WORLD ECONOMIC FORUM

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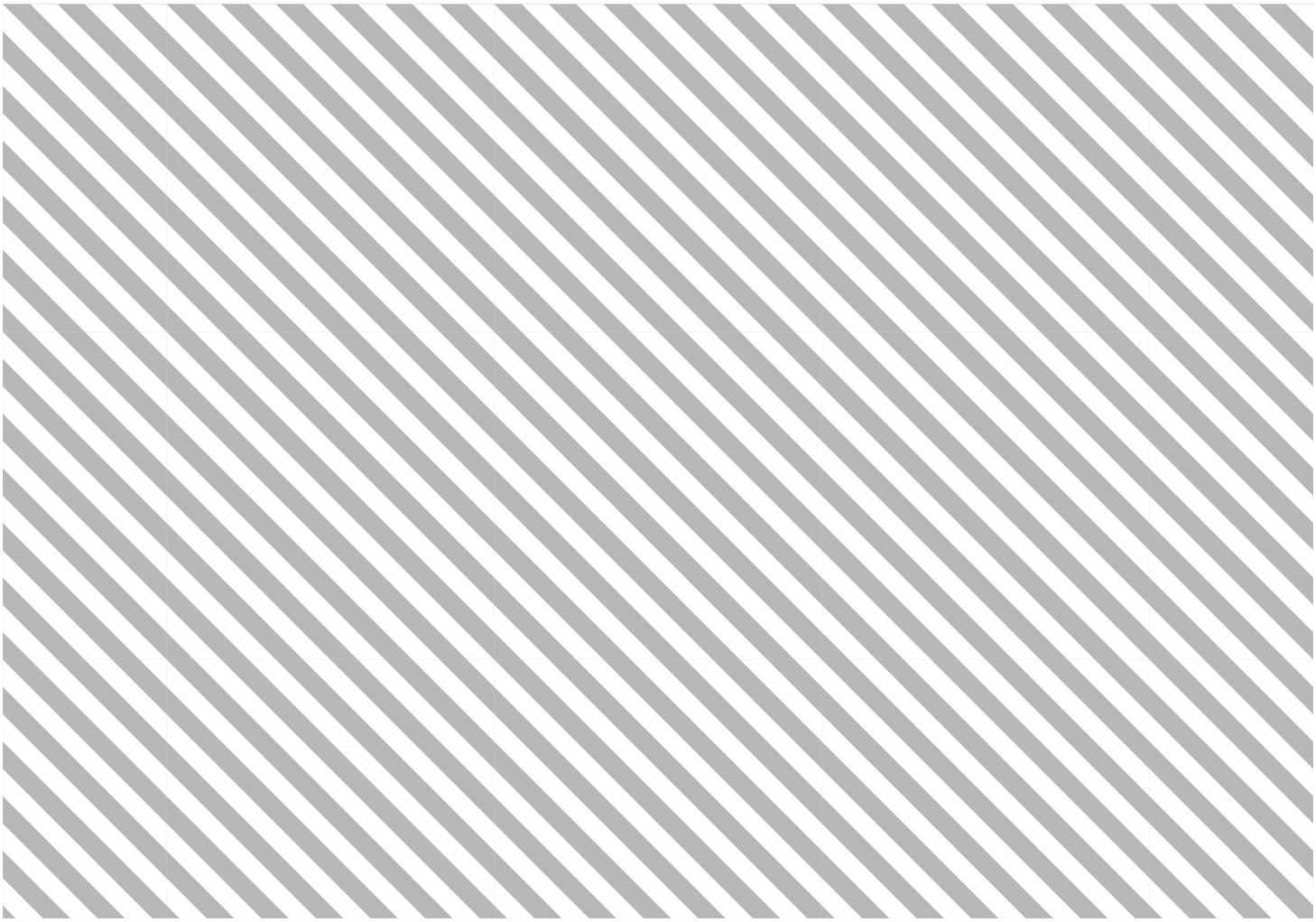
White Paper

Global Lighthouse Network:
Insights from the Forefront of the Fourth Industrial Revolution

In collaboration with McKinsey & Company

December 2019



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Foreword

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The Fourth Industrial Revolution is the latest chapter in a compelling story of human progress. The transformative power of our innovative technologies is leading to remarkable economic and societal advances. The Fourth Industrial Revolution is expected to create up to $3.7 trillion in value by 2025.[1]

In 2017, the World Economic Forum recognized the potential of advanced manufacturing technologies. Forty initial advanced manufacturing use cases were identified, as companies began to pilot these technologies with some success. In 2018, from among more than 1,000 examined production facilities, 16 companies were recognized as Fourth Industrial Revolution leaders in advanced manufacturing for demonstrating step-change results, both operational and financial, across individual sites.[2] They had succeeded in scaling beyond the pilot phase and their sites were designated advanced manufacturing "Lighthouses".

In 2019, 28 additional facilities were identified and added to the network, which now provides an opportunity for cross-company learning and collaboration, and for setting new benchmarks for the global manufacturing community. Fourteen of these 28 new sites have been recognized as end-to-end (E2E) Lighthouses, because they have emerged as leaders in extending Fourth Industrial Revolution transformation through their value chains and beyond manufacturing sites.

Lighthouses have succeeded by innovating new operating systems, including in how they manage and optimize business and processes, transforming the way people work and use technology. These new operating systems can become the blueprint for modernizing the entire company operating system; therefore, how they prepare for scaling up and engaging the workforce matters.

While many manufacturers have made strides towards technological transformation, the majority remain stuck in "pilot purgatory", unable to realize the full potential of such transformation at scale.[3] The importance of the operating system and essential enablers to scale has become even more apparent, given the growing performance gap between the leaders and the rest of the pack. In addition, a common thread across all Lighthouses is that they have recognized the centrality of their people and have discerned effective ways of empowering workers to realize the full potential of technology.

By working with a select group of advanced manufacturers over the past few years, we have identified the essential factors that differentiate the front runners from the majority. These factors are presented in this report. It is vital for organizations that remain in "pilot purgatory" to be attentive to these Fourth Industrial Revolution leaders, lest they be left behind.

Executive summary

Over the past three years, a leading group of manufacturers have made impressive progress scaling Fourth Industrial Revolution technologies within the manufacturing plant environment, earning the "Lighthouse" designation. A common thread among Lighthouses is that the digital journey begins with the transformation of the plant's system of operations and is then propelled through scale-up enablers, such as internet of things (IoT) integration and workforce engagement through reskilling and upskilling. Even as Lighthouses shine brighter today, however, the gap between the front runners and the majority grows wider.

Within this Lighthouse group, we are now seeing further exciting developments. While all Lighthouses have successfully transformed at the site level, 14 organizations have built upon the transformation already underway within the four walls of the plant environment. They have extended their Fourth Industrial Revolution innovation journeys through the end-to-end (E2E) value chain. These E2E Lighthouses demonstrate what is possible when the same innovative thinking that transforms factory sites is applied more broadly.

A detailed look at these E2E success cases reveals organizations that are driving outsized improvement in productivity, operating cost and speed to market. These E2E Lighthouses are using technology to drive value for the enterprise in three ways: customer-centred design, seamless connectivity across functions and continuous connectivity beyond organizations – indeed, across the broader supply chain. These value drivers are not new, but, for the first time, Fourth Industrial Revolution technology enables activation of the broader organization to employ them. Many of these increased efficiencies work towards reducing waste, resource consumption and emissions – thus yielding a positive impact in the context of environmental sustainability.

Transforming the entire manufacturing context from sourcing to delivery is no small feat; after all, when building digital connectivity on this broader level, complexity increases and stakeholder incentives differ. This requires companies to break down internal divisions, share data with external stakeholders and build new capabilities – thus demonstrating the continued importance of the human element in successful technology application.

Transforming the ways in which people work together is essential. Lighthouses, along with the integrating technology itself, have invested in their people, especially in building capabilities, adjusting the organizational structure and developing new ways of working. Lighthouses have thoughtfully invested in training to reskill and upskill their workers for the changing tasks and new skill sets, often partnering with educational institutions at the secondary and university levels. They have kept people at the centre, empowering them to realize their full potential alongside that of digital technology, demonstrating that true Fourth Industrial Revolution innovation is directly entwined with people and that the Fourth Industrial Revolution is, after all, a human enterprise.

The Global Lighthouse Network[4] provides a unique space for all companies to share and learn from best practices, incubate new collaborations and partnerships and accelerate the transition towards the future of manufacturing by deploying technology, transforming the workforce and escaping "pilot purgatory".

Section 1: Insights from the forefront of the Fourth Industrial Revolution

The Fourth Industrial Revolution is gaining momentum, but not broadly enough

The Fourth Industrial Revolution in manufacturing has fully taken hold and is making a major impact in a growing number of leading organizations, which are building on their lead with first-mover advantage. Since 2016, the World Economic Forum, in collaboration with McKinsey & Company, has been monitoring progress in advanced manufacturing worldwide, identifying the essential factors that differentiate the front runners – "Lighthouses" – from the majority.

The gap between forerunners and the rest grows

While many manufacturers have made strides towards technological transformation, more than 70% of the companies in the manufacturing ecosystem are falling further behind, with their Fourth Industrial Revolution efforts stuck in what we defined as "pilot purgatory": the attempt to implement advanced manufacturing technologies without realizing appealing returns on investment or measurable improvements in operational key performance indicators (KPIs).[5]

Major gaps in performance are already emerging: There are increasing disparities in productivity, efficiency and growth between the leaders and the rest of the pack; we may soon end up with a bipolar scenario, with only winners and losers. Delaying Fourth Industrial Revolution transformation is no longer a viable option. Companies that wish to remain competitive must embark on this journey.

The Global Lighthouse Network – helping companies navigate Fourth Industrial Revolution transformation

Aiming to close the gap between front runners and laggards while accelerating widespread adoption of advanced manufacturing technologies, the World Economic Forum, in collaboration with McKinsey & Company, launched the Global Lighthouse Network in 2018.[6] The network comprises a community of manufacturers showing leadership in using Fourth Industrial Revolution technologies to transform factories, value chains and business models to generate compelling financial, operational and environmental returns.

Lighthouses are identified through a comprehensive selection process led by the World Economic Forum. More than 1,000 companies from different industry sectors and across the globe have been assessed on objective results and use cases. Final selection is delegated to an independent panel of world-leading Fourth Industrial Revolution experts.

Network members today are actively engaged on a cross-industry learning journey that finds its core value in developing and sharing insights on top use cases, road maps and organizational approaches to deploy advanced technologies at scale while supporting the transition to more human-centred, inclusive and sustainable manufacturing.

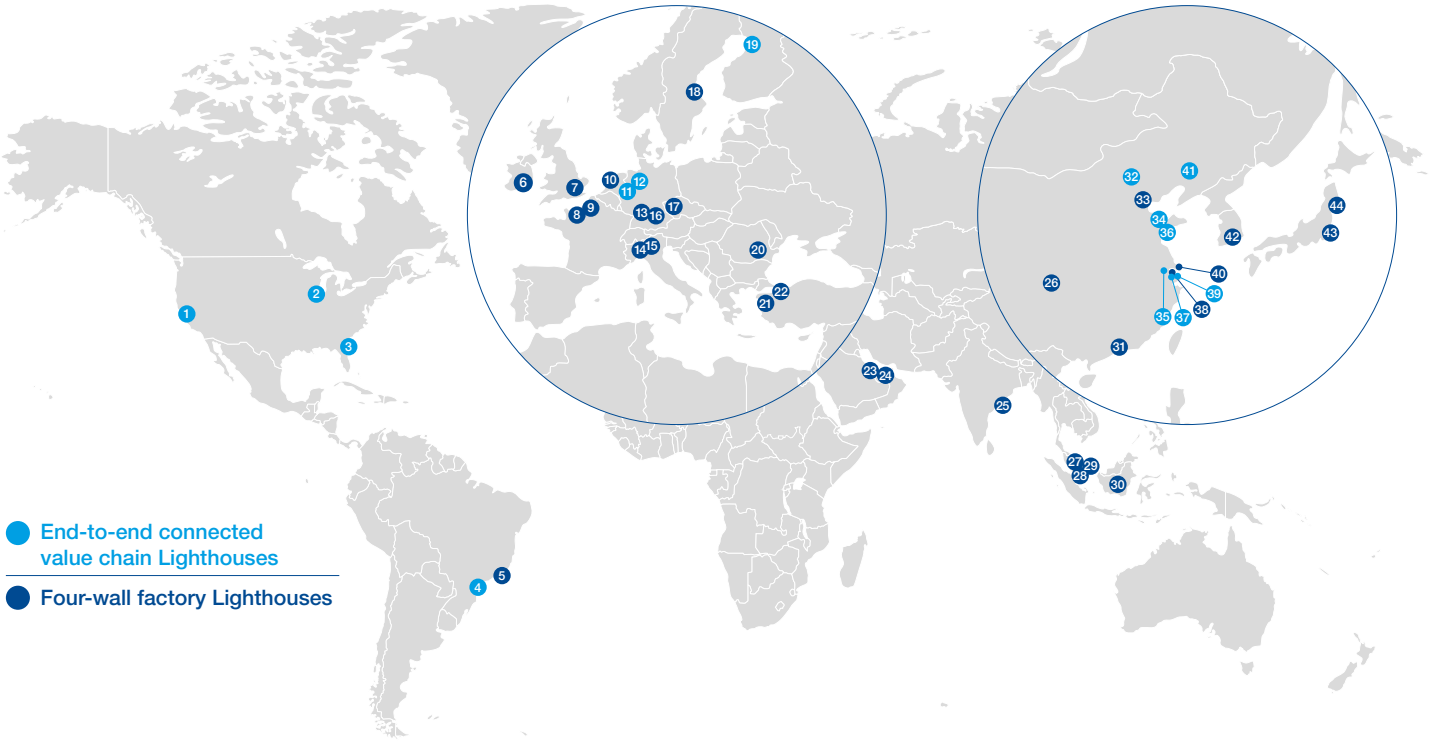
Fourth Industrial Revolution: where are we?

Twenty-eight Lighthouses have been added in 2019, bringing the Global Lighthouse Network to a total of 44 sites. These are leading the way in adoption of Fourth Industrial Revolution technologies, including digitization, automation, advanced and predictive analytics, virtual and augmented reality and the industrial internet of things (IIoT). New joiners add new insights, focusing on connecting their value chains end-to-end (E2E), along with deploying advanced use cases in their facilities (factories). We are also beginning to see companies scaling their new operating systems to other plants in their manufacturing network; all of them are designed for broader scale-up.

These leading Lighthouses are pushing benchmarks and demonstrating that the adoption of Fourth Industrial Revolution technology is resulting in tangible improvements on many metrics. Moreover, they are showing that when companies expand digital connectivity beyond the plant site and through the value chain, they deliver even greater results in terms of agility, speed to market and opportunities for mass customization. In addition, they have also demonstrated that digital transformation is possible without committing to an unsustainable outlay of capital resources.

