DESIGNING DISRUPTION

The critical role of virtual twins in accelerating sustainability

Virtual twin technology is an underutilized lever in operationalizing sustainability and the circular economy at speed and scale

Accenture Industry X

Foreword

The world is changing in ways that are impossible to ignore. As we continue to learn how the global pandemic will impact life in the years to come, it's important to recognize a vital lesson: we are placing increasingly dangerous pressures on the global commons and we must act quickly to avoid high-risk scenarios.

With this in mind, leaders across industry, government and civil society must increasingly work together to meet our Global Goals by 2030 and it is clear that we all need to employ urgency as we only have ten years left to prevent irreversible damage from climate change.

The complete transformation needed to achieve these goals will require new ways of managing products and services over their entire lifecycle, from design, use and end-of-life. To do this, we must find new ways of working together to create circular economies, drive competitiveness and responsible growth opportunities and collectively ensure that technological revolutions deliver on their promise of enhanced sustainability.

In response to these challenges, Accenture and Dassault Systèmes have partnered to further advance the thinking on the potential for virtual twin technology to accelerate this sustainable transformation towards a more circular economy. Virtual twins can help companies reduce their costs, resource use and carbon footprint and they can support disruptive innovation and agile, customer-centric, more circular business models.

They enable significant upside potential for sustainable innovation at scale, required to create more responsible global value chains, and present an opportunity to drive systemic progress towards more circular and significantly less carbon intensive economic systems.

This report examines these opportunities and the use cases where virtual twins can, or already are, modeling entire value chains as virtual experiences, demonstrating how the technology can unlock combined **additional benefits of USD $1.3 Trillion of economic value and 7.5 Gt CO_2e emissions reductions between now and 2030.**

Together, we are excited at the potential for these virtual twin technologies to design and deliver the new products and systems we need for our zero-carbon, circular economies. However, we must be sure to deploy these technologies at pace and with sustainability as a key driver, as only then will we be able to ensure our Global Goals are met by 2030.

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Executive summary

A virtual twin is a real-time virtual representation of a product, platform or ecosystem that can be used to model, visualize, predict and provide feedback on properties and performance. Virtual twin technologies provide an untapped opportunity to reduce operational costs and drive sustainable, circular, end-to-end disruption in value chains.

In 2020, the global virtual twin market is estimated at just over USD $5.4 Billion, and it is projected to grow at a CAGR of 36% over the next five years. However, its current reach is limited, and the market has only achieved 10% adoption globally as this technology is currently not fully mature and underutilized across many industries.

Despite a limited adoption rate to date, virtual twin technology can accelerate the delivery of the UN Sustainable Development Goals. This study examines use cases within the Construction, Consumer Packaged Goods, Transportation, Life Sciences and Electrical and Electronics industries to frame the realized and potential impact of the technology.

Five use cases have been assessed quantitatively for their business and sustainability impact, where data availability and/or technology maturity allow; others have been highlighted qualitatively for their high potential to drive change. **The analysis reveals that these five use cases alone can deliver combined incremental benefits of USD $1.3 Trillion of economic value and 7.5 Gt CO_2e emissions reductions between now and 2030.**

From this study, it is clear that the benefits of virtual twin technologies are numerous and their potential role in supporting a circular economy is significant. They enable reduced product development lifecycle times, improved manufacturing quality and control and more efficient use and recovery of resources across the lifecycle. But adoption has been limited due to several key barriers.

Chief among them are a limited understanding of technology use cases and benefits, difficulty in measuring combined business and sustainability ROI as part of the business case, and a potential lack of progressive executive leadership in adopting the technology for competitiveness and the sustainability agenda.

To overcome these barriers and accelerate the adoption of virtual twin technologies, executive leaders should consider these five key recommendations:

1

Tie together technology and sustainability agendas: Ensure leadership support for tying together the technology, sustainability and circular agendas, including measuring and tracking value, connecting to growth strategies and factoring in sustainable value into key investment decision-making;

2

Improve understanding: Improve understanding of virtual twin technology and potential use cases across the organization, including infrastructure requirements, legacy constraints;

3

Focus on disruptive, systems-change use cases: Focus on scaling solutions with transformational sustainability impact, moving beyond efficiency improvements and incrementalism, towards systemic change as presented by the circular economy and large-scale industry decarbonization;

4

Deploy responsibly: Deploy virtual twins based on responsible and inclusive principles, ensuring transparency, inclusion and accessibility are embedded from the start;

5

Rally ecosystem support: Build broad support with private, public sector and civil society to ensure long-term success and help de-risk and pilot use cases where return on investment may be perceived as too uncertain for private capital.

The Decade to Deliver

1

The crisis of the global commons is deepening

The environmental degradation inherent in our current models of production and consumption has reached critical levels. Continuing on this path is incredibly high risk as it could trigger non-linear, abrupt environmental change within planetary systems, and we are already feeling the effects across all our ecosystems:

Figure 1: Key examples of environmental degradation

Life on land	Earth's animal populations have decreased by nearly **70%** since 1970, in large part due to loss of habitat[1]. The three most recent years with available data (2016, 2017, 2018) experienced the three highest rates of primary forest loss since the turn of the century.
Life at sea	Nearly **90%** of the world's marine fish stocks are now fully exploited, overexploited or depleted[2] and the chemistry of the oceans is changing faster than at any point in perhaps 300 Million years, due to the absorption each year of around **25%** of anthropogenic greenhouse gas pollution[3].
Climate	GHG emissions need to fall by circa **8%** each year between now and 2030[4] if the world is to get on track to meet our goal of limiting temperature rise to close to 1.5° Celsius, as agreed by science and policy makers within the Paris Agreement. Despite this agreement, arctic summer sea ice could disappear as early as 2035[5] due to rising emissions.
Water	Severe impacts on the global water cycle have occurred due to increased abstraction and uncontrolled pollution; by 2030 we may face a **40%** shortfall in the freshwater we will need to drive our global economy[6].
Food system	Research has revealed that approx. **30%** of the world's adequate or high-quality food-producing land has been lost at a rate that far outstrips the pace of natural processes to replace diminished soil[7].

This is a critical decade for action

To address this crisis, we need to radically transform our systems of production and consumption. There are now less than ten years left to achieve the UN Sustainable Development Goals (SDGs, also known as the Global Goals) set out by governments, business and other stakeholders, and we are woefully off track. Incremental change is no longer an option.

SDG progress reports have revealed that despite improvement in a number of areas on some of the Goals, progress has been slow or even reversed, particularly following the COVID pandemic in 2020. Whilst we still stand a chance to change this trajectory, we need to understand that the next ten years are critical.

CEOs stand at the ready to ensure business plays its role in our collective response. In the fifth UN Global Compact—Accenture Strategy CEO Study on Sustainability from 2019, nearly half of the participating CEOs said business would be the most important actor in the delivery of the Goals.

Yet, only 21% of CEOs stated they believe that business is already fulfilling that potential by contributing to the Goals. Discontent with that status quo, CEOs agree the business community should be making a far greater contribution to achieving a significantly more sustainable world by 2030.

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Virtual twins are an underutilized accelerator of sustainability

To accelerate this sustainability transformation towards more circular models, business experimentation with new digital, physical and biological technologies has flourished in recent years. Some of the technologies have already matured considerably. The Internet of Things (IoT), for example, has become the new standard for devices and equipment. However, there has been less experimentation to date with the technology that is used to design, manufacture and build most complex goods today.

This technology is known as product lifecycle management (PLM) and it has evolved significantly in recent years with the advent of production innovation platforms. Virtual twin technologies stand on the foundation provided by PLM but enable much more disruptive forms of innovation.

Virtual twins are used to model complex systems, from cars to cities to human hearts, and simulate their functioning with an accuracy that allows the user to go directly from a virtual model to creation, without spending the years it normally takes to prototype and incrementally improve on existing designs.

This time-to-market speed and risk-reduction of complex projects explains why virtual twin technologies have been used in the development of 85% of the world's electric vehicles, more than 75% of global wind power, and breakthrough sustainability pilots such as electric furnaces, the world's first solar airplane, and new bio-materials[8]. Virtual universes allow users to design, test, and model disruptive new sustainable products and processes in record time.

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Explaining the twins: history, definition and applications

The smart industrialization agenda has breathed new life and potential into the digital twin concept. Academic and business thought leaders have written extensively about the topic over the past years and the terminology used spans a wide spectrum. In this paper, we refer to digital twins as virtual, reflecting the evolution of the concept.

To avoid any ambiguity, we define virtual twins as a real time virtual representation of a product, process, or a whole system that is used to model, visualize, predict and provide feedback on properties and performance, and is based on an underlying digital thread.

The latter is the interconnected network of process and digital capabilities that create, communicate and transact product information throughout the product lifecycle.

This allows the virtual model to be continuously updated across the lifecycle of the physical asset (or across the parameters of production processes), with additional data gathered from real-world interactions (see Figure 2).

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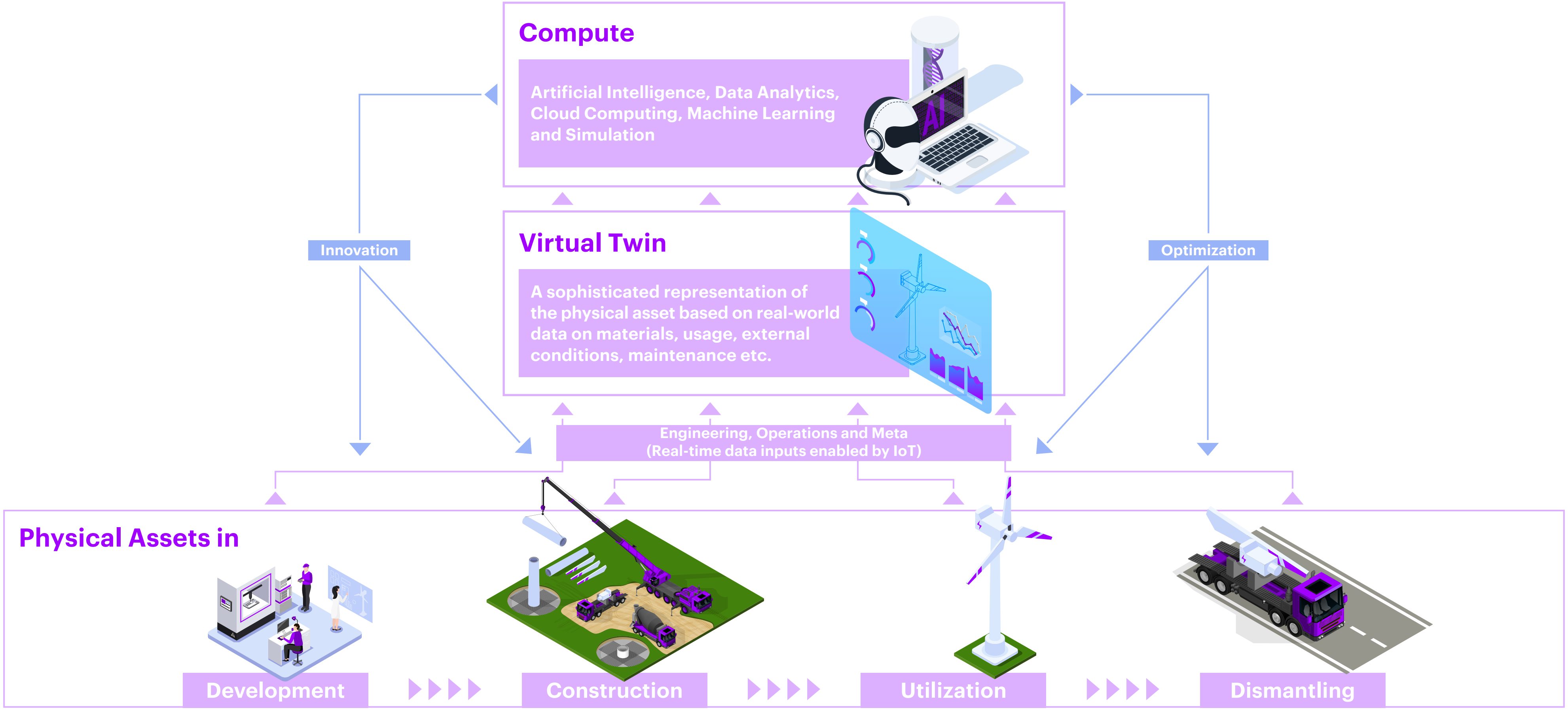
Figure 2: How virtual twins interact with the real world



Compute

Artificial Intelligence, Data Analytics, Cloud Computing, Machine Learning and Simulation

Virtual Twin

A sophisticated representation of the physical asset based on real-world data on materials, usage, external conditions, maintenance etc.

Innovation

Optimization

Engineering, Operations and Meta
(Real-time data inputs enabled by IoT)

Physical Assets in

Development

Construction

Utilization

Dismantling

Market overview: maturing technology poised for rapid growth

The commercial benefits of using virtual twins are wide-ranging and transformational, chief amongst which are richer design options and rapid prototyping, significant production process efficiency and quality improvement, enhanced asset operational performance and life extension, supply chain scenario planning and resiliency, and effective decommissioning planning and execution.

It is telling that 100% of the world's top EV manufacturers, and 90% of the top drug and healthcare laboratories, use virtual twin solutions. However, the vast majority of private and public organizations globally are yet to pilot and scale such solutions[9].

In 2020, the global virtual twin market is worth an estimated USD $5.4 Billion and is projected to grow at a 36% CAGR over the next five years[10]. In terms of adoption levels, virtual twins are poised for fast growth from a small base.

At present, virtual twins are only adopted at rates of 8 – 10% on average across industries[11], but future growth is expected to be led by the Transportation industry where the baseline is already relatively high (30 – 40% current adoption rates for EV startups, and 60 – 70% for best-in-class OEMs at present).

Growth is anticipated to also be significant across four additional industries: Construction (current adoption rate of about 1%), Electrical and Electronics (current adoption of less than 5%), Consumer Packaged Goods (current adoption of about 3 – 5%) and Life Sciences (currently at about 5 – 10% based on Pharma sector).

Given the growing ubiquity of virtual twins over the next decade, there is a disruptive potential to drive significant, and sustainable change, if harnessed responsibly—a unique opportunity in the Decade to Deliver.

36% CAGR

projected growth rate for the global virtual twin market 2020-2025[8]

Figure 3: Key virtual twin capabilities and observed impacts on business (non-exhaustive)

RESEARCH AND DEVELOPMENT

- Access to past product performance data
- In silico development of new molecules and materials
- Multidiscipline research collaboration
- Multiple scenario modelling
- Organized access to relevant data
- Visibility of lifecycle impact

DESIGN AND ENGINEERING

- Access to past product performance data
- Generative design
- In silico prototyping and testing
- Multidiscipline design collaboration
- Organized access to relevant data
- Visibility of lifecycle impact

MANUFACTURING

- New product trials and ramp-up
- Improved operational feedback at the point of worker interaction
- Intelligent monitoring and maintenance of equipment
- Manufacturing process simulation and optimization
- Plant facility layout simulation and improvement
- Plant and machinery controls automation based on real-time operating conditions

TRANSPORT AND LOGISTICS

- Algorithmic planning and route optimization
- Container tracking and management
- Fleet management
- Sensor-based shipments condition monitoring
- Virtualization and visualization of logistics facilities and infrastructure
- Virtualization and visualization of logistic networks

PRODUCT/ ASSET USE

- Advanced failure warning and risk management
- Over the air software performance optimization
- Intelligent asset service and maintenance
- Real-time generation of operational improvement insights
- Remote asset monitoring and diagnostics

DECOMMISSIONING AND END-OF-LIFE

- Data-based decom. planning/life-extension assessment
- Decommissioning process simulation and planning
- Decommission execution simulation and planning
- Detailed visibility into asset and component status, material composition and design
- Material and component recovery tracking

Cost of Goods Reduction

Operation and Product Footprint Reduction

Regulatory and HSE Risk Reduction

Cross-Functional Collaboration Enablement

New Service Models Enablement

Time-To-Market Reduction

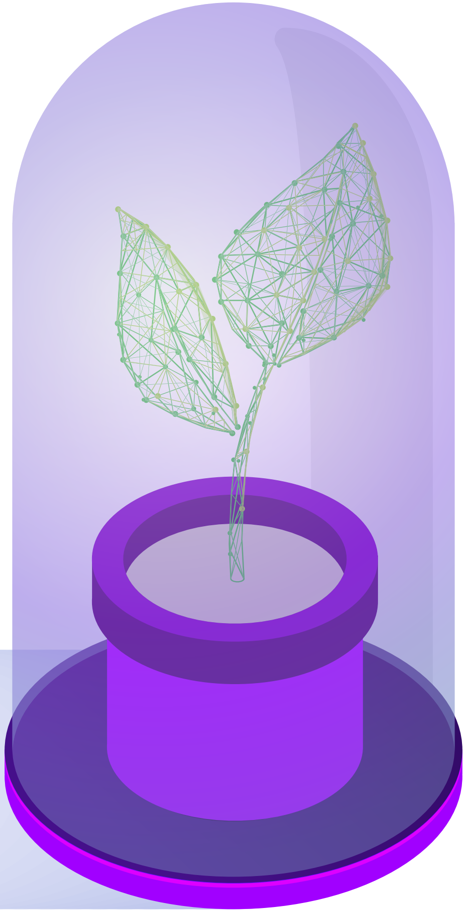
Study scope

The study focuses on five industries and virtual twin use cases, prioritized for their high potential to enable sustainable value creation, in addition to two industry agnostic use cases.

