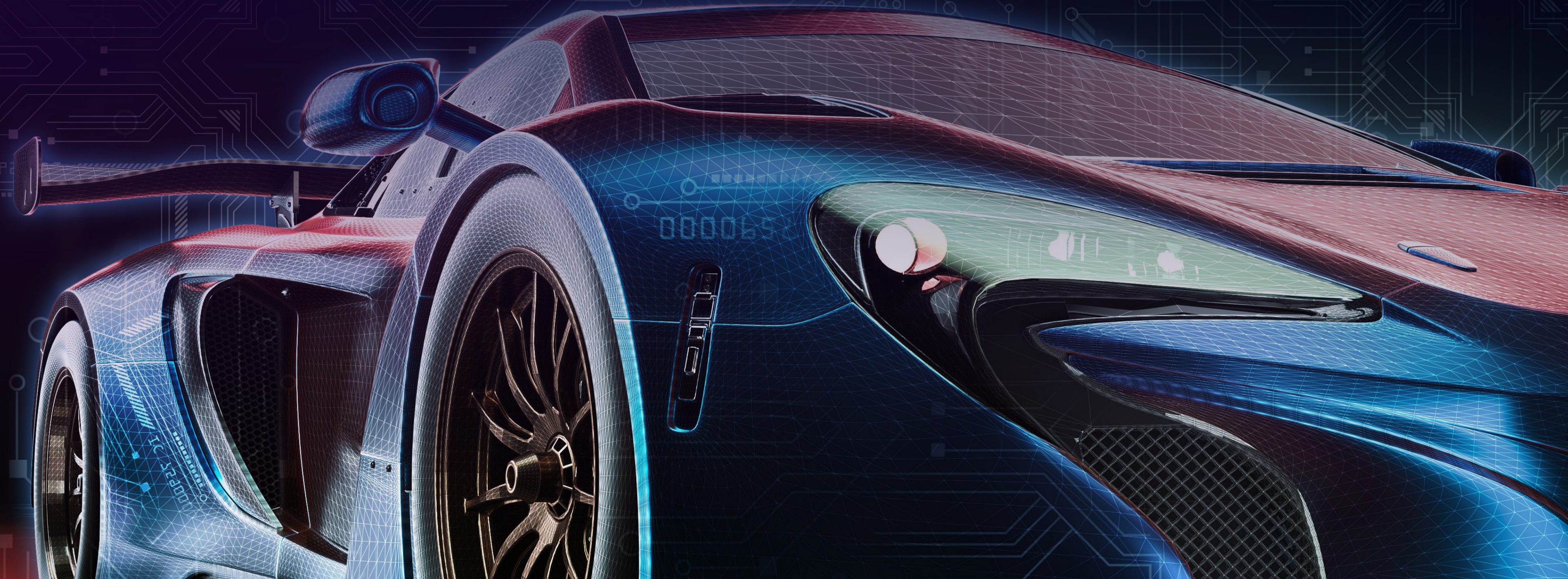




HARNESSING THE DIGITAL TWIN FOR REAL COMPETITIVE ADVANTAGE

A WHITE PAPER FUNDED BY



CONTENTS

EXECUTIVE SUMMARY	3
INTRODUCTION	4
LITERATURE REVIEW	6
PURPOSE	10
PROVENANCE	11
DIGITAL TWIN DEFINITION	12
DIGITAL TWIN TRAFFIC LIGHT SYSTEM	19
CASE STUDY 1 BMW's vision of a holistic digital twin using Nvidia's Omniverse	20
CASE STUDY 2 Porsche's digital chassis twin	22
CASE STUDY 3 Digital twin ensuring full transparency in the leather supply chain for JLR	23
CASE STUDY 4 Digital twin of the Formula Student car at Loughborough University	26
VALUE FOR MONEY	29
CONCLUSION	31
AUTHORS AND CONTRIBUTORS	33
WORKS CITED	34
WORKSHOP AND WEBINAR ATTENDEES	36

EXECUTIVE SUMMARY

A digital twin is seen as more than just an evolution of technology. It promises to revolutionise how products are conceived, created and consumed. Full-scale disruption is here, and it is not only affecting how businesses work today but also triggering a shift in the generation of product value. In future decades, software and digital components will provide 90% of a product's value, unlocking over \$100 trillion in economic value.^{1,2} Ambitious goals such as net-zero and connected autonomous vehicles can only be delivered by harnessing the power of digital technologies. Digital twins will be very likely to play a prominent role in delivering these ambitions.

The Institute of Digital Engineering (IDE), Loughborough University, University of Bath and the University of Warwick launched the digital twin initiative funded by the Advanced Propulsion Centre UK (APC) to develop a definition that can be applied to multiple sectors and which incorporates the unique requirements of the automotive and mobility sectors. Thorough research of available definitions was conducted, and several industrially-suited definitions were down-selected to

be built upon. Several workshops and open forum webinars were conducted across several industrial sectors to discuss the proposed definition, case studies, challenges and opportunities.

Through broad consensus, the definition serves to unify the development of digital twins for the sector and beyond. We believe that the definition presented here can be applied across multiple sectors. In-depth research on digital twins has also been performed to identify key attributes and to demonstrate the art of the possible.

This digital twin initiative culminates in the form of this white paper. In it we present: a digital twin definition, an overview of the current state-of-the-art in digital twins, several case studies to demonstrate the art of the possible, and critical considerations to define value for money metrics for digital twins.

INTRODUCTION

The Institute of Digital Engineering (IDE) developed and published *The Auto Council Digitalisation Roadmap* in March 2021. *The Digitalisation Roadmap* was developed over nine months and involved over six hundred hours of engagement with leaders from industry and academia across several sectors. There were six workshops, and in excess of ninety focused expert interviews, spanning seventy-six different organisations. In addition to the workshops and interviews, the IDE team performed an extensive horizon scanning and literature review. As a result, *The Digitalisation Roadmap* identified four core themes of digitalisation:

- Digital engineering environment
- Process and assurance
- Co-creative ecosystem and
- People.

The digital engineering environment combines new and existing digital technologies, improving the speed and efficiency of development processes and solutions within engineering, manufacturing, servitisation and end-of-life.³ Digital twins could be seen as an advanced manifestation of the digital

engineering environment, capitalising on and uniting underlying technologies to create a highly responsive and adaptable system. The use of digital twins is the key to accelerating innovation and removing time, cost and risk from the process of bringing innovation to market.⁴

FACING THE CHALLENGES OF THE DAY

‘A Cambrian Moment’ is an emotive article published by *The Economist*, explaining the seismic technological explosion transforming the foundations of almost every industry.⁵ Unforgiving and relentless, this is truly a moment of adapt or perish. To say the disruption has penetrated a stable, oligopolistic industry dominated by several big players that make up the automotive sector is an understatement.⁶ The disruption is further compounded by the exogenous shocks of the pandemic, critical component shortages and supply chain issues.⁷ These challenges on their own are formidable enough; together they can annihilate organisations or the entire industrial sector of a nation. Fortunately, digitalisation and the deployment of digital twins offer significant promise to stay ahead of the curve.

Digital twin could be seen as an advanced manifestation of the digital engineering environment, capitalising on and uniting underlying technologies to create a highly responsive and adaptable system.

Traditional business models must be adapted, changed or even scrapped to survive, let alone thrive.

THE ROLE OF DIGITAL TWINS IN DIGITALISATION

As the automotive sector rapidly pivots to deliver net-zero mobility products and services, next-generation digital engineering solutions will be critical in determining the UK's future role as a global industrial nation.⁸ Additionally, the rapid development of the digital economy is shifting consumer expectations, and traditional business models must be adapted, changed or even scrapped to survive, let alone thrive. Digitalisation will be at the heart of these transformations. It will enable the automotive industry to maximise opportunities, achieve first-to-scale advantages and stimulate innovation. Based on sequential approaches and extensive physical testing, existing engineering capabilities cannot deliver the accelerating complexities of future products and services. Digital twins are the key to accelerating innovation to market by providing a feasible route to innovate, engineer and manufacture highly complex products and services better, faster and cheaper.

A SHOCK WAVE IN THE VALUE CHAIN

Two areas of immediate focus in the automotive sector are the drive towards net zero and connected autonomous vehicles (CAV). The

challenges in CAV, electrification and achieving net-zero are complex and multidimensional and cannot be achieved without digitalisation at the fundamental core of the initiatives.

When assessed by counting the number of components, electric vehicles may possess a simpler powertrain than internal combustion engines. However, many new processes and techniques are used, and we lack a strong foundation of historical evidence and data to design these new systems. Combined with the wholly overwhelming challenges in software development, new architectures, integration of a servitisation ecosystem, fresh business models, artificial intelligence, and cyber security, they send a shock wave through the entire value chain. The challenges plaguing the automotive sector globally are exacerbated by demanding users with ever-shifting customer experience expectations. Using digital twins brings the potential to manage these challenging complexities and to achieve competitive value.

Digital twins are the key to accelerating innovation to market.