Figure 1: The Global Lighthouse Network

The Global Lighthouse Network includes 44 sites as of 6 January 2020



1 **Zymergen**
Biotechnology, US

2 **Fast Radius with UPS**
Additive manufacturing, US

3 **Johnson & Johnson Vision Care**
Medical devices, US

4 **Groupe Renault**
Automotive, BR

5 **MODEC**
Oil and gas, BR

6 **Johnson & Johnson DePuy Synthes**
Medical devices, IR

7 **GSK**
Pharmaceuticals, UK

8 **Schneider Electric**
Electrical components, FR

9 **Groupe Renault**
Automotive, FR

10 **Tata Steel**
Steel products, NL

11 **Henkel**
Consumer goods, DE

12 **Phoenix Contact**
Industrial automation, DE

13 **AGCO**
Agricultural equipment, DE

14 **Rold**
Electrical components, IT

15 **Bayer**
Division pharmaceuticals, IT

16 **BMW Group**
Automotive, DE

17 **Procter & Gamble**
Consumer goods, CZ

18 **Sandvik Coromant**
Industrial tools, SE

19 **Nokia**
Electronics, FI

20 **Arçelik A.Ş.**
Home appliances, RO

21 **Petkim**
Chemicals, TR

22 **Ford Otosan**
Automotive, TR

23 **Saudi Aramco**
Gas treatment, SA

24 **Unilever**
Consumer goods, UAE

25 **Tata Steel**
Steel products, IN

26 **Siemens**
Industrial automation products, CN

27 **Infineon**
Semiconductors, SG

28 **Schneider Electric**
Electrical components, ID

29 **Micron**
Semiconductors, SG

30 **Petrosea**
Mining, ID

31 **Foxconn Industrial Internet**
Electronics, CN

32 **FOTON Cummins**
Automotive, CN

33 **Danfoss**
Industrial equipment, CN

34 **Weichai**
Industrial machinery, CN

35 **SAIC Maxus**
Automotive, CN

36 **Haier**
Home appliances, CN

37 **Johnson & Johnson DePuy Synthes**
Medical devices, CN

38 **Bosch**
Automotive, CN

39 **Procter & Gamble**
Consumer goods, CN

40 **Baoshan Iron & Steel**
Steel products, CN

41 **Haier**
Appliances, CN

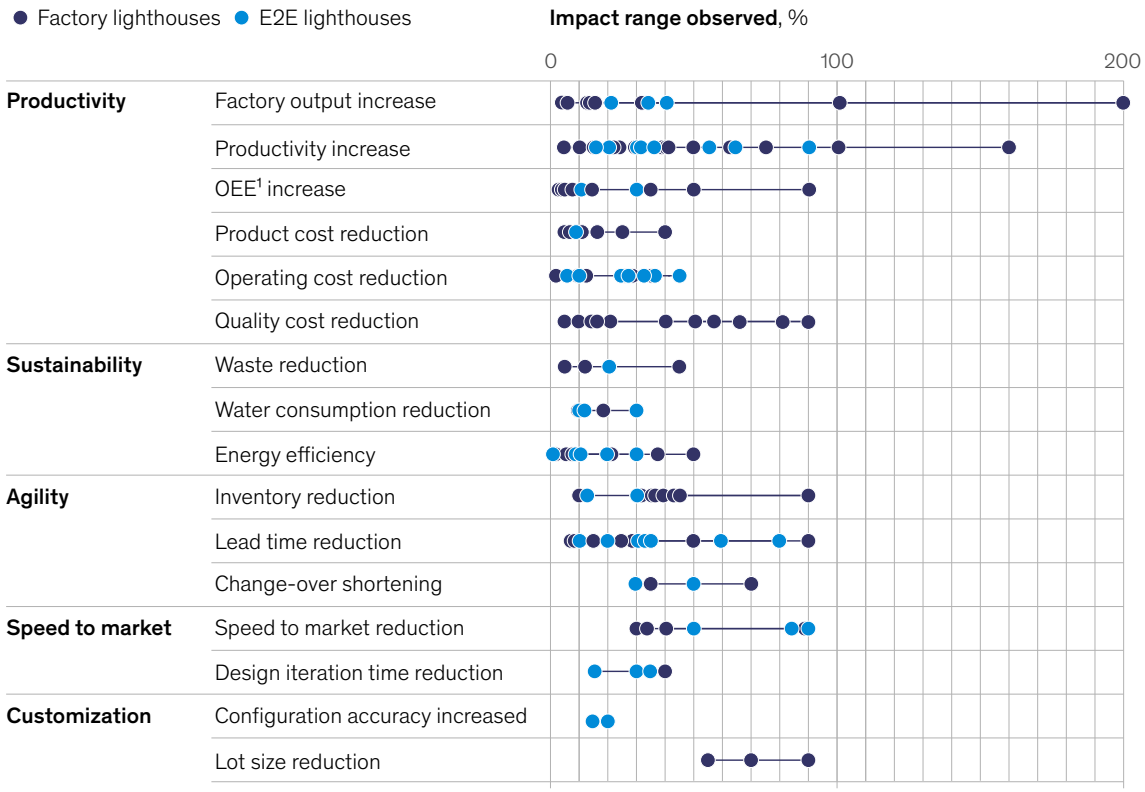
42 **POSCO**
Steel products, KOR

43 **GE Healthcare**
Healthcare, JP

44 **Hitachi**
Industrial equipment, JP

Figure 2: E2E lighthouses are able to leverage digital technology to generate impact beyond productivity to build a more agile and customer-focused organization.

Key performance indicator improvements



[1]Overall equipment effectiveness

Source: Mckinsey & Company

The impact chart summarizes the range of financial and operational impacts (in percentage) observed in factory or E2E Lighthouses. Every data point shown is from one or several of the 44 Lighthouses.

The new E2E Lighthouses have been able to scale up in-factory digital operations while removing barriers across functions in the value chain through digital connectivity. E2E Lighthouses have continued to push the envelope of technological advancement, expanding beyond the four walls of the factory site to drive exponential benefits and reshape the customer journey.

The repository of select Fourth Industrial Revolution solutions implemented by the companies in the Global Lighthouse Network comprises a toolbox. It has expanded from 40 to 92 high-impact use cases along the supply network, end-to-end product development, end-to-end planning, end-to-end delivery, customer connectivity and digitally enabled sustainability. As Fourth Industrial Revolution further matures, we believe that the toolbox will further evolve and expand. The true competitive advantage that Lighthouses develop by innovating a new operating system is that they can add new use cases in minimal time and at minimal cost, which means that they experience much higher return on investment (ROI) than companies with traditional operating systems.

Figure 3: Toolbox – 92 Fourth Industrial Revolution use cases for digitization across the end-to-end value chain, including manufacturing

Manufacturing

Digital assembly and machines

- Real-time locating system (RTLS) for key manufacturing components
- Cycle-time optimization through big-data analytics on production line PLCs
- Light-guided assembly sequence
- Mixed reality to enable digital standard work/trainings
- Advanced IIoT applied to process optimization
- Artificial intelligence-powered process control
- Digital lean tools (e.g. eKanban, eAndon, eSpaghetti)
- Artificial intelligence-guided machine performance optimization
- Digitally enabled variable takt time
- Digitally enabled modular production configuration

Digital maintenance

- Cost optimization of heavy operations through sensor analysis
- Machine alarm aggregation, prioritization and analytics-enabled problem-solving
- Predictive maintenance aggregating data based on historical and sensor data
- Real-time pipeline cost optimization based on edge sensors
- Remote assistance using augmented reality
- Analytics platform for deviation root-cause identification

Digital performance management

- Analytics platform for remote production optimization
- Digital dashboards to monitor OEE performance
- Digital twin for remote production optimization
- Enterprise manufacturing intelligence system to upgrade operations management
- Integration platform to connect machine-level data with enterprise software
- Real-time asset performance monitoring and visualization
- Sensor-based manufacture KPI reporting
- Digital tools to enhance a connected workforce
- Digital recruitment platform tailored to shop floor
- Digital twin of sustainability
- Digitally enabled man-machine matching

Digital quality management

- Scanning to replace and improve performance for high-cost CMM (scans)
- Automated in-line optical inspection to replace end-product manual inspections
- Digital work instructions and quality functions
- Digitized standard procedures for line operations with integrated workflow
- Mixed-reality glasses to guide operators in the end-of-line inspection
- Field quality failures aggregation, prioritization and advanced analytics-enabled problem-solving
- IoT-enabled manufacturing quality management
- Digital quality audit
- Quality improvement by predictive analytics

Digitally enabled sustainability

- Energy optimization by predictive analytics
- IIoT real-time energy data aggregation and reporting dashboard
- Sensor-based data collection for energy management

End-to-end value chain

Supply network connectivity

Aggregate demand across end-to-end supplier network

Should-cost modelling to support make-versus-buy decisions

Analytics-driven procurement supported by spend intelligence and automated spend cube

End-to-end real-time supply chain visibility platform

Supplier and materials quality tracking

Part traceability from unique digital tag based on surface scanning

Digital supplier performance management

Artificial intelligence to accelerate scaling of digital applications across sites

Joint data analytics with equipment OEM for process optimization

E2E product development

3D printing for rapid design prototyping

3D simulations/digital twin for product design and testing

Testing automation

Advanced analytics for performance management across the idea to market

Product development using robotics

Big-data/AI-enabled product design and testing

Virtual reality-supported prototyping

Digital thread implementation through product development life cycles

Rapid outsourced prototyping

Crowdsourcing and competitions to develop digital solutions

E2E planning

Predictive demand forecasting

Real-time sales and operations planning (S&OP)

Real-time inventory management (internal/external)

Dynamic production scheduling with digital twin

Dynamic network optimization

Predictive inventory replenishment

Analytics for dynamic warehouse resource planning and scheduling

Dynamic simulation for warehousing design

No-touch master planning (allocation to the plants)

Digital integrated business planning

Closed-loop planning

End-to-end real-time supply chain visibility platform

Advanced analytics to optimize manufacturing and distribution footprint

Production planning optimized by advanced analytics

E2E delivery

Dynamic delivery optimization

Robotics-enabled logistics execution

Digital track and trace

Asset use and yard management for logistics

No-touch order management

Digital-enabled picking and transport

Predictive maintenance in fleet assets

“Uberization” of transport

ATP based on real-time constraints

Digital logistics control tower

Customer connectivity

Connected devices to track and measure consumer behaviour

Mass customization and business-to-customer B2C online ordering

Delivering to customers wherever they are through new delivery solutions

Customer end-user interface to configure and order a product, and track delivery

Smart/intelligent packaging

Customer analytics enabled by radio-frequency identification (RFID)

Online communities for customer insights

GPS-based map and customer location

3D printing

Connected devices to track and measure product performance

Digital twin of customer system

Figure 4: 28 new industrial Lighthouses at the forefront of the Fourth Industrial Revolution

Site	Change story	Top 5 use cases	Impact
AGCO in Marktoberdorf, Germany	By combining digital solutions with intelligent line design, AGCO/Fendt can manufacture nine series of tractors – ranging from 72 to 500 horsepower – on a single assembly line with a batch size of one. This has increased productivity by 24% and reduced cycle time by 60%.	Digitally enabled variable takt time	↓ 60% Cycle time
		Virtual build for design to manufacture and line balancing	↑ 24% Productivity
		Intelligent transportation management system	↓ 28% Transportation costs
		Advanced analytics for quality monitoring	↓ 30% Time to identify field-quality issues
		Digital supplier performance management	↑ 25% On time delivery
Arçelik AŞ in Ulmi, Romania	This greenfield factory is a product of the Arçelik use case laboratory, where it was designed twice as fast as previous-generation factories. Since it was established, automation of low-value tasks has improved operational costs by 11%.	Smart factory – from concept to realization	↓ 45% Plant design time
		Fully automated inbound logistics	↓ 29% Indirect labour per product
		Digitized in-line QC with computer visioning	↓ 17% Indirect labour per product
		In-process connectivity and traceability	↓ 100% Wrong material usage
		Smart matching of human	↑ 3% OEE
Baoshan Iron & Steel in Shanghai, China	This 40-year-old factory adopted digitization early. Its extensive implementation of artificial intelligence and advanced analytics has allowed it to maintain its industrial competitiveness in the digital era, creating value for $50 million.	Production planning powered by advanced analytics	↑ 83% Planning efficiency
		Advanced IIoT applied to process optimization	↓ $15m Material and quality costs
		Predictive maintenance aggregating equipment and process data	↑ 30% Tool lifetime
		Visual inspection powered by artificial intelligence	↑ 70% Labor efficiency
		Logistics powered by real-time tracking, unmanned operations and automatic planning	↓ $27m Logistics costs
FORD OTOSAN in Kocaeli, Turkey	This site leverages digital manufacturing and advanced automation to move beyond lean, increasing its output by 6% and employee engagement by 45% without additional capital expenditure investment.	Digital tool and die	↓ 47% Die manufacturing time
		Real-time digital performance-management system for production and maintenance	↑ 6% Production output and employee engagement
		Robot data analytics	↓ 9% Per-year robot failures
		Real-time digital energy management	↓ NA Electric consumption
		Predictive maintenance	$100K Cost savings
Foton Cummins in Beijing, China	Foton Cummins self-deployed IoT and artificial intelligence across its end-to-end product life cycle throughout design, production and after service. By doing so, it has improved product quality and customer satisfaction by 40%.	Internet of vehicles-enabled fleet performance management	↑ 10% Uptime
		Digital operation platform	↑ 15% Productivity
		Visual inspection powered by artificial intelligence	↓ 100% Defects
		IoT-enabled manufacturing quality management	↓ 90% Time to identify production quality issues
		Quality warranty reduced by advanced analytics	↓ 80% Incidents per thousand vehicles
GE Healthcare in Hino, Japan	This GE factory, with more than 30 years of lean manufacturing, used Fourth Industrial Revolution technologies to transform into digital lean manufacturing. This has resulted in achieving the next level of performance – for example, cutting costs by 30% and reducing cycle times by 46%.	App-based eAndon on production lines	↑ 30% Efficiency
		Biometric authentication for operators	↑ 21% Efficiency
		Real-time production performance monitoring and visualization	↑ 40% Efficiency
		RFID-enabled material pull system (eKanban)	↓ 33% Labour
		eSpaghetti diagram for walking route optimization	↓ 43% Total walking distance for picking
Groupe Renault in Cleon, France	This Renault site uses a wide range of Fourth Industrial Revolution technologies (e.g. cobots and virtual reality) to support operators, eliminate waste, reduce energy consumption and automate repetitive tasks.	Digital-enabled service training	↓ 20% Cost, 50% safety incidents
		Connected workforce for performance driving	↓ 13% Waste elimination
		Process optimization through digital	↑ 10% Productivity
		Automated inplant truck flow	↓ NA Cost
		Digital and IOT energy management system	↓ NA Energy consumption and cost