These five industry-specific use cases are quantitatively assessed for their business and sustainability impact out to 2030 (with a focus on environmental sustainability and GHG emissions reduction for simplicity).

The report also features five additional industry-specific use cases presented qualitatively in Appendix 4.1 alongside illustrative case studies, as data is either limited or sensitive but existing evidence suggests that their potential to drive change is significant.

For full details on the study scope and methodology, please see Appendix section 4.2.



The opportunity from harnessing virtual twins

2

Five use cases alone can unlock combined additional benefits of USD $1.3 Tn of economic value and 7.5 Gt CO_2e reductions out to 2030

This study aims to highlight the growing and increasingly critical connection between virtual twin technologies and sustainability and the circular economy, by identifying and quantifying some of the major positive outcomes across use cases and industries. Our quantitative benefit analysis of five use cases highlights significant value-at-stake from the scaled deployment of virtual twin technology across industries beyond individual pilots and low-hanging fruit.

Despite this significant value, it is also important to note that this analysis is only related to this limited number of use cases and the total impact of the scaled deployment of virtual twins across global economic systems is likely to deliver significantly larger upside potential.

Furthermore, this output is most likely an underestimate, since key assumptions and sensitive parameters used in the analysis were based on the lower, conservative end of observed ranges.

Figure 4 provides an overview of the use cases analyzed quantitatively by industry. Additional use cases presented qualitatively are also available in Appendix 4.1.

USD $1.29 Tn

of combined cumulative economic value opportunity out to 2030 globally

7.52 Gt CO_2e

of total cumulative emission savings delivered across five industries by 2030

Figure 4: Focus use cases for the study across the in-scope industries

INDUSTRY	USE CASE (CONTEXTUALIZED FOR INDUSTRY)	DESCRIPTION
Construction and Cities	Building operational efficiency optimization enabled by virtual twin technologies	Use of virtual twin technologies to drive broad operational cost savings and optimize resource use for buildings in the use phase e.g., energy for lighting, heating, water usage etc.
Consumer Packaged Goods	Sustainable product development supported by LCA-based 3D modeling and simulation	Inclusion of product lifecycle assessment data in virtual modeling and simulation tools to make more efficient, durable, and recyclable products (including packaging)
Transportation and Mobility	Product design, prototyping and testing with virtual twin technologies	Using virtual twin technologies to accelerate the vehicle concept, detailed design and design verification stages, reducing physical testing and optimizing for lower embedded carbon footprint and (more) circular design
Life Sciences	Manufacturing plant optimization for pharmaceutical products with process virtual twins	Use of factory virtual twins in the pharma industry to identify process improvements leading to efficiencies across business and sustainability drivers e.g., capacity increase with existing assets, raw materials and energy usage reduction, product quality improvement, waste and rework reduction etc.
Electrical and Electronics	Waste Electric and Electronic Equipment value recovery supported by virtual twin	Data on the operating conditions informs decisions on whether to re-use, recondition, recycle, or scrap items. Material data can help to determine appropriate recycling steps. Data accumulated by the virtual twin during the lifecycle can enable better value recovery at end of life
Cross Industry Use Cases	1. Optimization of material flows and waste valorization 2. Parts and material recovery optimization for decommissioned assets	1. Use of supply chain virtual twin technology and applications to enable end-to-end visibility of key material flows and related KPIs 2. Use of product virtual twins and plant (facility) simulation technologies to help facilitate the recovery of valuable parts and materials

2.1. Construction and Cities

Industry context and sustainability challenges

The construction industry is estimated to be worth $8 Trillion worldwide, or 10% of global GDP, and is one of the largest sectors globally[12]. Additionally, it is a key source of demand for materials and resources, which creates significant environmental strain and reliance[13].

From a sustainability perspective, commercial and residential buildings currently use about 40% of global energy demand (60% of the world's electricity), account for 25% of our global water usage, and are responsible for approximately a third of global GHG emissions[14].

And these demands are only set to increase. Current estimates suggest that by 2030, there will be 706 cities with a least 1 Million inhabitants—up nearly 30% from 2018[15].

Despite these challenges, spatial concentration of people and economic activities has potential upsides, as it facilitates at-scale deployment of solutions. For example, urban buildings offer significant potential for achieving substantial GHG emission reductions globally.

Energy consumption in buildings can be reduced by 30 – 80% using proven and commercially available virtual twin technologies, often within the broader framework of smart cities[i].

Energy consumption in buildings can be reduced by 30 – 80% using proven and commercially available virtual twin technologies

Use case: Building operational efficiency optimization enabled by virtual twin technologies

USD $288 Bn incremental savings and 6.9 Gt CO_2e emissions

In this context, a virtual twin of a physical building behaves like its real-world twin, connecting buildings with energy and transport systems. 3D simulation and modeling software, real-time data and analytics enable the optimization of a building's operational performance and sustainability throughout its lifecycle.

Virtual twins are also a data resource that can improve the design of new assets, specify as-is asset condition and run "what if" scenarios. Advanced twins use two-way digital-physical interactions, allowing for remote and even autonomous asset control.

While twins can be created for existing and future buildings, this use case models the potential of implementing virtual twins in new construction globally between 2020 – 2030.

For this use case, we have prioritized and focused on two value drivers where impact is most evident[ii]:

- Building operating cost reductions
- Improved energy management

USD $288 Bn

reduction in building operating costs through reduction in energy consumption, maintenance, planning and commissioning costs

6.9 Gt CO_2e

reduction in building operations emissions as a result of improved energy management (12,032 TWh of savings)

Use case: Building operational efficiency optimization enabled by virtual twin technologies

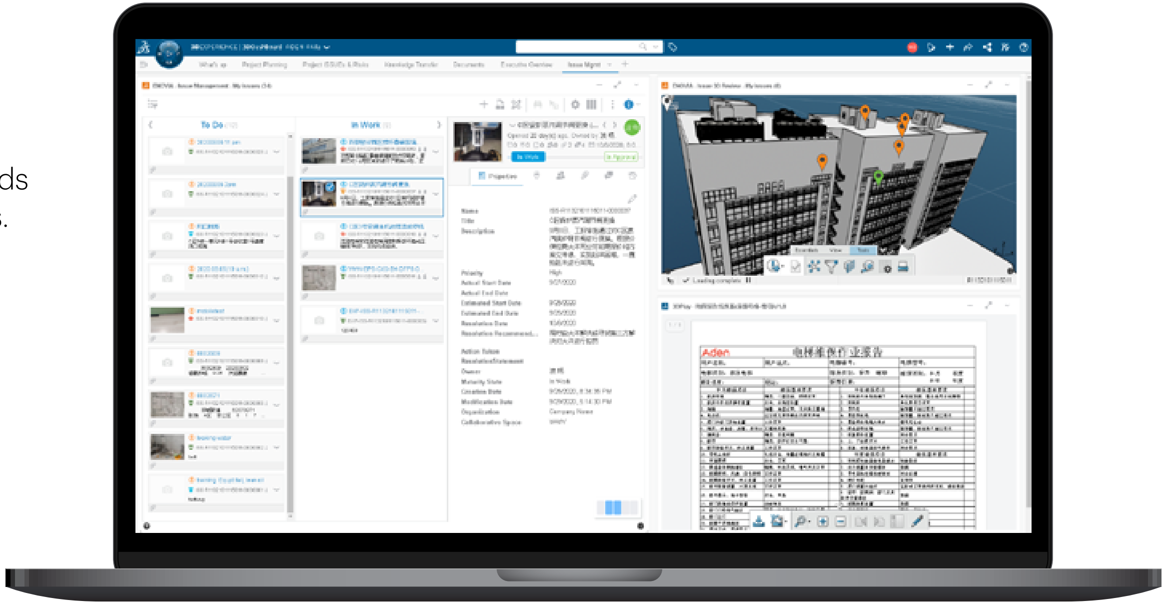
Case study: Aden, China facility

Aden is a leading integrated facility management service provider who has expanded from traditional facility management services to asset management and energy services. It recognized that virtual twins and analytics are critical to this transformation.

Aden has created a virtual twin for one of the commercial centers in Chengdu, China. The virtual twin monitors, aggregates and understands data to plan and execute inspection, maintenance and repair activities. 3D simulations to model and simulate the behavior of the building systems are used to predict and optimize the energy consumption under different operating conditions.

Expected benefits from this project include reduced annual energy consumption by 20%, lower water usage and waste generated and improved health and safety performance.

Figure 5: View of the asset from the virtual twin platform



2.2. Consumer Packaged Goods

Industry context and sustainability challenges

The Consumer Packaged Goods (CPG) industry currently accounts for two-thirds of international trade volumes and represents 10% of the national GDP in the United States[16] and is closely tied to many others, such as agriculture, chemicals, oil and gas and mining and natural resources.

Due to its size, the industry also faces significant sustainability challenges. Agriculture (including crop and livestock production), forestry and land use account for nearly a quarter of global GHG emissions, and a third of global food production is wasted across the value chain[17].

Virtual twin technologies offer the potential to limit resource use and enable cross functional collaboration from R&D to Marketing and back, helping establish the base for a new way of approaching sustainability by design, which is critical as design decisions can be linked to 80% of a product's environmental impact[18]. 3D modeling and simulation technologies can also help enable the sustainable design and manufacture of products by incorporating lifecycle footprint data and visibility.

> Design decisions can be linked to 80% of a product's environmental impact

Use case: Sustainable product development supported by LCA-based 3D modeling and simulation

USD $137 Bn incremental cost savings and 281 Mt CO_2e emission reductions

Here, we focus on product development and the integration of lifecycle assessment (LCA) footprint data[iii] within 3D modeling and simulation tools. This use case focuses on the analytical value of virtual twins and how the technology enables the integration of sustainability objectives at the start of the product lifecycle.

A significant portion of the environmental impacts of a product is determined by the decisions made in the early stages of design; it is also where 60 – 85% of the product's cost is determined[19]. Different eco-design tools exist using the LCA principle to support product and service decisions, however those are usually very complex and time-consuming.

More importantly, existing tools can only be used after concept development and design have significantly advanced already, therefore limiting the "menu of options" available to decision-makers.

Virtual prototyping also allows for faster design iterations and reduces the need for physical tests, driving significant CO_2 benefits.

For this use case, we have prioritized three value drivers where impact is most evident[iv]:

- Raw material cost reduction
- Product development cost reduction
- Reduced embedded carbon footprint

USD $131 Bn

reduction in raw material usage costs

USD $6 Bn

reduction in product development costs

281 Mt CO_2e

reduction in embedded product footprint as a result of better LCA output visibility and improved decision-making as a result

2.3. Transportation and Mobility

Industry context and sustainability challenges

In many developed countries, transportation accounts for 6% – 12% of GDP, whereas logistics can account for up to 6% – 25% of GDP alone[20]. But emissions from transport, broadly comprising of road, rail, air and marine, accounted for about 25% of global CO_2 emissions in 2016[21] and they are also projected to grow faster than any other sector's, posing a key challenge for efforts to decarbonize the global economy.

Research suggests that zero-emission and autonomous vehicles both have a critical role to play if we are to achieve global GHG reduction targets[22] and virtual twins have a long history in automotive applications[23].

It is estimated that by the end of 2020, 65% of automotive manufacturers would use simulation and virtual twins to operate products and assets[24].

Case studies suggest that virtual twin technologies accelerate time-to-market and help bring costs down for new drivetrains, lightweight body designs and EV batteries[25], and are indispensable in the development of autonomous transportation[26].

> By the end of 2020, 65% of automotive manufacturers would use simulation and virtual twins to operate products and assets

Use case: Product design, prototyping and testing with virtual twin technologies

USD $690 Bn in costs saved and 230 Mt CO_2e emissions avoided

Here, we focus on the avoidance of prototyping and physical testing enabled by 3D modeling and virtual simulation technologies when new vehicles are designed, prototyped and tested. With a virtual twin, an OEM can test out multiple designs and features, eliminating many aspects of prototype testing at part and vehicle level to help determine how the design measures against relevant policies, standards, and regulations. Typically, OEMs use hundreds of test vehicles per model across several models each year (depending on whether the design changes are major or minor). These can be drastically reduced if a virtual twin is leveraged during the early product development stage, leading to significant avoidance of waste—both in terms of materials, and product development costs.

In addition, the use of virtual twins in new vehicle development can drive other production costs down and shorten overall time-to-market considerably and is even being linked to reduction in costly vehicle recalls[27]. Finally, virtual twins are helping to enable faster development of autonomous vehicles, with a significantly reduced carbon footprint by substituting a big portion of the total test mileage required with simulations.

For this use case, we have prioritized and focused on four value drivers where impact is most evident[v]:

- AV development cost avoidance
- Product development cost reduction
- AV development emissions avoidance
- Emission reduction through decreased physical testing

USD $429 Bn

cost avoidance in autonomous vehicle development via simulation

USD $261 Bn

cost reduction in product development

227 Mt CO_2e

emissions avoidance in autonomous vehicle development

2 Mt CO_2e

emissions reduction from physical prototypes and test vehicles

Use case: Product design, prototyping and testing with virtual twin technologies

Case study: large European OEM, virtual design and verification

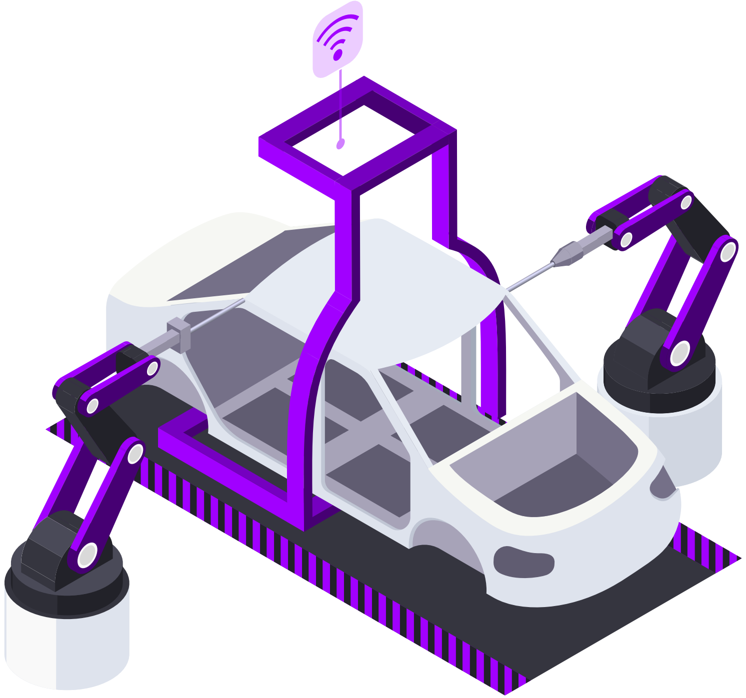
Automotive companies are under constant pressure to produce better cars that meet increasingly stringent legal requirements for safety and environmental sustainability, as well as growing consumer demands, and to bring them to market at speed and scale.