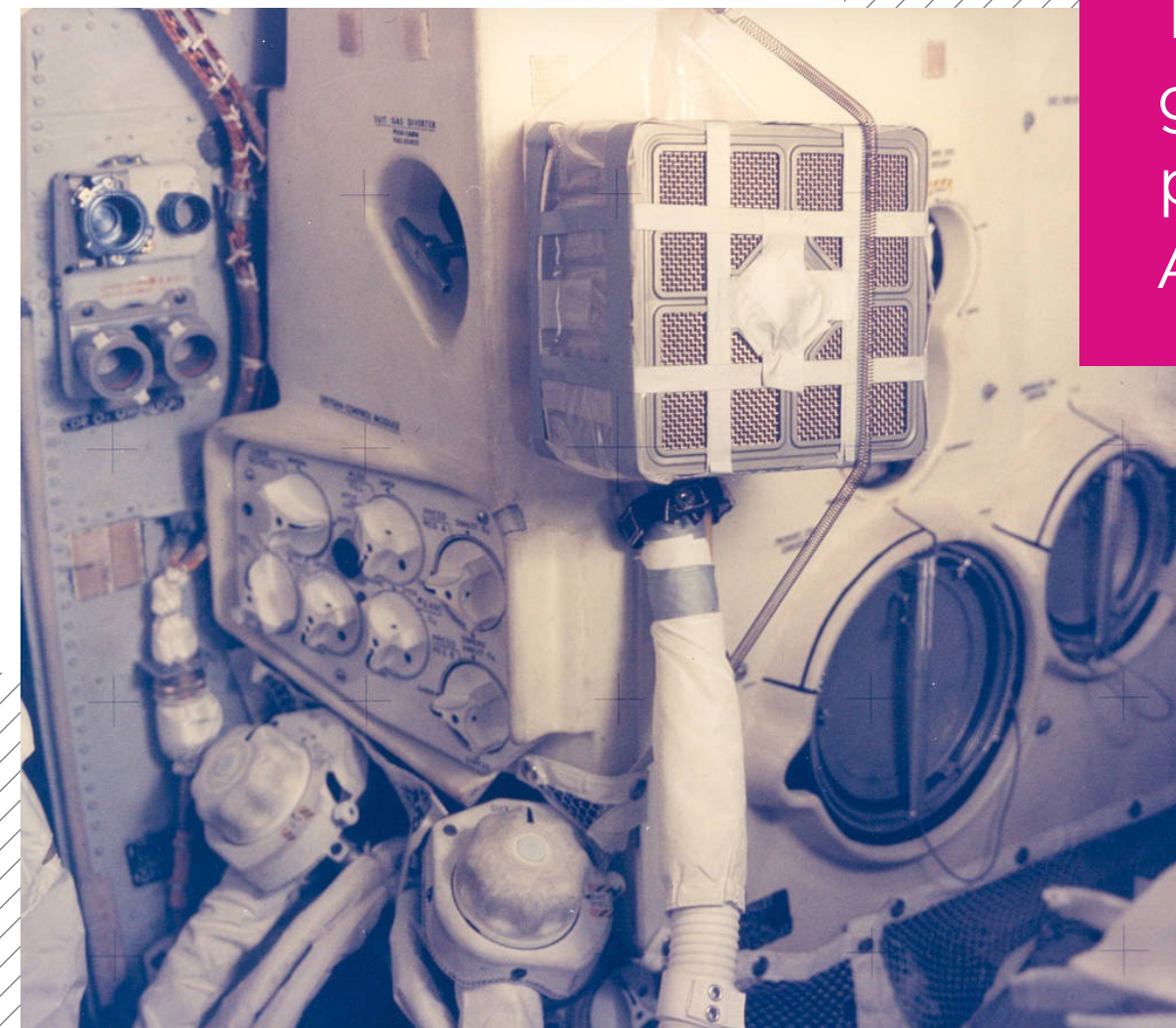


LITERATURE REVIEW

The history of the digital twin has been extensively researched and documented.^{9,10} It is widely recognised that the terminology and concept of digital twin were first introduced by Michael Grieves at the University of Michigan with credit to NASA in 2002.^{11, 12, 13} NASA has typically built and maintained physical twins of spacecraft on the ground since the 1960s, to troubleshoot problems without risk to the mission. The concept of twinning gained mainstream publicity through NASA's Apollo 13 programme, demonstrated to be invaluable during the troubled mission.¹⁴ There have been rapid advances in the technology blocks which make up the digital twin over the past couple of decades, and it has become a prominent feature in Gartner's strategic technology trend since 2015.¹⁵ Furthermore, there has been an exponential rise in the concept and application of digital twins, especially in the past five years, both in industry and academia.⁹

DIGITAL TWINS ARE EVERYWHERE

Digital twins are applied across a wide range of settings, from the agriculture industry to monitor crops, soil health, livestock and farm management,¹⁶ to their use in the healthcare industry



The concept of twinning gained mainstream publicity through NASA's Apollo 13 programme.

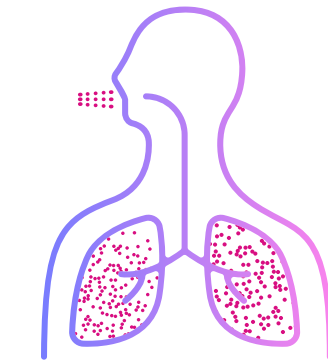
An interior view of the Apollo 13 Lunar Module and the "mailbox." The "mailbox" was a hack, which the Apollo 13 astronauts built to use the Command Module lithium hydroxide canisters to purge carbon dioxide from the Lunar Module. Lithium hydroxide is used to scrub CO₂ from the spacecraft atmosphere. Since there was a limited amount of lithium hydroxide in the Lunar Module, this arrangement was rigged using the canisters from the Command Module. The "mailbox" was designed and tested on the ground at the Manned Spacecraft Center before it was suggested to the problem-plagued Apollo 13 crewmen. Because of the explosion of an oxygen tank in the Service Module, the three astronauts had to use the Lunar Module as a lifeboat.

Picture and caption courtesy of National Aeronautics and Space Administration. ©NASA.



Virtual Singapore by
Dassault Systèmes

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By varying
parameters on
the digital twin,
scientists increased
the number of
particles reaching
their target from
20% to 90%

to develop virtual patients as a means of faster regulatory approvals and quicker, safer access to new treatments.¹⁷ Digital twins are used in the oil and gas industry for Floating Production, Storage and Offloading (FPSO) units, significantly improving health and safety by minimising physical inspections and providing support for planning in times of crisis, such as extreme weather events.¹⁸

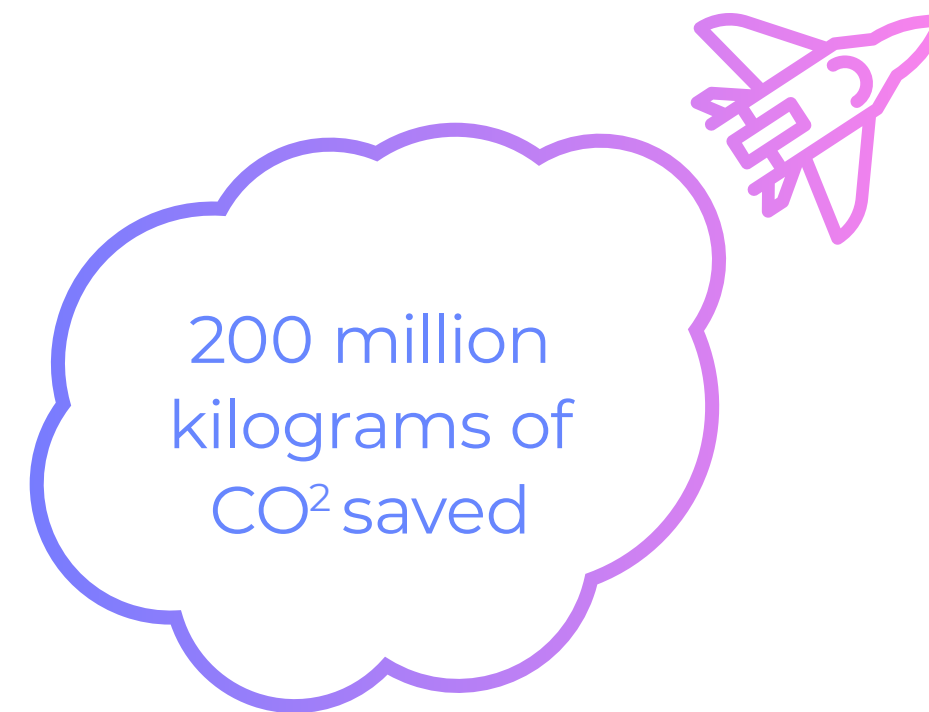
Digital twins of cities and nations are also being extensively researched and built. In Singapore, a 3D semantic model of the city has been built to represent land attributes, different forms of transport, and components of buildings and infrastructure.¹⁹ In the United Kingdom, the Centre for Digitally Built Britain launched the National Digital Twin Programme to support a network of digital twins in the UK, specifying and providing frameworks for a “system of systems” to incorporate

interfacing digital twins.²⁰ Scotland’s Orkney Islands developed a 5G-powered digital twin to deliver a new energy network.²¹

FASTER TIMES “FROM BENCH TO BEDSIDE”

Digital twins can dramatically lessen the need for expensive tests and physical prototypes, reducing the cost and increasing the speed of innovation and reducing time to market.²² The cost of developing new drugs, for example, reaches into the billions; preclinical testing phases alone take an average of three and a half years and it can take twelve years for new compounds to reach the market. Oklahoma State University developed a digital twin of an aerosol drug intended to reach lung tumours. By varying parameters on the digital twin, such as inhalation rate and particle size, scientists increased the number of particles reaching their target from 20% to 90%, sparing them the need to create several prototypes and shortening the testing process.²³

Since 2014, thanks to the Rolls-Royce digital twin, 85 million kilograms of fuel, equivalent to \$40m, and over 200 million kilograms of CO² have been saved.²⁴



CARBON REDUCTION

Rolls-Royce is developing and using digital twins to improve engine efficiencies, create new business models, optimise their supply chain and improve product reliability. According to Stuart Hughes, Chief Information and Digital Officer at Rolls-Royce, by combining historical information of an engine's usage, and streaming data directly from individual engines to its platform, the company is deploying digital twin technology, analytics, and machine learning to dramatically reduce the amount of carbon its aircraft engines produce, while also optimizing maintenance to help its customers minimise downtime. Since 2014, thanks to the Rolls-Royce digital twin, 85 million kilograms of fuel, equivalent to \$40m, and over 200 million kilograms of CO² have been saved.²⁴

DIGITAL TWIN PROJECTS ARE INCREASINGLY AMBITIOUS

Perhaps the most ambitious digital twin currently being built is by the European Union's Destination Earth (DestinE) programme, which is a digital representation of Earth.²⁵ DestinE is expected to be implemented in 2027.

The purpose is to monitor and simulate natural phenomena, including human activities. The goals of DestinE are to enable sustainable development and support the EU's environmental policies through the development and testing of scenarios. DestinE aims to integrate multiple data streams from various disciplines to provide a system-of-systems view of planet Earth.²⁶ Parallel to this initiative, Nvidia is building a digital twin of the Earth on their new supercomputer called Earth 2 (E2).²⁷ E2 will integrate and run several key technology components such as Modulus, a physics-grounded artificial intelligence framework for developing machine learning models and quantum technology, amongst others.²⁸

Destination Earth (DestinE) aims to integrate multiple data streams from various disciplines to provide a system-of-systems view of planet Earth.

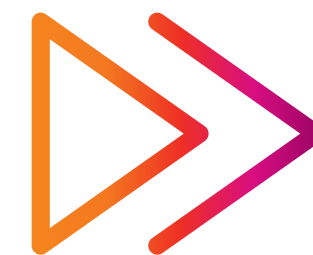
A universal definition that provides the framework for a digital twin is required to galvanise the development and application of digital twins.