Site	Change story	Top 5 use cases	Impact
Groupe Renault in Curitiba, Brazil	Renault Curitiba approached Fourth Industrial Revolution technologies with a focus on improving employee accountability and E2E connectivity, engaging its workforce and developing a connected ecosystem across value-chain players including dealers, customers and workers. Results include improving its productivity by 18%, without major capital deployment.	Customer connectivity: B2C e-commerce platform	↑ 10% Sales of one model
		Connected workforce driving performance	↓ 19% Non-value-added activities
		Flexible automation through AGVs and cobots	↓ 10% Cost per unit
		E2E vehicle delivery tracking	↓ 30% Shipping lead time
		Digital recruitment platform tailored to shop floor	↓ 20% Time to fill blue-collar positions
GSK in Ware, UK	This pharmaceutical site has applied Fourth Industrial Revolution technologies across its manufacturing operation, exploiting advanced analytics and neural networks to use existing datasets. It has improved line speed by 21%, reduced downtime and increased yield, delivering an OEE improvement of 10%.	Advanced analytics-based machine performance improvement	↑ 10% OEE
		Deep learning image recognition to detect quality defects	↑ … Cost avoidance
		Artificial intelligence-guided machine throughput optimization	↑ 21% Throughput
		Digital twin planning	↑ 13% Capacity
		Cycle time monitoring and visualization digital tool	↓ 9% Cycle time
Haier in Shenyang, China	The Haier Shenyang refrigerator factory is an example of a user-centric mass customization model. Achieved by deploying a scalable digital platform that connects end-to-end with suppliers and users, it has improved direct labour productivity by 28%.	Mass customization and B2C online ordering	↑ 44% Revenues
		3D digital twin for product development and testing	↓ 30% New product development time
		Supplier-connected digital platform	↑ 100% On-time delivery
		Digital pull system and shop-floor automation	↑ 79% Productivity
		Digital quality management	↓ 59% Product non-conformance rate
Henkel in Düsseldorf, Germany	Henkel has developed a unique cloud-based data platform that connects 30+ sites and 10+ distribution centres in real time. This helps to meet growing customer and consumer expectations on service and sustainability, while achieving double-digit cost and inventory reductions.	Digitally enabled real-time global OEE-boosting platform	↑ 30% Overall equipment effectiveness (OEE)
		Digitally integrated E2E demand sensing	↑ 20% Forecast accuracy
		Digital twin of sustainability	↓ 38% Energy
		Digital E2E dispatching and GPS tracking	↓ 12% Logistics cost
		Digitally steered lights-out warehouse	↓ 10% Processing costs
Hitachi in Hitachi, Japan	By leveraging a range of IIoT technologies and data analytics in engineering, production and maintenance operations, Hitachi Omika Works has reduced the lead time of core products by 50% without impacting quality.	Digitally enabled operator performance management	↓ 50% Production lead time
		Digitally enabled equipment performance management	↑ 30% Capacity
		IoT infrastructure for control systems	4,000+ Applications from railway traffic management to steel plant process control
		Digital twin to simulate customer systems	↑ 70% Inspection efficiency
		Energy management system	↓ 16% CO_2 emissions
Infineon in Singapore	Enabled by a digital backbone and people development, Infineon has used data, advanced analytics and automation in its manufacturing plant and supply chain network to reduce direct labour costs by 30% and improve capital efficiency by 15%.	IoT-enabled manufacturing system	↓ 10% Material cost
		Automated material-handling and process automation	↑ 40% Operator efficiency
		Advanced analytics-enabled scheduling and dispatching	↑ 50% Personnel efficiency
		Manufacturing control tower	↓ 100% Rework
		Real-time visibility on production network, including contract manufacturers	↓ 50% Time to quarantine material
Johnson & Johnson DePuy Synthes in Suzhou, China	This site has scaled standardized digital solutions developed in other J&J sites to drive performance improvements, including increasing productivity by 15%.	E2E supply-chain visibility platform	↑ 6% Customer service level
		Virtual reality-enabled training simulator	↑ 5x Safety training retention
		Digital dashboard to monitor OEE performance	↑ 20% Asset utilization
		Digital process recipe management	↑ 15% Operation efficiency
		Automated optical inspection	↑ 85% Efficiency

Site	Change story	Top 5 use cases	Impact
Johnson & Johnson Vision Care in Jacksonville, USA	Vision Care has digitally connected its value chain end-to-end from suppliers to consumers, as well as implementing reconfigurable manufacturing, to achieve double-digit cost reduction and sales growth.	Digital customer collaboration	↑ Double-digit Conversion rate of customers
		Modular platform for rapid line reconfiguration	↓ 30% Development and launch timeline
		IIoT-enabled advanced process automation	↓ Double-digit Cost
		E2E supply chain visibility platform	↓ 13% Inventory levels
		Vision-guided robotics order fulfillment	↓ NA FTEs
Micron in Singapore	This semiconductor fabrication facility has integrated big data infrastructure and IIoT to implement artificial intelligence and data science solutions, raising product quality standards and doubling the speed at which new products are ramped.	Automation of production and maintenance	↑ 4% Tool availability
		IIoT-enabled smart factory	↓ 22% Scrap
		Advanced analytics with OEM for process optimization	↓ 50% Time to market
		Deep-learning optical defect detection	↑ 2% Yield
		Integrated deviation management platform	↓ 50% Time to resolve quality issues
MODEC in Rio de Janeiro, Brazil	Leveraging advanced analytics for predictive maintenance, a digital twin of its process plant, and a proprietary data platform to accelerate development and enable exponential scale-up of new algorithms across oil production vessels, this offshore facility has reduced downtime by 65%, making it a leader in the industry.	Digital twin	↑ 65% Downtime in first year of operation
		Machine-learning predictive maintenance	↓ 10% Downtime throughout lifetime
		Artificial intelligence to accelerate scaling of digital applications across fleet	↓ 60x Productivity
		Digitally enabled people performance management	↑ 20% Organization health
		Advanced analytics-enabled process monitoring system	↓ 95% Process shutdown risk
Nokia in Oulu, Finland	Nokia's fully digitalized 5G factory focuses on bringing together design and production to introduce new products. Implementing a range of Fourth Industrial Revolution solutions, connected by a private wireless network, this site improved productivity by 30%, and now brings products to market 50% faster than before.	Virtualization of new product introduction (NPI)	↓ 50% Prototype lead-time and 70% transfer time to EMS
		Flexible robotics to ensure high productivity and agility for continuous new ramp-ups	↓ 60% Lead-time and WIP buffer reduction
		Private wireless network to speed up NPI line re-layout	↑ 40% Mobile robotics efficiency and reliability
		Cloud-based digital data control enabling real-time process management	↓ 50% Process defects
		No-touch internal logistics automation via connected mobile robots	↑ 100% Productivity
Procter & Gamble in Taicang, China	This young site leveraged Fourth Industrial Revolution technologies to build the first lights-off operation in P&G Asia and connect its E2E supply chain. It increased productivity by 2.5x, boosted its production agility enabling e-commerce growth and improved employee satisfaction.	E2E-synchronized supply chain planning	↓ Double-digit Product conversion costs
		E2E-integrated supply chain digital war room	↑ 2.5x Productivity
		Light-off operations in making	↑ 4x Productivity
		Machine learning 3D quality inspection	↓ 60% Customer complaints
		Distribution security system	↓ 98% Supply chain counterfeit incidents
Petkim in Izmir, Turkey	This 35-year-old petrochemical facility embarked on a digital journey to drive value creation. Self-developed artificial intelligence algorithms optimize process and product pricing by analysing billions of production scenarios, resulting in EBIT improvement of more than 20%.	Yield and throughput improvement using IIOT and advanced analytics	↑ 4% Yield
		Energy optimization by predictive analytics	↓ 2-7% Energy (fuel gas, steam)
		Quality improvement by predictive analytics	↑ 2% EBIT
		Virtual reality-enabled HSE training	↓ 90% LTIR[1]
		Digital maintenance	↑ 1% EBIT
Petrosea in Tabang, Indonesia	Challenged by its remote location, this mining service provider deployed multiple Fourth Industrial Revolution use cases (e.g. optimized truck dispatch, real-time monitoring, drone surveys) that transformed the mine from a loss-making entity into a profitable one in just six months	Digital dispatch (brain of the mine)	↓ 10% Number of trucks
		Real-time crew management app	↑ 32% Production output
		Digital maintenance system using predictive analytics	↑ NA Component lifetime
		Digital operational mine planning	↓ -95% Time for survey and plan creation
		Digital control tower	↓ 95% Time to produce reports

1. LTIR: Lost time incident rate

Site	Change story	Top 5 use cases	Impact
POSCO in Pohang, Republic of Korea	This plant leverages artificial intelligence to drive productivity and quality improvements in the steel industry. It is building its own smart factory platform through a collaboration with a local ecosystem of academia, small and medium-sized enterprises (SMEs) and start-ups.	Machine vision and deep learning	↑ 4% Production output
		Visualization and digitalization	↑ NA Production output
		AI-based BOF temperature control	↓ NA Cost
		Machine learning for rolling force	↑ 5% Productivity
		AI-based automatic control	↓ 60% Quality deviations
SAIC Maxus in Nanjing, China	A challenging market environment drove this site to implement a new model for mass customization. Digitizing the value chain end-to-end, from customers to suppliers, through an integrated digital thread resulted in improved sales and reduced costs.	Digital sales: online mass customization	↑ NA Sales growth (while market at -24%)
		Digital quality management	↑ 30% Productivity and zero quality escapes
		Digital twin in production	↓ 35% Preparation lead time
		Digital supply chain	↑ 20% Productivity
		Intelligent engineering	↓ 15% Configuration accuracy
Schneider Electric in Batam, Indonesia	One of Schneider Electric's nine smart factories, this location developed a full spectrum of Fourth Industrial Revolution solutions (e.g. IIoT platform) that were then shared with the wider Schneider Electric community, including customers and partners, thereby improving the operations of the entire ecosystem.	Maintenance 4.0	↓ 44% Machine downtime
		Digital performance management tools	↑ 12% Operation efficiency and 5% employee engagement
		Quality 4.0 for defect reduction	↓ 40% Scrap costs
		Quality 4.0 for traceability	↓ 24% Customer complaints
		Integrated supply chain	↑ 70% Supplier service rate
Tata Steel in Kalinganagar, India	This greenfield steel plant is helping to set a new standard in the speed at which a factory can achieve full capacity from complete nascency. It additionally improved time to market by 50%, thanks to significant investments in digital and analytics solutions, as well as capability-building to develop the digital skills of a relatively junior and inexperienced team.	Visualization of shape of cohesive zone in furnace	↑ 7% Throughput
		AI model to predict and control silicon	↓ 33% Quality variability
		AA-driven dynamic process control model	↑ 10% Throughput
		Control system to plan and schedule manufacturing processes from raw material to customer	↓ 50% Lead time for customer delivery
		Predictive maintenance deployment	↓ NA Unplanned downtime
Unilever in Dubai, UAE	In a drive to improve cost competitiveness, a local entrepreneurial team established a factory data lake and developed and deployed at scale Fourth Industrial Revolution use cases. With limited investment and in a short time period it achieved a cost reduction of more than 25%.	Digital dashboard to monitor OEE performance	↑ 15% OEE
		Advanced analytics for quality prediction	↓ 15% Cycle time
		Digitally enabled E2E quality management	↓ 42% Material waste
		Robotic process automation	↓ … FTEs
		Smart device maintenance management system	$0 Capex spent to roll out
Weichai in Weifang, China	Weichai launched a digital transformation across its end-to-end value chain to accurately understand customer needs and reduce costs. Powered by artificial intelligence and internet of vehicles, it shortened its R&D cycle by 20% and improved operating costs by 35%.	Digitally enabled product development	↓ 20% R&D lead time
		Customer-centric Internet of Vehicle	↓ 20% Failure rate
		Real-time asset performance monitoring	↓ 10% Maintenance costs
		Automated warehousing	↓ … Cost
		Digital supplier quality management	↑ 30% Supplier quality
Zymergen in Emeryville, USA	A digital native, this bio-engineering site is using robotics and artificial intelligence on processes that have traditionally been highly manual, resulting in a doubling of its innovation rate	Sensor network and data architecture	↓ NA Scrap
		Reconfigurable modularity	↓ NA Production line design and reconfiguration time from weeks to minutes
		Dynamic, digital work instructions	↑ 40% line output
		Real-time process monitoring and control	↓ 20% cycle time
		Dynamic simulations-based scheduling	↓ 50% labour

Section 2: Secrets to scaling fast

Lighthouses operate in an entirely new way

Lighthouses shed light on valuable insights from their position at the forefront of the Fourth Industrial Revolution. Organizations that remain behind this curve would do well to consider what these leading companies have experienced during their Fourth Industrial Revolution transformation, including how they have moved beyond pilot purgatory to reach scale. Lighthouses start by changing the way they operate as a business and go well beyond adding incremental digital tools. To innovate the operating system, Lighthouses work across four dimensions to create the intended systems change. They simultaneously innovate their business processes, management systems, people systems and IIoT/data systems. Lighthouses become the scale-up vehicle for their companies.

The secrets of scaling lie in the fact that the Lighthouses create a new operating system that becomes the standard blueprint for the entire company. When paired with the six scale-up enablers and put at the core of the digital transformation architecture, they escape pilot purgatory

Essential scale-up enablers are central to success

While Lighthouses have taken varied approaches to transformation, they have demonstrated that six essential enablers are central to the success of scaling the new operating system they are innovating. These scale-up enablers represent both technological and human elements; indeed, taken together, they illustrate that the benefits of new technology and innovative infrastructure are maximized when organizations keep human workers at the centre of their transformation. While all Lighthouses have engaged these enablers, E2E Lighthouses have taken these same six enablers and have applied them across an even broader context throughout the value chain.

Agile approach to iterate continuously

To achieve scale-up, companies have built on agile principles to innovate and transform in an iterative manner.[7] An agile working mode means that organizations can collaborate and manage change continuously; this enables them to anticipate technical limitations, and surpass them when encountered. For the Lighthouses, this means iterate quickly, fail fast and learn continuously, create minimum viable products (MVPs) in two-week sprints, and bundle use cases for fast transformations in several waves, each of a few months' duration. This agile approach stands in stark contrast to year-long pilots that are designed for perfection, but are outdated once completed as the technology has evolved more quickly than the solutions themselves.

Technology ecosystem enables new levels of collaboration

A technology ecosystem involves relationships supported by technology – that is, new levels of collaboration, including data sharing, are facilitated by a digital infrastructure. Leading organizations have expanded the network of companies with which they partner to bring new capabilities to the enterprise.[8] What is unique about these relationships is the mutual exchange of large amounts of data and collaboration on technology platforms to facilitate the exchange and consumption. This is a notable shift from the age-old idea of safeguarding technology solutions and data as a competitive advantage. Among Lighthouses, these partnerships have been observed with suppliers, partners in tangential industries and customers. Open collaboration and using best-available technology are essential to staying at the forefront. Lighthouses know about network benefits, and understand that acting alone would soon leave them behind.

IIoT academies boost workforce skills

Fourth Industrial Revolution leaders are using internal and external expertise to reskill and resource the transformation teams, ensuring that the workforce receives capability-building, guidance and the skills required as they adapt to continuous change. With the number of new capabilities needed across the entire organization, there is no way around upskilling the workforce and management at scale.[9] Given the need to reskill and upskill the workforce at scale, the development of effective learning methods focused on technology becomes critical. Examples include gamification, digital-learning pathways, VR/AR learning and AR and digital custom real-time work instructions.

IIoT/data architecture built for scale-up

Lighthouses are preparing existing IT systems to design and modernize the next generation of technology capabilities, ensuring that selected IIoT architecture is sufficiently adaptable and future-proof. While initial use cases can still be hosted on legacy IT infrastructure, more advanced use cases require latency, streaming and security capabilities that most legacy infrastructure is not able to provide. Many companies argue they are not ready for the more advanced use cases anyway, and delay the modernization of their IT/data stack. Lighthouses take a different approach. They know that speed matters; they know that it's about providing their workforce with a technology infrastructure that allows innovation in a matter of weeks, breaking down the technology isolation that long-winded year-long IT

Figure 5: Lighthouses become the scale-up vehicle of the entire company

Scale-up architecture

Lighthouses serve as scale-up vehicles, and together create a single, company-wide operating system comprising dozens of use cases and hundreds of deployments.

One

Company operating system
A new, consistent, enterprise-wide way of working across value chains, people, assets and sites

Few

Lighthouses
Each Lighthouse integrates at least 20 use cases that together innovate a value chain or factory, and form a building block for the infrastructure to reach scale

50+

Use cases
Digital innovations that change how a business process is conducted

500+

Deployments
Local transformations that change the way people work across the organization

Scale-up unit

Lighthouses create a minimum viable product (MVP) of the company-wide IIoT operating system. This unit can then be replicated across the company.