As a result, the vehicle design and development process within OEMs has evolved from one which previously incorporated key milestones involving physical prototypes, to one which seeks to largely eliminate physical prototypes and associated physical tests.

As part of these tests, crash simulation software can now accurately predict detailed behaviors which are known to have important influence on passive safety criteria.

A large European OEM has managed to achieve the following improvements based on virtual design and verification using virtual twin technologies:

- Reduced product development time by months
- Ability to accurately predict localized effects like material and connection failure leading to improved quality
- For vehicle models with limited design updates, between 70 – 100% reduction in physical prototypes
- For some models, physical prototypes were altogether eliminated



2.4. Life Sciences

Industry context and sustainability challenges

Life Sciences is an umbrella term for organizations that work toward the improvement of life[28], and broadly encompasses pharmaceuticals, biopharmaceuticals, biotech and medtech. It is also linked to a considerable part of venture capital flows[29] and is characterized by one of the most significant levels of R&D spending as a proportion of revenues in the private sector[30].

There is a growing recognition that the pharmaceutical industry, considered to be a medium-impact sector[vi], must do more to improve its sustainability performance[31].

Data suggests that the pharmaceutical industry's GHG emissions are increasing, despite efforts to decarbonize due to increasing drug demand globally[32]. Moreover, analysis of emissions per Million dollars of revenue finds that the global pharmaceutical industry is approximately 55% more emissions intensive than the automotive industry[33].

Virtual twin applications in production plants can drive benefits for the environment. For example, botanical pharmaceuticals manufacturing can achieve significant process time reduction (factors 5 – 20) resulting in cost of goods reduction (factors of 2 – 10) and GHG emissions abatement (factors 4 – 20)[34].

Virtual twin applications can help botanical pharmaceutical manufacturing, for example, to achieve GHG emissions abatement by a factor of 4 – 20

Use case: Manufacturing plant optimization for pharmaceutical products with process virtual twins

USD $106 Bn incremental opex savings and 61 Mt of CO_2e emission reductions

In this use case, the virtual twin is of the production process. The technological building blocks that enable such solutions include IoT, advanced analytics and machine learning. Chemical mixing processes and the use of solvents is one of the major drivers of process-related waste and emissions in pharmaceuticals manufacturing[35].

Simulations of these processes can enable scientists and plant operators to run multiple scenarios with the objective of finding the optimal configuration, accelerate the speed and accuracy and reduce waste, including related emissions.

In addition, recycling solvents, using fewer fresh solvents or burning less solvent waste has been shown to reduce total emissions for a process significantly[36]—something that process virtual twins can also help address.

For this use case, we have prioritized and focused on two value drivers where impact is most evident[vii]:

- Reduction in Cost of Goods Sold
- Reduced embedded carbon footprint

USD $106 Bn

reduction in cost of goods sold due to lower operating expenses (thanks to accelerated time-to-market and reduced material and energy cost base, improved quality in the production process)

61 Mt CO_2e

reduction in production GHG emissions due to efficiency improvements and lower solvent and material usage

Use case: Manufacturing plant optimization for pharmaceutical products with process virtual twins

Case study: Sanofi's Framingham lighthouse facility

The Framingham production facility is a digitally enabled, continuous manufacturing facility where the production process is connected with R&D. Virtual twin technology is used to optimize remote manufacturing through the use of real-time data capturing and analysis. The whole industrial process is digitalized and paperless and is 80 times more productive than a traditional factory. It can make medicines in less time for twice the number of patients and all within a smaller environmental footprint.

Observed performance indicator improvements include:
80% reduction in energy consumption and CO_2e emissions per year, 91% reduction in water footprint, 94% reduction in use of chemicals and 321 tons of waste reduction per year[37].

2.5. Electrical and Electronics

Industry context and sustainability challenges

The electrical and electronics industry holds significant importance in today's economy—the consumer electronics sector alone is estimated to have a market value of $1 Trillion worldwide[38]. These technologies have also become an inseparable part of modern life—half of the world's people now own a smartphone[39].

But the industry faces sustainability challenges such as the high rate of device replacement—the manufacturing stage of electronic equipment alone is responsible for more than a third of the associated CO_2e lifecycle emissions[40].

Appropriate disposal and recycling of products presents further challenges. With e-waste officially the fastest-growing waste stream in the world[41], it is imperative to improve value recovery, GHG emissions intensity and limit risks to human health[ix]. This is an especially grave challenge if we consider that in 2019, only 17.4% of the 53.6 Million tons of e-waste was properly disposed of, collected and recycled[42].

Virtual twins can help product designers embed and follow circular economy principles throughout each stage of design. Research has also focused on exploring how virtual twin technologies can help address the e-waste problem[43, 44].

In 2019, only 17.4% of global e-waste was properly disposed of, collected and recycled

Use case: Waste electric and electronic (WEEE) equipment value recovery supported by digital continuity

USD $73 Bn additional value generated and 36 Mt CO_2e emissions avoided

This use case focuses on the role of virtual twin technology in better managing e-waste, looking at how the technology can help extend product life by better facilitating repairs and reuse and increasing overall e-waste recycling rates by making information available to value chain participants downstream on material and chemical content.

In this use case, the technology supports the manufacturing and remanufacturing or repair of products from both process optimization and data continuity perspectives. It provides a virtual record reflecting the actual status of a device in terms of health and performance of its components, which can support the repair process planning.

Additionally, typically when a device reaches recyclers, a significant amount of data and knowledge has been lost—particularly from the product development, manufacturing and service life stages. Virtual twins, through enhanced digital continuity, can enable a constant flow of information between value chain participants. The recycler can initiate appropriate process steps without the need for additional tests or inspection[45].

For this use case, we have prioritized and focused on three value drivers where impact is most evident[x]:

- Added value from equipment re-use and refurbishment
- Emissions reduction through improved refrigerant release
- Emissions avoided through product life extension

USD $73 Bn

additional revenue from the increase in refurbishment and re-use of the equipment rather than recycling for material recovery

31 Mt CO_2e

emissions reduction from the release of refrigerants through better handling of relevant WEEE

5 Mt CO_2e

emissions avoided by decreasing the total amount of the informally processed e-waste and associated negative environmental impacts

Use case: Waste electric and electronic (WEEE) equipment value recovery supported by digital continuity

Case study: Circularise

Circularise is a Dutch start-up focused on commercializing blockchain-based transparency and traceability technologies for the circular economy.

Their solution enables a wide range of stakeholders across the value chain to share information on product material content and flows e.g., mining companies, electronics manufacturers, collection services and recycling companies. The final output is a QR code that provides important data for recyclers.

For example, some computer monitors have a mercury lamp that needs to be removed, however because no one knows which monitors are fitted with these lamps, all are often opened by hand for inspection. This same concept can be applied to electronic plastic components, many of which contain plasticizers and stabilizers which, over time, get regulated and pose a barrier to recycling when difficult to identify and measure. The start-up has also developed proprietary methodology to safely manage IP rights and avoid the sharing of commercially sensitive information within the industry ecosystem[46].

2.6. Other notable use cases enabling circularity

Overview

This chapter seeks to shift away from the industry-specific context and highlight additional use cases for virtual twin technologies that can support sustainable business outcomes across multiple industries, with significant circular value potential.

The two use cases, shown in Figure 6, both support the circular economy and increased resource efficiencies and are based on maturing solutions which, in technological terms, combine supply chain virtual twins, digital threads and advanced scenario modeling techniques.

Figure 6: Use cases highlighted in this chapter

USE CASE	KEY INDUSTRIES FOR IMPLEMENTATION	DESCRIPTION
1. Optimization of material flows and waste valorization	• Mining and basic materials • Industrial goods • Automotive	Use of supply chain virtual twin technology and applications to enable end-to-end visibility of key material flows and related KPIs, including waste and by-products. This includes key supply chain elements such as material inflows and outflows, factory locations, suppliers, stocking points and routes. Building a detailed, live picture of material flows is a fundamental step toward achieving a more circular economy.
2. Parts and material recovery optimization for decommissioned assets	• Industrial goods • Automotive	This use case is based on the use of product virtual twins and plant (facility) simulation technologies together, at the end-of-life, or decommissioning stage, for manufactured assets. Process optimization analysis and scenario modeling capabilities help facilitate the recovery of valuable parts and materials in an efficient and economically viable way. This helps limit the extraction and consumption of virgin raw materials.

Use case spotlights

Use case 1: Optimization of material flows and waste valorization

The circular economy is a key framework for sustainable growth, widely accepted by business leaders across industries, as well as policymakers. Client work and research delivered by Accenture over the years has demonstrated countless times that it is feasible to transform discrete linear processes, facilities and supply chains to more circular capabilities and operations, leading to improved material and resource use—often with limited or no capital investments.

To truly pivot toward a circular economy, organizations need more and better information on how they use materials, where and what waste streams arise and whether those can be converted to resources and re-used, internally or externally.

Therefore, end-to-end, dynamic visibility of material flows is fundamental to measuring and improving resource productivity. We measure material intensity at the macroeconomic level and have broadly established that sectors that are less material intensive have higher rates of productivity[47]. Yet, only a few organizations track business material intensity to inform their circular economy or sustainability strategies.

Virtual twin technologies, by virtue of their capacity to bring together data from all stages of the product and production lifecycles, weave information together and analyze it to identify opportunities for improvement, track performance and inform decisions.

These technologies can be used to operationalize targets to become more material and resource efficient and drive financial benefits, including valorizing waste streams. This is particularly relevant for material and energy-intensive businesses involved in the production of intermediate goods such as in the metals industry.

The table below outlines key value drivers, together with supporting illustrative examples, to frame the benefits this use case enables as factually as possible (see Figure 7).

Use case spotlights

Figure 7: Use case key value drivers (non-exhaustive and illustrative)

VALUE CATEGORIES	KEY VALUE DRIVERS (NON-EXHAUSTIVE)	DESCRIPTION AND EXAMPLE (ILLUSTRATIVE)
Business (economic value)	Enhanced revenue from waste valorization	The process of steelmaking produces a number of by-products that can potentially be recycled. One of these is Linz-Donawitz (LD) slag; ArcelorMittal Tubarão (Brazil) makes as many as 30 new products from LD slag, mostly for construction applications[48]
	Lower material procurement costs	Jaguar has processed over 360k tons of scrap back into its vehicles since 2013[49], or about 51k annually; this equates to ~1/3 of its annual usage of aluminum[50]; whilst the economics are not public information, we assume a strong business case given the longevity and progress of the initiative
	Reduced inventory levels and costs	Dassault Systèmes' client in the Mining and Basic Materials industry has achieved better utilization of scrap enabling a reduction of inventory at any given time (8 – 10k tons)
Sustainability value (environmental and /or social)	Reduced biodiversity impact from resource extraction	Mining affects biodiversity at multiple spatial scales (i.e., site, landscape, regional and global) through direct (i.e., mineral extraction, waste/tailings generation) and indirect processes (e.g., via industries supporting mining operations)[51]
	Reduced impact from resource extraction on water	Water (surface and ground) pollution and consumption from mining operations is a major concern; withdrawals estimates vary considerably from case to case but the "average" gold mine uses ~0.350 m^3/metric ton of ore-grade rock (2013)[52]
	Reduced climate emissions from resource extraction	Creating recycled aluminum uses around 90% less energy than raw material production[53]; delivering on the 2-degree climate scenario implies 50-80% emissions reduction from mining

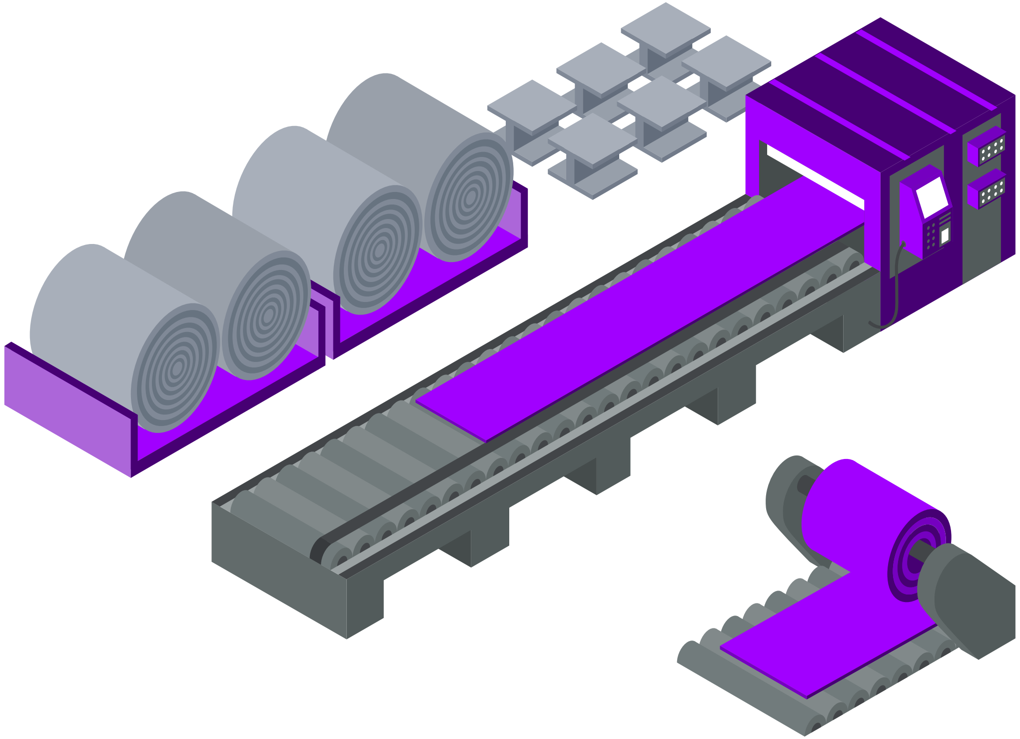
Use case spotlights

Case study: Global aluminium company

An aluminum company was looking to reduce raw virgin material use and achieve end-to-end visibility of material flows. It’s main challenge was the maximization of scrap utilization rates, both from scrap generated during the production process and post-consumer scrap flows recovered by third parties.

Approximately 50% of the production cost was attributable to the cost of raw material, and metals market volatility is a persistent risk, so this challenge was business critical. As an indication, a 1% increase in scrap usage represents more than €1 Million in savings annually. Deploying a supply chain virtual twin solution provided plant operators with improved, more detailed visibility and orchestration capabilities of operations, enabling better utilization of aluminum scrap.

This resulted in a reduction of inventory, by circa 8 – 10k tons at any given time. It also accelerated a push from the company’s procurement teams to establish new strategic partnerships with third party scrap providers, helping to further formalize the metal scrap industry and strengthen the commercial prospects for secondary raw materials.



Use case spotlights

Use case 2: Parts and material recovery optimization for decommissioned assets

This use case highlights the value of virtual twins for end-of-life management, helping to improve the efficiency and economics of decommissioning, including parts and material recovery, which are key elements to delivering a more circular economy. 3D virtual twins and simulation technologies, in combination with asset operational data, can be used to simulate every dismantling step before execution starts. This provides an opportunity to identify and define an optimal, safe decommissioning process and provides enhanced visibility of raw materials, valuable parts and components—whether from a building, vehicle, ship, airplane or energy asset. The collaborative nature of virtual twin solutions enables teams from design and engineering to decommissioning to work together in developing a process that yields the highest volumes and quality of resources. In addition, the capability to retrieve design, material and operational data and share it downstream, means that any material or recovered part can potentially be exchanged for its true value, avoiding downcycling where possible.

For example, metal recycling techniques for end-of-life vehicles (ELVs) are based on mechanical treatments to recover mainly steel, aluminum, copper, and zinc alloys. However, a vehicle can use more than 60 metals, which end-up downcycled and are functionally lost[54].

