaption to environmental uncertainties. By not relying on physical tests experts stated it helps to adapt to changing requirements 3x faster (Interview ID C, G). Further, it allows

for more flexibility and better coordination since it is synchronized between all departments and analysis can run parallel to each other. This allowed the OEM to make faster business decision.

Second case: How can DTT in automotive production help mitigate and promote adapting to environmental uncertainties.

The pandemic in 2020 and political conflicts in 2022 hit OEM production processes with shortages of materials. OEMs cannot get semiconductor chips delivered, an essential component in the production of the car, because suppliers are not able to produce them and if OEMs obtain chips, they are expensive. A microchip, like any other electronic device, is required for a vehicle to drive. It includes features such as touch screens, lights, wireless charging, safety features, and even lower emissions by improving engine efficiency (Interview ID D). This situation will affect the assembly. Further, the employees involved are machine operators, test engineers, painters, inspectors, logistics, assemblers, analysts, dispatchers, and more. The OEM needs to make business decisions on how to adapt to such changes.

Adaption without versus with DTT:

The literature review and expert interviews have shown that the first step for OEMs is to halt or cut production in case of material shortages (Norberg-Bohm & Rossi, 2010). To adapt, they need first to make an analysis of: (1) availability of materials and resources thus checking technologies, robot modules, and resources contained in production, (2) the layout of the production system to check when it can be expanded in case of changes, and (3) the duration of process times to see if and where robots are available and how long they need to adapt the vehicle within the entire production process and (4) the relationship between predecessor and successor production stations (Biesinger, Kraß, & Weyrich, 2019). This means that production a stoppage will last at least 4-6 months (Interview ID C, G).

Without the help of DTT, past research and experts agreed this implicates coordination difficulties since different technological resources are needed for analyses: CAD, CFD, or CAE programs which are widely used by analysts in this situation (CAD models show the status of materials and how fast the machines are running to check time savings by slowing down the process). Thus, independent analyses with different models are needed to create an overview of their facilities, production lines, and materials which can take between 3-4 weeks (Interview ID A, D, H). After analyses, the OEM can make further decisions. In the case of semiconductor chip shortage, the OEM decided to move the vehicle model to another facility and eliminate as

many chips as possible to continue production. This was described as the most common tactic to adapt to material shortages (Interview ID A, D, H, E; Dyerson & Pilkington, 2005). To integrate a vehicle model into another facility, OEMs need to make further analyses with production simulations and expert input from facility managers and operators. Further, since the assembly process is mainly done by humans with robot assistance, it is important to know the retooling needed, changes in production lines and workstations, employees, connections between different stations and more. The goal is to keep changeover times as low as possible (Ashtari, Jazdi, Schloegl, & Weyrich, 2018) However, this step has been described as time-consuming and non-flexible taking up to two months (Interview ID A, D, H, E). At the same time, they used CAD and CAE models to analyze the vehicle's performance and where it is most efficient to remove chips. After making a decision, the vehicle must undergo several physical tests in test stations to check if it can be verified by for instance tech engineers. This process can take another two months because test stations are also filled with other vehicle models. Further, financial components such as costs and pricing must be analyzed and approved (Interview ID C,G). Both academic research and experts explained that technical resources are the main cause of the failure or long delays in the face of adapting to environmental uncertainties (Dyerson & Pilkington, 2005). There is current testing for physical prototypes in test stations and independent analyses of the facility, production layouts and processes, and materials. This is a time-consuming and costly process to coordination and complexity issues. Additionally, the literature review and expert interviews have shown how crucial it is to create a more stable ecosystem in which flexibility and efficient coordination is key. The goal is to avoid closing factories, leaving products unfinished for a long time which results in damages (Interview ID A, D, E, H, C, G).

Now, the same process will be explained with the help of DTT. The first decision of the OEM was to move the vehicle model to another facility. DTT helps to shorten the time of analysis and increase the efficiency of coordination between different teams. Experts selling DTT to OEMs, experts working with DTT, and literature research demonstrate how it provides a digital visualization of the facility, the vehicle, production layout and processes linked to each other appear in one big picture. All simulations and analyses are run dependently, parallel to each other. If one changes a feature of the vehicle or includes the vehicle into another facility, it automatically analyses and updates production layout etc. and vice versa (Please refer to *Figure 4*). Thus, if the OEM decides to move one vehicle model to another facility, they do not need to run a separate analysis for the facility, production layouts and processes (Interview ID A, D, E, H, C, G). Moreover, experts and the literature have highlighted the integration twin

which helps gathering up-to-date information from the factories showing the status and connections between different stations in production and joining parts (Biesinger & Benedikt Kraß, 2019). Further, the reconfiguration twin can show retooling needed for the production line, changes in workflows and workstations, employees needed and facility layouts (Ashtari, Jazdi, Schloegl, & Weyrich, 2018). This information provided by DTT has proven its benefits such as 50% lower complexity, 72% increase in production planning quality, and faster adaption to changes (Biesinger & Benedikt Kraß, 2019). Additionally, DTT synchronizes automatically between all teams involved and everyone can interact with the DTT. Thus, it increases coordination efficiency, and one needs to rely less on expert input by contacting them and sharing information. Hence, it decreases analyze times of steps 1-4 by around 3 weeks (Interview ID C, G).

At the same time, the OEM can analyze data faster such as it is most efficient to remove semiconductor chips. Instead of analyzing the vehicle's performance with physical prototypes and different modules, DTT provides a geometric twin which shows how individual vehicle parts are connected and how the assembly and performance of the vehicle changes if you remove chips from different vehicle features. This twin can be also linked to the other twins such as reconfiguration and integration (Interview ID C, G; Heber D. , Michelbach, Morelli, & Groll, 2018). Beyond this, a significant feature was highlighted by experts: OEMs are also able to connect DTT to VR. Now, service technicians and assemblers can see the vehicle in front of them and enter the facility as avatars. With this feature, they can train the assembly by removing certain features from the vehicle before it gets into physical production. Experts emphasized this as being cost and time efficient since mistakes can be avoided (Interview ID G). This allowed the OEM to make faster business decisions on where to remove semiconductor chips.

Based on primary and secondary data, DTT can be posited as an important factor for helping OEMs to reduce costs, optimize processes, creating a more a stable ecosystem, faster coordination between departments, and flexibility when adapting to environmental uncertainties. Moreover, it allows for efficient and early parallelization of analytical processes. Time delays of getting to market can be decreased by 20% and to less physical retesting needed, and costs decreases by 25% according to experts (Interview ID C, G).