People systems

Upskilled workforce with future of work-ready profiles via an IIoT academy. Agile operating model fostered through agile digital studio

Business processes

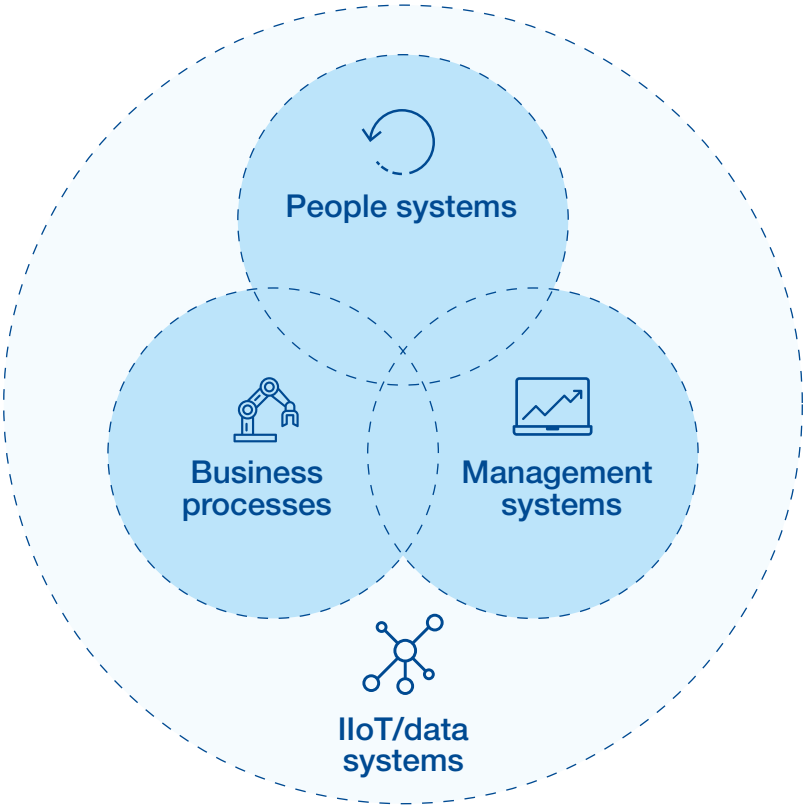
Augmented operators,[1] robotics and leaned-out and automated processes are simulated and optimized by using a digital twin

Management systems

Digital performance management – with AI-powered, personalized dashboards and alerts – creates one source of truth and eliminates all waste in decision-making

IIoT/data systems

Modernized IIoT stack and data model allows cyber connection between reality (e.g. shop-floor sensors) and IT systems,and agility to add use cases in a matter of weeks (technology democratization)



Scale-up enablers

Six enablers provide essential reinforcement in the scaling of advanced manufacturing use cases.

Agile approach	IIoT stack	IIoT academy
Agile digital studio	Tech ecosystem	Transformation office

1. Operators whose work is augmented by technologies such as artificial intelligence, augmented reality, collaborative robots (cobots) or virtual reality

projects have created. Ambitious chief information officers have been able to increase their technology-release volume and speed by a factor of 10. The building of IIoT architecture should be intentional, such that it is designed for scale-up so as to avoid technical limitations. Companies that implement this in the very early stages of (or even before) their digital transformation best enable exponential scaling across the organization.

Agile digital studios to support innovation

Leading organizations are focused on creating spaces for development teams to organize and operate using the agile approach, better engaging employees and supporting innovation across all levels of the business. To be agile, co-location of translators, data engineers, ERP systems engineers, IIoT architects and data scientists is essential, as is direction by product managers and an agile coach who makes sure that results are delivered in sprints and iterated fast.

Transformation office to support enterprise-wide change

E2E front runners have demonstrated that having clear governance to provide value assurance for an enterprise-wide programme is essential to success. Lighthouses that achieve scale across E2E and sites have established governance models to support exchange and prioritization of best methodologies, with a focus on impact and solutions, as opposed to focusing principally on technology. A successful transformation office helps drive results in three ways:[10]

- Increasing the speed of change by instituting a focused governance structure with regular action-oriented meetings
- Adding transparency and focus on impact by keeping score and maintaining accountability
- Reinforcing change management goals through open communication and interaction with all levels of the organization and recognition of employees.

Lighthouse case studies

IIoT-integrated data backbone at Fast Radius

Fast Radius, a US firm offering additive manufacturing solutions, couples a strong data backbone with digital planning to overcome inefficiencies by using total data transparency across functions.

The company's analytics platform captures data throughout the manufacturing process and uses machine-learning algorithms to provide specific feedback to all segments of the value chain. This enables root-cause problem-solving across all functions by using the feedback to target deficient areas. The platform is enabled by an open communication protocol among all of the factory's sensors in the line and central cloud data storage.

This data feedback loop yields improved design, which in turn permits a progressive reduction in quality issues and rework. Furthermore, the use of digital twins facilitates remote production, which can be viewed across all sites. This enables particular jobs to be allocated to particular sites while optimizing logistics and capacity, leading to a 36% inventory reduction. All of this has yielded a 90% reduction in time-to-market.

Agile sprint teams at Unilever

The business case designed to create the Unilever Dubai Personal Care Site (DPC) was focused on achieving a competitive advantage through improved cost and increased responsiveness. In order to accelerate DPC's progress, it was imperative to fuel its growth through entrepreneurial spirit and to embody new ways of working in the Fourth Industrial Revolution journey. This has enabled the site to focus on creating a dynamic structure that adopts sprint deployments of value creation. Additionally, these efforts have unlocked growth while improving cost and responsiveness to customers. Meanwhile, it has facilitated reorganization of workflows focused on empowerment, sustainability and value creation directly linked to driving business results.

Having realized the scope of the challenges and the cost constraints of deploying numerous third-party solutions, the factory management quickly identified an in-house team that combined a deep understanding of the challenges with the passion to develop digital solutions. An ex-process engineer was appointed to lead digital projects, supported by a team of engineers and technicians who would engage these projects on top of their current responsibilities. During the entire process of developing and delivering numerous apps affecting the routines of operators across the factory, the team adhered to some common principles: All apps depended on the common data lake, were designed on open-source platforms, provided straightforward user interfaces and employed mobile technologies wherever possible.

Along the journey, DPC also developed partnerships with start-ups that were ready to adapt their solutions rapidly to factory needs. The factory maintenance team worked with a start-up company to deliver a cloud-based, user-friendly and yet capable maintenance management system (CMMS). The software was deployed with minimal financial investment and with very low subscription cost.

DPC's digital journey was fundamentally enabled by engaging the right resources, facing everyday challenges, deploying and maintaining numerous in-house solutions – all without any major financial investments. Rather, the investment lay in the concerted efforts of passionate workers willing to collaborate on innovative efforts.

IIoT academy to drive Fourth Industrial Revolution transformation at Petkim

Petkim is Turkey's first and only integrated petrochemical company and an important supplier of raw materials for the

industry. Several use cases have been developed internally and delivered by cross-functional teams of front-line employees, with a focus on impact and value generation for the company. Essential enablers include a digital academy, incentive mechanisms for value creation and agile ways of working. As a result of these efforts, Petkim has improved its yield and throughput, energy efficiency and product quality. Digital transformation at Petkim has created $51.9 million in total financial impact, which corresponds to more than 20% of its 2018 earnings before interest and taxes (EBIT) figures.

As part of this value creation programme, Petkim established a digital transformation department. By prioritizing use cases on an impact-feasibility matrix, the company determined the initial list of projects for the digital transformation road map. Talent requirements were defined in line with use-case prioritization, and the company built both a digital transformation team and a digital institute to augment employees' digital know-how. These approaches enculturated digital ways of working on a daily basis. By bringing together digitalization and operation teams with an agile working methodology, the company has gained several benefits.

This realization became clear across the organization. Workers came to understand how using process data with advanced analytic tools could help drive improvement. By using artificial intelligence (AI) and advanced analytic tools, the plant achieved significant yield and throughput improvement. Along with the most financially impactful use cases, many additional digital enablers' projects have been put in place, including a virtual reality HSE training and assessment programme, along with maintenance operations using Fourth Industrial Revolution technology.

Senior leadership at Petkim has expressed that the Petkim Digital Institute was essential to augmenting digital awareness and capabilities within the company.

Section 3: In-depth perspectives on E2E value-chain Lighthouses

E2E Lighthouses have implemented technology that enables them to develop partnerships with value-chain stakeholders – together reshaping the customer experience. Digital technology equips these organizations to mass-produce customized products on demand, and real-time data sharing with suppliers provides the agility to react rapidly to demand fluctuation. Additionally, supplier integration enables process optimization through shared data science and advanced/predictive analytics.

This kind of value-chain connectivity also enables smart shipments. The end result of this "smart value chain" is a transformed customer experience from order to delivery.

End-to-end Lighthouses show three ways of driving value

An in-depth look at the Lighthouses has revealed the most important value drivers that led to the success of Fourth Industrial Revolution front runners. Lighthouses have been able to achieve clear impact on tangible metrics in productivity, agility and mass customization through a few essential value drivers. Specifically, E2E Lighthouses model three distinct ways to create value:

1. **Customer-centricity:** Organizations are transforming their interaction with customers. By placing the customer at the centre of process design and operations, they improve both the initial purchase experience and use of the product over its lifetime.

2. **Seamless connectivity across functions:** Seamless data exchange and transparency across functions reduces friction, allowing for more efficient decisions and a reduction of redundant communications.

3. **Continuous connectivity across organizations:** Fourth Industrial Revolution technologies enable unprecedented data collection, exchange and processing; this allows organizations to create new systems in the manufacturing space.

Lighthouse case studies

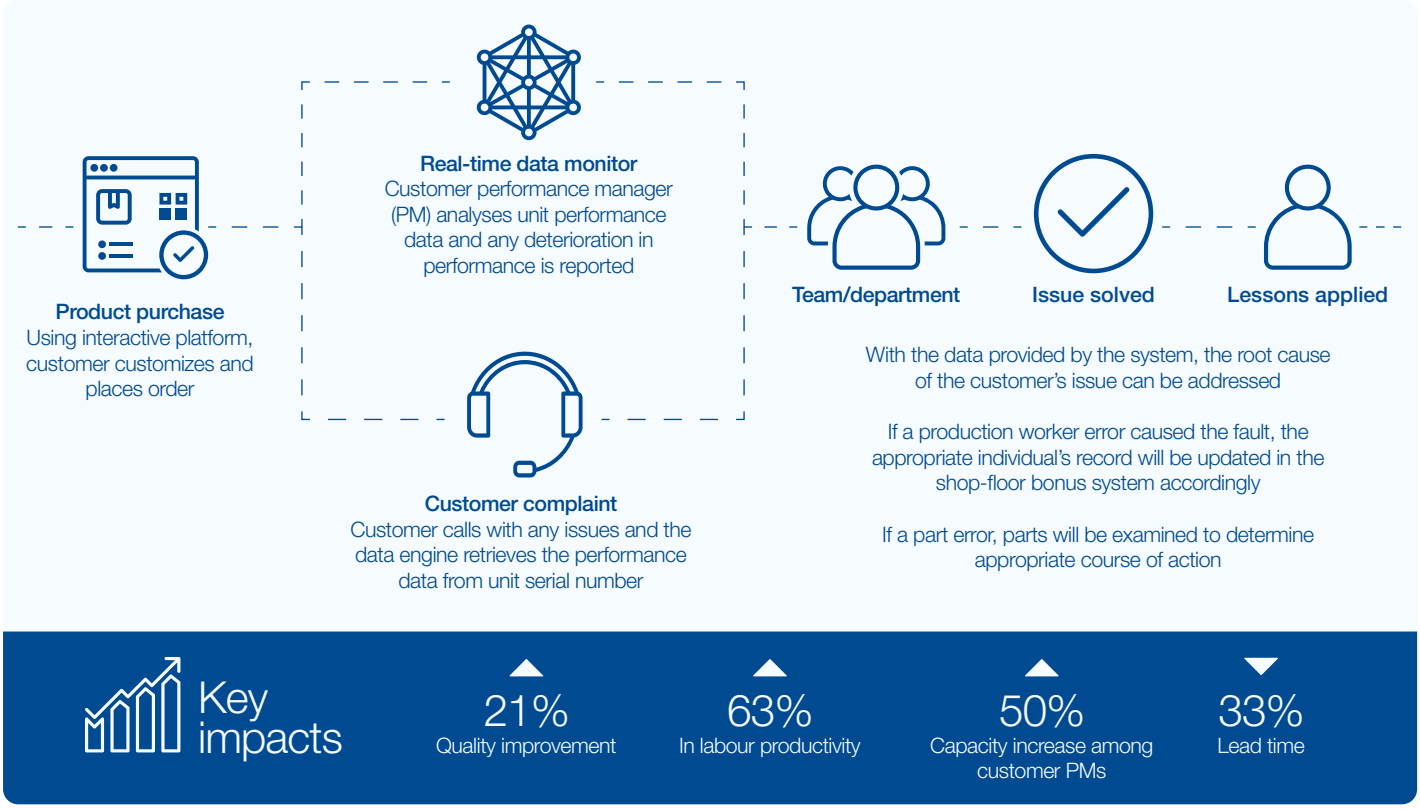
Connecting the customer with a customer-centric product ecosystem at Haier

E2E leaders place customer experience at the core of their strategy and use technology to establish a link with performance management. China-based manufacturer Haier's air-conditioning unit is achieving its transformational goal of moving from a one-time customer mindset to a lifetime user mentality by using digital technology to connect customer experience with daily operations. The impacts of Haier's approach include measurable increases in quality improvement (+21%) and labour productivity (+63%), coupled with notable reductions in lead time (-33%) and improved capacity of customer performance monitoring personnel (+50%).

The company has developed an interactive platform that enables the consumer to design and order a customized product. A customer performance monitor (PM) uses real-time data monitoring to analyse product performance, reporting any deterioration to the manufacturer. Should a customer contact Haier for support, the data engine retrieves the performance data from the unit serial number. The root cause of the customer's issue can be identified, and a correct course of action undertaken efficiently. The system helps trace accountability. If a production worker error caused the fault, the appropriate individual's record will be updated in the shop-floor bonus system accordingly. If it is a part error, components will be examined to determine the appropriate course of action to prevent further issues.

Figure 6: Haier's air-conditioning unit uses digital technology to connect customers with operations

Haier's air-conditioning unit is achieving its transformational goal of moving from a one-time customer mindset to a **lifetime user mentality** by using digital technology to connect customer experience with daily operations

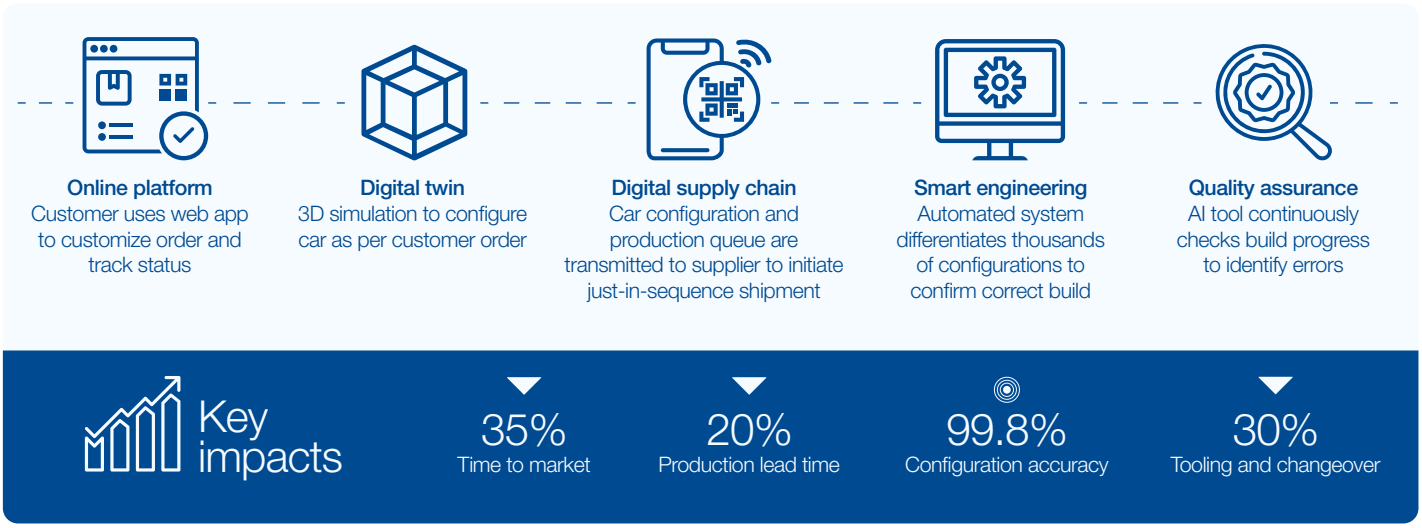


Engaging the customer in product configuration at SAIC Maxus

E2E Lighthouses continue to generate value outside the four walls of the factory site by creating solutions that enable a differentiated customer-centric experience. Chinese automotive company SAIC Maxus's application of digital solutions has dramatically improved the mass production of customized vehicles to provide significant new service levels to its customers with an order-to-delivery time of under four weeks. Impacts include a notably shorter time to market (-35%) and production lead times (-20%), near-perfect (99.8%) configuration accuracy and a substantial reduction in tooling and changeover time (-30%).