Additionally, the untapped potential to increase plastics circularity in transportation assets is also high and new policy measures in Europe are likely to accelerate this[55].

Finally, even out at sea, we are only just starting to plan for the decommissioning of offshore wind energy projects that are approaching the end of their 20 – 25-year lifecycles, and virtual twins can help us better plan and manage their decommissioning in advance.

The table below outlines key value drivers of this use case, together with supporting illustrative examples (see Figure 8).

Use case spotlights

Figure 8: Use case key value drivers (non-exhaustive and illustrative)

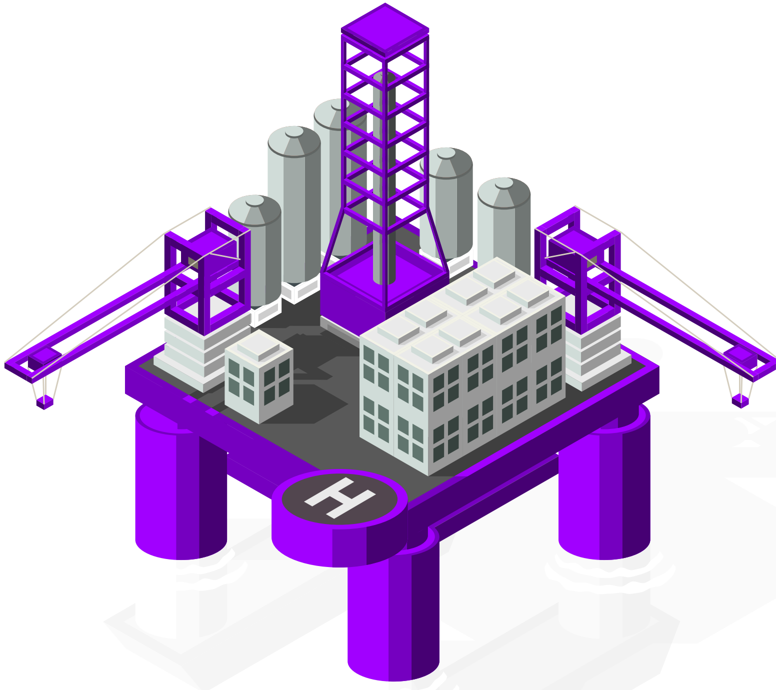
VALUE CATEGORIES	KEY VALUE DRIVERS (NON-EXHAUSTIVE)	DESCRIPTION AND EXAMPLE (ILLUSTRATIVE)
Business (economic value)	Reduction in decommissioning costs and time	Increase in the quality and quantity of recovered materials and parts due to better process management and enhanced data availability at the decommissioning stage
	Enhanced regulatory compliance	Aircraft dismantling must comply with existing rules and regulations issued by the ICAO relating to aircraft airworthiness, general and hazardous waste management and recycling[56]
	Enhanced infrastructure reuse	Significant efforts are being undertaken to reuse end-of-life energy infrastructure. Examples of re-use include conversion of offshore rigs into CO_2 storage tanks and reef-like infrastructures[57]
	Value from decommissioning insights for continuous improvement	This is particularly important for new, low-volume waste streams that are expected to grow exponentially in the future, such as aircraft and wind turbine composites[58]
	Enhanced employment opportunities	Some studies suggest that the employment gains from resource efficient and circular economy policies range between 0 – 2%, with one study predicting employment gains of up to 7%[59]
Sustainability value (environmental and /or social)	Improved recovery for "more difficult" materials	Globally, copper recoverability is relatively low for a metal, at only 40 – 60%, primarily because it is more dispersed, hard to collect, is intermingled with other materials and is non-ferrous
	Reduction in downcycling	Based on previous Accenture research, only a tenth of the recovered iron and steel from scrapped vehicles is used to make new cars; rare metals and engineered alloys end up downcycled[60]
	Reduction in waste sent to incineration or landfill	Despite the high recycling rates (95% mandated by law), more than 10% of the weight of a car in Europe is still sent to energy recovery at end-of-vehicle-life
	Improved environmental performance in asset decommissioning	Energy asset decommissioning will ramp up as the world shifts away from fossil hydrocarbons—these activities should be handled carefully in order to minimize environmental impact

Use case spotlights

Case study: Offshore energy asset decomissioning

Oil extraction is coming to an end across most of the North Sea as the world continues to move towards more sustainable sources of energy. This situation also extends to other corners of the world. As operators of these oil platforms begin to plan their decommissioning at the most optimal costs, it is essential to ensure the structures' removal in an environmentally sound, safe and circular way. The structures will be disassembled into manageable pieces, loaded onto barges, and brought to shore for re-use, recycling, or disposal.

The latest intelligent solutions for plant decommissioning combine a virtual twin of any marine or offshore asset with data analytics, modeling and scenario simulation, allowing operators to make the right choices faster to improve efficiency, safety, integrity, performance, return on investment and reduce their carbon footprint. In selected case studies, savings between 9-30% are possible for decommissioning activities ranging from topsides and jacket removal to subsea infrastructure, facilities, "de-energizing", operator costs, onshore recycling and site remediation and monitoring[61].



3

Perspectives from industry leaders and the way forward

Perspectives from industry leaders and the way forward

To identify how the adoption of virtual twin technologies can increase to drive greater sustainability benefits and move towards systemic transformation and circular economies, we spoke with business leaders and experts from our selected in-scope industries[xi]. These discussions, along with our research and analyses, informed five key recommendations for how we can better harness the potential of virtual twin technologies (see Figure 9).

1. **Tie together technology and sustainability agenda**
2. **Improve understanding**
3. **Focus on disruptive, systems-change use cases**
4. **Deploy responsibly**
5. **Rally ecosystem support**

We spoke with business leaders and experts from our selected in-scope industries

1. Tie together technology and sustainability agendas

Leaders must help drive change toward measuring and tracking value from sustainability, connecting it tangibly to corporate and growth strategies, and factoring that value in technology and innovation investment decision-making. This should start with internal change management and alignment of technology and sustainability priorities, as well as broader external and practical support for harnessing technology for sustainability e.g., multilateral initiatives, public endorsement, thought leadership etc.

> **"This meeting is the first time we discuss how twins can impact the long term, the environment."**
>
> Global Pharma Co

2. Improve understanding

Organizations must first develop a clear, data-driven view of their own pain-points and requirements. Limited awareness of the topic means most organizations struggle to identify the right use case for their needs. This is compounded by the need to understand the broader infrastructure requirements and how to bypass legacy constrains from installed footprint in production facilities, gaps in terms of data exchange and real-time virtual twin capability.

> **"Quite a few barriers... but one of the biggest ones is the identification of the right use case."**
>
> Global Tech Co

3. Focus on disruptive, systems-change use cases

Efforts to scale solutions must be concentrated at the systems transformation level. Efficiency improvements are a good starting point, particularly in industries where there are significant "quick wins" to be made. However, over time stakeholders must shift their focus on high-effort, high-impact interventions, such as the enablement of the circular economy and industry decarbonization at scale, which will require more tailored solutions. This should be done at speed and at scale to ensure we meet our Global Goals. Industry stakeholders should use the opportunity to test, learn, adapt and deploy, to find and scale these disruptive use cases quickly and effectively.

> **"Efficiency alone will not get us to net-zero or get us to a circular economy."**
>
> Global FMCG Co

4. Deploy responsibly

Technology vendors and buyers have a responsibility to ensure virtual twin solutions facilitate a standardization of methods, metrics and data transparency. There is also a risk that smaller businesses and start-ups are priced-out, as current focus centers on large multinational organizations based in the Northern hemisphere. Particular attention must be given to emerging and developing markets where the need for "sustainability-minded" solutions is high, but awareness, accessibility and affordability are often limited.

> **"Ensure that SMEs and startups are not excluded, priced-out from these technologies."**
>
> Electric Mobility Co

5. Rally ecosystem support

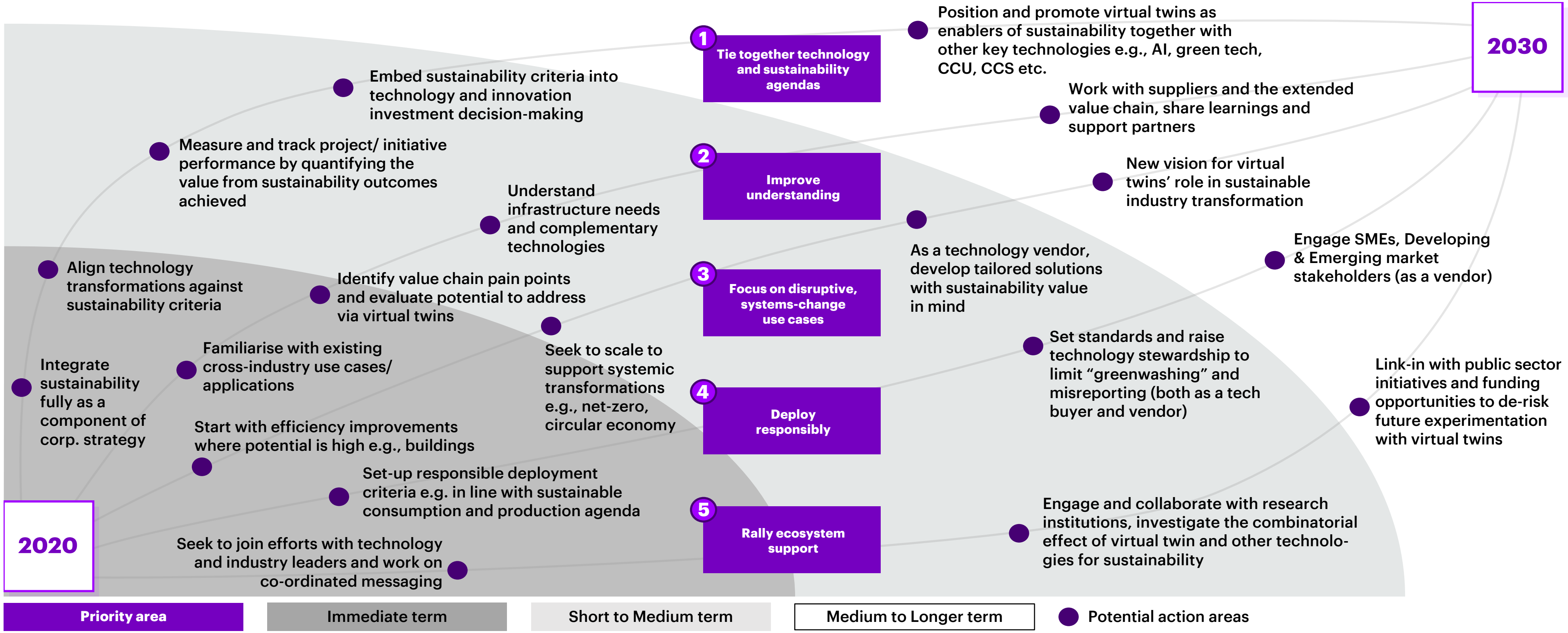
Virtual twin technologies are often used for designing complex, industrial-scale sustainability breakthroughs. As these are vast projects with broad implications, organizations must work towards building a broader coalition of support across the business community and other key stakeholder groups. This can help provide best-in-class learning opportunities across and within industries, help drive greater adoption of virtual twin technologies at scale, moving past pilot implementations, and provide improved and inclusive technology development.

There is also an opportunity to link initiatives with relevant public sector programs, such as those driven by the European Union in the domains of sustainable innovation, circular economy, climate change mitigation and adaptation. Collaboration with these institutions could help de-risk use cases where private capital may be too risk-averse to support, and provide leading thinking and greater support.

> **"Digital twins could be key for the circular economy, which is the future of design."**
>
> Global Tech Co

Harnessing virtual twins for sustainability would require stakeholders to focus on five priority areas out to 2030

Figure 9: Five priority areas of action for the future



2020

Embed sustainability criteria into technology and innovation investment decision-making

Measure and track project/ initiative performance by quantifying the value from sustainability outcomes achieved

Align technology transformations against sustainability criteria

Integrate sustainability fully as a component of corp. strategy

Understand infrastructure needs and complementary technologies

Identify value chain pain points and evaluate potential to address via virtual twins

Familiarise with existing cross-industry use cases/ applications

Start with efficiency improvements where potential is high e.g., buildings

Seek to scale to support systemic transformations e.g., net-zero, circular economy

Set-up responsible deployment criteria e.g. in line with sustainable consumption and production agenda

Seek to join efforts with technology and industry leaders and work on co-ordinated messaging

1 Tie together technology and sustainability agendas

2 Improve understanding

3 Focus on disruptive, systems-change use cases

4 Deploy responsibly

5 Rally ecosystem support

Position and promote virtual twins as enablers of sustainability together with other key technologies e.g., AI, green tech, CCU, CCS etc.

Work with suppliers and the extended value chain, share learnings and support partners

New vision for virtual twins' role in sustainable industry transformation

As a technology vendor, develop tailored solutions with sustainability value in mind

Engage SMEs, Developing & Emerging market stakeholders (as a vendor)

Set standards and raise technology stewardship to limit "greenwashing" and misreporting (both as a tech buyer and vendor)

Link-in with public sector initiatives and funding opportunities to de-risk future experimentation with virtual twins

Engage and collaborate with research institutions, investigate the combinatorial effect of virtual twin and other technologies for sustainability

2030

Priority area | Immediate term | Short to Medium term | Medium to Longer term | ● Potential action areas

In conclusion

This study aims to demonstrate and frame the disruptive potential of virtual twin technologies. We have looked at a variety of industries and use cases to demonstrate the breadth and potential of the technology, and illustrate how it can be used throughout product life cycles to drive significant end-to-end benefits.

Through the five uses cases studied, virtual twins can deliver combined **incremental benefits of USD $1.3 trillion of economic value and 7.5 Gt CO_2e emissions reductions between now and 2030.** In addition to these sizeable benefits, virtual twins also have the potential to create more disruptive innovation and designs, enable new service development, reduce regulatory and HSE risk and enable cross-functional collaboration and co-working.

These benefits will not only improve business competitiveness, but will also **drive systemic progress towards a more circular and significantly less carbon intensive economic system** and help us achieve our Global Goals to 2030, which is a critical step in the Decade to Deliver.

To support this transformation at the speed and scale we need, we must drive a greater understanding of the technology use cases and benefits, and look to better measure combined business and sustainability ROI as part of the business case. We hope that this paper is a first step on that journey, showcasing the potential for disruptive innovation, and can inspire the next wave of leadership to think about the combined benefits of technology and sustainability.

Appendix

4

Figure 10: Focus use cases for the study across the in-scope industries

INDUSTRY	USE CASE (CONTEXTUALIZED FOR INDUSTRY)	DESCRIPTION
Construction and Cities	Enhanced urban design through simulation, planification and optimization	Use of virtual twin technologies to visualize, scenario-model and optimize urban building and infrastructure systems to enhance citizen experience, resource efficiency, climate change resilience etc.
Consumer Packaged Goods	Manufacturing plant optimization for FMCG products with process virtual twins	Use of factory virtual twins in the CPG industry to identify process improvements leading to efficiencies across business and sustainability drivers e.g., capacity increase with existing assets, raw materials and energy usage reduction, product quality improvement, waste and rework reduction etc.
Transportation and Mobility	After-market performance optimization via virtual twin technologies	Capturing performance data via virtual twins and digital threads from assets in the use phase and analyzing it to provide actionable insights to improve product and support system efficiency and increase asset life
Life Sciences	Virtualization of clinical trials enabled by virtual twin technologies	Combining data science, virtual collaboration, modeling, and simulation (including of the human body), for "in silico" drug/device development, reducing impact on animals and people, use of resources and time-to-market
Electrical and Electronics	Circular electrical and electronic product design enablement	Use of virtual twin technologies to embed sustainability at the design stage by considering material footprint and facilitating circular economy principles e.g., reuse, reduce, repair, recycle

Use case: Enhanced urban design through simulation, planification and optimization

Opportunity for GDP uplift, municipal cost savings and improved urban sustainability, resilience and citizen well-being

To be sustainable and resilient, cities need to have the ability to change, adapt and transform. Virtual twins enable a more informed vision for the future through analysis, visualization and experimentation. Their ability to consolidate large swaths of data, anticipate possible scenarios and help plan climate change adaptation measures is key to maintain a city's attractiveness.