THE NEED FOR CLARITY

As evidenced, there is an abundance of resources available on digital twins. To date, there are over a hundred definitions of digital twin.^{10, 29} However, these resources can often be overwhelming, providing nebulous definitions and competing terminologies.³⁰ There lacks clarity on why we should develop a digital twin and what value a digital twin can provide. A universal definition that provides the framework for a digital twin is required to galvanise the development and application of digital twins.

In the automotive sector, digital twins are more prominent in manufacturing processes, asset management or machine performance.^{31, 32} Digital twins have the potential to unlock significant value when applied to the automotive sector's overall product and service lifecycle – enabling radical design

improvements, establishing an enhanced and robust customer experience, and developing sustainable products.³³ Furthermore, catalysed by the unprecedented disruption facing the automotive sector, namely in electrification, new business models and autonomy, digital twins offer a significant opportunity for organisations to stay relevant and globally competitive.³⁴



PURPOSE

The key issues plaguing the understanding and adoption of digital twins in the automotive and mobility sector are the lack of:

- A definition which considers the unique needs of the sector
- Consensus on an appropriate definition
- Relevant case studies demonstrating the value of digital twins beyond local scenarios.

Recognising the confusing landscape of digital twinning and the value digital twin can unlock in the automotive and mobility sector, The Institute of Digital Engineering, Loughborough University, The University of Bath and The University of Warwick organised a series of workshops and webinars on digital twins for the automotive and mobility sector. The primary purpose of these sessions was to derive an appropriate definition and achieve broad consensus from the sector.



PROVENANCE



LITERATURE REVIEW



An extensive literature review was conducted to investigate available definitions which are applied across several industrial sectors such as...



AEROSPACE



AUTOMOTIVE



CONSTRUCTION



GAMING



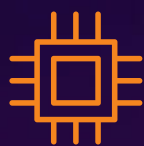
ENERGY



FINTECHS



PHARMACEUTICALS



SOFTWARE AND
TECHNOLOGY

7

DEFINITIONS



Seven definitions were selected as the most relevant for the automotive and mobility sector to build upon. The selected definitions were from...

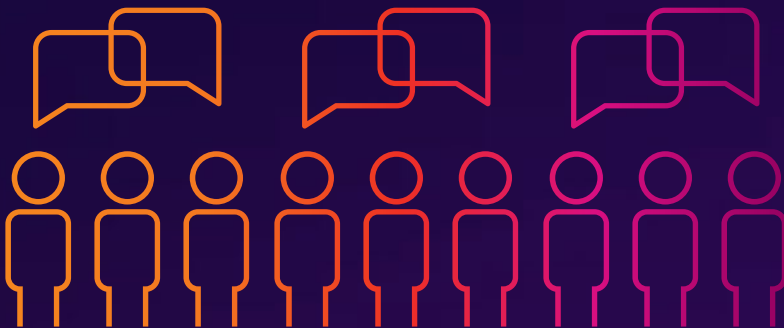


3

WORKSHOPS



Three workshops were held, with the IDE team refining the definition after each iteration for review.



Industrial and academic leaders were invited to a workshop to discuss the selected definitions and develop a relevant and appropriate definition for the automotive and mobility sector.



CONSENSUS



A consensus was achieved within the group, and this definition was presented to 125 attendees at the APC Road to COP26 event in September 2021.



54

WEBINAR ATTENDEES

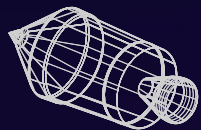
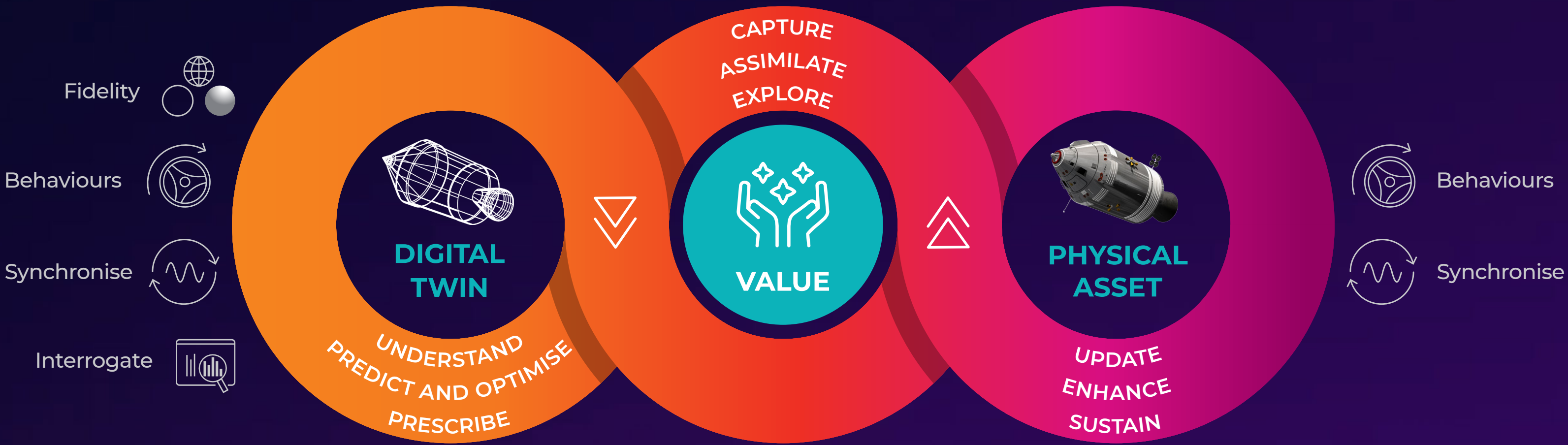
IDE held an Open Forum Webinar to promulgate the digital twin definition most widely accepted by the automotive and mobility sector. 54 attendees from several sectors attended the webinar, including automotive, aerospace, and construction.



The digital twin definition developed was recognised as being the most comprehensive and relevant definition for the automotive sector.

DIGITAL TWIN DEFINITION

A digital representation at the appropriate fidelity of a physical asset and its behaviours, that is synchronised with its physical counterpart and interrogated to deliver value.



DIGITAL REPRESENTATION

Representation of a real-world entity, system or process in a virtual environment through data, models, simulation or visualisation.



APPROPRIATE FIDELITY

The required level of realism portrayed in the digital representation to achieve the intended output.



PHYSICAL ASSET

Real-world entity, system, process or ecosystem which will be the basis to create a digital representation. The physical asset can include software and the integration of hardware and software.



BEHAVIOURS

The characteristics and cause-and-effect relationships of the physical asset and relevant software interactions.



SYNCHRONISED

Connectivity and communication link between the digital representation and physical asset at the required frequencies to transmit and receive data, such as telemetry and updates.



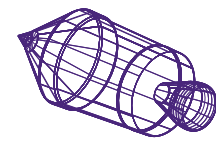
INTERROGATED

The connectivity between the product and its digital representation is not a closed-loop exclusively. The ability to analyse the digital representation to derive insights and make changes in the real world must exist.



VALUE

Provides benefit to an individual, organisation, society or environment derived from its intended purpose.



DIGITAL REPRESENTATION

Representation of a real-world entity, system or process in a virtual environment through data, models, simulation or visualisation.

Fundamentally, a digital representation is a recording of an item using a finite set of symbols that are infused with meaning through a process of encoding and decoding the symbols. The technical world has adopted digital representations for practically every possible purpose – to record sights, sounds, sensor measurements, and mechanical device internal states. It has done so because digital representations provide two tremendous benefits over physical ones.

First, digital representations are transferable: after the initial loss of fidelity in converting a physical scene to a list of numbers, this numerical version can be stored and transmitted with no further loss, arguably forever. A physical image on canvas or film, in contrast, degrades, at least a little, essentially every time it's reproduced or even handled, creating an inexorable erosion of the information.



A **digital representation** at the appropriate fidelity of a physical asset and its behaviours, that is synchronised with its physical counterpart and interrogated to deliver value.

Second, digital representations are manipulable: with an image represented by numbers, you can brighten it, sharpen it, or add visual effects to it simply using arithmetic on the numbers.³⁸ The intentional design of digital representations is becoming increasingly important; they are the foundations on which massive software systems and internet platforms run, and the results we achieve will be determined by the care we take in their building.

Digital representation includes, but is not limited to, combinations of the following categories:

- Physics-based model and data
- Data-driven models
- Time-series data and histories
- Transactional data
- Master data
- Visual models
- Computations.



APPROPRIATE FIDELITY

The required level of realism portrayed in the digital representation to achieve the intended output.

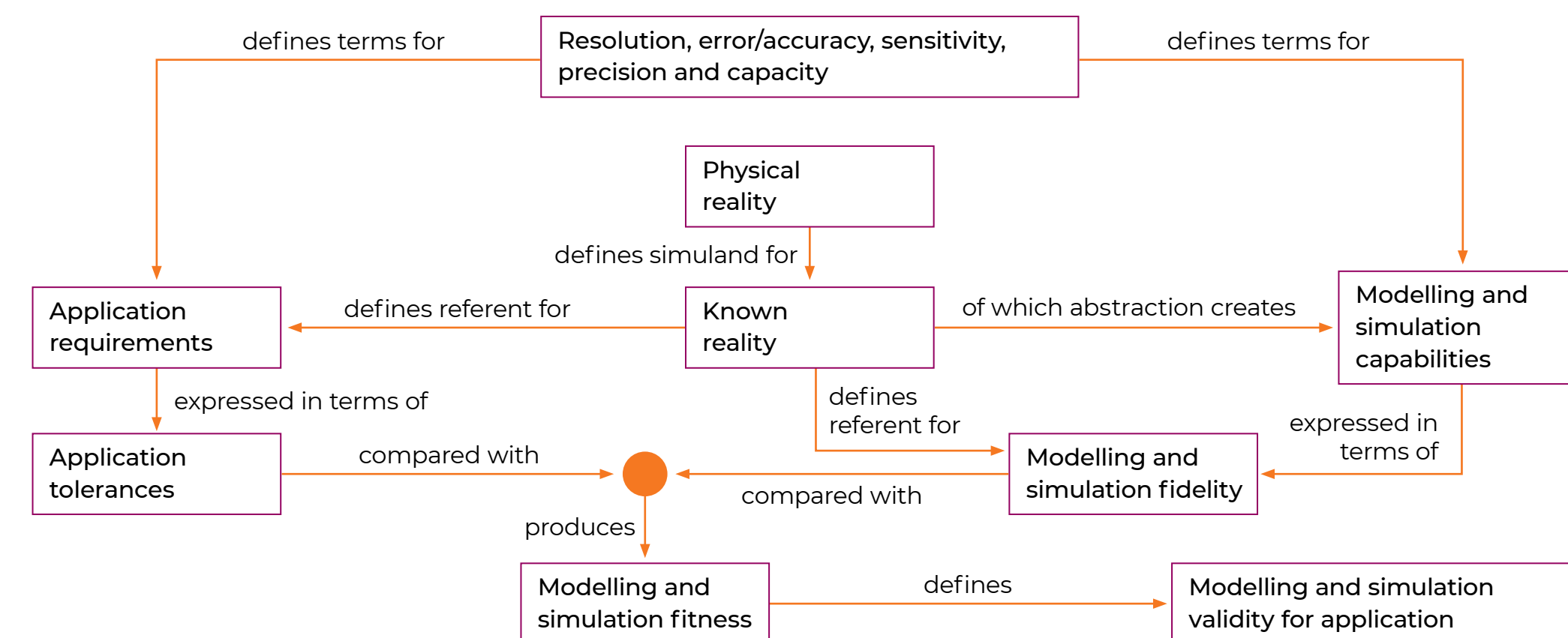
The fidelity required for tasks depends on the question being asked and the minimum viable realism necessary to provide the intended output. Depending on the goals of the digital twin, a mixed higher and lower fidelity system may be required. It is both cost- and time-effective to choose the model's fidelity based on the specific needs of the digital twin and apply distinct levels of fidelity, as needed, for different process areas or at various stages of the digital twin.