Using a web app, customers customize and place their orders, then are able to track production status. The manufacturer uses 3D simulation and digital twin design to configure cars according to customers' orders. With the efficiency of a digital supply chain, each car's configuration and production queue are transmitted to the supplier to initiate just-in-sequence shipment. An automated smart engineering system differentiates thousands of configurations to confirm the correct build, while an AI quality assurance tool continuously checks build progress to identify errors.

Figure 7: SAIC Maxus uses digital solutions to improve customized vehicle mass production



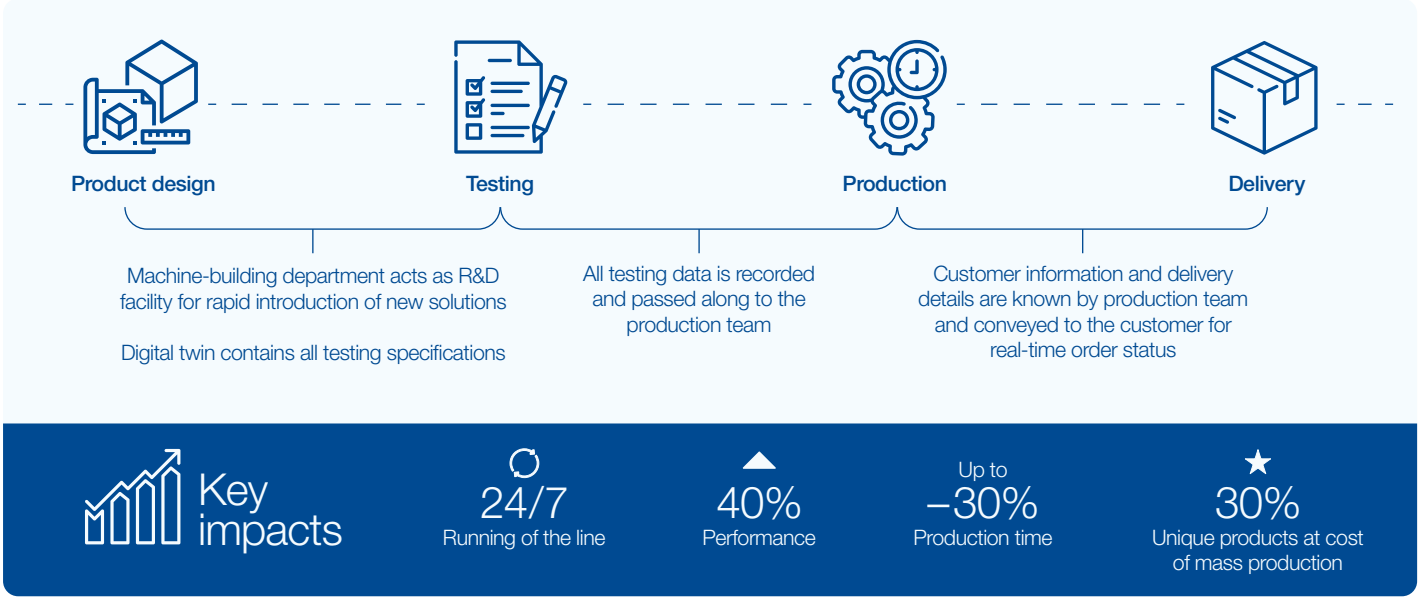
Data transparency creating greater value at Phoenix Contact

Phoenix Contact, a German manufacturer of industrial automation solutions, maximizes data connectivity and transparency to yield value creation greater than the sum of each step in the value chain. By using RFID tags containing vital information, the company ensures the transparency and accessibility of data at all steps of the process. This connectivity enables 24/7 line operation, and has yielded a 40% performance increase while lowering production time by 30%. Ultimately, this has helped Phoenix Contact realize customized products at the cost of mass-produced products.

Part of the success of Phoenix Contact's approach lies with its integrated research and development (R&D), meaning the company's machine-building department also acts as an R&D facility. This enables the rapid introduction of new solutions. For example, it can mass-produce more than 1,000 different device versions of isolation amplifiers. The company makes efficient use of digital testing and data sharing. Digital twins contain all testing specifications, and all testing data is recorded and passed along to the production team. Additionally, there is direct production-to-customer connectivity. The production team has access to customer information, enabling the provision of real-time order status and delivery details to customers.

Figure 8: Phoenix Contact uses RFID tags to endure data transparency and accessibility

Phoenix Contact uses **RFID** tags that carry information, ensuring transparency and accessibility of data in all steps of the process



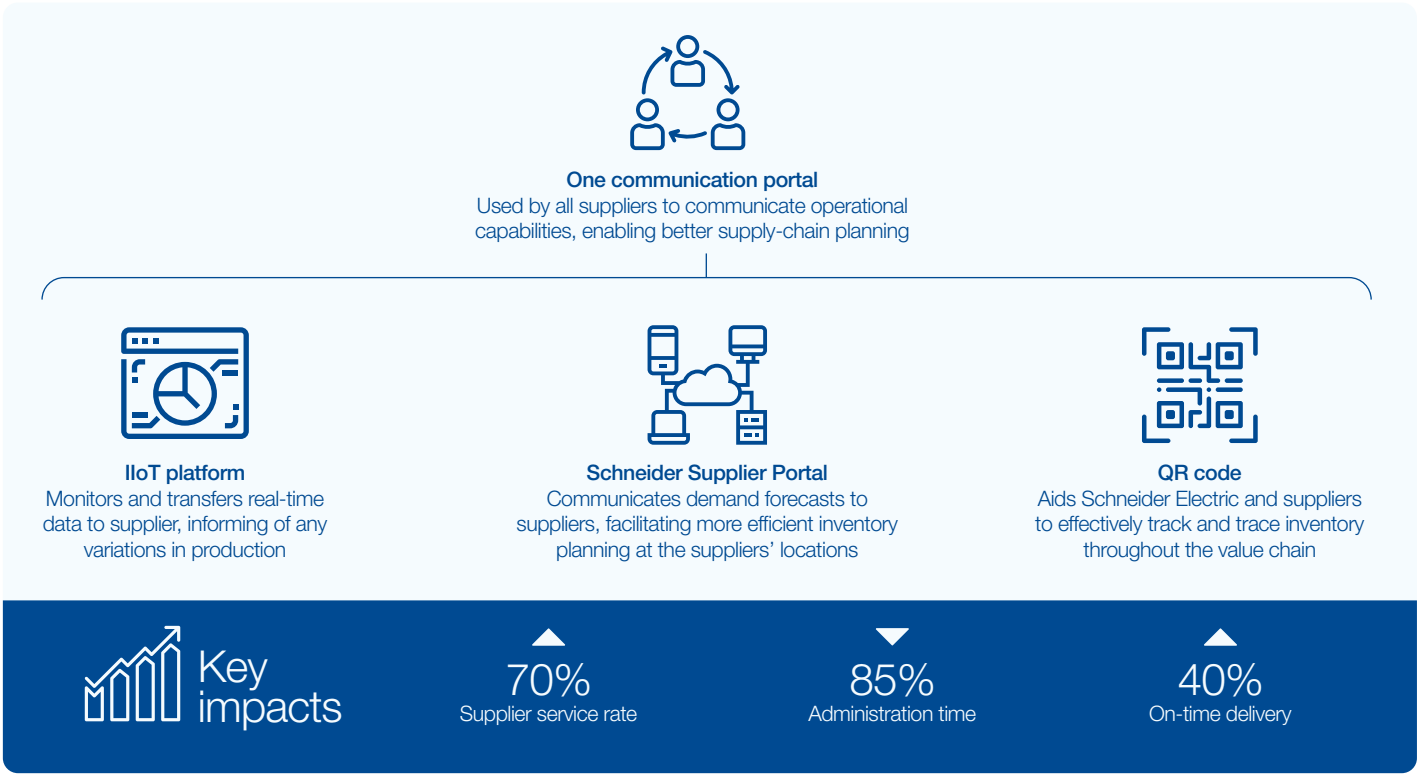
Replacing departmental divisions with cross-functional collaboration at Schneider Electric

Twenty-first-century manufacturing depends upon a complex value chain, from sourcing materials to delivering products. Anomalies and disruptions anywhere on the chain can create negative effects elsewhere, and minimizing this type of impact maximizes efficiency. Digital technology improves connectivity throughout the value chain, enabling organizations to minimize the effects of production deviations. Schneider Electric in Batam has created a platform for stakeholders to monitor and adjust for anomalies within its manufacturing processes.

Schneider's platform has established one communication portal used by all suppliers to communicate operational capabilities, thus enabling better supply-chain planning, with an overall 85% reduction in administration time. Several features of this platform are essential to its success. The IIoT system monitors and transfers real-time data to suppliers, informing them of any variations in production. This enables smart inventory planning by providing demand forecasts to suppliers, who in turn are able to undertake more efficient supply planning. This has yielded a 70% increase in supplier service rate. Finally, a smart tracking system using QR codes enables effective inventory tracking throughout the value chain. On-time delivery has increased by 40%.

Figure 9: Schneider Electric's platform monitors and adjusts for anomalies

Schneider Electric in Batam has created a platform for stakeholders to monitor and adjust for anomalies within its manufacturing processes



Lighting the way for the future of production

Business processes, management systems and people systems continue to evolve as they are integrated with Fourth Industrial Revolution digital systems. True Fourth Industrial Revolution front runners have succeeded in transforming their systems, culture and workforce to realize tangible short-term benefits throughout the value chain.

Various use cases have proven that modest investments can bring meaningful benefits to committed organizations; however, ambition and perseverance are essential to successful transformation. Vision is vital – both to see beyond the confines of traditional divisions (and break them down), and to detect potential for connecting beyond the factory.

These leaders have kept their focus on the people at the core of their operations, investing in the training and upskilling necessary to help workers maximize their potential alongside revolutionary technology. Indeed, these Lighthouses are guiding lights for the manufacturing ecosystem as it navigates the future of production.

Section 4: Human-centred future of production

Lighthouses prepare the workforce for Fourth Industrial Revolution transformation

Lighthouses highlight how a wide range of companies of different sizes and in different industries and geographical locations improved the productivity, performance and engagement of their workforce as part of their Fourth Industrial Revolution transformation. Adoption of Fourth Industrial Revolution technologies has significantly affected the tasks performed by workers. Fourth Industrial Revolution leaders have successfully navigated these changes by engaging in efforts to maximize the potential of workers across six common actions.

Common actions Lighthouses are taking to prepare the workforce:

- Empowering front-line workers to innovate by using technology and data
- Proactively building capabilities, both technical and soft, and managing talent development
- Adjusting the organizational structure to enable Fourth Industrial Revolution transformation
- Implementing new ways of working such as agile methodologies and increased transparency
- Augmenting day-to-day assembly and operational tasks through automation and technology
- Increasing levels of problem-solving and collaboration on the front line.

The following "from-to" graphic provides glimpses of these common actions playing out in the context of front-line workers' daily work and engagement. Following that, specific examples from Lighthouses will illustrate these actions in detail.

Figure 10: Common actions taken by Lighthouses to prepare their workforce (1/2)

	Lighthouse examples	From	To
Empowering the front line to innovate, using technology and data	P&G, Schneider Electric, Ford Otosan	Innovation in my production line is generated from the top	I own innovation in my production line – we all come up with ideas
		I spend my time confirming data accuracy and inputting it into multiple report templates	My data is tracked automatically from hundreds of sources and feeds in real time into scorecards
Proactively building capabilities, both technical and soft, and managing talent	P&G, Petrosea (Member of Indika Energy Group)	I learn the basics to perform my job, but have limited opportunities to develop other skills	I have a customized reskilling programme, adjusted for my abilities, with digital technologies and accelerated multiskilling
		My company relies on our internal knowledge and experience to train our team, and it is limited to the first week on the job	Partnerships with universities and other companies offer new learning opportunities to learn from others, as part of an online platform with an individual training journey
		The talent-management system is one-size-fits-all, relying on expertise	My company uses innovative external methodologies for training, blending on-the-job coaching, rotations, augmented reality and virtual stations or a digital learning centre
Adjusting the organizational structure to enable Fourth Industrial Revolution transformation	Bayer, Bosch (Invented for life), Nokia, Arçelik, Schneider Electric	I see many departmental divisions between IT functions and operations	We have a new cross-functional team focusing on digital deployment
		My team is production only – we focus only on running equipment	My team merges production and maintenance, with technicians and operators running automated operations

Figure 10: Common actions taken by Lighthouses to prepare their workforce (2/2)

	Lighthouse examples	From	To
Implementing new ways of working such as agile and increased transparency	arçelik NOKIA FORD OTOSAN BOSCH Invented for life	Solution development is finished outside of our operations before being tested	To develop a fit-for-purpose product, the agile team involves us early in minimum viable product (MVP) development, though sprint review
		My discussion with my supervisor is based on the last hour or day, with limited data that does not help us problem-solve – so it is mostly just a review	My discussion with my supervisor uses real-time and relevant data for the losses we are having, so we can diagnose root causes and make decisions quickly
Improving day-to-day assembly and operating tasks through automation and technology	Danfoss PHOENIX CONTACT	More than 90% of my shift tasks are repetitive and manual	For basic tasks, I have help from automation and cobots
		I rely on few support tools, mostly paper standard operating procedures (SOPs)	I have digital tools for real-time help (electronic SOPs, augmented reality)
		I can manage only a few machines since they have frequent breakdowns, and I have to make adjustments based on my experience	My machines are self-learning with automated centrelining and other settings, which eliminates most breakdowns and allows me to track more machines in parallel
Increasing levels of problem-solving and collaboration on the front line	arçelik Schneider Electric FOXCONN	I spend most of my time gathering data, yet most sessions lack all relevant data	I have relevant data available in a centralized source to use when needed
		Decisions in my line typically are based on experience, not data	My team relies on self-diagnosing machine-based data to make decisions

Empowering the front line to innovate using technology and data

A culture focused on engaging the front-line workforce facilitates successful implementation and ongoing adoption of technology. The importance of such an engaged culture became evident as Lighthouses were surveyed about worker satisfaction. On a scale of 1–10, with 10 meaning that front-line workers are satisfied with and actively embracing Fourth Industrial Revolution transformation, the average response was 8. The culture of these companies has allowed them to have a bias for action. In most sites, therefore, workforces were accustomed to thinking about and seeing constant change and innovation.