This use case focuses on 3D modeling, simulation and data tools that can create accurate digital copies of entire cities, enabling planners, designers and engineers to improve their designs and measure the effect of potential changes by running what-if scenarios in a safe, virtual environment.

In addition to map and terrain data, these platforms can incorporate real-time traffic and weather data, logistics networks, demographic and climate information, enabling informed decision-making for a wide range of stakeholders. Virtual twins enable smart cities—a key solution to achieve sustainable, resilient urbanization.

Virtual twins of cities create value for a broad range of stakeholders across the public, private and societal spectrums. Still in early stages of adoption around the world, it is difficult to develop a detailed benefits analysis, however the table below outlines key value drivers, together with supporting examples (see Figure 11).

Use case: Enhanced urban design through simulation, planification and optimization

Figure 11: Use case key value drivers (non-exhaustive and illustrative)

VALUE CATEGORIES	KEY VALUE DRIVERS (NON-EXHAUSTIVE)	DESCRIPTION AND EXAMPLE (ILLUSTRATIVE)
Business (economic value)	Economic growth uplift	Research examining the impact of smart city technologies on GDP (e.g., 5G; low-power, wide-area roadside sensors; IOT, etc.), has highlighted up to 3% incremental uplift and USD $20 Trillion in additional economic benefits by 2026[62]
	Cost savings from enhanced city management and automation	Cost savings from improved efficiencies of city operations, such as waste management. Pilot schemes with smart, IoT-connected waste containers have seen collection frequency reduced by 70-80%; a town in Ireland achieved €200,000 annual savings and a reduction of 69 tons of CO$_2$e[63]
	New revenue streams from data monetization	For example, via open access to city-related real-time data for third-party developers, start-ups, and businesses; open data policies can generate incremental economic gains of up to USD $500 Million for a typical megacity in a developed country[64]
	Enhanced urban resilience to weather events	For example, the 2012 Toon monsoon caused £8 Million worth of damage in Newcastle when a month's rainfall fell in just two hours during rush hour. A city virtual twin could predict which buildings would likely be flooded, which infrastructure will be closed and enable better planning and response[65]
Sustainability value (environmental and /or social)	Decreased waste from inefficient infrastructure management	Helping to address poorly/inefficiently scheduled infrastructure maintenance and mapping of services in the ground e.g., digging up roads; damage to energy, data and water networks; inability to identify leaks underground etc.
	Enhanced urban energy efficiency	For example, for Nanyang Technological University in Singapore, 3D planning and operational modelling of 21 buildings, virtual testing, and performance optimization identified energy savings of 31% per annum[66]
	Reduced emissions from urban traffic	A real-time view and control of assets (e.g., a traffic signal) and entire infrastructure systems (e.g., a major city road, ring road, etc.) gives operational teams the ability to predict issues, smooth traffic flow, mitigate risks etc.[67]
	Decreased health risk from poor urban air quality	Air quality can vary widely from one street to another in dense cities due to differences in traffic and ventilation conditions. Access to real-time street-to-street variations in air quality information and health risk information can enable users to make informed decisions concerning daily outdoor activities

Use case: Enhanced urban design through simulation, planification and optimization

Case study: Virtual Singapore

Virtual Singapore is led by the National Research Foundation Singapore together with the Singapore Land Authority (SLA) and Infocomm Development Authority of Singapore (IDA). It was commissioned in 2015 and aims to create a high-fidelity, real-time data virtual twin of the city.

Powered by sophisticated analysis of images and data collected from public agencies and real-time sensors, Virtual Singapore is designed to give a whole new meaning to the term "smart city"—it aims to capture all moving parts of the city and track what is happening in real time.

Virtual Singapore will enable city planners to test various responses to everything from population growth and resource management to public events and building patterns, and implement those that create the safest, most positive experiences.

Figure 12: Virtual Singapore

Use case: Enhanced urban design through simulation, planification and optimization

Additional focus: EU project "Destination Earth (DestinE)"

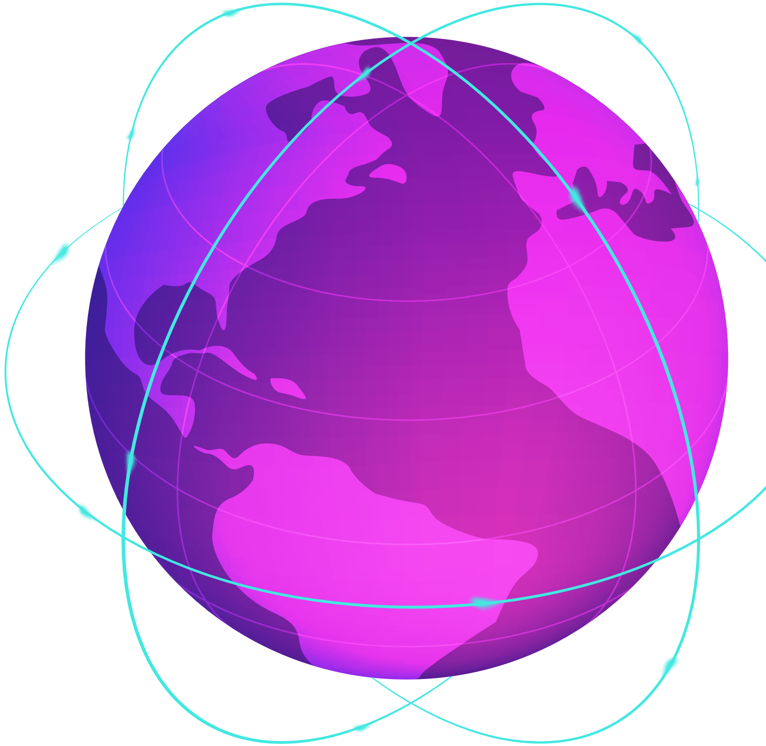
Destination Earth (DestinE) is the European Union's project to create a virtual twin of the planet and will unfold over this decade. The objective of the Destination Earth initiative is to develop a very high precision virtual model of the Earth to monitor and simulate natural and human activity, and to develop and test scenarios that would enable more sustainable development.

DestinE will contribute to the European Commission's Green Deal and Digital Strategy. It will unlock the potential of virtual modelling of the Earth's physical resources and related phenomena such as climate change, water/marine environments, polar areas and the cryosphere, etc. to accelerate the green transition and help plan for major environmental challenges.

At the heart of DestinE will be a federated cloud-based modelling and simulation platform, providing access to data, advanced computing infrastructure, software, AI applications and analytics.

It will integrate virtual twins of planetary sub-systems, such as weather and climate, food and water security, global ocean circulation and the biogeochemistry of the oceans, etc. —giving users access to thematic information, services, models, scenarios, simulations, forecasts, and visualizations.

The platform will enable application development and the integration of users' own data.



Use case: Manufacturing plant optimization for FMCG products with process virtual twins

Opportunity for cost, energy and waste reduction and quality improvement in manufacturing consumer packaged goods

Manufacturing operations have long been an area of focus for the implementation of virtual twin technology (both for process and asset optimization). It is a data-rich environment that is relatively insulated from the external world.

Virtual twins in this context allow designs to be optimized for manufacturing and layouts, material flows and processes to be tested, refined and automated.

Modelling and simulation of discrete production processes or entire factories enable plant operators to analyze enormous amounts of information, find productivity improvements, cut costs and make production processes more efficient, flexible and less resource intensive per unit of output.

In addition, the implementation of such technologies across plants can support digital skills transformation in the workforce.

Virtual twins for FMCG manufacturing are in the early stages of adoption around the world and CPG case studies with publicly available data on observed improvement ranges are still relatively few. The table below outlines key value drivers, together with supporting examples (see Figure 13).

Use case: Manufacturing plant optimization for FMCG products with process virtual twins

Figure 13: Use case key value drivers (non-exhaustive and illustrative)

VALUE CATEGORIES	KEY VALUE DRIVERS (NON-EXHAUSTIVE)	DESCRIPTION AND EXAMPLE (ILLUSTRATIVE)
Business (economic value)	Productivity uplift from enhanced automation	Unilever pilot in Brazil saw a 1 – 3% productivity increase[68]; Henkel has reported a 30% overall equipment effectiveness (OEE) improvement from its real-time global OEE-boosting platform[69]
	Cost savings from optimized resource use	Dassault Systèmes report that its 3DEXPERIENCE twin Model Based Systems Engineering (MBSE) solutions have yielded COGS reductions of up to 27% across client case studies[70]
	Increased capacity within the plant	Production optimization with virtual twin technologies can enable the freeing up of capacity in the factory without installing extra equipment; up to 18% increase in throughput[71]
	Product design optimization enablement	Production data capturing and analytics can be used to inform design and management decisions at the product portfolio level
	Fewer interruptions and downtime	Unilever has been able to reduce the number of alerts requiring action by 90% per day, ensuring far fewer interruptions[72]
Sustainability value (environmental and /or social)	Reduced energy consumption	Henkel has set-up a cloud-based data platform that connects 30+ sites and 10+ distribution centers in real time; a virtual twin for sustainability solution has yielded a 38% reduction in energy[73]
	Reduction in production waste	Solutions help to remove bottlenecks and assign the right materials to the right orders to reduce waste; Unilever has reduced its material waste by more than 42% in its Dubai, UAE, factory as a result of digital E2E quality management[74]
	Enhanced employee upskilling opportunities	Training techniques can be tied to the technology, and include gamification, digital learning pathways, virtual reality and augmented reality learning tools

Use case: Manufacturing plant optimization for FMCG products with process virtual twins

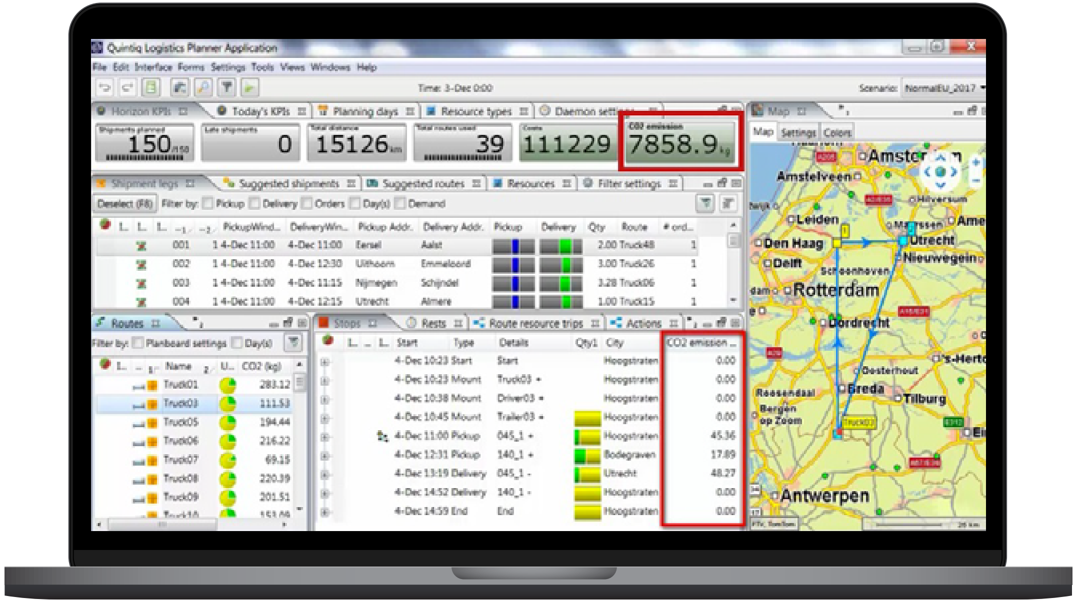
Case study: Virtual twins in logistics

One critical part of any supply chain optimization effort is constructing an adequate level of transparency and visibility of the supply chain itself. This is especially important when the focus is on improving your environmental or social footprint in forward and reverse logistics. For example, reducing CO_2 emissions by only focusing on reducing miles driven provides limited results.

While there is a strong correlation between a reduction in driving distance and a reduction in CO_2 emissions, there are other considerations that can be taken into account such as vehicle type, local carbon tax and type of driving (e.g., urban versus highway, road topography etc.) that can greatly impact the CO_2 emissions of a fleet.

Capturing these differences in CO_2 emission calculations via a virtual twin tool can help create a logistics plan via mathematical optimization according to the goal of minimizing CO_2 and in consideration of a range of key variables beyond only minimizing distance.

Figure 14: The KPIs for CO_2 emission displayed prominently and tracked for each leg of a route



Time: 3-Dec 0:00

Shipments planned: 150/150

Late shipments: 0

Total distance: 15126 km

Total routes used: 39

Costs: 111229

CO2 emission: 7858.9 kg

Filter by: ☐ Pickup ☐ Delivery ☐ Orders ☐ Day(s) ☐ Demand

L...	_1	_2	PickupWind...	DeliveryWin...	Pickup Addr.	Delivery Addr.	Pickup	Delivery	Qty	Route	# ord...
	001	1	4-Dec 11:00	4-Dec 11:00	Eersel	Aalst			2.00	Truck48	1
	002	1	4-Dec 11:00	4-Dec 12:30	Uithoorn	Emmeloord			3.00	Truck26	1
	003	1	4-Dec 11:00	4-Dec 11:15	Nijmegen	Schijndel			3.28	Truck06	1
	004	1	4-Dec 11:00	4-Dec 12:15	Utrecht	Almere			1.00	Truck15	1

Filter by: ☐ Planboard settings ☐ Day(s)

Name	U...	CO2 (kg)
Truck01		283.12
Truck03		111.53
Truck05		194.44
Truck06		216.22
Truck07		69.15
Truck08		220.39
Truck09		201.51

Start	Type	Details	Qty1	City	CO2 emission ...
4-Dec 10:23	Start	Start		Hoogstraten	0.00
4-Dec 10:23	Mount	Truck03 +		Hoogstraten	0.00
4-Dec 10:38	Mount	Driver03 +		Hoogstraten	0.00
4-Dec 10:45	Mount	Trailer03 +		Hoogstraten	0.00
4-Dec 11:00	Pickup	045_1 +		Hoogstraten	45.36
4-Dec 12:31	Pickup	140_1 +		Bodegraven	17.89
4-Dec 13:19	Delivery	045_1 -		Utrecht	48.27
4-Dec 14:52	Delivery	140_1 -		Hoogstraten	0.00
4-Dec 14:59	End	End		Hoogstraten	0.00

Use case: After-market asset performance optimization enabled by virtual twin technologies

Opportunity for cost and waste reduction, new revenue streams, improved safety and longer asset lives

This use case focuses on the application of virtual twins for performance optimization during the vehicle use phase, and as a way to provide better service and reliability for owners. Once on the road, the physical asset remains connected to its virtual twin, feeding it data on use patterns and performance and driving conditions and servicing needs, improving the predictive capabilities of the virtual twin over time.

The virtual twin also feeds back software updates based on the needs of that individual vehicle. It can make recommendations for maintenance and servicing that are tailored and prescriptive, minimizing inefficient allocation of resources associated with traditional time and condition-based maintenance approaches.

Based on these applications, virtual twins are reported to enable 20 – 30% improvements in asset life extension due to timely software and hardware interventions.

Additionally, the data and insights gathered over the life of an asset are invaluable in enabling the development of improved iterations in the future, particularly relevant for the mass adoption of electric vehicles.

Virtual twins for vehicle operations optimization and monitoring are at the early stages of development but are increasingly becoming essential for the development and scaled adoption of electrified powertrains. The table below outlines key value drivers and supporting examples (see Figure 15).