5. Conclusion & Managerial Implications

The subject of this research is the automotive industry in Germany focusing on OEMs. Moreover, this research has explored how DTT helps OEMs to mitigate and promote adapting

automotive development and production processes to environmental uncertainties. This research consists only of qualitative data: through primary data gathering technique like expert interviews and secondary literature research, an explanatory case study was conducted. The case study shows how the data gathered is in accordance to answer the research question. The researcher interviewed experts working for OEMs in automotive development and production, and experts selling DTT to OEMs. To note, the case study is from an early development stage of DTT and primarily based on expert knowledge rather than working experience. Further, this research only provides qualitative opinions, beliefs and knowledge and no quantitative factual data.

All experts confirmed that the goal of OEMs is to keep costs low and efficiency high at all times for all processes to stay competitive (Interview ID A-H). However, the development and production processes of a vehicle are vulnerable to uncertainties beyond the control of the OEM. Hence, environmental uncertainties (Friedlaender, Winston, & Wang, 1983). Three areas of environmental uncertainties have been explored affecting OEMs: changing market regulations, market price volatility leading to material shortages, and product market feasibility (Rothenberg & Ettl, 2011). If for instance the OEM is facing material shortage of steel during production, they need to find another type of steel that is available and adapt their vehicles by exchanging materials. However, all experts working in production explained that every adaption will affect the vehicles performance and its production processes and needs efficient simulation and prediction first to make the right business decision. This decision needs to be made by multiple actors involved requiring efficient interactions (Interview ID A, D, E, H). Additionally, both experts and past scholars agree that such situations result in information overload creating coordination and flexibility issues across actors involved in the problem space and is further challenged by lack of innovative technical resources (Interview ID A-H; Norberg-Bohm & Rossi, 2010). Current technological resources include for instance different modules and simulations to analyse the situation, such as 3D simulators, CFD, CAD or CAE modules and further heavily relying on physical testing. Two experts selling DTT solutions confirmed, relying on multiple modules creates confusion and no single source of truth (Interview ID C, G). However, qualities like good coordination and flexibility and innovative technical resources are needed when adapting the vehicle and processes to sudden changes due to environmental uncertainties. This has been supported by TCT and real option theory explaining the importance of OEMs to create a stable ecosystem (Williamson O. , 199; Sanchez, 1993).

Due to these issues, DTT was explored - the digital twin of its physical counterpart. DTs can be created for the facility, the vehicle or even work processes (Interview ID C, G). If the

objects function or performance changes, so does the DT. Hence, the DT can simulate and predict the objects behaviour (Biesinger, Kraß, & Weyrich, 2019). Because past scholars proofed its benefits such as 50% lower complexity, 72% increase in planning quality, and better adaption capabilities, DTT became a possible technological solution to deliver the qualities needed (Biesinger, Kraß, & Weyrich, 2019).

All experts working for OEMs in development explained that development processes were mostly influenced by uncertainties such as sudden changes in market regulations (Interview ID B, F). Further, all experts working for OEMs in production explained production processes were mostly affected by uncertainties such as market price volatility leading to material shortages (Interview ID A, D, E, H). This information formed the case study: The first case explored automotive development dealing with changing market regulations. The second one explored automotive production dealing with shortages. In both cases, a comparison was made between the incorporation of DTT versus no incorporation.

Based on the findings, the following managerial implications can be provided: First, all experts agreed that DTT allows for fluidity of knowledge across the OEM and thus inclusivity (Interview ID A-H). Because DTT automatically synchronizes insights from different types of DTs (geometric twin, engineering twin, incorporating twin etc.), actors, systems, and processes across all actors involved in the problem space. Moreover, two experts working with DTT confirmed information overload will decrease because the data is transformed quickly into visualization and can support coordination between actors involved (Interview ID E, F). Visualizing the actors involved and work processes within the problem space provides multiple perspectives and unified knowledge helping decision-makers. Second, the visualization of processes and integrated simulations allows to explore and evaluate business decisions digitally first, before continuing with physical actions. Third, DTT allows for linkages between different types of DTs, lifecycles, and levels instead of discrete analyses and simulations with 3D, CFD, CAE and CAD modules. For instance, if the OEM needs to exchange materials, by linking the DT of the production facility with the DT of the vehicle, it shows immediately how the vehicles performance will change, how it affects other materials, facility layout and assembly processes, to all actors involved. Allowing to analyze the problem in more immersive and interactive ways allowing to form a quicker business decision. Hence, DTT provides a single source of truth. The last implication is that DTT can be combined with VR providing better training opportunities for actors involved such as service technicians. For instance, when a vehicle needs to be adapted they can train assembly virtually first and avoid more mistakes in physical assembly (Interview ID C, G).

This research can help managers to learn about DTT and how it can be used in multiple ways, to innovate how they adapt to environmental uncertainties. Ultimately, allowing for greater flexibility and coordination.

6. Limitations & Future Research

This research explains early concepts of DTT since this technology is still at an early stage of its deployment in the automotive industry. Further, there is an imbalance between the number of experts who work with DTT and who do not. Six experts work in the field of development and production but only two work with DTT. Most of the expert's input relies on their current knowledge about DTT and not working experience. Thus, there are trade secret details that were not communicated. This limitation also affected the case study: The imbalance of expert interviews and limited information available can impact the depth of the case study. Additionally, the case studies are described with early concepts of DTT thus providing a broad concept still showing its importance. Lastly, the researcher was able to collect qualitative data only. Furthermore, the study is based on opinions, behaviours, beliefs, etc., and not quantitative data, which would provide a factful comparison between OEMs who use DTT and who do not. For instance, experts explained how DTT can adapt faster to environmental uncertainties and decreases costs because physical testing is reduced. Therefore, this research cannot prove 'how much faster' or 'how much costs are reduced by using DTT to adapt. Hence, future research should focus on quantitative data to explore variables of time and costs and when the concepts of DTT are more developed. The researcher came across another interesting field of additional research. First, the combination of DTT and VR for training purposes of service technicians. Because this topic was discussed very little, future research can explore its benefits and how it can be extended to other teams such as engineers and designers. Additionally, this would change the way teams communicate with each other and affects coordination and communication in large entities using DTT and VR.