Several properties directly relate to the fidelity of a digital twin. For example, the accuracy of the digital twin to its physical counterpart, the trustworthiness of the digital twin, the repeatability of the outputs and the scope of the digital twin, amongst others.³⁹ Higher fidelity may not necessarily provide a more accurate result as the parameters may be insensitive to increased fidelity, thereby adding costs without providing benefits. A novel multi-fidelity digital twin is demonstrated by The University of Texas for a sub-scale downwind wind turbine rotor blade integrating manufacturing information,



A digital representation at the **appropriate fidelity** of a physical asset and its behaviours, that is synchronised with its physical counterpart and interrogated to deliver value.

design specifications, modal and static structural testing data, aeroelastic simulations and calibration processes to successfully design controllers for in-field tests, providing additional data for further evaluation and optimisation.⁴⁰



The USA Department of Defense Modelling and Simulation Enterprise has a thorough analysis of fidelity. The Fidelity Conceptual Framework presented above provides the semantic relationship between associated terminologies and offers a guide to consider for the fidelity assessment of a digital twin.⁴¹



PHYSICAL ASSET

Real-world entity, system, process or ecosystem, which will be the basis to create a digital representation. The physical asset can include software and the integration of hardware and software.

Physical assets represent the fundamental element in the creation of a digital twin. The digital twin must represent a tangible asset from which value is derived. This can be a physical object such as a body panel, a system such as a powertrain, a process such as a manufacturing process of components, or an ecosystem containing multiple interoperable digital twins.

Vehicles have been progressively becoming more software-driven, and this trend came into mainstream prominence in 2019 when Volkswagen CEO Herbert Diess claimed Volkswagen would be a software-driven company, focusing on the software-oriented automotive transformation.⁴² The challenges of integrating software and hardware are not trivial, to the point of delaying the launch of flagship models.⁴³ Physical assets include software and integration of software and hardware, recognising this changing and complex landscape.



A digital representation at the appropriate fidelity of a **physical asset** and its **behaviours**, that is synchronised with its physical counterpart and interrogated to deliver value.



BEHAVIOURS

The characteristics and cause-and-effect relationships of the physical asset and relevant software interactions.

So far, the behaviours of a system have been modelled mainly through physics-based approaches within the engineering community. Generally, the approach consists of observing a phenomenon, developing a partial understanding of it, translating it into mathematical equations and solving the observation either through physical experiments, numerical simulations or both.

However, due to partial understanding of the underlying observations, numerous assumptions made, and scalability of approaches, significant aspects of the underlying behaviours of a system can be omitted. However, data-driven modelling and analysis hold promise to elicit a system's full behaviour as it corrects for previously-made assumptions and uncovers the full physics.⁴⁴ With the availability of sensors, data analysis methods, and relatively cheap computational resources, understanding the system's behaviour through the synergistic relationship of physics-based and data-driven approaches can be achieved.



A digital representation at the appropriate fidelity of a physical asset and its behaviours, that is **synchronised** with its physical counterpart and interrogated to deliver value.

Intrinsic and abstract characteristics such as user experience can be further understood as the data captured can be analysed to provide insights on cause-and-effect relationships. These insights, merged with a complete physics understanding of the system, would be invaluable for product optimisation, improved customer experience and future product creation.



SYNCHRONISED

Connectivity and communication link between the digital representation and physical asset at the required frequencies to transmit and receive data, such as telemetry and updates.

Connectivity between a physical asset and its digital counterpart is fundamental to creating a digital twin. The two-way communication link enabling the exchange of information will be the backbone of a digital twin. Connectivity will typically be agnostic and dependent on the use case of the digital twin, but wireless is a preferable option where suitable. The rapid

development of mobile connectivity is powering a paradigm shift in communication, with 5G and 6G networks being designed and optimised to handle the demands of digital twins.⁴⁵

Up-to-date information is key to any decision-making process. This is further compounded when dependent processes are reacting to information received. The synchronisation between the physical asset and its digital representation is critical for a digital twin. The varying clock speed required by individual digital twin processes will dictate the levels and frequencies of synchronisation between the physical asset and its digital representation. For example, a navigation system may require a live communication link for traffic and weather conditions updates. In contrast, Software over the Air (SotA) updates may only need a communication link at scheduled intervals.



INTERROGATED

The connectivity between the product and its digital representation is not a closed-loop exclusively. The ability to analyse the digital representation to derive insights and make changes in the real world must exist.

One of the objectives of a digital twin is to explore ‘what-if’ scenarios in the virtual environment to aid better decision making. The ability to cross-examine the real-world system, with high confidence in the digital twin, is crucial to the purpose of a digital twin.

The digital twin goes beyond embedded systems, whereby users can perform the various analyses required and adjust the digital twin to relay updates to its physical counterpart. Engineers can automate certain basic functionalities in the digital twin or use machine learning to uncover further trends. However, the ability to interrogate and investigate must exist within the digital twin to amplify the creativity of engineers.



VALUE

Provides benefit to an individual, organisation, society or environment derived from its intended purpose.

The purpose of a digital twin is to generate value. Insights gained through a digital twin of an asset, process or system are actionable. These insights provide value through improved productivity, intimate customer knowledge, reduced time to market or accelerated sustainability efforts. The rapid advancement in underlying technologies facilitates fuller scope of product life cycle and interfacing systems to be modelled.

The value derived from a digital twin goes beyond immediate tangible benefits. A digital twin is an evolving system as it ingests more data and is continually optimised by the user. Digital twins have demonstrated a significantly positive return on investment. For example, Tesla has a digital twin for each of its cars, enabling remote condition monitoring to improve reliability, reduce disruption or downtime, and improve customer experience. Furthermore, this allows intimate knowledge of its products



A digital representation at the appropriate fidelity of a physical asset and its behaviours, that is synchronised with its physical counterpart and **interrogated** to deliver **value**.

as used by customers, empowering market-leading product creation that is better, faster and cheaper than competitors.

The intangible value of a digital twin is overwhelmingly powerful. For example, the ability to understand and visualise the effects of climate change and create actionable plans to mitigate and adapt, based on high-integrity data, can only be achieved through a digital twin. The long-term benefits are profound and ripple through individuals, organisations, societies and the environment as a whole.

The resultant value of a digital twin can be exponential to its initial investment and must be considered beyond just immediate monetary benefits.



DIGITAL TWIN TRAFFIC LIGHT SYSTEM

Digital twins are made up of technology building blocks such as modelling and simulation, data assimilation, sensors and machine learning, amongst others. These individual technologies answer specific challenges and deliver significant benefits to organisations in their own right. Digital twins are not designed to replace these existing technologies; instead they orchestrate these technologies harmoniously to deliver a greater benefit to organisations, society and the environment as a whole. Creating a digital twin has to be strategic and purpose-driven to ensure appropriate value is derived.

We have created a simple traffic light checklist as a guide to achieving a digital twin, based on our definition. The benefits of establishing a digital twin can be realised throughout the journey and not only once the digital twin is established. The traffic light checklist provides a basis of focus for the manifestation of a digital twin. Once the criteria in the definition are fulfilled, a digital twin is established. The digital twin will continually evolve as required to deliver against its purpose, ensuring value is maximised.



A digital representation at the appropriate fidelity of a physical asset and its behaviours, that is synchronised with its physical counterpart and interrogated to deliver value.

CRITERIA

	Does not satisfy requirements and cannot be further modified.
	Satisfies some requirements. Requires additional work to achieve a digital twin.
	Satisfies these requirements to be a digital twin.

EXAMPLE ASSESSMENT OF CHARACTERISTICS

	Is it a digital representation of a physical asset?	
	Does the digital twin represent the behaviour of the physical asset?	
	Is it at an appropriate fidelity?	
	Is it synchronised with data?	
	Is it interrogable?	
	Does it deliver value?	

IS THIS AN EXAMPLE OF A DIGITAL TWIN?

CASE STUDY 1

BMW'S VISION OF A HOLISTIC DIGITAL TWIN USING NVIDIA'S OMNIVERSE

The purpose of the digital twin (challenge to be addressed)

BMW has 31 factories located where each of its factory lines can produce up to 10 different cars. There are over 100 options for each car, and more than 40 BMW models. Therefore there are 2,100 possible ways to configure a new BMW.⁴⁶

The purpose of the digital twin is to improve product quality, reduce manufacturing costs and unplanned downtime while increasing output, and ensuring workers' safety.⁴⁷ Furthermore, the digital twin enables siloed disciplines and geographically dispersed teams to collaborate efficiently and effectively.

How the digital twin resolved the challenge

BMW's global teams now collaborate in real-time to design and reconfigure its factories, utilising multiple software programmes such as Revit, Catia, or point clouds to build and plan the plant in 3D, and all modifications are visible in real-time on Omniverse.