Use case: After-market asset performance optimization enabled by virtual twin technologies

Figure 15: Use case key value drivers (non-exhaustive and illustrative)

VALUE CATEGORIES	KEY VALUE DRIVERS (NON-EXHAUSTIVE)	DESCRIPTION AND EXAMPLE (ILLUSTRATIVE)
Business (economic value)	Incremental R&D benefits	By calibrating and improving the fidelity of a virtual twin with operational data coming from vehicles on-the road, OEMs can later use that intelligence in the development of new products
	Decrease in warranty and service costs for vehicles	In general, automotive OEM's spend 2 – 5% of their revenue on service and warranty costs, a range between $4 – 7Bn; conversely, Tesla's warranty cost has been 0.9 – 1.8% since 2016
	New revenue streams from data monetization	Depending on legal constraints, OEMs could potentially share data with interested third parties to offer asset owners related goods and services
	New business models and revenue streams	Virtual twins can facilitate software over-the-air (SOTA) strategies and business models, where OEMs can develop new revenue streams based on SOTA updates, paid for upgrades, infotainment and telematics applications and services
Sustainability value (environmental and /or social)	Extended asset life	Manufacturers of EV batteries and components report a potential 20 – 30% life extension for EV batteries
	Optimized resource usage	As maintenance becomes tailored and prescriptive, unnecessary time-based servicing is minimized or eliminated completely
	Facilitated remanufacturing, reconditioning	Data records and information from vehicle usage can enable more cost-effective remanufacturing or reconditioning at the end of first life
	Increased operational safety	Advanced warning and prediction of serious failures that are potentially harmful to humans

Use case: After-market asset performance optimization enabled by virtual twin technologies

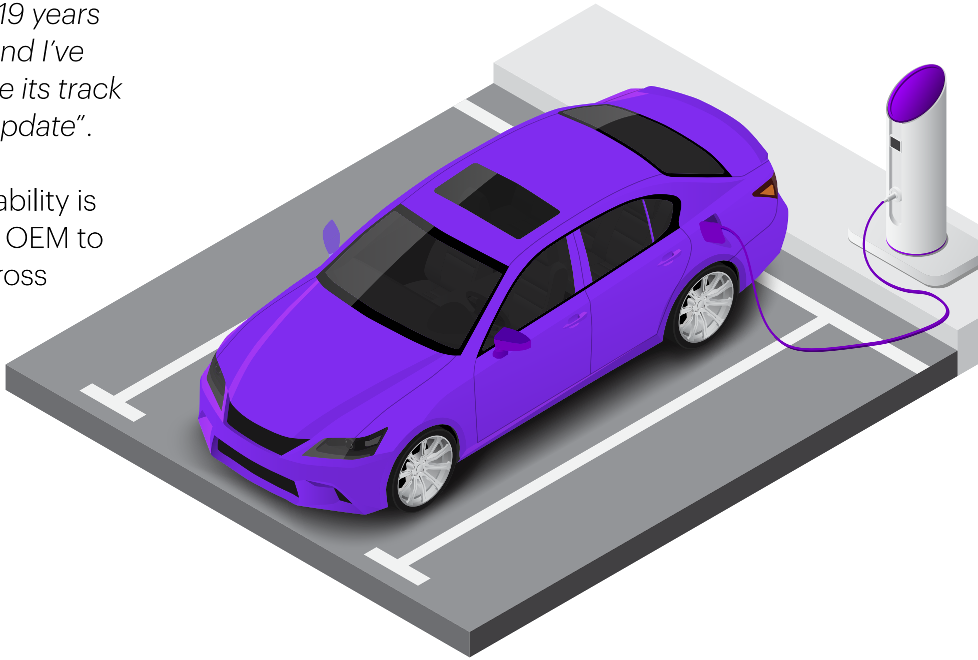
Case study: Tesla Model 3 breaking issue fix

Consumer Report reported “big flaws” in Tesla’s Model 3 on its “long stopping distance” in its emergency braking test. As a result, it did not recommend the model and this was a serious blow to Tesla, a company who prides itself on its safety record.

That weekend, Tesla pushed out an over-the-air software update, one that the carmaker says tweaked the calibration of the vehicle’s antilock braking algorithm to cut the vehicle’s 60 mph stopping distance by 19 feet, to 133 units, about average for a luxury compact sedan. Nine days later, Consumer Report updated its review to give the Model 3 its recommendation.

Jake Fisher, the director of auto testing at Consumer Report said in a statement that: “*I’ve been at Consumer Report for 19 years and tested more than 1,000 cars, and I’ve never seen a car that could improve its track performance with an over-the-air update*”.

Tesla’s operational virtual twin capability is so advanced that it also allows the OEM to collect the mileage from its car across different locations with different wind conditions and calibrate its virtual twin aerodynamics (drag coefficient), so that its virtual twin is a true representation of reality.



Use case: Virtualization of clinical trials enabled by virtual twin technologies

Opportunity for increased access to clinical trials, improved patient experiences and reduced GHG emissions intensity

Greater patient involvement in clinical trials is becoming increasingly popular. Trial sponsors and clinical investigators are exploring new ways to immerse patients in trials—including their perspectives and better informing them about risks, benefits, and disease progression.

Additionally, data can now be collected outside the traditional clinical setting, thanks to the ubiquity of mobile technologies and networks, which has legitimized digital consumer devices as data collection sources that can generate reliable clinical information outside of the clinic. This has created a new challenge in managing the quality, quantity and validity of this data.

Here, we focus on how virtual twin technologies can support virtual clinical trials. For example, they can help create a comprehensive, virtual avatar of the individual patient based on data, designed to predict the outcomes of various therapies, enabling patients in partnership with their clinicians to “try” alternative interventions such as a new drug, in electronic simulation, via their virtual twin, before selecting the one likeliest to be beneficial.

Trials that are 100% virtual (all interactions are conducted remotely) are still the exception, but they exploit the fullest potential of digital connectivity and threads, allowing patients to participate in even long-term trials without leaving their home and sponsors to benefit from higher patient participation and cost savings[viii].

Research into the sustainability impact of virtual and hybrid clinical trials is limited and typically focuses on the human well-being factor. Whilst the available data does not allow for an in-depth analysis of environmental sustainability impacts, existing qualitative evidence does suggest a strong potential to achieve environmental benefits. The table below outlines key value drivers, with supporting examples, to frame these benefits (see Figure 16).

Use case: Virtualization of clinical trials enabled by virtual twin technologies

Figure 16: Use case key value drivers (non-exhaustive and illustrative)

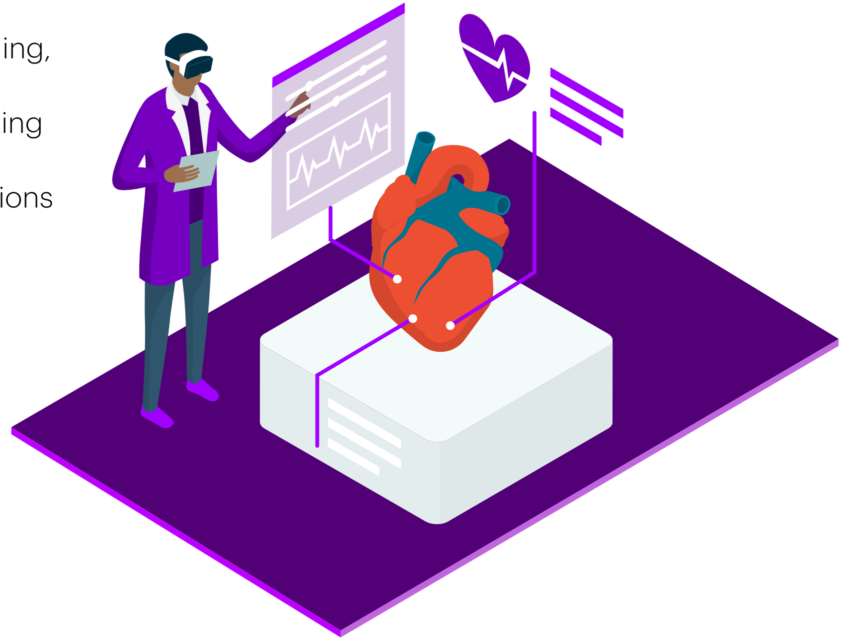
VALUE CATEGORIES	KEY VALUE DRIVERS (NON-EXHAUSTIVE)	DESCRIPTION AND EXAMPLE (ILLUSTRATIVE)
Business (economic value)	Cost savings from reduced total time spent in trials	Total time spent in trials is shorter on average due to more efficient enrolment, lower dropout rates and faster, more accurate data collection[75]
	Cost savings from more efficient patient recruitment	Patient recruitment is a key reason for clinical trial delays, with 80% of trials failing to meet enrolment targets and timelines. Patient recruitment via site visits and geographic location-based limits are a key hurdle[76]
	Cost savings from enhanced patient retention	Virtual trials can theoretically help reduce the current high drop-out rate of patients involved in phase III studies by circa 40%[77]
Sustainability value (environmental and /or social)	Improved human health through early access to treatments	10,000 patients were able to use Medtronic's MRI-compatible pacemaker 2 years earlier than what would have previously been possible due to the use of computer models to get it approved[78]
	Improved patient convenience, safety and experience	Virtual clinical trials can be used to improve the comfort, convenience, and confidentiality for research participants[79]; "live" collection of data allows investigators to calibrate, modify, and possibly even interrupt a study more easily[80]
	Improved patient diversity	Virtualizing a significant component of clinical trials can help improve participation of underrepresented demographics and ethnic groups of people[81]
	Emissions reductions from reduced energy use	Main sources of energy use in clinical trials are from premises and travel; during a 1 year audit of a sample clinical trial, GHGs were estimated at 126 tons of CO_2e[82]; for comparison the EU27's annual carbon footprint is estimated at 7 tons/person (2018)[83]

Use case: Virtualization of clinical trials enabled by virtual twin technologies

Case study: The Living Heart Project

The Living Heart Project brings together cardiovascular researchers, educators, medical device developers, regulators, and practicing cardiologists on a mission to develop and validate highly detailed personalized digital human heart models.

These models aim to establish a unified foundation for cardiovascular in silico medicine and serve as a common technology base for education and training, medical device design, testing, clinical diagnosis and regulatory science—creating an effective path for rapidly translating current and future cutting-edge innovations directly into improved patient care.



Use case: Circular electrical and electronic product design enablement

Opportunity for enhanced revenues and customer centricity, GHG emissions and waste reduction

This use case focuses on the use of virtual twin technologies to develop electric and electronic products which better embed and follow circular economy principles to optimize the use of resources throughout the product lifecycle.

3D modeling and simulation enables product designers and engineers to explore unlimited sustainable innovation options. For example, advanced tools can support in silico exploration and development of battery materials, specifically looking at modular architecture development, visibility of embedded footprint and sourcing risks.

More broadly, these technologies enable OEMs to decrease their product impact by design, economically and with minimum risk thanks to virtual simulation, data analytics and enhanced collaboration between designers, engineers and production operators.

The positive value created spans the entire product lifecycle: more durable and efficient products that are easier to repair, put apart and recycle at the end of their useful lives.

It is not objectively feasible to attribute discrete sustainability outcomes to the use of virtual twin technologies in the design of electric and electrical products at the industry level. Individual case studies, however, help highlight the role of these technologies as an important enabler of sustainability. The table below outlines key value drivers, together with supporting examples, to frame the value of this use case (see Figure 17).

Use case: Circular electrical and electronic product design enablement

Figure 17: Use case key value drivers (non-exhaustive and illustrative)

VALUE CATEGORIES	KEY VALUE DRIVERS (NON-EXHAUSTIVE)	DESCRIPTION AND EXAMPLE (ILLUSTRATIVE)
Business (economic value)	Decrease in raw material costs	For washing machines, estimations show net material cost savings of more than 12% of total industry input costs, assuming 50% of EOL machines are refurbished and 50% are recycled[84]; 30% average weight savings achieved by generative design
	New revenue streams from service models	In 2019, HP's sustainability program drove more than USD $900 Million of new revenue based on circular business models and re-use of plastic materials, a 35% increase from 2018[85]
	Revenue increase from price premiums for durable products	For Electrolux in 2019, the top range of home appliances accounted for 23% of total units sold, but 32% of consumer product gross profit[86]
	Reduced compliance risk and potential financial losses	In 2019 for the first time, measures under the EU Eco-design Directive were included to support the reparability and recyclability of products[87]
Sustainability value (environmental and /or social)	Reduced use of raw materials (from enhanced durability)	Given similar material compositions and production, replacing 5 x 2,000-cycle life machines with 1 x 10,000-cycle life machine yields ~180 kg of steel savings and >2.5 tons of CO_2e savings
	Lower embedded product footprint	For Apple, the use of recycled materials cuts the CO_2e footprint of products by ~50% on average[88]
	Increased product efficiency (during use phase)	In Europe, which represents 38% of total Electrolux sales, energy efficiency has improved by an average of 2% per year since 2015 as a result of eco design initiatives[89]

Use case: Circular electrical and electronic product design enablement

Case study: Global Tech Co

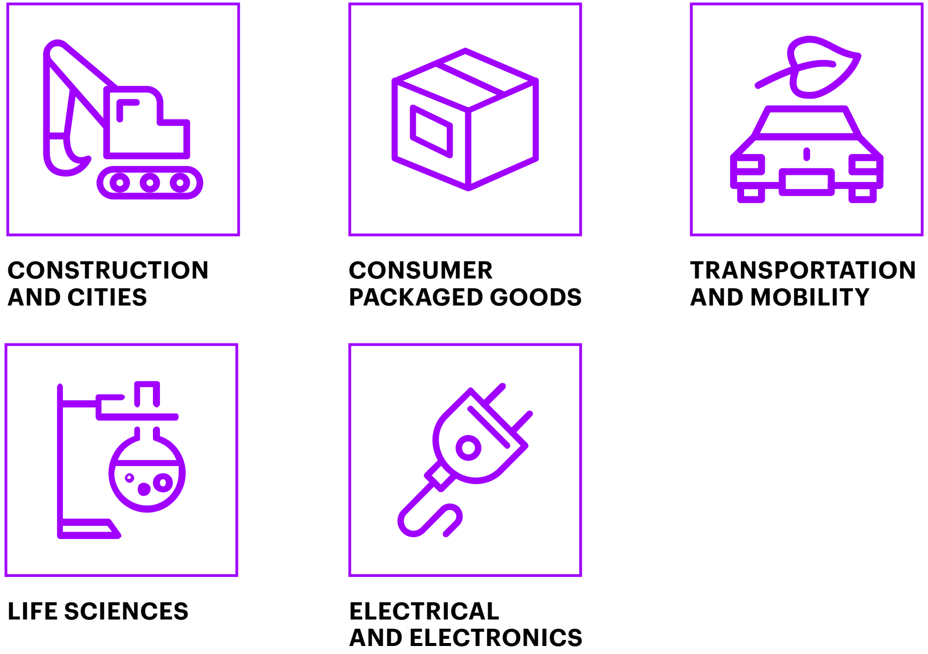
A global manufacturing computer hardware Tech Co set a goal to reduce the embedded carbon footprint of their new product by 45% and increase the use of recycled structural materials by 50%.

Virtual twin simulation technology makes it possible to study significantly more design options and optimize product performance whilst delivering on sustainability KPIs. Product developers studied the virtual prototype behavior with a wide range of scenarios across thermal and acoustic performance and electromagnetic behavior. Generative design and advanced mechanical simulation and optimization led to lighter structural parts as well as higher torsion and flexion performance. They also allowed a significantly higher-than-usual rate of recycled materials.

Importantly, virtual twin technologies enabled the company to reach its sustainability goals: the new computer has a lower carbon footprint of 47% compared with the previous generation, and a shell made of 100% recycled materials.