7. References

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8. Appendices

Appendix 1. Overview of Interviews

Interview ID	Role	Company type	Reasons for interviewing
Interviewee A	Co-Facility leader of production	Automotive OEM	To obtain an overview of the automotive production process and its challenges about environmental uncertainties. Further, this Automotive OEM does not work with DTT yet and we can compare this scenario to one who does. The individual is responsible for the management of the production facility.
Interviewee B	Product engineer/ developer	Automotive OEM	To obtain an overview of the automotive development process and its challenges about environmental uncertainties. Further, this Automotive OEM does not work with DTT yet and we can compare this scenario to one who does. This Automotive OEM does not work with DTT yet and we can compare this scenario to one who does. The individual works with design models, modifies and supervises the development process. Additionally works in detail with the OEMs technologies to improve the development of a vehicle.
Interviewee C	Digital twin expert, scientist for action engineering	Automotive Consultancy	To obtain an assessment about DTT, its purpose and functions regarding automotive development and production. Further, the individual assesses the potential regarding environmental uncertainties.
Interviewee D	Vehicle Integration → production management and control	Automotive OEM	To obtain an overview of the automotive production process and its challenges about environmental uncertainties. Further, this Automotive OEM does not work with DTT yet and we can compare this scenario to one who does. Further, this individual develops processes in production and pre-series phase.
Interviewee E	Analyst series production	Automotive OEM	To obtain an overview of the automotive production process and its challenges about environmental uncertainties. Further, this Automotive OEM works with DTT, and we can compare this scenario to one who does not. The individual analyses series production and optimizes vehicle assemblies.
Interviewee F	Overall vehicle development	Automotive OEM	To obtain an overview of the automotive development process and its challenges about environmental uncertainties. Further, this Automotive OEM will work with DTT in the future, and we can compare this scenario to one who does not yet. The individual checks requirements, consults engineers and documents the process.
Interviewee G	Digital twin engineer	Technology company	To obtain an assessment about DTT, its purpose and functions regarding automotive development and production. Further, the individual assesses the potential regarding environmental uncertainties.

Interviewee H	Project management → digitalization production	Automotive OEM	To obtain an overview of the automotive production process and its challenges about environmental uncertainties. Further, this Automotive OEM works with DTT, and we can compare this scenario to one who does not. The individual works on projects including the digitalization of the production process.
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Appendix 2. Expert Interview A

Questionnaire

1. What can you tell me about the production process of a vehicle?

a. What step is most vulnerable to environmental uncertainties?

- First, we need to buy and collect raw parts, materials, add-on parts, accessories
- We are working with a lot of steel and tubes for the frame, underbody, plastics for fittings, doors etc. → collected on the world market.
- Production is very complex because it is manufactured on the assembly line, there are few storage costs because there is little range of individual parts, it is a just-in-time business.
- The suppliers for the individual parts are scheduled in advance, so that the vehicle that is being manufactured on the assembly line is produced in the moment the individual parts are delivered to the assembly line.
- Then raw parts are processed to machine centers → grease, cooling lubricants, paint, circlips, screws, grub screws, things we do not produce ourselves
- Followed by coordination → parts are brought to individual machines for the final product and when machining is complete everything goes through a check → all individual components are checked for quality.
- Then the assembly begins → individual components are assembled → engine, gearbox, shafts, joints etc. The assembly process is mainly done by humans with robot assistance.
- This is followed by another testing process → the vehicle is for instance measured for load, overload, and safety reserve.
- If testing goes well, the vehicle is passed on to painting and interior alignment and if it is not correct, the individual components are disassembled and checked again individually.
- Each vehicle is subjected to a test drive at the end of a few kilometers for quality control.
- Then it is forwarded to the customer/dispatch for further delivery.

- Each step is highly vulnerable to environmental uncertainties because we are in mass production. But I would say especially when the materials need to be delivered.
- A vehicle can be fully assembled within a day in production. We can produce up to 110 vehicles a day.
- 75% of the production is done by a robot since the processes are the same for the vehicles thus, we are not able to change a lot of the production since we employees do not go into depth of the production.
- There are the technical parts: Dispatchers who are responsible for ordering the materials etc., incoming goods inspection, forwarding to the warehouse with order pickers, machine operators, outsourcers, fitters, test engineers, painters, final inspectors, shipping employees, logistics and warehousemen.
- And the commercial part like salespeople etc. who work with us together.

2. Based on research, the production process of a vehicle is vulnerable to environmental uncertainties such as market regulations, market price volatility of materials and product feasibility.

a. Tell me about a time when you had to deal with such uncertainties?

b. What was the damage? (e.g., production stops or failures?)

- We are mostly affected by market volatility such as price increases. We then must switch materials due to bottlenecks which affects the production process → this is a huge deal in automotive production and happens all the time because those environmental uncertainties affect our work every day.
- I can give you several situations but for instance within the last year we had delivery bottleneck for screws and rings, cooling lubricants, couplings, etc. did not arrive and without this the product cannot be assembled.
- The problem is when a product cannot be finished in time and must be stored in the facility corrosions can happen and make the products unusable.
- Also, we have many examples where we had to switch to different types of plastic granulates which are important for the vehicles safety and production stopped immediately.

- I can give you another example → There were incidents when we had to switch to different materials and were already 20% through production (where the ship was stuck in the Suez Canal in Egypt).
- This does not necessarily mean we have to take several steps back, but the other material needs to be tested in combination with the other product parts and thus lead to a stop in production for 4-5 months.
- We also had to switch to a different type of steel and the problem with steel is that it exists in different tensile strength classes. Thus, we had to do different stress tests and we had to recalculate the weight for other vehicle parts. It can result in endless retesting.
- Also, if e.g., as far as cool lubricants are concerned, we must test again whether it tears off the lubricating film or whether it does not cause another thermal development in the product, which is detrimental to its longevity. Further, when we had to use a different type of oil and had to retest everything for its viscosity.
- And regarding damages, what affects us the most is conventional punishment since products are not delivered on time.

3. What do you do to adapt to sudden changes due to environmental uncertainties?

a. Are there any problems?