Back-end integration services, such as real-time integration with ProjectWise, BMW internal systems Prisma and MAPP, and



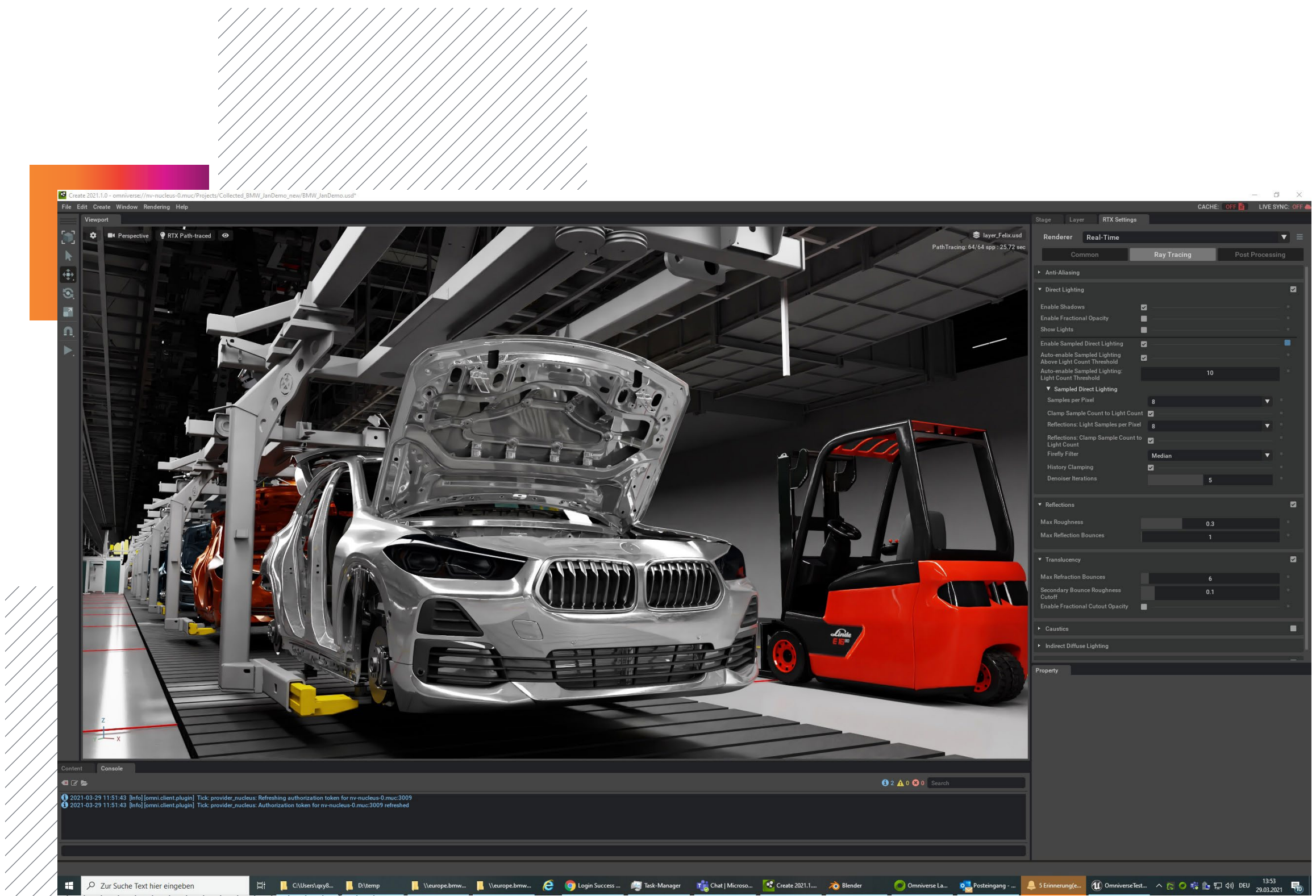
Tecnomatix eMS, are fundamental to its architecture. On the front end of their tech stacks, BMW relies on Omniverse Connectors, which provide live sync with each application. Many prominent 2D and 3D computer-aided design (CAD), real-time visualisation, product lifecycle management (PLM), and advanced imaging technologies are available as front-end applications. BMW chose Nvidia Omniverse as the unified platform for integrating diverse back-end and front-end technologies at scale, allowing its tech stack to scale and support analytics, AI, and digital twin simulations across 31 manufacturing sites.⁴⁷

With NVIDIA's Omniverse platform, the BMW Group is revolutionizing the design of highly complex manufacturing systems. The virtual factory planning tool integrates various planning data and applications and enables real-time collaboration without compatibility limits.

Image and caption courtesy of BMW Group © 2021 BMW Group

What value was derived from the digital twin?

According to Milan Nedeljković, member of the Board of Management of BMW AG, the capability to operate in a digital twin revolutionises BMW's planning process.⁴⁸ BMW's product customization strategy is successful because every system required for production is synchronised on the Nvidia Omniverse platform. As a result, each step in customising a particular model reflects customer needs and is also shared in real time with each production team. Furthermore, BMW claims that real-time production monitoring data is utilised to measure digital twin performance. BMW engineers can immediately discover where and how each single model's production sequence might be improved, using digital twins of a complete factory. BMW employs digital humans and simulation to test innovative workflows for worker ergonomics and efficiency, training digital humans with data from actual colleagues as an example. They're also doing the same with the robotics that are now in place on plant floors.⁴⁷ Integrating actual production and process monitoring data with simulated results allows BMW engineers to immediately identify areas for improvement, allowing them to exceed quality, cost, and production efficiency targets.⁴⁷



With NVIDIA's Omniverse platform, the BMW Group is revolutionising the design of highly complex manufacturing systems. The virtual factory planning tool integrates various planning data and applications and enables real-time collaboration without compatibility limits.

Image and caption courtesy of BMW Group © 2021 BMW Group

CASE STUDY 2

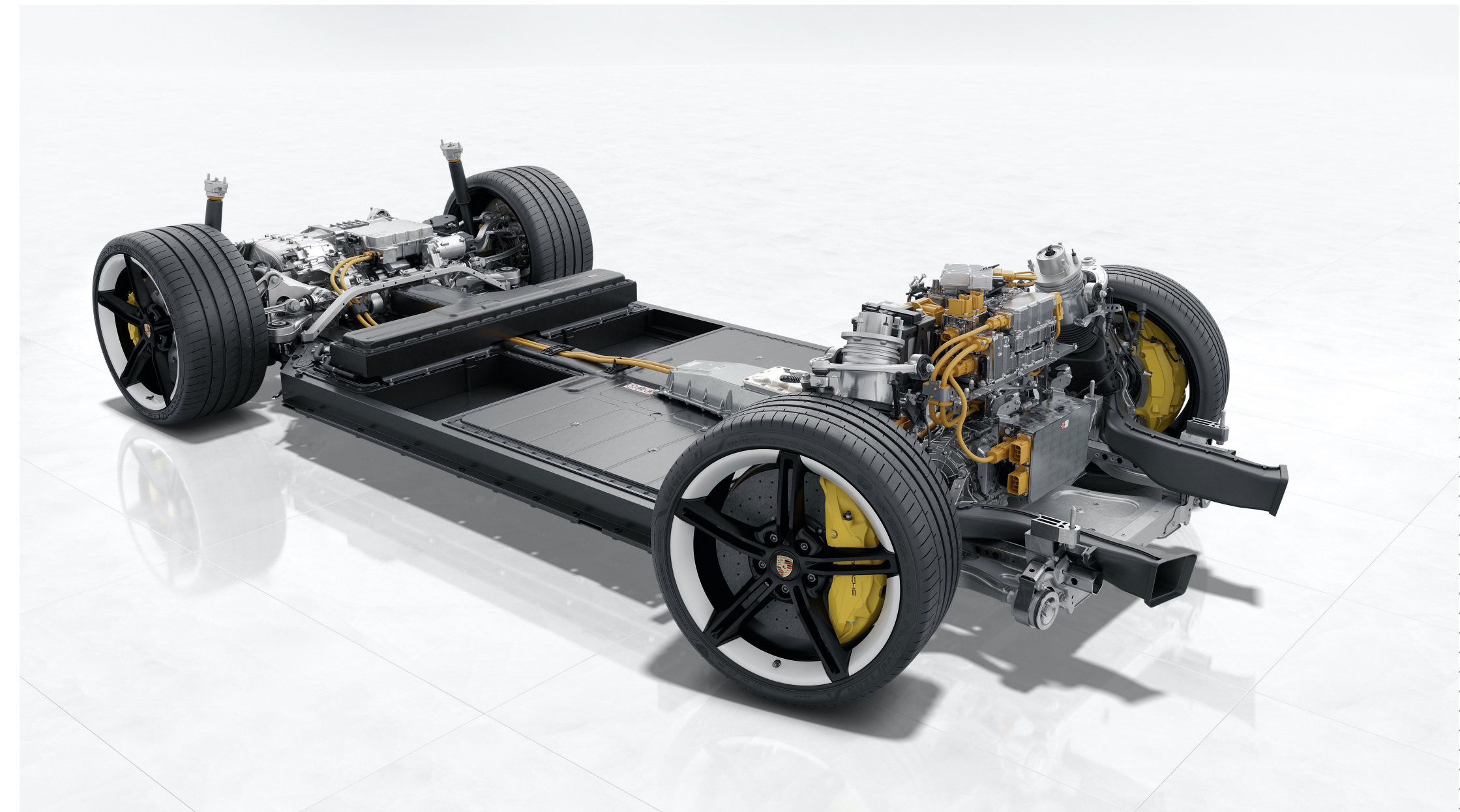
PORSCHE'S DIGITAL CHASSIS TWIN

The purpose of the digital twin (challenge to be addressed)

The chassis of the vehicle is subjected to the most strain, especially on racetracks.⁴⁹ The strain on the chassis can be monitored within the vehicle and communicated to the driver owing to sensor technology and sophisticated neural algorithms utilised for centralised analysis. Any specific flaws are discovered swiftly, even before the driver or the workshop sees a problem indicated by either noise or vibration. This intelligent utilisation of data makes the vehicle safer for its occupants.⁵⁰

How the digital twin resolved the challenge

The digital chassis is already being utilised for its first real-world test: monitoring the components of the Porsche Taycan's air suspension. This project's primary goal at this point is to collect data on body acceleration. The data is analysed and sent to the central backend system via Porsche Connect. This system compares the data from each vehicle to the fleet data on a regular basis. Based on this comparison, the algorithm determines thresholds, and if they are surpassed, the client is



warned via the onboard Porsche Communication Management system (PCM) that the chassis may require inspection at a Porsche Centre. While this method guarantees that wear does not exceed set limits, it also aids in the prevention of consequential damage.⁵⁰

Artificial intelligence within the vehicle and within the centralised intelligence system is always improving contingency planning and algorithm correctness. Initially, sensor data from mechatronic components will be assessed, laying the path for future features such as functions that calculate wear on

A digital chassis twin for predictive driving functions and component status updates.