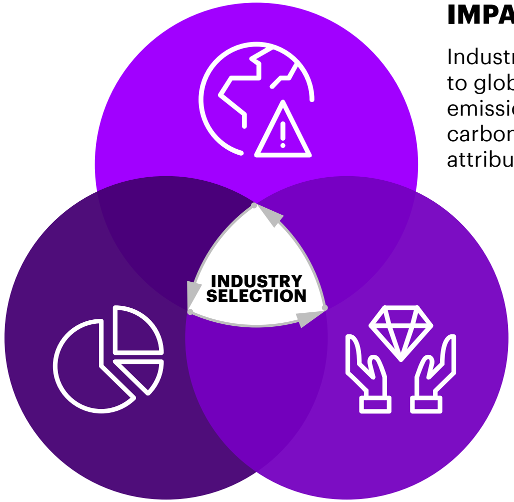
Industry scope

Figure 18: Focus industries for research



The figures below depict the criteria, definitions and industry prioritization output

Figure 19: Proposed criteria focuses on business relevance, carbon and economic impact



BUSINESS RELEVANCE TO DASSAULT SYSTÈMES (3DS)

Industry commercial significance for 3DS e.g. proportion of revenue attributable to industry, level of business investment

Portfolio relevance i.e. availability of high-potential tech use cases

CARBON EMISSIONS IMPACT

Industry contribution to global carbon emissions (e.g. % carbon emissions attributable)

ECONOMIC VALUE IMPACT

Relative industry contribution to economic development (e.g. % GDP attributable, market size)

Figure 20: Criteria for industry prioritization: High/ Medium/ Low definitions

	BUSINESS RELEVANCE TO 3DS	CARBON EMISSIONS IMPACT	ECONOMIC VALUE IMPACT
HIGH	Industry/market is a key revenue stream for the business and/or high investment area	Direct or indirect contribution to more than 10% of global GHG emissions/carbon equivalent	Industry amongst the top 10 globally in terms of worth/$-size; global GDP contribution, where known is >10%
MEDIUM	Industry market is a secondary revenue stream but encompasses potentially strategic tech use cases to assess and raise awareness on	Direct or indirect contribution to less than 10% of global GHG emissions/carbon equivalent but more than 2%	A smaller size industry but important for employment, intellectual capital development etc.; global GDP contribution, where known, is 2-10%
LOW	Industry/market is a secondary revenue stream with limited tech use case potential	Direct or indirect contribution to 2% or less of global GHG emissions/carbon equivalent	A smaller size industry; global GDP contribution, where known, is <2%

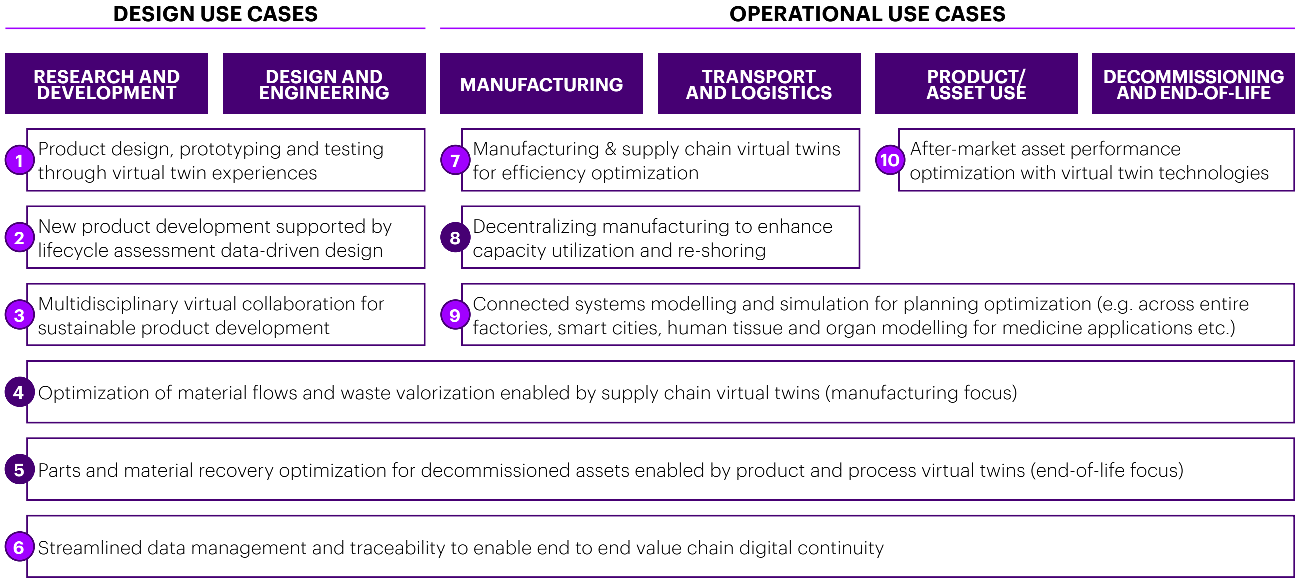
Figure 21: Industry prioritization output

INDUSTRIES	BUSINESS RELEVANCE TO 3DS	CARBON EMISSIONS IMPACT	ECONOMIC VALUE IMPACT	FURTHER NOTES AND RATIONALE (EDITED FOR SENSITIVE INFORMATION)
Aerospace and Defense	Medium	Medium	Low	• Carbon impact low-medium (5% attributable to defence; less to Aerospace manufacturing) • GDP contribution ~2% in US (2018); 0.5% in UK (2016); $705 Bn globally (2019) or <1%
Construction and Cities	High	High	High	• Appx. 13% of global GDP (2017) • Appx. 10% of global carbon emissions attributable (28% incl. operational/ use phase, 2019)
Consumer Packaged Goods	High	High	Medium	• GDP contribution ~3% in US (2019); ~14% in UK (2019) • 90% of the sector's carbon emissions lie in the value chain (2019); upstream links to Agriculture, Transportation and Industry, proximity to end consumers – strategic importance for carbon
Energy and Materials	Low	High	High	• Significant carbon impact e.g., Electricity and heat generation accounts for ¼ of global GHGs • Significant value impact e.g., energy, oil and gas among the biggest industries globally
Electrical and Electronic Tech Hardware	High	Medium	High	• Carbon footprint of the ICT sector is about 1.4% of global GHGs; acute e-waste problem • In many dev. markets, the tech sector accounts for a significant portion of economic activity
Home and Lifestyle	Medium	Medium	Medium	• Medium carbon and economic value impact
Industrial Equipment	High	Low	Low	• Low-Medium importance to total value added in EU e.g., 3% in 2010 to the non-financial economy • Low carbon impact e.g. <1% of UK emissions in 2018 attributable to mfg. of equipment
Life Sciences	High	Medium	High	• OECD countries spent ~10% of GDP on health care in 2016; Pharma highly revenue-GHG intense • Health carbon footprint in 2014 constituted 5.5% of the total national carbon footprint in OECD
Marine and Offshore	Medium	Medium	Medium	• Assumed of medium econ. value due to strategic importance to global trade and economy (UN sources) • Maritime transport is ~2.5% of global GHG emissions; upstream energy emissions 5-37% of total
Transportation and Mobility	High	High	High	• Transport plays a key role in today's economy and has a large impact on growth & employment • Transport accounts for 1/3 of GHG emissions globally, with road the biggest proportion of that

Technology use case formulation and prioritization

The study is based on bottom-up research of virtual twin-related technology solutions already available on the market or currently in development, which hold a potential to operationalize sustainability objectives. The formulation stage was based on capturing a detailed use case for each technology-led solution (building a long list), a quick prioritization for relevance to sustainability objectives, aggregation and a simplification exercise. This helped to narrow the selection to ten aggregated use cases (the short list).

Figure 22: Industry agnostic list of ten use cases with potential to drive sustainability benefits; the seven circled in bright purple were prioritized for further analysis and inclusion in the final paper



DESIGN USE CASES

OPERATIONAL USE CASES

RESEARCH AND DEVELOPMENT

DESIGN AND ENGINEERING

MANUFACTURING

TRANSPORT AND LOGISTICS

PRODUCT/ ASSET USE

DECOMMISSIONING AND END-OF-LIFE

1 Product design, prototyping and testing through virtual twin experiences

2 New product development supported by lifecycle assessment data-driven design

3 Multidisciplinary virtual collaboration for sustainable product development

4 Optimization of material flows and waste valorization enabled by supply chain virtual twins (manufacturing focus)

5 Parts and material recovery optimization for decommissioned assets enabled by product and process virtual twins (end-of-life focus)

6 Streamlined data management and traceability to enable end to end value chain digital continuity

7 Manufacturing & supply chain virtual twins for efficiency optimization

8 Decentralizing manufacturing to enhance capacity utilization and re-shoring

9 Connected systems modelling and simulation for planning optimization (e.g. across entire factories, smart cities, human tissue and organ modelling for medicine applications etc.)

10 After-market asset performance optimization with virtual twin technologies

Figure 23: Use case prioritization heatmap with use cases on the Y axis and Industry, Business and Sustainability impact on the X axis; shades of purple denote H/M/L index impact; grey denotes low industry relevance of use case

	ELECTRONIC AND ELECTRICAL EQUIPMENT		**CONSTRUCTION AND CITIES**		**CONSUMER PACKAGED GOODS**		**LIFE SCIENCES**		**TRANSPORTATION AND MOBILITY**	
USE CASES	Business Impact	Sustainability Impact	Business Impact	Sustainability Impact	Business Impact	Sustainability Impact	Business Impact	Sustainability Impact	Business Impact	Sustainability Impact
1	**High**	**High**	**Medium**	**Medium**	**High**	**Medium**	**High**	**Medium**	**High**	**High**
2	**Low**	**Medium**	**Medium**	**Medium**	**High**	**High**	**High**	**Medium**	**Low**	**Medium**
3	**Low**	**Low**	**Medium**	**Medium**	**N/A**	**N/A**	**N/A**	**N/A**	**Medium**	**Medium**
4	**Low**	**Low**	**Low**	**Medium**	**Medium**	**Low**	**Low**	**Medium**	**Medium**	**High**
5	**Medium**	**Low**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**Medium**	**High**
6	**High**	**High**	**Medium**	**Low**	**N/A**	**N/A**	**Medium**	**Medium**	**Medium**	**High**
7	**Low**	**Low**	**N/A**	**N/A**	**High**	**High**	**High**	**High**	**Medium**	**Medium**
8	**Low**	**Low**	**N/A**	**N/A**	**Medium**	**Low**	**Low**	**Low**	**Medium**	**Medium**
9	**N/A**	**N/A**	**Medium**	**High**	**N/A**	**N/A**	**High**	**High**	**Low**	**Medium**
10	**Medium**	**Medium**	**High**	**High**	**N/A**	**N/A**	**Medium**	**Medium**	**High**	**High**

The ten aggregated use cases were researched in detail to determine their relative potential to deliver sustainability and business benefits in an industry context.

Seven unique use cases were prioritized for further analysis for each industry based on evidence for both business and sustainability value creation potential.

Two additional use cases with a cross-industry applicability are highlighted in chapter 3.6. for their relevance in enabling the circular economy (Figure 23, use cases 4 and 5).

Figure 24: Impact categories and criteria for individual use case analysis in drawing the final short list of technology use cases for the study. These were used in the heatmap analysis depicted above to determine the High/Medium/Low assessments for each use case across business and sustainability impact dimensions and all 5 industries

DEFINE IMPACT CATEGORIES AND KPIs	• Use cases assessed based on potential business impact and sustainability impact dimensions	• **Business Impact KPIs:** Productivity (output increase, productivity increase, product cost reduction, COGS reduction, quality cost reduction, etc.); agility (inventory reduction, lead time reduction, etc.); speed to market (speed to market reduction, design iteration time reduction, etc.)	• **Sustainability Impact KPIs:** Waste reduction, raw materials reduction, water consumption reduction, energy intensity reduction
DEFINE QUALITATIVE RANKING CATEGORIES (H/M/L IMPACT)	• **High Impact:** Evidence for systemic improvements vs. business as usual scenario in given industry i.e.: can enable change at scale	• **Medium Impact:** Evidence for significant improvements vs. business as usual scenario in given industry e.g.: 20% and above	• **Low Impact:** Evidence for incremental improvements vs. business as usual scenario in given industry e.g.: less than 20%

CONSTRUCTION AND CITIES

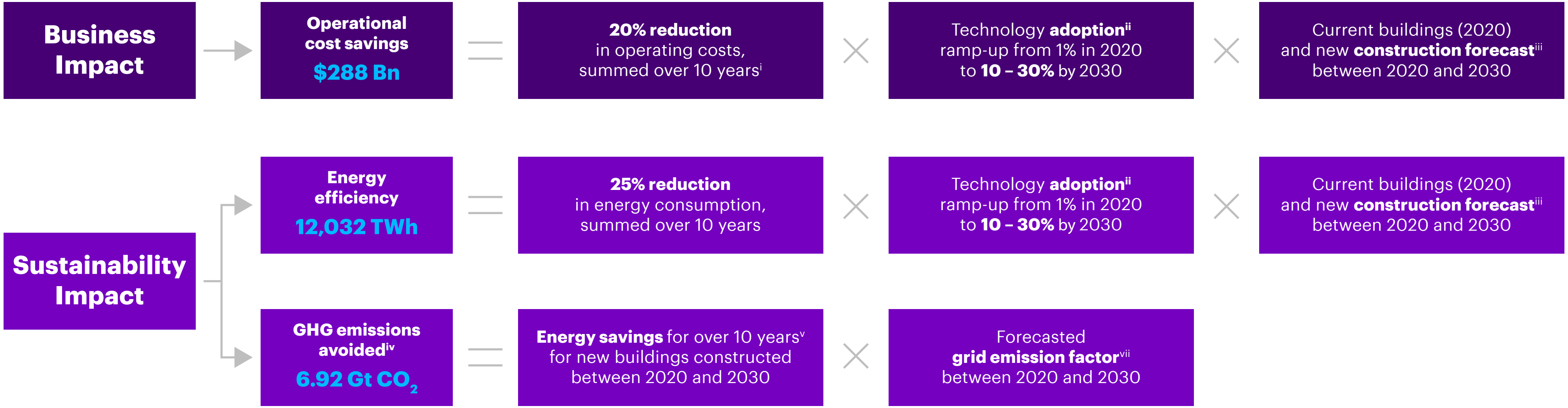
Benefits analysis of use cases

Building operational efficiency optimization enabled by virtual twin tech.

- Scope includes global residential and commercial building footprint; excludes industrial construction
- Includes both new buildings that will adopt virtual twins and existing buildings that would be retrofitted by 2030
- New construction between 2020-2030 assumed to have the same commercial to residential proportion as seen presently
- Impacts accounted for cover only 10 years of building lifecycle after implementation of virtual twins
- Calibrated for difference in adoption rates and regulatory requirements across EU, North America, Asia, etc.
- Emissions savings only consider the energy efficiency and not the higher share of renewables in the energy mix over time, even though virtual twins have been found to increase the renewable uptake in buildings

CONSTRUCTION AND CITIES

High-level estimation methodology



Business Impact → **Operational cost savings** **$288 Bn** = **20% reduction** in operating costs, summed over 10 years[i] × Technology **adoption**[ii] ramp-up from 1% in 2020 to **10 – 30%** by 2030 × Current buildings (2020) and new **construction forecast**[iii] between 2020 and 2030

Sustainability Impact → **Energy efficiency** **12,032 TWh** = **25% reduction** in energy consumption, summed over 10 years × Technology **adoption**[ii] ramp-up from 1% in 2020 to **10 – 30%** by 2030 × Current buildings (2020) and new **construction forecast**[iii] between 2020 and 2030

Sustainability Impact → **GHG emissions avoided**[iv] **6.92 Gt CO_2** = **Energy savings** for over 10 years[v] for new buildings constructed between 2020 and 2030 × Forecasted **grid emission factor**[vii] between 2020 and 2030

Key Assumptions: i. Operating cost savings through reduction in energy consumption, maintenance planning and execution costs, decommissioning costs[90]; ii. Technology adoption in Rest of World (includes Oceania, Africa, LatAm, Middle East) assumed to be same as in Asia. Different adoption rates are assumed for new construction and existing buildings[91]; iii. Building stock growth forecasts for the industry[92] between 2015 and 2050 and assumed a 90:10 split between residential and commercial buildings (based on the current split in the US market); iv. Impact of lower grid emissions over time not accounted for as it cannot be attributed to the application of virtual twins (mainly a factor of price drop and availability/capacity increase of renewable energy generation); v. Impacts aggregated over 10 years even though they will accrue over the entire building lifetime, to be conservative in our estimate and assuming that new technology would become business-as-usual in 10 years' time; vi. Benefit estimation has been calculated separately for existing and new buildings since adoption rates and impacts will be different, the lower range of values have been assumed to arrive at a conservative estimate; vii. Regional factors from multiple sources[93], [94], [95] reduced annually in line with IEA global estimates[96].