- I would not necessarily say it helps us to adapt during the production process but yes, we are working with CAD programs together which are for instance able to show us where the material or product part is currently at, how fast the machines are running, what is occupied and the next steps for each part, the timeline, who is working on it etc. However, a first analysis takes around 4 weeks. Also, if the product is behaving differently than it should we can look at the whole process and find the mistake faster.
- For instance, we create different scenarios where certain materials are most likely not to be delivered and we must take other materials. Therefore, when we purchase our materials on the world market, we have second choice suppliers which are more expensive and thus pre-order those materials as well to have them in stock (which increases our costs by 20%). But by having back up materials I wouldn't call it prevention or support for an easy adaption since we always must go through physical testing again. For instance, when we nowadays buy different types of steel you cannot just use aluminum since it doesn't qualify for the stress tests.

- Also we are most likely to move the vehicle to another facility.
- Besides slowing down the production process, we use stockpiled material first, switch to different materials but also focus on other valuable vehicles.
- I would say the main problem is that those procedures are very unstable and we have to do several loops of physical retesting.

4. What do you know about the digital twin technology in the production process of a vehicle?

a. Do you work with it?

- Yes, I heard about this technology and its impact can be massive and I would explain it like this → A product can be represented virtually in the computer and has a basic model where you have a duplicate and you can change this duplicate as you wish without having to change the basis.
- No, I do not work with it.

5. What is DTTs potential for better adaption to sudden changes due to environmental uncertainties?

- I do see a lot of potential → we are permanently trying to test the physical model with different types of materials which happens by hand. With DTT we can do this physically first.
- It would make a lot of sense to use it internally → production also deals with a lot of theory and experienced people would be able to work with the digital twin and can recognize options for optimization faster or test it based on the physical model. Also since Digital twins are linked to each other its very efficient since they update automatically if changes are made.
- Also do not get me started on coordination → when we had the problem of our materials being stuck on the ship in the Suez Canal, it can take weeks to get in contact with someone from the testing stations, engineers, manufacturers etc. who have an influence on how to proceed with different materials. Thus, everyone would be able to work with the digital twin in the cloud and does not physically have to come to the facility .

- I also think that firms who use such technology are more competitive since it gives flexibility and options.

Appendix 3. Expert Interview B

Questionnaire

1. What can you tell me about the development process of a vehicle?

a. What step is most vulnerable to environmental uncertainties?

- Typically, everything starts with the general concept and design ideas. The designer creates first sketches of forms that are related to the brand, a general product idea and its requirements.
- Besides, there is also heavy market and competitor analysis and benchmarking. We also define potential costs, prices, market regulations, potential technologies we need to use.
- Then if the design idea gets accepted first models are created and we use clay, 3D printers and CFD and CAE programs which are very important later for simulation. Also, the first digital prototypes are created.
- CFD models are used in this case to analyze the vehicles' dynamics, combustion, heat, or flow distribution when different types of materials are used since they affect the vehicle's performance. The CAE program is an engineering computer software helping to analyze the vehicle's engine and system. However those are independent analyses.
- When for instance the clay product exists, we can change the vehicle, create tests, and make quality controls by just using the clay model. This all related to extreme costs and labor. Besides that, we also get in contact with the suppliers to check the materials we need and order for our first physical prototypes.
- But if everything gets approved, we would be ready for full scale production.
- Years ago, the typical development process was 10 years and now its 5 years. Therefore, you must imagine how much quicker we must act based on competition and the world market and how much accuracy and flexibility got lost.
- The most vulnerable part is when we are about to produce the physical prototype.

2. Based on research, the development process of a vehicle is vulnerable to environmental uncertainties such as market regulations, market price volatility of materials and product feasibility.

a. Tell me about a time when you had to deal with such uncertainties?

b. What was the damage?

- Based on my experience we are mostly affected by market regulations and product market feasibility .
- Also based on your examples, emission laws, fuel efficiency requirements or additional taxation of fuels is a huge topic and increase our costs which is contra productive since we are always trying to reduce those costs. And those factors affect how we develop the engine and the design flows of the vehicle.
- This can also affect our choices we made on materials since the whole vehicle's performance will differ based on the use of aluminum or steel.
- OEMs include those scenarios in the development package because they know those situations will happen. And the reason is because they are so focused on saving costs that also efficient testing is lacking.
- But I do have another example. While my colleagues were at the stage of creating the first physical prototype and working with the engine and catalytic converter, later in the process did analyse the road conditions properly. Road conditions can affect the catalytic converter which breaks down chemical emissions produced from the engine. Hence, we would produce more emissions than allowed. Therefore, we did have to take a step back and first analyse again the road conditions with for instance data mining methods and world data on public roads on our computers. And based on the results we then had to make changes in the engine etc.

3. What do you do to adapt to sudden changes due to environmental uncertainties?

a. Are there any problems?

- First, we have to decide whether the project gets rejected or if we shut it down for some time to come up with a solution.

- We use CFD and CAE models to run simulations, benchmarking, functional simulations, vehicle, and drive train configurations. We can look at the chassis, interior models etc. This is very important in the concept phase to develop 3D models where we can do detailed modifications if we need to change something.
- However, there is a limit to this, and this is very important especially once the physical prototype has been produced or even the first physical parts used for the prototype. With the models we can predict what can happen in the future and thus the vehicles performance, but it does not tell us what is happening right now since it is not linked to its physical counterpart and other important processes within development.
- Also when we do physical retesting, it takes many months. Like at least 2 months.

4. What do you know about the digital twin technology in the development process of a vehicle?

a. Do you work with it?

- Yes of course I heard about it, and I think it's amazing. I would describe it as a physical prototype that is linked to its physical counterpart, and you can make modification on the digital prototype without actively changing the physical counterpart yourself. It collects real time data based on for instance sensors and it's all available in the cloud so everyone with access can work on it and collaborate.
- Currently I do not work with it since I know it's not that established now. However, I do know people who work with it in the automotive industry and competitors do have an advantage.

5. What is DTTs potential for better adaption to sudden changes due to environmental uncertainties?

- I particularly see potential when it comes to physical prototypes but also in the design phase → designers can see and touch the prototype via VR instead of producing clay models and modifying those clay models. We can validate the physical behavior of the vehicle, the software, mechanics etc. and better identify potential problems which can be caused by such environmental uncertainties.
- Therefore, it allows for collaboration.

- And you do not have to manually adapt its physical counterpart which is in certain areas super-efficient and cool especially considering the time and cost pressure we are facing in the development phase.
- Therefore, I do think that in the development phase it has a lot of potential to reduce times and to not lose efficiency.
- Overall, allowing for better collaboration between teams which leads to faster business decisions and validation. Validation is really important because everything we change needs to be accepted.