Every new generation of Porsche benefits from the improved performance of its integrated sensors, networking and data processing capabilities, which in turn uncovers new possibilities for effectively using these capabilities. One of these possibilities is known as a 'digital twin'.

Image and caption courtesy of Porsche © 2022 Dr. Ing. h.c. F. Porsche AG

specific components without the use of physical gauges. For example, if numerous vehicles require wheel alignment or track rod replacement and multiple sensors have already recorded relevant deviations, this data can reveal a trend. If the same data is discovered on another car, the driver will be directed to a Porsche Centre.⁵⁰

What value was derived from the digital twin?

Early diagnoses in this style might help prevent subsequent damage, such as worn tyres caused by track misalignment. Because the exact components responsible for a failure can be replaced, the fault-finding procedure at the workshop will be faster, reducing throughput times in the workshop and saving customer costs. Aside from vehicle operation, the digital twin provides additional benefits to customers. Digital vehicle data can be used to illustrate a car's residual worth, making the purchasing and selling of used vehicles more transparent. Furthermore, manufacturers may consider providing an extended certified warranty based on a frictionless recording of component status updates, as well as a certificate with a price recommendation for selling the car.⁵⁰



The digital twin allows data-driven analysis, monitoring and diagnostics without the challenges and constraints of real-world tests. The digital twin of a vehicle comprises not only the operating data it collects but also any related data, such as information collected during planned maintenance work and unexpected repairs.

Image and caption courtesy of Porsche
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CASE STUDY 3

DIGITAL TWIN ENSURING FULL TRANSPARENCY IN THE LEATHER SUPPLY CHAIN FOR JLR

The purpose of the digital twin (challenge to be addressed)

Jaguar Land Rover (JLR) is dedicated to providing its customers with more sustainable and responsible material options for their car interiors. JLR collaborated with supply chain traceability provider Circular, top UK leather manufacturer Bridge of Weir Leather Company, and the University of Nottingham to conduct a world-first trial of traceability technology in the leather supply chain.⁵¹

How the digital twin resolved the challenge

A digital twin of the raw material was constructed as part of the Innovate UK-funded research, allowing its passage through the leather supply chain to be followed both in the real world and online. Using blockchain technology, a combination of GPS data, biometrics, and QR codes were utilised to digitally verify the movement of leather at each stage of the process.⁵²



Jaguar Land Rover partners with Circular, Bridge of Weir Leather Company and University of Nottingham on industry-leading leather trial. 'Digital twin' created to track entire leather production process using GPS, biometrics and QR codes.

Image and caption courtesy of Jaguar Land Rover.
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By defining the verification procedure, a repeatable blueprint for tracing a single piece of leather at each stage has been developed. It can be used throughout JLR's global supply chain as well as by other industries that require leather, such as fashion and footwear. The development is part of JLR's Reimagine strategy, which is a sustainable blend of modern luxury, one-of-a-kind customer experiences, and beneficial societal impact. By 2039, Reimagine hopes to have achieved net-zero carbon emissions across its supply chain, goods, and operations.⁵² According to Dave Owen, Executive Director of Supply Chain for JLR, "This is one step in our journey to net-zero carbon emissions across our supply chain, products and operations by 2039, enabled by leading-edge digital capabilities."⁵²

What value was derived from the digital twin?

In addition to tracking compliance, the digital approach allowed JLR to evaluate the carbon footprint of its leather supply network, tracing their leather from farm to completed piece. JLR's goal is to obtain premium materials while increasing transparency about the provenance, welfare, and compliance of suppliers across its networks.⁵²

The technique could be used to track other commodities as well. Blockchain technology is presently being utilised to improve the traceability of minerals used in electric vehicle batteries. Customers will have increased confidence that the sustainable supply chain is genuine and that all resources have been sourced sustainably because blockchain technology is hard to manipulate or tamper with.⁵²

CASE STUDY 4

DIGITAL TWIN OF THE FORMULA STUDENT CAR AT LOUGHBOROUGH UNIVERSITY

The purpose of the digital twin (challenge to be addressed)

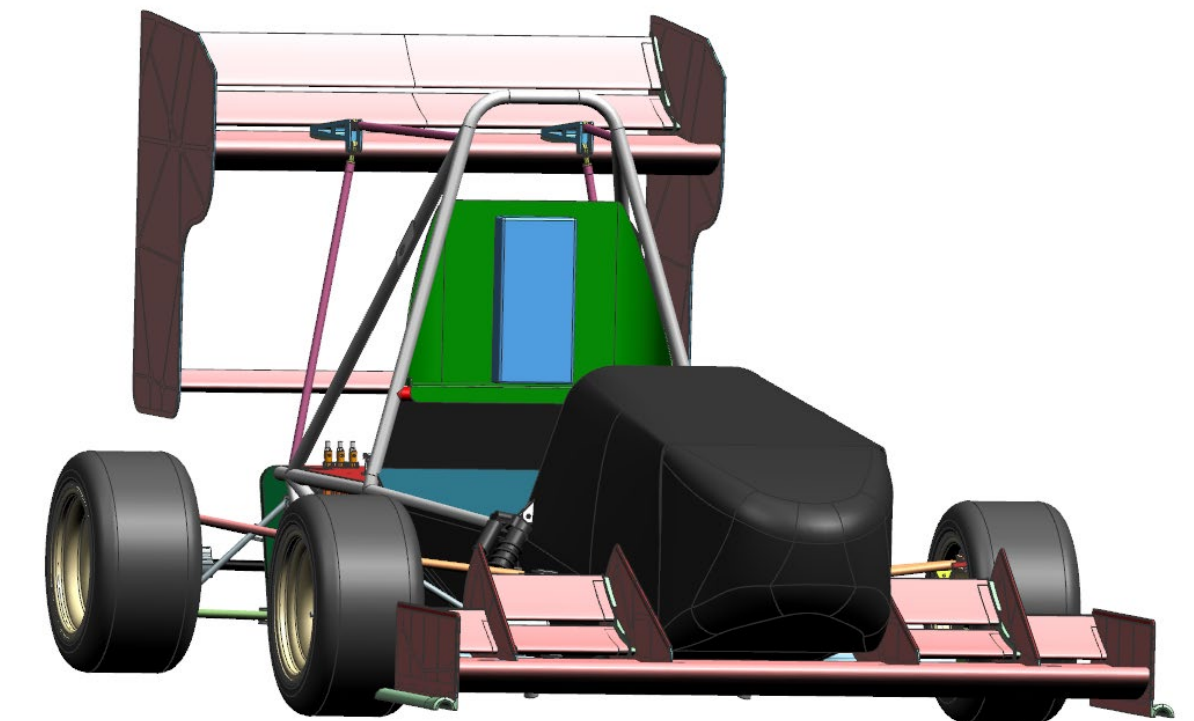
Formula Student (FS) is a global university competition where students worldwide participate by designing, manufacturing, and racing their own vehicles. The FS activity is embedded in the fourth year of the Automotive Engineering course at Loughborough University, with students working in groups to address specific areas of vehicle development. For more than a decade, the Performance Simulation group has been developing simulation models of the complete vehicle, which have helped predict performance and optimise vehicle set-up. During this time, the approach has evolved from creating isolated/siloed simulations to developing a fully connected and synchronised digital twin of the vehicle. This evolution stems from the recognition that models that are not systematically synchronised with the real product can only provide limited insight into the system's behaviour and its evolution.

A particular challenge for the Loughborough FS team is predicting tyre performance. Vehicle simulation models may use nominal tyre data, but this data is rarely representative of the

behaviour of tyres on actual road surfaces. Obtaining tyre data on such surfaces is very costly and, in many cases, prohibited by the relevant motorsport regulations. A digital twin of the vehicle can be used, coupled with measured data from the real vehicle, to infer unknown tyre parameters and allow fine-tuning of the set-up for optimum performance.

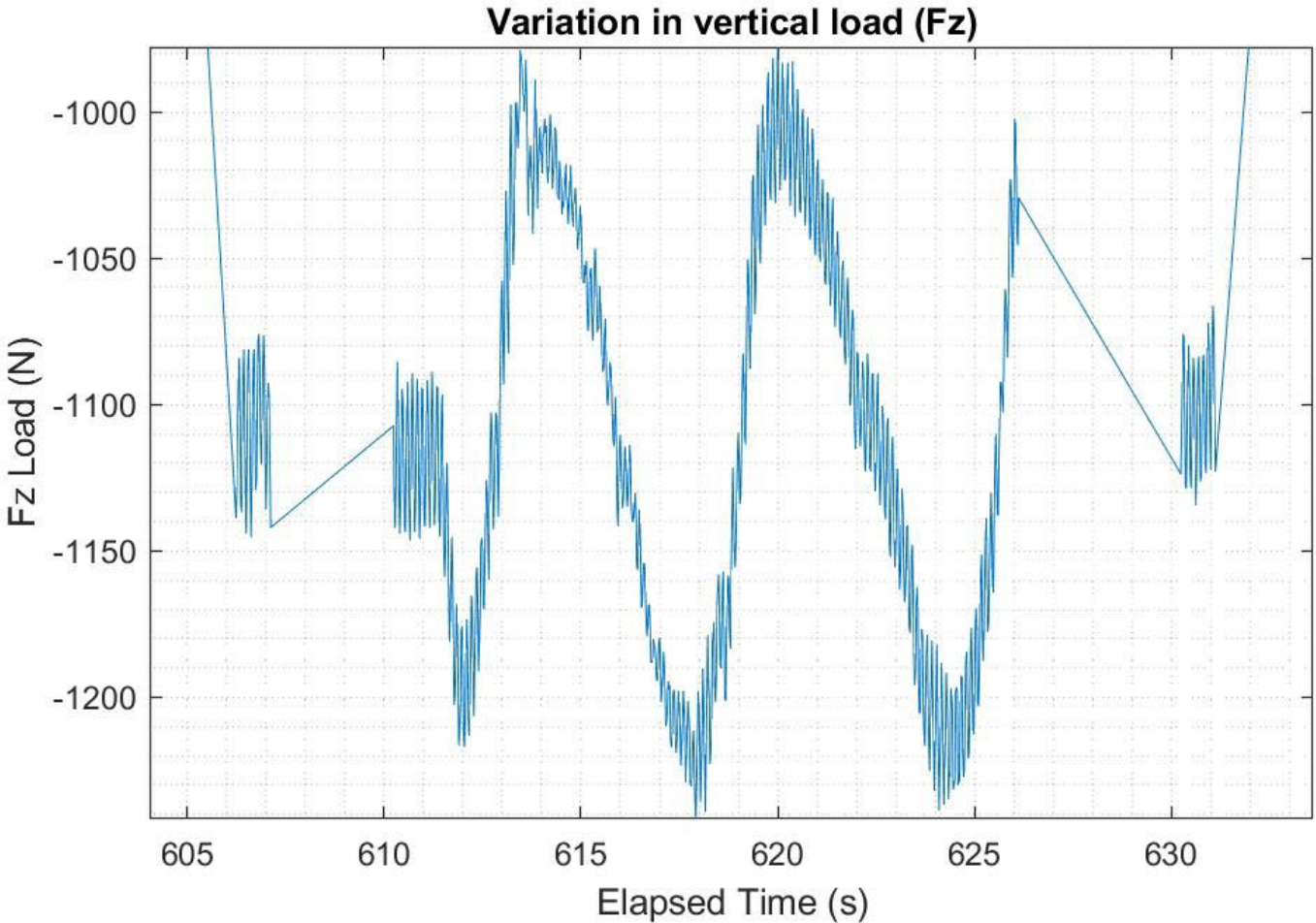
How the digital twin resolved the challenge