CONSUMER PACKAGED GOODS

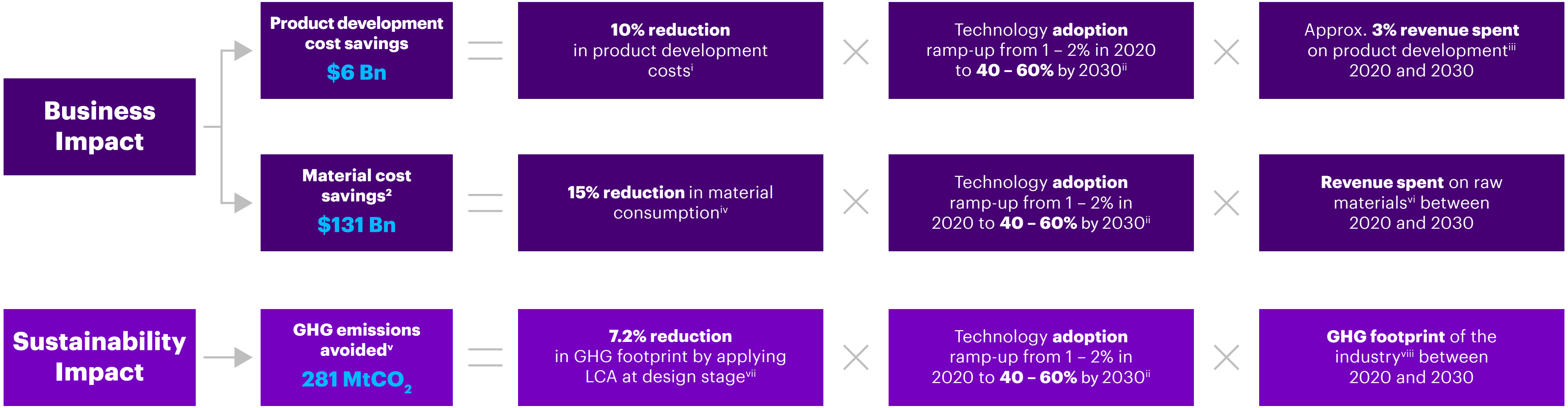
Benefits analysis of use cases

Sustainable product and packaging development supported by lifecycle assessment (LCA)-based design.

- The impact modeling has been done for Consumer Packaged Goods and excludes Retail given the significant difference in operating models and cost structures
- The business impact covers cost savings during product development and arising from lower material consumption
- Impact of conducting an LCA at the design stage has been estimated based on research comparing a granular LCA vs high-level LCA[97]
- The impact of LCA is assumed to be high in the first 1-2 years and expected to be lower in subsequent years through ongoing improvements

CONSUMER PACKAGED GOODS

High-level estimation methodology



Business Impact

Product development cost savings **$6 Bn** = **10% reduction** in product development costs[i] × Technology **adoption** ramp-up from 1 – 2% in 2020 to **40 – 60%** by 2030[ii] × Approx. **3% revenue spent** on product development[iii] 2020 and 2030

Material cost savings[2] **$131 Bn** = **15% reduction** in material consumption[iv] × Technology **adoption** ramp-up from 1 – 2% in 2020 to **40 – 60%** by 2030[ii] × **Revenue spent** on raw materials[vi] between 2020 and 2030

Sustainability Impact

GHG emissions avoided[v] **281 $MtCO_2$** = **7.2% reduction** in GHG footprint by applying LCA at design stage[vii] × Technology **adoption** ramp-up from 1 – 2% in 2020 to **40 – 60%** by 2030[ii] × **GHG footprint** of the industry[viii] between 2020 and 2030

Key Assumptions: i. An average of improvement ranges provided by Dassault Systèmes based on client case studies; ii. North America estimates; adoption is expected to be approximately double that in Europe and half that in Asia and Rest of World; based on market data provided by Dassault Systèmes; iii. External Statista estimates used for global R&D spending[98]; iv. An average of improvement ranges provided by Dassault Systèmes based on client case studies; v. Emission avoidance through reduction in material consumption is not considered, since the GHG reduction estimate for the industry already factors in the material impact, to avoid double-counting; vi. Material costs account for about 40-50% of the revenues for consumer-packaged goods companies. This share is lower for big brands and oligopolistic markets, but on average assumed to be 45% for the industry[99]; vii. Based on a meta-analysis of 800+ LCA studies where impact of doing a detailed LCA was compared with high-level LCA. While impacts from applying LCA on the 3D prototype should be higher, the incremental benefit of doing a detailed LCA has been taken as a proxy for the impact[100]; viii. While the direct emissions (Scope 1 + 2) attributed to the industry are about 4% of global emissions, the lifecycle impact (including scope 3 emissions) is about 40%, since 90% of the GHG impact of FMCG companies resides upstream or downstream (CDP)[101].

TRANSPORTATION AND MOBILITY

Benefits analysis of use cases

Product design, prototyping and testing with virtual twin technologies.

- Given the globally distributed nature of the automotive value chain, the assessment is done at a global level rather than separately by region (as in other use cases)
- Impact calculations are based on passenger vehicles, hence understated as impact would be higher if commercial vehicles were also accounted for
- Benefits arise from increased share of virtual prototyping during product development and maximizing simulations while developing autonomous driving systems
- Cost and emissions savings for simulating autonomous driving have been estimated using EVs as a reference point, which have lower operating costs and emissions per km than ICE vehicles. Therefore, the estimate is conservative
- Business impact is a significant value and about 60% of it is cost avoidance attributed to physical autonomous vehicles (AV) testing. This shows that the recent growth in development of AVs has been made possible, in large part, thanks to the availability of low-cost simulation technologies. Pursuing AV development via conventional testing is extremely economically challenging (estimated testing required is 14 Billion km per system[102])

TRANSPORTATION AND MOBILITY

High-level estimation methodology

Business Impact	**Product development cost reduction** **$261 Bn**	=	**30% reduction** in product development costs by adopting the technology[i]	×	Increase in virtual prototyping from 35% in 2020 to 80% by 2030[ii]	×	**Revenue spent on product development** between 2020 and 2030
	Costs avoided by simulated AV testing **$429 Bn**	=	**Approx. 9% AV testing** done through simulation each year[iv]	×	Ramp up of AV testing between 2020 and 2030[v]	×	Cost avoided per km of physical testing on the road[v]
Sustainability Impact	**GHG avoided by simulated AV testing** **227 Mt CO_2**	=	**Approx. 9% AV testing** done through simulation each year[iv]	×	Ramp up of AV testing between 2020 and 2030[v]	×	Emissions avoided per km of physical testing on the road[v]
	Embedded footprint of prototypes **2 Mt CO_2**	=	**80% reduction** in usage of physical prototypes during product design[vii]	×	Increase in virtual prototyping from 35% in 2020 to 80% by 2030[ii]	×	Lifecycle emission footprint per prototype vehicle or part

Key Assumptions: i. An average of improvement ranges provided by Dassault Systèmes based on client case studies; faster time to market is also an important benefit, whose impact is difficult to quantify, but a reduction of 1-2 years has been observed in many cases; ii. Technology adoption is high among European automakers and the adoption levels will be very high in mature markets by 2030. These estimates however are for the overall auto industry, accounting for different geographies and product segments; iii. Automakers typically spend 5% of their revenues on product development[103]; iv. Based on a comparison of annual physical testing[104] and simulation by leading automotive and tech companies[105]; v. Emissions[106] and cost[107] savings are based on electric vehicle-miles to provide a conservative estimate. However, the savings would be higher considering usage of ICE vehicles, Robo-taxis and commercial vehicles. A 90% percent reduction is assumed in the cost when taking into account the cost of hardware, storage, simulation tools, etc.[108]; vi. Current levels of AV testing approximated at 30 – 35 Billion kms based on data from leading companies[109] in the autonomous driving market. AV testing assumed to grow at the same rate as the autonomous driving market[110] which is projected to grow at a CAGR of 22% between now and 2030; vii. An average of improvement ranges provided by Dassault Systèmes based on client case studies; viii. Conservative estimate based on an electric car as reference[111]. However, the footprint of an AV test vehicle and installed equipment would be expected to be much higher.

LIFE SCIENCES

Benefits analysis of use cases

Manufacturing plant optimization for pharmaceutical products with process virtual twins.

- Given the globally distributed nature of the pharmaceutical value chains, the assessment has been done at a global level, but with differentiation for generics and brands

- Solvents are a major contributor to the material consumption and GHG emissions in the lifecycle of a pharmaceutical product and the emission reductions have been calculated based on the solvent savings, ignoring other minor reductions

LIFE SCIENCES

High-level estimation methodology

Business Impact[i] → **Material savings and improved quality** **$106 Bn** = **25% lower COGS** due to better quality and lower material consumption[ii] × Higher share of processes adopting virtual twins to reach 30 – 50% by 2030[iii] × **Industry revenues** that go into COGS between 2020 and 2030[iv]

Sustainability Impact[i] → **GHG reduction from lower solvent use** **61 $MtCO_2$** = **50% reduction** in solvent use by adoption of the technology[v] × Higher share of processes adopting virtual twins to reach 30 – 50% by 2030[iii] × **Industry footprint** based on revenue growth and emission intensity reduction between 2020 and 2030

Key Assumptions: i. The impact of continuous manufacturing has been taken as a proxy for the impact of virtual twins since having a virtual twin for real-time process data is a critical enabler[112] for the transition from batch to continuous processing; ii. This takes into account quality increase, higher yields, lower wastage, etc. to arrive at a consolidated impact on COGS; iii. Currently technology market adoption is at about 5% on average but can reach 30-50% based on data provided by Dassault Systèmes. These values are for full process implementation and not for virtual twins for selected unit operations within a plant; iv. Cost structures for generics[113] and branded[114] pharmaceuticals are significantly different, and a weighted average has been taken to arrive at COGS as a percentage of revenues for the industry; v. A conservative estimate given that a reduction of 70 – 90% has been seen in many case studies[115] involving significant solvent use reduction; vi. The industry emissions intensity needs to fall by 59% from 2015 levels by 2025 to adhere to the 1.5°C scenario under the Paris agreement[116]. This has been used as a benchmark and virtual twins and continuous processing would be major contributors to the reduction which is required.

ELECTRICAL AND ELECTRONICS

Benefits analysis of use cases

Waste electric and electronic equipment (WEEE) resource recovery enabled by virtual twins.

- The analysis is global in scope and based on available estimates of e-waste volumes and growth projections out to 2030
- An improvement in formal handling is assumed over the next 10 years by adopting digital threads that promote adherence to e-waste laws and better refurbishment rates
- Since recycling is also possible with low-tech solutions, the possible increase in recycling rates has not been considered while estimating the impact
- While e-waste categories such as smartphones have high formal recovery, refurbishment rates and value generation from reuse, we have assumed conservative values that are representative of the overall stock of e-waste

ELECTRICAL AND ELECTRONICS

High-level estimation methodology

Business Impact	**Added value from reuse vs. recycling** **$73 Bn**	=	Increase in formal e-waste handling adoption of the technology[i]	×	Higher share of reuse in the formally handled WEEE to reach **40%** by 2030[ii]	×	**3x increase** in value by reusing WEEE instead of recycling[iii]
Sustainability Impact	**GHG avoided by reuse instead of recycling** **5 MtCO$_2$**	=	Increase in formal e-waste handling adoption of the technology[i]	×	Higher share of reuse in the formally handled WEEE to reach **40%** by 2030[ii]	×	**0.29 tons of CO$_2$** per ton of e-waste saved by reuse in place of recycling[iv]
	HFC emissions avoided by better handling **31 MtCO$_2$**	=	Increase in formal e-waste handling adoption of the technology[i]	×	Higher share of reuse in the formally handled WEEE to reach **40%** by 2030[ii]	×	**Global warming potential of refrigerants in e-waste**[v] between 2020 and 2030

Key Assumptions: i. A linear increase from 17% in 2020 to 43% by 2030, assuming global formal handling rates will reach the current best practice (taken to be in EU) by 2030[117]; ii. Currently re-use is about 5% on average but can reach 40-50% based on recent estimates of possible refurbishment rates[118], [119]; iii. This is an average increase based on a comparison of value of e-waste recovery from Global E-waste Monitor – 2020 (UN) with the increase in value by reuse for different e-waste categories such as smartphones, televisions, laptops[120] and washing machines[121]; iv. Based on the difference between emissions savings from reuse versus recycling estimated by Clarke et al. for UK[122] and estimated for global e-waste; v. It is assumed that in case of proper (formal) handling and / or re-use of discarded refrigerators and air-conditioning equipment, none of the HFCs are released into the environment.

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i. Implementing technology solutions at the systems level to improve urban energy efficiency, transport, and public services.

ii. The analysis is based on a comparison between a business-as-usual (what is likely to happen anyway) and an accelerated scenario where we have increased technology adoption rates from 9 - 30% by 2030, based on geography, building type and age; scope of analysis is global, inclusive of commercial and residential new construction and existing building stock, using current building operative energy intensity averages as a baseline; cumulative output over 10-year period; for full details of analysis, please see Appendix.

iii. Data on the environmental impacts associated with all the stages of the lifecycle of a product and/ or the raw materials used to make it, process or service.

iv. The analysis is based on the global CPG industry and a comparison between a business-as-usual (what is likely to happen anyway) and an accelerated scenario where we have increased use case deployment rates to the maximum feasible level by 2030. Publicly available case studies do not yet exist, as this is a unique solution combining sustainability impact analysis with 3D modelling and design tools in early days of testing. For full details of analysis, please see Appendix.

v. The analysis is based on quantifying the emissions avoidance contributions from virtualizing conventional passenger vehicle development and testing (within the limits defined by local regulation), and the use of simulated driving for the development of autonomous passenger vehicles, globally and out to 2030. The cost and emissions savings for simulating autonomous driving have been estimated using EVs as a reference point. The business impact is a significant value and about 60% of it is a cost avoidance attributed to physical AV testing. For more details, please see Appendix.

vi. Pharma industry emissions are estimated to be about 52 Mt CO_2e globally for Scope 1 and 2 emissions (i.e. not accounting for indirect value chain emissions, which will increase that figure substantially); taking a WRI estimate of global emissions from 2016 at 46.1Gt, this equates to 0.11% of global CO_2e emissions.

vii. The analysis is based on the global Pharma industry and a comparison between a business-as-usual (what is likely to happen anyway) and an accelerated scenario (where the use case adoption levels by 2030 could be 20% higher than the BAU adoption). While plants may have partial adoption of process twins for selected unit operations, the estimation has been calculated for virtual twins of complete processes. Cost structures for generics and branded pharmaceuticals are significantly different, and these have been accounted for while estimating the material and production cost savings. For more details, please see Appendix.

viii. It is important to note that there are many clinical trial aspects that can be virtualized and there is no one common definition to clarify at what point a trial becomes hybrid or virtual. In addition, there are clear limitations to this approach including unclear regulatory landscape, data integration and safety challenges.

ix. Informal recycling of electric and electronic waste has been linked to worker exposure to toxic fumes of various heavy metals through inhalation and contact form skin surface.

x. The analysis is based on an increase in the formal handling of WEEE globally from the current level of 17% to reach 43% by 2030 (latest estimate for formal handling in Europe). A further improvement realized by adopting digital threads is that for the WEEE that is formally handled, the level of refurbishment and reuse can increase significantly by providing better information about the service life and material composition of the product. While e-waste categories such as smartphones have high formal recovery, refurbishment rates and value generation from reuse, we have assumed conservative values that are representative of the overall stock of e-waste. For full details of analysis, please see Appendix.

xi. For the aggregated insights from interviews, please see Appendix.

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