Appendix 4. Expert Interview C

Questionnaire

1. What can you tell me about the digital twin technology in the automotive industry?

a. In which areas are they used?

- Each part of the vehicle, for instance the engine or the whole vehicle whatever you choose, has its own digital representation and with real time sensors you gather data. Very easy concept.
- Companies approach us to use technology to optimize their supply chain, particularly logistics, production planning and execution, and development, (design and prototyping).
- Development → DTT incorporates information like physical and virtual factors of the vehicle or facility such as capacities, competition, systems, model structure and customer data.
- When it goes into detailed design it includes product function, performance, material properties etc.
- Further, the designers' job is checking the product performance as early as possible, and the DT can be used to predict the accuracy of the process in a virtual space to replace verification process via physical prototypes. Thus, a prototype and simulation twin.
- There is a performance digital twin where the digital twin will process any information gathered from its physical counterpart and make product performance predictions, design optimization etc.
- Production → Around 35% of DTT applications are used in production.

- The Digital twin prototype is very important for the production processes since it can simulate different scenarios, testing and evaluate even before the production process begins. So, you get the options to do experiments with virtual tests which is less time and cost consuming than physical tests.
- The engineering applications of the digital twin have the goal to predict future behavior and the performance of a physical system. So, it helps to adapt to changing requirements way faster and better.
- The Geometric twin in production which shows assembly of the vehicles and how individual vehicle parts are connected, robots etc. needed in the facility. Also, how well the parts come together in a production.

2. You said companies approach you from areas such as production and development. Since this is the focus of this research, can you tell me what challenges they want to resolve?

- Well, it can be everything from optimizing supply chain, failure analysis, predictable maintenance, production efficiency, or for instance 36% of our past clients stated its about parts shortage where production is affected.
- It is also about more efficiency dealing with situations outside of the clients control thus for instance for better risk and change management → whether it was the pandemic, the current political situation in Germany or past catastrophic events which will always influence the development and production process. And clients are looking for a technology which helps them to make changes quickly, be more flexible, save time and costs.
- Often, clients approach us with the goal saying last year we have made a loss of millions of dollars, full production stop and vehicle parts they cannot use anymore because they weren't able to adapt quickly enough during or include scenarios in their analysis.

3. Based on research, the automotive industry is vulnerable to environmental uncertainties such market regulations, market price volatility of raw materials and feasibility.

- a. How do OEMs adapt to these environmental uncertainties before they approached you?**

- Let's say we deal with a situation of material shortage, companies get creative → I have seen instances where they keep producing the vehicle with all the parts they have and as far as they can go and hope the problem will be resolved in the meantime.
- Second, depending on the type of material that's missing, and it is not that important, it does happen that they just leave it out to keep up with the time to market. If mistakes happen in the vehicles performance the consumer must deal with the consequences.
- Also, if consumer expectations changed during the development process or requirements have changed which would have impacted verification, they just continue because they include those losses into their strategy.
- Other than that, of course a lot of downtime, production stops of minimum 4-6 months.

4. How can DTT in development and production processes help OEMs to adapt to environmental uncertainties?

- First, I am aware of those uncertainties and that's one of the reasons why vehicle makers approach us for this technology. In fact, since the start of the pandemic the interest of OEMs who do not use this technology rose to 25%. This number is based on the OEMs who reached out for consultancy.
- Your first and second part of the question that's very easy to do → Let's say vehicle makers want to determine the vehicles future success (testing for feasibility) and it looks good in the beginning and the concept gets approved. But it happens a lot that whether customer needs change, competition etc. things which cannot be controlled by the company, the digital twin is able to include emerging data technologies such as data mining to provide mass information.
- Also, regarding production → I like to divide production into the planning part and execution part → in the planning phase of production they can include such environmental uncertainties in their simulations. For instance, what happens the most is material shortage due to market volatility. Since the facility simulation enables to simulate and optimize material usage and flows, they can enable a more flexible production → How well the parts come together in a production cell, it gives recommendations if you exchange material x with y how does it affect assembly, energy flow, emissions produced, safety,

requirements etc. And they can run those simulations completely digital and what's even better is if they change the physical counterpart it synchronizes in real time with the digital model, and everybody can interact. It is really about flexibility when they must adapt quickly.

- Also, those uncertainties we are talking about are in the execution phase most dangerous since we have entered series production, hundreds of vehicles a produced within a day now.
- DTT helps to adapt 3x faster and decreases costs of retesting by 25%.

Appendix 5. Expert Interview D

Questionnaire

1. What can you tell me about the production process of a vehicle?

a. What step is most vulnerable to environmental uncertainties?

- We can sort out the process of a vehicle into 5 steps.
- Press Process, BIW Welding Process, Painting Process, Assembly Process, and Inspection.
- First, the Press Process. This is 99% automated system, and some firms also call it stamping process.
- Second, we would have a look at the Welding Process. As we have transformed the vehicle parts, we need to weld them to put them together. Precision is highly needed.
- Third, painting. Painting enhances the beauty of itself but also prevents a highly corrosive substance.
- Fourth, the final step is assembly. We finally combine BIW to other parts such as tires, seats, suspensions and so on.
- Lastly, you need to inspect the completed vehicle. You check on it with various tests.
- Normally, we can produce within 90 vehicles a day.
- The whole process is most vulnerable because we are mass producing and not in the development phase anymore.
- It is a just-in time business and materials are delivered when they are needed.
- I would say assembly is most vulnerable to environmental uncertainties because you are close to dispatching and if vehicle parts need to be changed or removed, it increases time to market.

2. Based on research, the production process of a vehicle is vulnerable to environmental uncertainties such as market regulations, market price volatility of materials and product feasibility.

- a. Tell me about a time when you had to deal with such uncertainties?**
- b. What was the damage? (e.g., production stops or failures?)**

- When you think of last year, there were heavy shortages of steel, semiconductor chips for vehicles, lithium, plastics etc. Therefore, our main environmental uncertainty is market volatility of raw materials leading to shortages.
- Semiconductor chips include features such as touch screens, lights, wireless charging, safety features, and even lower emissions by improving engine efficiency
- It results in damages such as cutting production of up to 50%, removing certain features from models and delays (the customer is waiting around 6-12 months longer for their vehicle). Also, we experience a loss in market share in China. Especially in the case of steel, demand has risen as well plus a shortage is not so good.
- But one should also consider the Pandemic because it has hit our factories hard and were not able to run them anymore.
- Honestly, we try to be well prepared in this kind of unpredictable situation and establish a system to minimize loss of our business. We are collecting all the information in relation to this and inspect our systems to be more adapting.