As an operator at the P&G site in the Czech Republic explained, regular problem-solving discussions can identify sources of loss and plan for a digital solution to help avoid them. If the source of loss is at the top of the Pareto curve, it will be prioritized and digital resources put against it. As a next step, a data scientist will spend time with operators to define the problem and design the solution. Using agile methodology, the data scientist will do several sprints to build a minimum viable product (MVP), always reviewing preliminary outputs with operators. This will continue until MVP testing and confirmed elimination of the source of loss.

Ford Otosan uses a talent development agile team with HR, manufacturing and vocational training to develop Fourth Industrial Revolution skills of innovation, working with data and creativity. “The team that used to do the measuring business is now tasked with the analysis of the data that is automatically generated,” commented a supervisor at Ford Otosan. “Now I have one tool where I can do all the admin tasks, access metrics and submit new ideas.” Workers are actively involved in each step, from evaluating and selecting new technologies to working with engineers and experts to set up new technologies in the plant.

At Schneider Electric, “digital week” uses a facilitated “hackathon” to generate new ideas. “More than 50 employees have been involved. It’s now a natural reflex for employees to suggest new ideas,” explained a manager.

Proactively building capabilities, both technical and soft, and managing talent

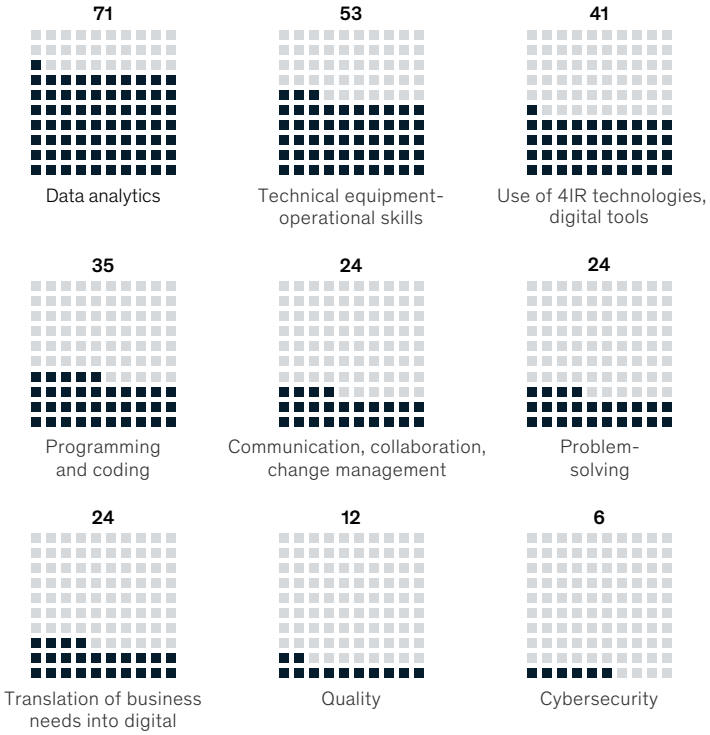
Whereas in the past, operators would learn basic skills directly related to their jobs but have limited opportunities to develop other proficiencies, now customized reskilling programmes can be tailored to workers based on their digital affinities. This builds workers’ capabilities across a broader skill set, enabling them to contribute in new ways while learning about topics of personal interest.

Similarly, companies have taken skill development beyond the on-the-job training. Innovative programmes use rotations, temporary assignments, exchanges and internships to develop skills. “Adoption of technology has allowed us to attract new talent, especially from international sources, through internships and rotations,” commented an HR manager at P&G. Effective and dynamic content delivery now blends on-the-job coaching with new approaches such as augmented reality, virtual reality and digital learning centres. An operator at Petrosea offered an insight about new types of training, such as “gamification”, which employs competitive, game-based learning tools: “When gamification for training was first introduced, I was sceptical, but became excited when I realized how fast and easy it made learning digital skills.”

Lighthouses' reskilling efforts have focused on a number of data-specific and Fourth Industrial Revolution-specific skills, most commonly addressing the increased use and availability of data, as well as site-specific technology (as shown in the figure below).

Figure 11: Manufacturing Lighthouses have targeted reskilling to support new and existing roles

Top skills that require training in Fourth Industrial Revolution plants, % of Lighthouses that mentioned a skill



Source: McKinsey & Company

Notably, no Lighthouse executed Fourth Industrial Revolution transformation entirely on its own. Each used partnerships, either to acquire new knowledge or collaborate in developing new knowledge. According to a 2019 survey, 55% of Lighthouses are using partnerships with universities or other educational organizations to gain knowledge and talent. Moreover, 71% of Lighthouses have used internal academies and capability centres in some ways to build capabilities.

Adjusting the organizational structure to enable Fourth Industrial Revolution transformation

The mix of roles is changing, with traditional roles now incorporating a different combination of data-related tasks while new roles are added to meet increased data, programming and digital needs. Some of these new roles are at the plant level, while others have emerged at the central level, with a focus on the Lighthouse sites. In total, 71% of companies adjusted their organization in one or more ways to enable and make Fourth Industrial Revolution transformation a priority.

Older models of organizational structure, which typically resulted in divisions between IT functions and operations, are seeing new, cross-functional teams focusing on digital deployment. Ad-hoc pilot projects run by central teams with little involvement of the shop floor are being replaced by a model that sees data scientists and data engineers working closely with front-line workers. As a digital project manager at Bayer explained, "We have hired data scientists on site to help drive our AA use cases and translate business needs." The following are several examples of new site level and central digital roles.

Digital manufacturing manager (DMM): At Arçelik, a DMM is reporting directly to the chief digital officer in the interest of better support from general management. This makes for a direct link between production and IT. The DMM supports the plant manager in reaching the production KPIs related to quality and throughput. As a result, the division between production and IT has been eliminated.

Digital transformation department: At Schneider Electric, Batam, this new department facilitates the rotating in of a project manager, who typically spends one year in position but has the flexibility to stay for a longer or shorter duration. The role's purpose is to work on digital transformation projects that have been selected for the road map. Focus areas include development of solutions with the SME, line leaders, managers etc. in the relevant departments.

Corporate-level programme: Bosch's corporate-level programme focuses on enabling digital transformation, including methods (agile methodology, transformational leadership etc.) and technology (IT, data analytics etc.).

Small expert team: Nokia has created a small expert team of 10 people for technical development and implementation of new technologies. It employs a new engineering team set-up, including focus on cross-function for Fourth Industrial Revolution innovations and deployments at scale.

Implementing new ways of working: agile and increased transparency

The use of technology at plants has introduced agile methodology to develop tools and applications in a shorter time frame while incorporating the perspectives of people at all levels of the organization; this has brought a new level of transparency and communication tools for the front line and the management team.

Lighthouses have most commonly employed agile methodology for Fourth Industrial Revolution use cases, R&D and IT projects. Two-thirds of Lighthouses mentioned using it in some way for application development and computer programming-related use cases. Nokia uses agile methodology for the above-mentioned expert teams. Arçelik has applied it to project management in order to execute Fourth Industrial Revolution use cases and to manage its R&D and IT projects. The company created agile teams with members from production, maintenance, engineering and quality as needed, depending on the project. While front-line workers are not engaged day-to-day with the agile

methodology, they are consulted and shown the MVPs periodically. Similarly, many Lighthouses are "loosening up" on the ROI-centric project approval process, to avoid limiting Fourth Industrial Revolution idea generation.

Communication within plants has become more efficient and transparent with the use of smartphone apps and real-time availability. Whereas discussion between operators and supervisors was previously based on limited data from the last day's or hour's operations, those parties can now use real-time data and facts to diagnose and make well-informed, expeditious decisions.

Push notifications and status availability on smartphone apps present multiple modes and rounds of point-to-point communication, e.g. from a line manager to a quality engineer, to a second-shift line manager. At Ford Otosan, a custom-designed mobile app contains numerous functions, including a dashboard that provides visibility of all KPIs, allows supervisors to make and approve investment requests, and submit and manage ideas. Bosch uses an internal communication platform that enables people to interact using chat and video applications. Smartphone applications share data, production notifications and other types of communication electronically. This efficiency of communication enables front-line supervisors to spend more time in face-to-face problem-solving with their teams.

Augmenting day-to-day assembly and operating tasks through automation and technology

While companies have focused on automating basic motions for many years, not all assembly tasks can be automated yet due to complexity. Hence, companies have concentrated on eliminating non-value add time and making the jobs of the operators easier through digital tools such as electronic standard operating procedures (eSOPs) and augmented reality. Where companies previously had few support tools and mostly paper standard operating procedures (SOPs), automated data collection now enables improved tracking of production and quality. Digital help tools have replaced paper documentation and quality guidance manuals, enabling workers to spend more time on activities such as problem-solving and basic machine maintenance. At Lighthouse sites, Fourth Industrial Revolution transformation has involved movement from repetitive manual tasks for more than 90% of the shift to some automation or "cobot" partial automation of basic tasks.

Based on an interview with the team at Danfoss, the advantage of digital "poka yoke" error-prevention tools and dynamic eSOPs lies in the ability to check quality at each step. Phoenix Contact has developed an application that guides operators through steps and tracks their accomplishment, helping operators build success in their jobs. The company reports that 100% of operators who work with the Fourth Industrial Revolution machines prefer working with them, and an operator commented, "Working on Fourth Industrial Revolution machines gives me more opportunity to learn and more time for maintenance and trouble-shooting." In another example of digital approaches to procedures, Bayer has integrated the use of wearables to improve and digitize paper-based SOPs to reduce changeover time.

Increasing levels of problem-solving and collaboration on the front line

Problem-solving tasks have been transformed and have become more frequent, more targeted and more efficient through the use of single-source-of-truth data visible and available to all parties across a plant. In the past, most time was spent gathering the data required to solve problems, yet most work sessions lacked relevant information. Now, relevant data is available from a centralized source. Whereas past decisions were typically based on historical experience, teams can now rely on self-diagnosing machines. A machine operator at Foxconn reflected on this change, commenting, "My role has changed from loading and other manual tasks to monitoring, diagnostics and problem-solving."

Thanks to spending less time gathering data and building reports, supervisors have more time to spend on the shop floor working directly with their teams. Effectively, then, the true role of middle management in this new dynamic is as a coach leading front-line teams who are actively engaged in problem-solving. Supervisors at Arçelik describe spending the whole day on the shop floor, instructing operators in navigating the new systems and coaching them through product introduction, helping with the ramp-up of fresh variants. As one remarked, "Now that I don't need to spend time collecting data, I can spend more time on the shop floor to problem-solve and coach my team members."

Schneider Electric, Batam, has realized efficiency gains through real-time performance tracking "from shop floor to top floor" by implementing digital escalation and a capacity to stop the line if there are quality issues. By enabling quicker responses and faster decisions, this has boosted operational efficiency while improving employee engagement. The transparency of data has yielded cultural improvements – with more trust in the data has come increasing trust among people, as workers feel empowered by the digital tools. Other gains in efficiency have come from shifting to paperless approaches, reducing informal communication (phone calls, social media chat applications) as well as less wasted time spent following up or chasing people for more data.

Section 5: Call to action

In this section, we present four opportunities for the Global Lighthouse Network to further strengthen its impact and footprint. Corresponding to each, we issue one or more challenges for the network to take on.

Achieve carbon-neutral manufacturing by 2025

Manufacturing accounts for 54%[11] of the world's energy consumption and is responsible for 20%[12] of CO2 emissions globally. While industry leaders recognize a need to alter this status quo, they struggle to define actions with a clear business case for investments that reduce their environmental footprint. However, some Lighthouses are already leading the way on the environmental front. Recent advances in manufacturing that combine technological innovations with emergent business models provide an opportunity for companies to build a carbon-neutral manufacturing ecosystem while driving competitiveness and growth.

– *Challenge: All Lighthouses commit and act to become carbon neutral by 2025.*

Enable technology diffusion across production networks, including SMEs

The full benefits of the Fourth Industrial Revolution in manufacturing can be realized only if complete value chains and production systems are transformed, by taking SMEs on board. Lighthouses need to exercise responsible leadership by actively supporting the diffusion of Fourth Industrial Revolution technologies through their entire production networks, which include suppliers of all sizes. This will not only lead to improved overall results and return on investment in technologies, but also ensure knowledge is spread more equally to accelerate innovation.

– *Challenge: Nominate first company-wide Lighthouses in 2020, recognizing companies that have scaled Fourth Industrial Revolution technologies throughout their production networks.*

– *Challenge: Develop a coaching programme for each Lighthouse to support and sponsor a select group of SMEs in its value chain, in order to accelerate their transformation and be recognized as SME Lighthouses by 2022.*

Invest in capability-building and lifelong learning

Public and private organizations, academia and civil society must work together to help the workforce transition towards the future of manufacturing. This will require retooling the education system, investing in large-scale reskilling and upskilling efforts and developing a learning environment favourable to lifelong learning that enables continuous adaptation. This will help workers increase their mobility opportunities and help companies fill the existing skills gap, which has been recognized by Lighthouses as one of the barriers preventing the scale-up of use cases.

– *Challenge: Lighthouses form a consortium to identify the skills most critical for the future of advanced manufacturing, and shape the development of new training curricula.*

– *Challenge: Lighthouses endorse the Global Standard for Lifelong Learning and Worker Engagement to Support Advanced Manufacturing.*[13]

Upgrade regulations, policies and industrial development strategies

Governments can play an active role in supporting and accelerating the ongoing transition by putting in place new strategies, initiatives and programmes aimed at ensuring the diffusion and adoption of technologies. Some countries have already invested in national public-private platforms to raise awareness of the Fourth Industrial Revolution in manufacturing, support the development of new use cases and enable collaboration between research institutions and companies.

– *Challenge: Global Lighthouse Network facilitates public-private dialogue and shapes the development of regulations, policies and strategies through a series of activities and learning opportunities designed for policy-makers.*

Annex: Inside perspectives from the Global Lighthouse Network

AGCO/Fendt: manufacturing of high-complexity and low-volume products

AGCO/Fendt, Marktoberdorf, Germany

Farmers need advanced agricultural technologies to meet the demands of a growing global population. For AGCO/Fendt, a global manufacturer of tractors and agricultural machinery, this has sparked product portfolio expansion and the invention of new technologies. Providing users with a range of different products is crucial to meeting these demands; however, offering this range requires flexibility in manufacturing. AGCO/Fendt has achieved this by applying digital solutions coupled with intelligent line design. This has enabled the company to build nine tractor series – ranging from 72 to 517 hp, including the biggest standard tractor on the market – at a batch size of one, on a single assembly line, with efficiency and flexibility. As a result, 95% of Fendt tractors built in one year are unique configurations.

Peter Bebersdorf, Director Tractor Operations, outlined the industry challenges: "Natural hedging in manufacturing caused by global uncertainties, increasing customer centricity and disruptive innovations force assemblies to become more flexible than ever. Fourth Industrial Revolution methods help us to handle these new challenges, extending flexibility, securing quality and increasing productivity with satisfied employees." Digitalization has been crucial to manufacturing high-complexity and low-volume products. To tackle the challenge in manufacturing, digitalization is divided into three main elements: digital consistency, digital twin and technology. Digital consistency – uniform design of systems – is the foundation of all digital solutions, including software and hardware. Digital twins are subdivided across product, process and system twins. Intelligent combining all three provides the simulation insights needed to optimize manufacturing processes, materials and product flow across low-volume lines handling complex products. Technology is fundamental to product line solutions, such as a variable takt time solution, virtual build and advanced analytics.