Student efforts at Loughborough have focused on developing a digital platform for collecting, visualising, and processing measured data from the vehicle in – or very close to – real-time. For this purpose, a custom-designed network of onboard sensors, data acquisition and telemetry systems have been combined with a student-created data visualisation/processing software, akin to the tools used by professional motorsport teams. Notably, the previously isolated full vehicle simulation is now part of the intelligent data processing and is seamlessly integrated with data acquisition, creating a functional digital twin.



Visual representation of the Formula Student car

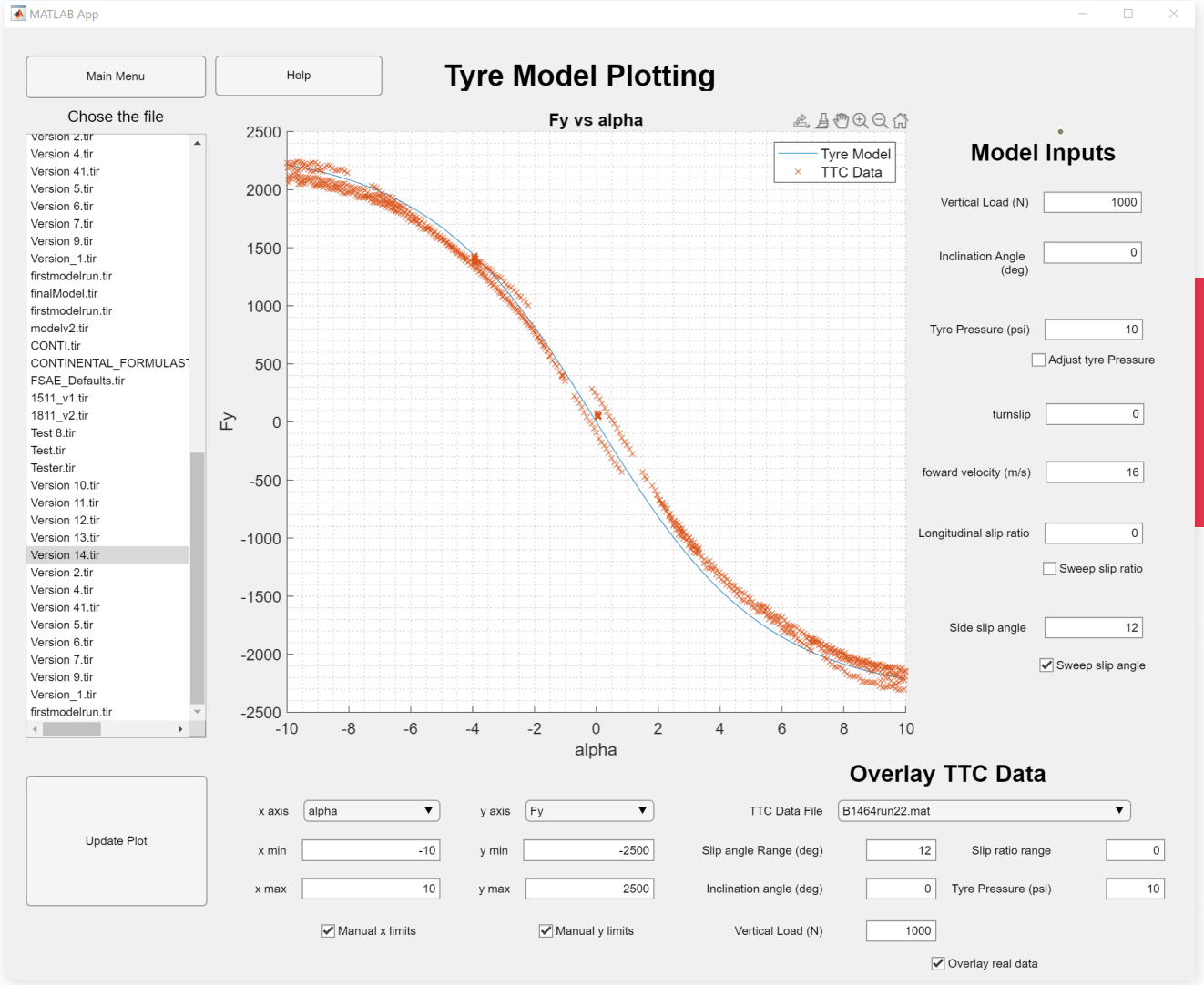
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Tyre testing, vertical load variation

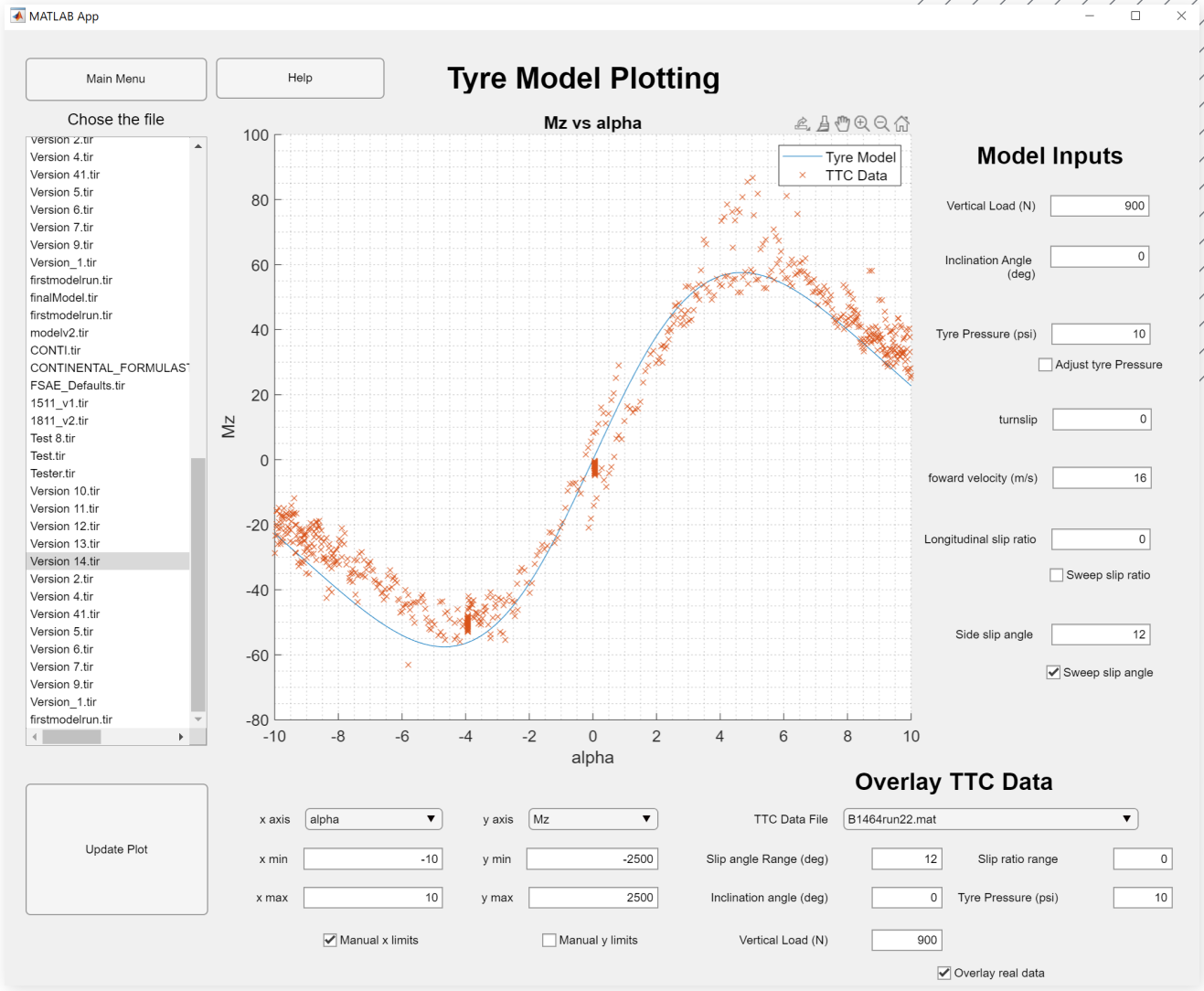
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In practice, the simulation model accepts measured inputs and generates simulated outputs which are contrasted to the corresponding measured variables. Then, optimisation is used to fine-tune model properties and infer parameters that may be environment dependent, or even change during the course of an event. The coefficient of tyre-road friction is one such parameter with a profound effect on the performance envelope of a vehicle. Using the digital twin, it is possible to estimate friction on-the-fly, correcting the nominal tyre model parameters and responding to changing racing conditions.



Examples of lateral slip angle plot – the orange points show TTC data overlaid on the tyre model values

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What value was derived from the digital twin?

For Loughborough students, the value of developing and using a digital twin of the FS car is two-fold. At a competition level, it allows estimation of hidden, internal states of the real vehicle, as well as identification of elusive model parameters pertinent to the tyres. Knowledge of these parameters supports better decision-making during events and offers a much better understanding of vehicle performance. In the medium term, this information can be built into a database that will support future vehicle design iterations. With every interaction between the digital twin and the physical vehicle, both simulation and experimental uncertainties are reduced simultaneously, resulting in additional confidence on the simulation during the next design phase. The benefits include reduced development time and a much more competitive vehicle.