3. What do you do to adapt to sudden changes due to environmental uncertainties?

- a. Are there any problems?**

- First, we continued to produce until we cannot anymore. This leaves us with the problem that the vehicle is almost ready but can't be delivered yet.
- Besides we also conduct analysis via CFD, CAE and CAD programs but the analysis takes some time since it involves many steps.

- Second, switch our focus and cost to high-value vehicles. For instance, we improved the performance of one of our models, and despite the heavy market losses of up to 2m euros in 2020, we were able to rebound by roughly 2m euros at the end of 2020 and an additional cost reduction plan.
- Third, we always do expedite → by paying higher fees to our suppliers we do try to get as much material instead of them giving it to someone else.
- We adopt digital technology to optimize and produce efficiently. For example, digital design, and smart sensors at 3D printing can be used in other value chains such as R&D, Production, Sales, and so on.
- Talking about 3D Printing, it took so much time to make a complete prototype. But this allows to gain speed in production and save costs. This technology can make one metalwork within one day.
- We also implement moving vehicle models to different facilities to better coordinate production stops and the analysis for doing so (where its most efficient to put them) and doing it takes around 2 months.
- Main problems are inflexibility and nothing is stable because so many business decisions are made under a lot of stress and many teams do not have a complete overview.

4. What do you know about the digital twin technology in the production process of a vehicle?

a. Do you work with it?

- No, I do not work with it. But it is my job to be invested into upcoming technologies.
- Yes, I have. Let's say we manufacture a vehicle model in a virtual world. And we simulate it in lots of circumstances. After we test it out in a virtual world, we get the data and interlock in a real world and innovate the product itself and production as well.

5. What is DTTs potential for better adaption to sudden changes due to environmental uncertainties?

- This digital twin technology will need a lot of time to build immense of database. But once you establish this, you can drastically innovate the production process with a small outlay.

- Most important mentioning is the flexibility you get. Because every process or product can be within a huge system of DTTs. It is linked with the whole facility, and you can digitally see how the production process will change. Thus, it is highly efficient. Usually, we must run several analyses and consult with different teams which is very time consuming.

Appendix 6. Expert Interview E

Questionnaire

1. What can you tell me about the production process of a vehicle?

a. What step is most vulnerable to environmental uncertainties?

- When we create a new production line, we plan a digital facility first because we have different models running on the same production system. And everything that happens in the real facility also happens digitally.
- Besides that, we start with the stamping. This means we have collected our raw materials like steel and then press the sheets into body parts.
- After we have the sheet metal where we join this and the aluminum parts together.
- Then we have the paint area which is very important. Because if the body does not get painted, corrosion might happen and therefore we must seal the vehicle.
- And then we have another inspection step and lastly the assembly where the mechanical elements are joined by our workers and assistance of robots etc.
- And then it goes into a series of testing and safety checks before the final product gets verified.
- This is also my task to analyze the whole process and see where we can optimize because our goal is to keep costs as low as possible.
- We produce approximately 50 vehicles a day and I work together with the technical development, pre-series center, planning and quality assurance.
- Most vulnerable to environmental uncertainties is the whole production process, I could not pin it down to a single step. But compared to development, production is more vulnerable.

2. Based on research, the production process of a vehicle is vulnerable to environmental uncertainties such as market regulations, market price volatility of materials and product feasibility.

a. Tell me about a time when you had to deal with such uncertainties?

b. What was the damage?

- Material shortage is one of the biggest problems in production. We got hit hard this year due to a shortage in semiconductor chips. For a vehicle to drive it needs a microchip.
- In the case of a vehicle, it's responsible for the system, displays, cameras, etc.
- What makes it more complicated is that those chips can only be manufactured by specialized factories. In our case, it was due to the corona pandemic, but I know other OEMs when there was a fire in the facility, a storm that stopped the production of the microchips, anything can happen anytime.
- The results were that we had to stop production immediately and had to close the facility of two of our models.
- In general, the shortage cost us around 1 million in lost revenue and the loss will continue throughout 2022 with an expected loss in units of at least 500k vehicles.
- It takes another two years to catch up with the projected demand which will happen again in 2025. And still, a 20 percent shortage in the long run because adding production capacity takes time.

3. What do you do to adapt to sudden changes due to environmental uncertainties?

a. Are there any problems?

- For instance, we stockpiled those microchips.
- We had to slow down 8 of 44 factories and move vehicles to other factories which is very complicated and time consuming.
- I know other OEMs who continued to run the vehicles down the line, skipping some components, and hoping that more chips will arrive down the road, but they are left with almost finished vehicles as an additional inventory in the facility.
- Some are trying to reduce the number of chips needed and deliver vehicles without features like automatic start-stop, wireless charging, automatic passenger seats etc.
- We also take prevention by having additional deals with other suppliers for the future.

- We are removing features from the vehicles to ration semiconductor supply and we had to get rid of for instance wireless phone charging and electronically adjustable steering columns had to be removed.
- Buyers had options whether to purchase the vehicle at a lower price or wait until items become available again.
- Problems include long waiting times and inefficient coordination and analysis takes a long time → you need to know current state of materials, production process, layouts, factories etc.

4. What do you know about the digital twin technology in the production process of a vehicle?

a. Do you work with it?

- I do. Like I mentioned in the beginning, we use this to create a digital facility and our vehicles → we can create a digital twin of everything in the facility and the vehicles and we are able to do prototypes and run processes before it happens in the real world.

5. What is DTTs potential for better adaption to sudden changes due to environmental uncertainties?

- Based on the example I have mentioned in question 2, we are able to better adapt to such situations because we can check within the digital prototype where we can continue without microchips → In this case we chose to not include wireless charging and electronically adjustable seating.
- The digital twin is more than just showing the digital model of its physical counterpart it immediately showed us how to change the production layout because we had changes in the production steps and needed to adapt the robots, the build dates etc. Also, we can see the impact on costs and potential losses because we would offer this vehicle to the consumer for 400-600 euro less.
- Second, due to this incident we want to move even faster towards battery-powered vehicles and the digital twin technology helps us tremendously by doing virtual assembly and prototypes.
- It increases productivity by at least 20%, saves resources and money.