The variable takt time solution is a vital use case for managing complex, batch-size-one assembly of multiple products on a single line. The use of IoT and a holistic manufacturing execution system (MES) allows each specific takt to be adjusted independently of other products without interfering with them. The combined impact across AGCO/Fendt has led to a 60% lower cycle time and a 37% assembly line volume increase. Upstream product development innovation also contributes to the successful manufacture of highly complex, low-volume products. Advanced analytics have been particularly impactful in quality monitoring, shortening the field failure detection response time and solution implementations, leading to a 30% reduction in time-to-identify quality issues. This facilitates early identification of field quality failure trends, despite the limited volume of production. Key enablers have included a consistent data platform across all systems, a dedicated manufacturing innovation team, pilot showcases on the factory floor and a Fourth Industrial Revolution ecosystem, providing links to universities and start-ups. Ekkehart Gläser, Vice-President Manufacturing and Quality, commented on this inclusive approach: "By implementing digitalization into the Fendt 2020 Strategy, we've ensured that the entire organization, from front-line worker to managing director, knows about the importance of this topic. This can only be achieved in a cross-functional effort towards a clear common goal."

Volker Kurfess, Director Global Quality, explains how digitalization has helped tackle high-complexity, low-volume manufacturing: "Digitalization unleashes an important effectivity potential, which lies in the front-loading of activities where different functional areas need to work together to reach an optimized solution … For example, when it comes to the early detection of field failures, advanced analytics and the automation of intelligent algorithms help to create alarm lists. Hence, cross-functional expert teams can concentrate on problem resolution and not on identification. With both examples, teams have embraced the new way of working, leading to superior results and bottom-line impact."

By coupling digital solutions with intelligent line design and advanced analytics, AGCO/Fendt has achieved the kind of heightened versatility that enables it to engage in highly complex, low-volume manufacturing of its range of agricultural machinery in a viable, efficient manner.

Ford Otosan: leader, evangelist-driven digital transformation

Ford Otosan, Gölcük, Turkey

Ford Otosan began this change journey after making a major modification to its vision back in 2015. Describing innovation and engagement with the Fourth Industrial Revolution as one of its strategic pillars, the company changed its organizational structure and priorities. It took almost a complete year of search and benchmarking to understand that the Fourth Industrial Revolution was not fully deployed anywhere in the automotive space. Use cases

were present, but they were general and vague. The inability to adapt to existing proven use cases triggered the problem-based design approach. The impact of the approach is substantial, including a 6% increase in overall output without additional robots or labour, die-manufacturing time reduced by 47% and capacity increased by 31%.

Like most automotive manufacturers, Ford Otosan embarked on this journey with some advantages relative to other industries. It had well-integrated automation systems with interconnectivity features already installed. Two important elements were missing, however. The first was a framework that could facilitate data collection and analytics. The second was the type of mindset change that would enable the firm to assess the projects during the initial phases when uncertainty about ROI presents a challenge. Once the framework was set, it became clear that projects resulted in double the expected ROIs. Robot failures accounted for 49% of total failures, and an annual 8.7% failure rate reduction was achieved through a system that enables real-time robot data collection and analysis. Together with automatic bottleneck analysis tools and a cycle-time management system, the site realized an increased overall output of 6%. Nurullah Com, maintenance technician, explained the benefits. “Better data resolution increases our corrective measure effectiveness. We have a sense that we are managing the line and making the decisions, not falling victim to unforeseeable events.”

Problems were listed and sorted according to their risks and costs. Making sure that scarce resources were spent in the correct places, the company applied agile principles to form cross-functional groups combining IT and plant teams, establishing shared ownership of issues. Drawing on this change, Ford Otosan increased efficiency, capacity and employee engagement simultaneously without significant investment. In parallel, the Ford Otosan team employed an inclusive, bottom-up approach: making all team members part of the transformation and empowering the shop-floor management team to maintain ownership of the solutions. This became a strong enabler for the organization to internalize the changes and increase the effectiveness of the projects as implementation times got shorter each time.

After a few successful projects, Otosan’s whole organization embraced the approach and started to divert their resources more towards Fourth Industrial Revolution projects. The momentum generated became “a virtuous cycle within the organization”. The factory became more inclusive, spurring projects kicked off both by leadership and field employees – some of which were even scaled into different companies within the group. This inclusive approach went even further as practices were enhanced by expanding the knowledge into the local university. Additionally, Ford Otosan built and donated to the local community a vocational high school with operational production stations and a specific Fourth Industrial Revolution lab capable of demonstrating eight different automotive production use cases. This facility enables students to be trained before starting to work for any firm; moreover, it helps with upskilling of existing Ford Otosan employees. The company cites a 45% increase in employee engagement scores across three years as another proof of acceptance of the mindset and culture change driven by this inclusive approach.

Transformation of tasks and jobs comes with Fourth Industrial Revolution transformation. Alper Özçift, Body Shop Production Manager, explained this experience. “With new shop-floor information system applications, our job descriptions changed drastically. We used to have three highly analytical members of our team to check cycle-time conditions of every station for every different derivative. Having the data enables services that check for irregularities and provide instant notifications. Workers who used to devote efforts to measure cycle time are now freed up to work as data analysts, finding improvement possibilities and creating far more value than they could before.”

Güven Özyurt, Operations Assistant General Manager, offered reflections on the transformation. “It might be seen that there were no reasons for a competitive firm like Ford Otosan to make such a radical change. Many companies drive for change when they are in difficult times. But our belief was that past achievements do not assure the future, so we chose to maximize our potential by refining our vision. The bottom-up approach was difficult at the outset, but we are proud that the whole organization is working as one body towards a common goal. We are not just preparing our facilities and our employees for future, but also considering the total value chain around us to deliver impact to our customers in the best way.”

Henkel: driving sustainability in concert with quality and cost

Henkel Laundry and Home Care, Germany

Henkel operates in three primary business sectors: adhesive technologies, beauty care, and laundry and home care. The firm aims for “climate-positive” sustainability, with a goal of tripling its value creation in relation to its environmental footprint by 2030. The company’s efforts engage a data-driven strategy under the banner of the “Laundry Data Foundation”. According to Dirk Holbach, Senior Vice-President and Chief Global Supply Chain Officer, Laundry and Home Care, “The Henkel Laundry Digital Backbone is a digital E2E platform based on advanced cloud technology. It connects all locations worldwide in real time to form an ecosystem that gives us a strong edge in digital transformation.” The company has transformed its factories to be more integrated, cost-effective, sustainable and efficient. Henkel estimates that its efforts translate to a 36% lower sustainability footprint. The achieved energy savings alone is equivalent to the energy consumption of approximately 400,000 people. Meanwhile, Henkel has seen a 10% reduction in processing costs and a 25% reduction in logistic costs.

The groundwork for the data foundation was laid in 2013 with a digital backbone connecting all factories to a central data repository in order to collect real-time energy consumption data. The impetus came during certification

for the new ISO 50.001 Energy Management Standard, when auditors challenged Henkel to take measures to better understand the company's global specific consumption. Since then, the company has built a unique, scalable platform based on real-time, always-on and globally connected digital shadows of 33 sites and 10 distribution centres. Johannes Holtbruegge, Senior Manager, Digital Transformation, describes the growth. "It has been thrilling to see the development of the digital backbone from the first screens coming to life in 2013, showing operators simple line diagrams, to having real-time analytics, benchmarking and machine learning insights now in 2019."

Henkel has augmented data acquisition while integrating data evaluation and optimization tools, which it pilots on a small scale and rolls out quickly into the global production network, ensuring standardization of measurements and calculation of KPIs. The main measures are sustainability score cards, online real-time metering at the individual process level, online benchmarking and monthly reporting. The backbone enables Henkel to collect, store and visualize data globally. A single-source-of-truth connects to legacy systems, enabling cross-domain knowledge generation for all 6,500 employees. Approximately 3,500 interconnected sensors measure electricity, fossil fuel, water, compressed air and steam consumption, while standardized equipment enables global benchmarking of energy consumption and identification of optimal parameter deviations. This has reduced Henkel's energy consumption by 38% and its water consumption by 28%, despite an increasing market share of liquid detergents.

One vital success factor is data transparency. Henkel's Data Foundation has more than 1,800 internal users from all levels of the organization with full access to any site, process or sensor around the globe. Wolfgang Weber, Head of Global Engineering and Digital Transformation, Global Supply Chain, explained the enthusiasm and changing workforce needs. "We've sensed a tremendous interest in digital tools and processes in all our plants worldwide. We collect data at over a billion data points daily and growing. We need employees with new profiles and qualifications, such as engineers with an affinity for digital technologies, data analysts and data scientists, as well as IIoT experts."

Using fifth-generation cloud computing and a systematic digital upskilling programme, Henkel has engaged a successful data-driven Fourth Industrial Revolution approach to sustainability, in concert with quality and cost. It has achieved a substantial increase in production of heritage products and gained a market-share increase, all while reducing its energy use, water use and waste production in a safer, more cost-effective factory.

Johnson & Johnson: reducing time to market and enhancing patient experience

Johnson & Johnson Vision Care, Jacksonville, Florida

The global contact lens market has grown by more than 5% annually since 2014. As a market leader, Johnson & Johnson Vision Care strives to bring new wearers into the market while developing new products for them. Reducing cycle times for the launch of innovative products is vital to this effort. To tackle this challenge, the company built on its long history of using technology as a competitive advantage. It developed an adaptive flexible modular platform (FMP) for rapid new product introduction. This involved interchangeable blocks for rapid line reconfiguration, advanced simulation for accelerated scale-up and a modular software platform for seamless line qualification. This has enabled a 30% faster time to market on new products.

In order to create the additional production capacity dedicated to accelerated new product development and new production volumes, production lines were upgraded with Fourth Industrial Revolution technologies. These included an IIoT-enabled, fully validated closed loop, adaptive process control, advanced robotics and intelligent material handling. Those applications have maximized yield, reduced downtimes and resulted in an 11% overall equipment effectiveness (OEE) improvement and enabled a 50% reduction in the time to scale worldwide volume of new products.

The innovation to bring new products to market faster with enhanced patient experience extended into overall planning, the supply chain and final delivery. A complex chain serving 12,000 daily personalized delivery services and capable of accelerated scaling of new products into the pipeline is powered by an interconnected, visual-value-chain control tower. The tower provides all functions (warehouse, manufacturing, planning, sales) with real-time data at hand, enabling effective, immediate decisions. This optimizes manufacturing efficiencies, inventory and service levels using 3D-vision-guided robots powered entirely by sunlight. Michael Mullaney, Director, Vision Care Customer and Logistics Services, commented on the downstream impact, "The technology deployment across all aspects of our supply chain and commercial team has eliminated transactional activities, allowing the business to focus on personalized customer interactions while sustaining service levels and offerings across a rapidly expanding product portfolio, ensuring we fill more customer needs."

The timely introduction of new products needed to be matched by an enhanced patient experience to secure market penetration and user loyalty. To meet this need, J&J Vision Care developed augmented-reality tools for testing product comfort, along with a mobile/web platform powered by advanced analytics algorithms to connect manufacturer, patient, professional opticians and retailer. The impact has been a double-digit improvement in the conversion rate of

fitted consumers to purchasers, which in turn led to double-digit global sales growth over five years.

The journey to deliver new solutions and better patient experience has been enabled through standardized collaboration models with academia, internal centres of excellence, industry partners and government. Barry O'Sullivan, Vice-President of Manufacturing, Vision Care, summarized how accelerating time-to-market and the supply chain has benefitted customer service. "Since 2014, we have identified and resourced user-led analytic programmes that have enabled us to repurpose and enhance our supply chain and better support our sales growth. These initiatives have been led by people closest to the customer: our planners, our quality team, our delivery team, our manufacturing engineers and operations management in the plants. This enables everybody closest to our customers, and closest to the challenges, to make better-informed, faster decisions, not just for today, but also for the longer term. Most importantly, it enables better job satisfaction for all of us as well!"

Petrosea: overcoming a shortage of skilled labour

Petrosea Mining – Kalimantan, Indonesia

The mining industry faces many challenges, including uncertainties in the commodities market, a shortage of skilled labour and increasing input costs. A remote location limiting its proximity to major population centres and universities compounded these challenges for Petrosea Mining, located in Kalimantan, Indonesia. The company responded by focusing on worker upskilling and training through innovative programmes, taking advantage of new digital tools for a connected workforce to build knowledge, enthusiasm and capability while optimizing daily operations at its remote site.

Iman Darus Hikhman, General Manager, Mining and Mine Services, offered a senior leadership perspective on the experience. "For a long time, our mining operation had been running as a traditional business with continuous improvement, but with no step-change innovation … We had too many variables, with too much data to analyse; or, we had no data; or the available data was not integrated such that we could draw insights and develop actions plans from it." For Petrosea, digitization presented the kind of step-change that enabled the company to harness data and connectivity for genuine transformation. Aiming to become a leaner organization while developing skills essential to Fourth Industrial Revolution adaptation, Petrosea has prioritized technical and business skills training along with leadership and character building.

To bolster technical capability, Petrosea implemented an intensive training programme for operators and mining supervisors. Supervisors were trained weekly on the most effective mining practices and using new technology tools. The trainers also supported field deployment of these new ways of working to ensure implementation without any detrimental impact on day-to-day operations. At the same time, thousands of front-line workers were trained in new digital tools. Petrosea has launched a technical training mobile app with a popular gamification aspect. It has digitalized the learning process while building excitement and further inculturating continuous learning. Workers are now able to focus training on topics of interest, anywhere, at any time, and engage in competitive learning with colleagues. It encourages employees to read standard operating procedures (SOPs) to better understand and deploy them. In the old system, SOPs comprised digitized documents running to several pages, accessible through the company intranet. The redesigned approach presents SOPs via the Minerva mobile app, which enhances learning by favouring visuals over text and employing animation. To create more excitement and compliance towards reading and understanding the procedures, workers compete by responding to more than 3,000 questions on various operating procedures. As they engage with these quizzes, they compete for a placing on a leaderboard, which ranks them from "soldier" to "general". The approach has increased compliance to the highest level ever and has created a positive safety culture.

Moreover, the gamification aspect gives company leadership a valuable insight into employees' understanding of SOPs. "I am very excited and happy with the Minerva mining operations digitalization," commented H. Katimin, Deputy Project Manager, Tabang Project. "Now information about production, equipment, productivity and performance is readily available in our pockets. We can identify problems and act immediately. This has also helped us in training our workforce with specific skills based on their operational behaviours." Petrosea also selected 20–30 top performers and potential future leaders in the organization to be change agents. They were given a customized training programme focused on developing leadership skills and personal character. Various topics such as problem-solving, teamwork, communication and interpersonal coaching were covered on this six-month programme, with direct on-the-job practice to ensure the skills had relevance to their daily work.

Lastly, Petrosea launched a reskilling programme to bridge the gap to the new world of digital and analytics. Digital boot camps were launched to educate selected members of the workforce on the concepts of agile methodology, big data, IT security and digital analytics. The programme equips workers with new skills, enabling them to fill new positions such as data analyst, system developer and digital product owner. Iman Darus Hikhman, the Mining and Mine Services General Manager, provided an insight into the substantial effects of digitization at Petrosea: "Not only can the team react faster, but they can also predict what will happen next time. In a span of six months, we saw performance improvements along with boosted spirits. We now see optimism and renewed energy as we face challenges. The results we have achieved are tremendous, from increased production to cost reduction. Digitization has done more than improve performance. It has shifted the mindset of our people."

Groupe Renault: scaling across the production network – from one plant to many

Groupe Renault Curitiba plant, Brazil and Cléon plant, France

The fast-paced evolution of the vehicle market poses unprecedented challenges to the automotive sector. To address increasingly complex consumer needs, emerging mobility services and the future arrival of autonomous/connected vehicles, Groupe Renault embarked upon digital transformation in 2016. Groupe Renault's Cléon and Curitiba plants are at the forefront of this transformation, having launched unique digital projects that have since been scaled to other manufacturing sites.