While the technical value of the digital twin can be game-changing, the educational benefits can also be profound in terms of preparing the next generation of engineers to lead innovation in the digital space. The digital twin fundamentally challenges the traditional notion that simulation competes

with the real product and real-world data, with simulation typically required to prove its correlation with the real world. Instead, it promotes the concept of a model that interacts intelligently with real data to create better understanding and better designs while reducing development costs. From an educational viewpoint, working towards a digital twin presents the ideal platform for combining methods, knowledge and skills from across science and engineering – including deterministic, stochastic and machine-learning-based models, data acquisition and processing, connectivity, hardware and embedded systems. Working within a group to address collectively all of the above creates a unique experience for university students and instils a mindset for digital innovation.

While the technical value of the digital twin can be game-changing, the educational benefits can also be profound.



VALUE FOR MONEY

The digital twin market as a whole has seen a meteoric rise in recent years. The global digital twin market size is estimated to have a compound annual growth rate (CAGR) of 50% between 2020 and 2030, valued at \$184.5 billion.⁵³ According to Research and Markets, the highest growth under sector segment is predicted within the automotive sector in the next eight years with a CAGR of 51.8%.⁵⁴ The primary reason for the rocketing growth of digital twins is the promise of substantial returns. According to a study conducted by KPMG and Atkins, investments in a well-thought-out and implemented digital twin will yield a 6:1 return.⁵⁵

Investments in a well-thought-out and implemented digital twin will yield a 6:1 return.⁵⁵

Some organisations, however, will be held back from successfully implementing digital twins and reaping the promised benefits due to a lack of understanding and a clear strategy. In addition, the cost of designing and deploying digital twins can quickly become out of hand if done carelessly. For example, a comprehensive analysis was performed by the U.S. Department of Defense to implement digital twins in the U.S. Air Force. The cost was estimated between \$1 and \$2

trillion with timescales beyond current aircraft development timelines.⁵⁶ Although this may be an extreme example, it demonstrates further the significance of ensuring a strategic and purpose-driven development and implementation of digital twins.

The underlying outcome from the existing evidence and case studies covered in this whitepaper is that the nature of the value – economic, social, or environmental – enabled directly by the use of digital twin is strongly context-specific and requires a case-by-case review. This adds to the challenge for governments and corporate leaders in assessing value for money and striving to standardise a credible evidence basis of the wider value released by digital twin development and use. The established valuation methods outlined in government appraisal guidance are relatively complex and rarely applied by public or private organisations to understand the specific impacts of investing in digital twins. Furthermore, these valuation approaches necessitate reliable input data on improvements in consumer, societal, and environmental benefits, which are facilitated by digital twins, but difficult to separate from other aspects of the intervention.⁵⁷

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29

KEY CONSIDERATIONS

A comprehensive benefits framework was developed by KPMG and Atkins and published in a report commissioned by the University of Cambridge's Centre for Digital Built Britain (CDBB). This framework highlights several key considerations to demonstrate productivity gains as well as wider value for customers, society, the environment and the economy.⁵⁷ Building upon this and *HM Treasury's Green Book* guidance,⁵⁸ the points below provide an overview in building a business case, based on value for money, for the development of digital twins.

1 Quantifying productivity gains

Creating metrics to assess direct productivity improvements from digital twin creation and implementation. Increased efficiency, increased asset utilisation, improved compliance, innovation, decreased risk, and increased resilience can all lead to productivity advantages. These measurements are not exhaustive and may differ depending on the organisation.

2 Intangible benefits

Intangible benefits are not readily quantifiable monetarily, yet they have a substantial business impact. Enhanced staff health and safety, improved workforce culture, improved reputation and the ability to attract and retain talent, for example, are all intangible benefits that play a significant role in overall impact assessment.

3 Wider impacts

Wider impacts are defined as advantages that benefit society and the environment as a whole. For example, developing safer and more dependable products has the potential to improve society's quality of life while also expediting the fulfilment of long-term net-zero goals.

4 Counterfactuals

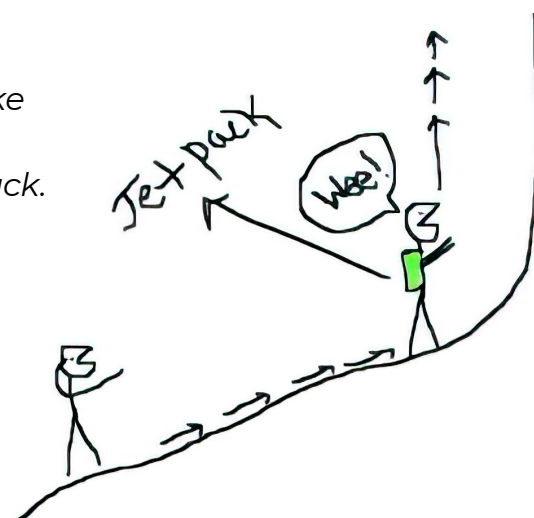
A critical element in understanding the benefits of digital twins is determining what would happen in their absence. This can be quantified by analysing competitive metrics and determining a scenario of 'do nothing' or business-as-usual. Typically this can be achieved by benchmarking against similar projects or competitors and using expert judgement supported by quantitative evidence where possible.

CONCLUSION

Change is not just constant. The pace of technological change is accelerating exponentially.⁵⁹ According to Kurzweil in his seminal essay, *The Law of Accelerating Return*, “We won’t experience 100 years of progress in the 21st century – it will be more like

“We won’t experience 100 years of progress in the 21st century – it will be more like 20,000 years of progress (at today’s rate).”⁶⁰

The acceleration of acceleration: it's bit like climbing a mountain and receiving a jet pack.



20,000 years of progress (at today’s rate).”⁶⁰ Exponential breakthroughs in enabling technologies have reached a tipping point where they could spark disruptive transformation in industries ranging from artificial intelligence to robotics to health. As a result, many experts believe that the world of tomorrow will be unrecognisable from the world of today.⁶¹ The evolution of technological change is sensational as not only the individual enabling technologies

face exponential growth, but for example, when grouped together to develop digital twins, this combination triggers a “second-level” of exponential growth capable of greater ‘returns’

of technology. Digital twins could be seen as the technology to harness enabling distinct technologies to truly deliver whole solutions that are far greater than the sum of its parts.

TECHNOLOGICAL INNOVATION IS ESSENTIAL FOR GROWTH

Productivity and economic growth are underpinned by technological innovation.⁶² The modern economy is mainly driven by new technology, ideas and innovation. There is a wealth of evidence on the patterns of technological adoption and penetration among UK businesses that present a consistent tale. High-productivity firms employ new technology, which subsequently spreads swiftly and broadly throughout the organisation. Innovation happens quickly, and it spreads widely. Companies whose technology adoption has been slow or non-existent, on the other hand, have seen neither rapid nor widespread innovation or diffusion. As a result, the productivity performance of these organisations has been low and stagnant.⁶³ It is inevitable that technology advancement is critical to improving productivity and that digital twins will play a central role in future technology portfolios.

It is inevitable that digital twins will play a central role in future technology portfolios.

Building on ongoing research programmes, a tailored digital twin initiative for the automotive and mobility sector is imperative.

The complexities facing the automotive and mobility sector ranging from net-zero and CAV to supply chain challenges are multidimensional and interwoven. Furthermore, there is a data dilemma that is rapidly approaching. According to Stephan Heinrich from Lucid Motors, a single vehicle at a lower level of autonomy could generate approximately 434 terabytes of data in just one year.⁶⁴ Ambitious and aspirational goals such as net-zero and CAV will be almost impossible to achieve feasibly without a system such as a digital twin to manage, make sense of and exploit the data.

DIGITAL TWINNING IS OF STRATEGIC IMPORTANCE

Digital twinning is of strategic importance to the UK. It is recognised through establishing a National Digital Twin Programme primarily for the built environment, a partnership between the University of Cambridge and the Department for Business, Energy and Industrial Strategy.²⁰ Furthermore, digital twins are recognised as an important capability to develop in the UK Innovation Strategy.⁴ An inspirational and ambitious initiative

called the Cyber-Physical Infrastructure is currently undergoing public consultation to take digital twinning to the next level by creating a network of system-of-systems and ecosystems, seamlessly connecting virtual and physical spaces.⁶⁵

Building on ongoing research programmes, a tailored digital twin initiative for the automotive and mobility sector is imperative. The sector's issues are unique, and they must be addressed promptly if the UK is to maintain its leadership in the global automotive race. "Research and Development" (R&D) is commonly thought of as a rhyming couplet. In the instance of the United Kingdom, the R and the D do not appear to rhyme. As a world-leading innovation hub, the United Kingdom excels at R. However, it does poorly in D, where D refers not only to development but also to the diffusion and dissemination of innovation in order to expand the UK supply chain base.⁶³ This whitepaper provides a definition, context and demonstrates the art of the possible that can be realised with a digital twin. The journey must begin now to underpin and integrate numerous efforts to support organisations in developing and deploying digital twins to address the productivity puzzle. Government intervention and leadership is absolutely crucial in delivering this national endeavour. ■

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Bradley leads IDE, working with government, industry and academia to drive the transformation of the UK's industrial capabilities through harnessing new digital science and

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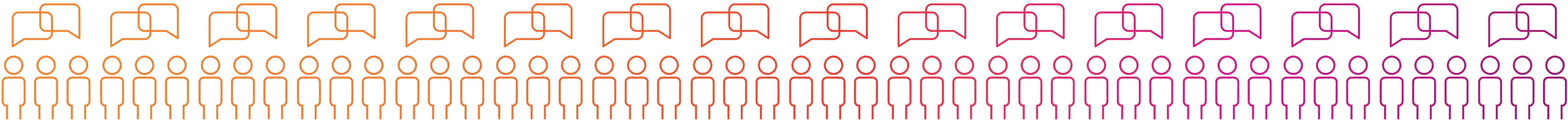
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WORKSHOP AND WEBINAR ATTENDEES

Airbus	Ceres Power	IPG Automotive UK Ltd	STFC Hartree Centre
Alten	Coventry University	JLR	TaBA Associates Ltd
AMRC	Cranfield University	Just Practising Limited	Telstra
APC	DEOS Digital	Larsen & Toubro Defence	Tevva
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