- We are also combining this digital twin with VR and our service technicians can do the assembly virtually and work on the prototypes virtually before we go into series-production. This helps them also to train and avoid more mistakes when working with the physical product, it saves us resources for physical prototypes and reduced need for business trips.
- It helps with product validation. You can imagine it like a skype call where you put your glasses on and can touch and play with the vehicle and walk virtually through the facility and remodel the production steps.

Appendix 7. Expert Interview F

Questionnaire

1. What can you tell me about the development process of a vehicle?

a. What step is most vulnerable to environmental uncertainties?

- I work together with component engineers and employees in the assembly sequence. Also, the legal team, departments from testing, safety and production, after-sales, durability, etc.
- We begin with the pre-development phase. The main purpose is to integrate development partners and system suppliers. We also analyze feasibility, specifications of requirements and product evaluation against competition and target market, resource, and budget planning.
- We move from first ideas to sketches to geometrical specifications for proportions, dimensions, and graphic illustrations.
- We move forward to a first physical prototype in form of a clay model and virtual models where we can change the dimensions, geometry, etc. and we do scaled modeling.
- Concept development and validation → most important part is the digital prototype (We use scanning and milling machines to create first full scale prototypes and the details are produced by hand).
- Mass production development → we are working with physical prototypes and run tons of tests for functional safety, failures etc.
- After the development activity of the product is complete.

- The development process takes around 5 years and, in my opinion, when we reach mass production development, we are most vulnerable to environmental uncertainties because we are already preparing for mass production.

2. Based on research, the development process of a vehicle is vulnerable to environmental uncertainties such as market regulations, market price volatility of materials and product feasibility.

a. Tell me about a time when you had to deal with such uncertainties?

b. What was the damage?

- We have many examples. First, for instance in 2017 when the European commission communicated new emission rules lowering pollutants. They said that within 2 years for new vehicles, we need to bring down the factor to 2.1 and will be under annual reviews starting 2017. Also, in 2019 the regulation of the European parliament required us the add new mandatory safety features such as intelligent speed assistance and therefore equipment such as tires, wheels, lightning, brakes, and gears are subject to such changes.
- Those situations result in overtime, temporary shutdowns of the development process and expenses of millions of dollars.
- And those factors also affect how we develop the engine and the design flows of the vehicle. This can also affect our choices we made on materials since the whole vehicle's performance will differ based on the use of vehiclebon or steel.

3. What do you do to adapt to such environmental uncertainties?

a. Are there any problems?

- For instance, the example with changing market regulations → we work with CFD analysis and three-dimensional modeling to optimize the vehicles performance → we need to adapt the vehicles design by using our CFD simulation, changing the shape of the vehicle, trying to reduce certain materials which add to the production of pollutions etc.
- All of this happens while we slowed down the development process.
- The complicated part is collaborating with different teams since we need to adapt to changes as fast as possible because of the costs.
- Also since we do analysis with different types of models, it is very inflexible.

4. What do you know about the digital twin technology in the development process of a vehicle?

a. Do you work with it?

- A digital copy of the physical product.
- Yes, we are in the process of implementing Digital twins, it's a long and complex process to set up at first.

5. What is DTTs potential for better adaption to sudden changes due to environmental uncertainties?

- DTT shows how the workflow will change. The workstations are updated based on the materials we need which is important for mass development production, it shows us how it adapts suppliers, investment strategy and coordination is way easier since everyone can access the digital twin.
- Since the digital twin is connected to its physical counterpart, we can adapt systems easier, and we are able to see all changes needed to be done in the mass production development process.
- It synchronizes across every department → The issue is that in development as design and engineering teams increasingly use three-dimensional technologies to build in more immersive and engaging ways. However, after the project is finished, these teams lose visibility into how their inventions are being used and if they are behaving in accordance with the original goal.
- It allows designers and simulation to keep simulation data in sync with design.
- It is also used to train technicians before it even goes into testing which reduces errors and increased efficiency.
- It is great for more flexibility and coordination.

Appendix 8. Expert Interviewee G

1. What can you tell me about the digital twin technology in the automotive industry?

a. In which areas are they used?

- You can create a digital twin of the whole world including vehicles or factories and work on this digital twin without changing the physical counterpart. However, it only becomes a digital twin once the physical counterpart exists, if it is not in existence yet it is a digital model. It is before anything is physically build.
- Digital twins are primarily used in manufacturing, research, and development, as well as facility management. It is useful for facilities or factories before they are built because it covers tool design and programming for systems and robotics. For instance, it can show a single employee working on a product in the facility and simulate how these individual processes vehicle parts, assists the robotics and we can assess the results. Therefore, it is helpful to use DTT as a training method too.
- However, most of the DTT applications focus on production since it is most useful.
- For production it includes anything from mechanical hardware, electronics, electrical distribution systems or onboard software.
- We have the simulation twin, geometric twin, or prototype twin, those are the most important ones.

2. You said companies approach you from areas such as production and development. Since this is the focus of this research, can you tell me what challenges they want to resolve?

- First because they want to be competitive and innovative. Their constant goal is to reduce costs and optimize processes. To do so, they require adaptable solutions for producing more complex products, putting multiple models of different vehicles on the same facility line, creating workstations, and digitally building the facility and the vehicle before investing in real time production. They require it to run better analyses and incorporating customer feedback into development phase.
- Especially since the pandemic they need a very stable ecosystem. The problem with shortages is factories need to be closed and this is a damage of millions of euros. In such situations, you need to make better business decisions.
- Clients approach us saying last year we made a loss of millions of euros, full production stop, and vehicle parts they can't use anymore because they weren't able to adapt quickly enough.

- Also, because they want to manage their risks and uncertainties better because they need a solution to adapt faster to changing situations which is possible with DTT.

3. Based on research, the automotive industry is vulnerable to environmental uncertainties such market regulations, market price volatility of materials and feasibility.

a. How do OEMs adapt to these environmental uncertainties before they approached you?