The 60-year-old plant at Cléon in France managed to increase productivity by 45% and cut warranty costs by 20% by adopting smart automation solutions and digitalization while leveraging partnerships with start-ups and universities. Renault installed cobots and AGVs to optimize plant flow and process ergonomics, while reducing cycle times. Digital tools connected the workforce for faster decision-making and collaboration, increasing shop-floor operations by 12.5%. A full digital energy management system reduced consumption by 5.8% over one year of deployment.

Renault Curitiba in Brazil improved production metrics and connected the supply chain end-to-end with customers. Each year 290,000 vehicles are tracked using RFID towards delivery, reducing shipping time by 30% and boosting on-time delivery to 95.4%. An online digital sales platform led to sales of more than 10,000 units, sharing real-time data on orders with supply and production. In terms of process automation, AGVs and cobots supported a 30% reduction in per-unit conversion cost, allowing the Curitiba plant to climb up 10 positions in internal performance ranking in three years.

Groupe Renault then faced the challenge of deploying the same transformation across its manufacturing network, including approximately 73,000 employees in 40 factories and 13 logistics sites in 16 countries. Giuliano Eichmann, Head of Industry 4.0 for Latin America, described the impact at work: "Today we have a massive amount of data available; now my challenge is to turn it into simple, relevant information for users. With agile methodology, we can find all the power that advanced analytics can provide. To succeed, it must be accompanied by a digital-driven organizational change." Other factors critical to effective scale-up included global digital governance that translates into local digital governance for each plant and the "copy and paste" of technical foundations. A "connected plant" task team has been established to deploy the IT infrastructure, installing Wi-Fi over more than 4,900 ha of buildings, 60 local data servers and the LoRa network in all Renault plants. Renault began digital deployment across all manufacturing plants and the supply chain in 2018, in most cases avoiding getting stuck in the proof-of concept (POC) phase.

Today, more than 70 Fourth Industrial Revolution technology projects are under deployment in all sites. Innovation comes from the shop floor: 80% of projects start from local teams in plants or logistics divisions. There are many examples. A paperless initiative from Douai has now spread to all plants. The Operator digital workstation project is based on programs from multiple plants' initiatives: "Help call" from Maubeuge, "OK start check" from Douai and "Defect detection guidance" from Curitiba. The supervisor tablet program started in Valladolid has now been deployed in all plants. According to Luis-Javier Fidalgo-Aller, a front-line assembly-line supervisor, "The tablet is like having a mobile office. Before, I spent almost two hours moving between my office and workstations or end of line. I now save about 45 minutes, not having to move around. I also have access to everything in real time along with useful features, such as a camera. The tablet adds value, allowing me to stay on gemba, check actions and perform better. My experience? Fantastic. It's the factory of the future!"

Eric Marchiol, Head of Industry 4.0 for Renault and the Alliance, emphasized that strong management support is critical to success in scaling across the production network. "To achieve worldwide roll-out, mindset change was as important as technology updates. We have trained our managers to be Industry 4.0 pro-active. No more PowerPoint slide decisions, but rather real-time actions based on live feed data … This revolution is happening today in our advanced plants with daily routines like QRQC (quick response quality check) fuelled with instant data instead of Excel reports, or in supply-chain teams with real-time tracking … Exposing our managers to start-up and advanced tech companies in 'learning expeditions' was the key catalyst for them to be leaders in this transformation."

SAIC Maxus: C2B mass customization and business model innovation

SAIC Maxus Automotive Nanjing, Jiangsu, China

China's automobile industry has undergone nearly 30 years of rapid development. The product technology and user services based on the business-to-consumer (B2C) mode employed by automobile enterprises are becoming increasingly homogenized. In order to differentiate themselves and earn a place among front-runner organizations, companies will need to create new technology and generate a better user experience grounded in a consumer-to-business (C2B) mode. Fourth Industrial Revolution intelligent manufacturing and cloud-based big data solutions provide elements essential to the pursuit of C2B mass customization in the car industry. According to Wang Rui, General Manager of SAIC Maxus, "SAIC Maxus is striving to transform itself into a new type of user-driven company. The concept is to let users take the initiative and form a direct relationship with them."

Through iterations of C2B models, SAIC Maxus has not only realized mass customization for its entire vehicle series but also successfully realized the direct connection of the value chain (R&D, production and sales) through digital platforms. The company has identified direct digital connection among the enterprise, users and partners through the internet and cloud computing as a core value of the Maxus C2B business model. This involves interaction of users in the full product life cycle (definition, design, verification, pricing, selection and feedback). Through active participation in decision-making throughout the value chain, users are able to develop an amicable business relationship with a company creating customized products and services for them.

Addressing the need for an industrial ecosystem of digital technology, Wu Gang, Chief Digital Officer and leader of the C2B project team, said, "In order to respond to customer needs, we need to share information, including structured and unstructured data, with users, suppliers and distributors in real time and comprehensively." The company's efforts have focused on building three systems: digital user operations, digital marketing and digital R&D and manufacturing:

– Digital user operations: Maxus's self-built platform attracts nearly 7 million users to gather through digital user operation. Each user activity generates corresponding labels. Based on this data, Maxus can optimize its marketing and after-sales service efforts to provide a seamless consumer experience.

– Digital marketing system: Traditional product pricing modes and processes of automobile enterprises are reconstructed through a digital platform to engage consumers in product strategy, engineering design, marketing, manufacturing supply chain and other business areas, facilitating mass customization in the automobile industry.

– Digital R&D and manufacturing system: A 3D-design platform realizes multidisciplinary real-time online and associated design; improves design efficiency; reduces design waiting and data errors; and promotes crowdsourcing mode, along with other benefits.

To meet customization requirements, Maxus established an online process management system to realize on-site visual process guidance. A virtual simulation platform improves manufacturing digitalization, and digital design and process verification is realized from the workstation, reducing problems associated with physical vehicle building. This improves efficiency while affording greater manufacturing flexibility, thus enabling faster delivery.

Taking a C2B approach demands an innovative disposition to the entire business model. As General Manager Wang Rui said, "It means pushing down the original organizational structure, concept and model process of the whole company – and turning it into a user-driven company."

Weichai: optimizing E2E product development connectivity

Weichai Power Company, Weifang, China

The Weichai Power Company, a powertrain, vehicle and construction machinery producer in China, is an E2E Lighthouse that has achieved technology-enabled connectivity across multiple functions. Faced with rising market competition, Weichai embarked on a plan to focus on "costs, core technologies and quality", guided by an emphasis on customer satisfaction. Zhiyue Cao, Vice-President and Chief Information Officer, explained that "with the application of new technologies, Weichai has gradually formed a smart R&D system, a customer-centric smart internet of vehicles (IoV), lean-oriented intelligent manufacturing management and flexible automated intelligent warehousing, all of which have enabled Weichai to achieve end-to-end, full value-chain connectivity".

Through digital rapid modelling design, virtual development simulation and intelligent IIoT-based testing, Weichai has built an end-to-end product development system that has shortened new product development from 24 months to 18 months. Using modularization and parametric design, designers are able to input model parameters, whereupon the system automatically pushes the most relevant modules or automatically generates new 3D and 2D models. Relative to traditional manual drawing, the product design reuse rate has increased by 30%.

Weichai's engineers use virtual simulation technology to create digital prototypes for product design parameters. Simulation enables timely discovery and handling of design problems, reducing test costs by more than 20%. Operators are able to carry out test-bench transformation, taking advantage of increased sensors that provide real-time acquisition and uploading of test results. A mobile app allows for intelligent control of operations, reducing labour costs by 75%, shortening the R&D cycle by more than 20% and reducing design failure by 20%. Yanpeng Zhang, a test worker and dispatcher, remarked that "we used to be able to monitor only one test bench in the lab. We also had to learn different monitoring software, and manually switch the monitoring parameters. With the application of intelligent testing, we can monitor and manage multiple test benches on one screen … The system can predict test-bench failure and push the pre-warning to my mobile phone and mailbox in real time, so that I can eliminate the fault in advance."

To better understand the performance metrics of engines in real-world operation, Weichai built an IoV system to collect real-time data on engine speed, fuel consumption and power under various working conditions. Customer connectivity intersects with E2E product development as big data analysis shapes engine design using real vehicle data from actual user driving habits, road conditions and engine performance. Feng Han, Deputy Director of the R&D Center, explained the impact: "Traditionally, engine R&D relied mainly upon the personal experience of design engineers, making it difficult to fully understand engine reliability after it

is put on the market. With deep application of information technology and digital technology, traditional engine R&D is being subverted."

Weichai's emphasis on customer connectivity and E2E product development has also been reflected in post-market efforts. Weichai carried out four connectivity-powered initiatives to improve the quality of service. First, an app-based car networking platform provides users with efficient service solutions including repair orders, customer support and satisfaction reports. Second, a customer member management system builds loyalty through a membership system, articulates member rights and privileges and implements a point mall (including dynamics for collection and consumption of points). Third, remote maintenance guidance conducts online fault diagnosis, assists on-site maintenance personnel, and saves time for customers. Engine maintenance time is reduced by 15%, saving 20% of document audit workload. Finally, the generation of visual AR models for Weichai engines supports pre-sale technical exchange, engine assembly and after-sales maintenance guidance. Unrestricted by location or by the physical exhibition machine, this AR method improves training and on-site support while enhancing the company's image. This end-to-end linkage shows the power of interconnectivity of functions throughout the value chain, extending to the customer.

Zymergen: a digital native company using the Fourth Industrial Revolution to transform biotech

Zymergen, Emeryville, California, USA

Zymergen aims to be a catalyst in a new industrial revolution, creating a vibrant, sustainable future through biology. Using a proprietary platform that integrates genetics, bioinformatics, machine learning (ML) and advanced automation, Zymergen is applying Fourth Industrial Revolution innovation to transform lab work and a traditionally slow production process heavily dependent upon manual labour. Jed Dean, Founder and Vice-President of Operations, described the origin of the approach: "We wanted to create a company built around the premise of using data and algorithmic learning to expand what was possible in biological research . . . Our machine-learning infrastructure, layered on top of automated and high-throughput facilities, helps our scientists and engineers design and run thousands of experiments at once."

Modular automation, an advanced sensor network and a shared big-data repository combine to create a factory taking advantage of digital connectivity to transform how it operates. The company has realized a 46% increase in labour efficiency, a 40% increase in line yield and a 50% reduction in lead time. Moreover, a digital scheduling system has helped lower operating costs by 42% by optimizing capacity, inventory and personnel logistics.

Zymergen's platform builds data sets and microbial genome models that allow for continual optimization and acceleration of strain improvement and discovery of novel molecules. Automated experimentation driven by data science facilitates faster, more consistent and more cost-effective product development than traditional rational engineering approaches. With these methods, Zymergen is currently addressing unmet market needs in agriculture, personal care, electronics and industrial applications.

As a digital native company, Zymergen has used machine learning and automation to expand the capacity for engineering microbial genomes. A flexible, scalable automation platform improves accuracy, reduces the number of human errors and increases experimental speed compared with traditional laboratory workflows. These workflows also use data science and ML to improve experimental design through the iterative design-build-test-analyse-learn (DBTAL) process. Over time, the accumulation of data from ML-directed experimentation enables Zymergen scientists and engineers to optimize genetic modifications in a way that outpaces solely rational-driven approaches and overcomes the limitations of human intuition. In addition, Zymergen's library of genomic diversity is the largest in the world, and serves as an ML-enabled search platform for genes, pathways and natural products. As Will Serber, Technology Associate Director, Automation Platform, explained, "At scale, pulling tiny scientific signals from biological 'noise' demands extensive automation and data capture. Zymergen was founded on this core premise, and we've invested in creating an automated high-throughput biomanufacturing system that can be reconfigured in minutes and can scale to fill a factory."

This digital native approach leads Zymergen and its clients towards a results-based understanding of both traits of interest and the extended network of genes that affect those traits. Ultimately, Zymergen's committed strategy to unlocking the power of biology through technology will position it for success in building a more sustainable future. According to company founder Jed Dean, "With this platform, we get to start with rational genetic engineering based on our employees' vast expertise, and then move to ML-driven, genome-wide surveys to discover traits we would never find through hypothesis testing alone. This combination is changing the way we do science, while still respecting and requiring input from some of the best scientists in the world."

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During 2019, the project team has collaborated closely with the World Economic Forum constituent base, representatives from the factories recognized as Lighthouses, and with a panel of experts who recognized the most advanced factories. The World Economic Forum would like to extend its gratitude to these individuals and their organizations.

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Endnotes

1. "The Next Economic Growth Engine Scaling Fourth Industrial Revolution Technologies in Production", World Economic Forum, http://www3.weforum.org/docs/WEF_Technology_and_Innovation_The_Next_Economic_Growth_Engine.pdf (link as of 12/12/19)
2. "Fourth Industrial Revolution: Beacons of Technology and Innovation in Manufacturing", World Economic Forum, http://www3.weforum.org/docs/WEF_4IR_Beacons_of_Technology_and_Innovation_in_Manufacturing_report_2019.pdf (link as of 12/12/19).
3. Andreas Behrendt, Richard Kelly, Raphael Rettig and Sebastian Stoffregen, "How Digital Manufacturing Can Escape 'Pilot Purgatory'", July 2018, McKinsey & Company, https://www.mckinsey.com/business-functions/operations/our-insights/how-digital-manufacturing-can-escape-pilot-purgatory (link as of 12/12/19).
4. The Global Lighthouse Network is a major initiative of the World Economic Forum's Platform for Shaping the Future of Advanced Manufacturing and Production.
5. Behrendt, Kelly, Rettig and Stoffregen, "How Digital Manufacturing Can Escape 'Pilot Purgatory'".
6. "Europe, Asia Lead the Way to the Factories of the Future", World Economic Forum, https://www.weforum.org/press/2018/09/europe-asia-lead-the-way-to-the-factories-of-the-future/ (link as of 12/12/19).
7. Wouter Aghina, Karin Ahlback, Aaron De Smet, Gerald Lackey, Michael Lurie, Monica Murarka and Christopher Handscomb, "The Five Trademarks of Agile Organizations", January 2018, McKinsey & Company (link as of 12/12/19).
8. "Platforms and Ecosystems: Enabling the Digital Economy", World Economic Forum, https://www.weforum.org/whitepapers/platforms-and-ecosystems-enabling-the-digital-economy (link as of 12/12/19).
9. Pablo Illanes, Susan Lund, Mona Mourshed, Scott Rutherford and Magnus Tyreman, "Retraining and Reskilling Workers in the Age of Automation", January 2018, McKinsey Global Institute, https://www.mckinsey.com/featured-insights/future-of-work/retraining-and-reskilling-workers-in-the-age-of-automation (link as of 12/12/19).
10. Kurt Chauviere, Ben Maritz and Jasper van Halder, "The Role of the Transformation Office", November 2016, McKinsey & Company, https://www.mckinsey.com/business-functions/rts/our-insights/the-role-of-the-transformation-office (link as of 12/12/19).
11. "International Energy Outlook 2016: Industrial Sector Energy Consumption", 2016, US Energy Information Administration, https://www.eia.gov/outlooks/ieo/pdf/industrial.pdf (link as of 12/12/19).
12. "Sources of Greenhouse Gas Emissions", United States Environmental Protection Agency, https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions#industry (link as of 12/12/19).
13. "A Global Standard for Lifelong Learning and Worker Engagement to Support Advanced Manufacturing", World Economic Forum, https://www.weforum.org/whitepapers/a-global-standard-for-lifelong-learning-and-worker-engagement-to-support-advanced-manufacturing (link as of 12/12/19).

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