- They try to analyse the situation as fast and best as possible to minimize the damage such as loss in profit or units produced because they typically always shut down facilities, slow down or stop production. Thus, they cannot meet their target numbers. Based on the analysed data they try to use the inventory they have available to the best use and might use it for another model which can be finished. However if they exchange materials they also need to do retesting with their physical vehicles which can take up to 2 months.
- However, they already include those potential losses into their strategy and when they for instance face material shortages they keep producing until a point where they cannot produce any longer and store it and just take the losses.
- Sometimes depending on the reason, they shift models from one facility to another facility. They try to optimize workstations by including several models into one production line.
- Also, they plan with different outcomes based on past experiences and potential scenarios and try to shift their strategy. Let's say they cannot produce one model anymore because of material shortages or changes in market regulations, they try to put their focus onto high value products and put their efforts into producing another model.
- In development they use CFD and CAE models which they use for simulation purposes, and they run those models again and again with the changes made. However, those tactics happen individually in teams and is not connected between different processes.

4. How can DTT in development and production processes help OEMs to adapt to environmental uncertainties?

- Development → DTT helps to simulate various scenarios such as the use of different raw materials, climate adaptations, or anything else the vehicle manufacturer wishes to simulate. It saves a lot of time and money compared to traditional prototyping and testing in physical test stations (around 35%). Because of the precise digital model of the product process that corresponds to the exact physical form. It also includes information such as customer feedback and makes recommendations based on customer needs or market conditions. It incorporates this information into the product design. It also displays digital workflows in which everyone involved can interact.
- Production → DTT shows you how to adapt your production process, such as retooling, changeover times, which robots are appropriate for the model, and automatically proposes how the entire facility would change. For example, consider the comprehensive twin, which integrates the lifecycle of the facility and products. Therefore, it helps to fasten adaptation.
- Beyond that, more innovations are on the way, such as digital threads. With digital threads you can digitalize employees' activities and see within the DTT the parts that need to be worked on. Imagine you have the virtual vehicle in front of you (Its even better if you see it via VR) and when you look at the engine you see windows in the corner with the tasks that need to be done, who is responsible etc. Thus, it improves the DTT and provides automation, traceability, and standardization.
- It is a single source of truth (All DTTs are linked) which means it makes it easier for everyone involved to develop an optimized production or development process and predict design performance before parts are being put. It increases time to market by 20% and therefore lowers time of adaptation to changes. Further, it can reduce costs by 25% since physical retesting becomes less.

Appendix 9. Expert Interview H

Questionnaire

1. What can you tell me about the production process of a vehicle?

a. What step is most vulnerable to environmental uncertainties?

- To produce the vehicle, we first press metal sheet parts into the desired design, and this is done for every part of the vehicle.

- After those parts are pressed, they are passed to all the workstations in the facility to be assembled by robots and employees.
- Then we do other details like the inside of the vehicle, painting and materials for protection are applied.
- While employees are working on the press and painting, employees on other workstations are already working on the engine, systems, tires etc. which are then assembled to the vehicle after painting etc.
- Within those steps it will undergo several inspections and tests.
- We produce a vehicle within a day, and we produce up to 80 vehicles a day, but it depends on the model and thus its complexity.
- Many people interact with each other in the production process, we have the manufacturers, engineers, painters etc.
- I would say most vulnerable to environmental uncertainties is the most complex steps which is assembly. At this step, all the systems and final parts for the vehicle to function are delivered. The systems are coded, and the performance is as it should be.

2. Based on research, the production process of a vehicle is vulnerable to environmental uncertainties such as market regulations, market price volatility of materials and product feasibility.

a. Tell me about a time when you had to deal with such uncertainties?

b. What was the damage? (e.g., production stops or failures?)

- We experience shortages the most. Especially due to market volatility. Currently, we experience losses due to the political situation between Russia and Ukraine. This will cost us millions of units this year. The availability of materials and changes in market prices due to the sanctions and trade impacts play a huge role. This creates supply problems and is very difficult when vehicles are within production and cannot be finished.
- We had issues with the wiring systems because we did not receive connectors, adapters and so on. We had to cut production in Europe by around 450k units for 2022. Also, following Russia's invasion, nickel prices rose from \$18,000 per ton to \$100,000. Nickel is a vital elements because it helps the body parts to be durable.

- Since we are dependent on those materials from Russia and in general from many other countries, we, and many other OEMs, try to source those materials within Germany and fasten options such as EV vehicles where certain materials are not needed anymore.

3. What do you do to adapt to sudden changes due to environmental uncertainties?

a. Are there any problems?

- First, we analyse the situation with different models such as CAD, CFD or CAE depending on what we want to analyze.
- I mean there are adaptations for the long term and adaptations in the short term.
- For the long term → We need to make different volume decisions, the number of units we produce with the predicted number of materials. As I mentioned we try to source the materials in Germany and focus on new markets with EV adaptations. Therefore, we can get rid of some of the materials needed in non-EV vehicles. However, this is a very complex process.
- In short term we are trying to increase capacity by moving a product to another facility which can give us around 6 months. However in order to do so the analysis takes around 1-2 months.
- We switch quickly to different suppliers who might charge higher prices
- Other tactics are to use vehicles which got recalled and tear them apart again to use those materials for other models. If they are reusable.
- The problem is that those tactics require time and time is very costly. Although material shortages happen all the time, no one can predict the future and its different every time.
- Since it is a rather unstable ecosystem, we have huge problems with coordination and approval processes if changes need to be made.

4. What do you know about the digital twin technology in the production process of a vehicle?

a. Do you work with it?

- Yes, and we use it. The information of a physical product is transferred back to its digital counterpart and therefore we can change the digital model without changing its physical

counterpart but being able to see how it would behave because they are connected. And we use this not only for the vehicles itself but for the whole facility.

5. What is DTTs potential for better adaption to sudden changes due to environmental uncertainties?

- I want to give you some information why it is so important to use digital twins: We have many different production models in our factories, and one of the biggest challenges is figuring out how to produce products with our suppliers. Experience tells us that things usually don't go the way we expect them to. We must take action to address the negative consequences of the facility to keep it running optimally.
- That's when digital twins became very helpful → The best way to integrate models into new production lines or existing ones is to do it at the lowest cost. The digital twin is always synchronized with data from the real facility and vehicles within the facility and enables an efficient and early parallelization of production planning and process. Therefore, it also helps to better plan the production process with the supplier.
- Now imagine we're in the middle of a production run, and things are changing. Due to changing requirements, new technologies, products, material shifts, and other factors, there will be disagreements between the supplier, OEM, and facility staff. It is always complicated, no matter how well one prepares for such changes. OEMs who typically use CFD models only work with a digital model, not a digital twin. A digital twin also allows for the integration of different materials, products, or changes in the manufacturing process.
- It reduces time to market by 20% and costs of up to 25%.