FUTURE NETWORK SERVICES 6G

Edging toward the 6G wireless factory

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White paper

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Imagine replacing all the communication in a factory, both between and inside the machines, with ultra-low-latency, ultra-high-bandwidth and highly reliable wireless connections, and then moving all the software intelligence from the local controllers, sensors and actuators to a single central brain.

This would open up a world of opportunities for hyper-flexible and hyper-evolvable industrial automation offering extensive AI-powered machine insights and adaptivity. Such a 6G wireless factory is one of the applications envisioned by the National Growth Fund-enabled Future Network Services 6G program.

Introduction

To stay competitive in today's fast-paced global industrial landscape, factories in Europe have to constantly innovate and adapt to the ever-evolving market demands. The multiformity of their equipment only exacerbates the challenges. Typically, the machine pools are a mix of various makes and models, from modern to more than a decade old, fitted with a multitude of sensors, actuators and embedded systems from a range of suppliers. This makes maintenance and updates a daunting task during the equipment's long lifespan.

Within the Future Network Services program, supported by the Dutch National Growth Fund, software development solutions provider Cordis Suite and telecom company KPN are spearheading a consortium to develop a vision for the factory of tomorrow. Together with semiconductor equipment giant ASML, industrial IoT and automation specialist Weidmüller and Eindhoven University of Technology, they're exploring how 6G communication and a revolutionary centralized software architecture can help the European manufacturing industry lead the pace of change. At the Brainport Digital Factory, located on the Brainport Industries Campus (BIC) in Eindhoven, the Netherlands, a production line demonstrator has been implemented to show the initiative's advances toward fully wirelessly connected intelligent machines. The Eindhoven cluster was already recognized by the European Patent Office (EPO) to be the most innovative in the 4th Industrial Revolution in Europe.

> *Typically, the machine pools are a mix of various makes and models, from modern to more than a decade old*

"We're exploring a completely new application of wireless connectivity," elaborates Paul Cobben, Portfolio lead KPN Campus at KPN. "Whereas 5G is targeted at the communication between the IT systems and OT systems in a factory, with 6G we're looking to take the wireless connection *inside* the machine, directly connecting to the sensors and actuators inside the machine, bringing further the centralization of machine logic that we currently can already do with (private) 5G and on-premise edge computing. This collaboration will contribute to the development of the upcoming 6G technology by delivering the requirements for using 6G wireless networks inside machines. One element of research is to determine how 6G can work well with all the

electromagnetic interference inside machines." That is why NXP is undertaking research and development to craft an architecture and design a 6G base station capable of operating in potentially new frequency allocations such as 5-24 GHz and 100 GHz-THz bands.

With 6G connectivity inside the machine, a new domain for cellular communication, combined with on-premise edge computing, the machine control can be simplified and the risk of errors reduced. By centrally combining and analyzing the machine data, production processes can be made substantially more efficient and adaptive. In addition, the simpler technology, easier error detection and data-driven predictive maintenance will increase the uptime and time-to-repair of the production line. When looking at the current (private) 5G technology, it makes factory floor layouts easier to rearrange when production processes change. 6G technology is expected to enhance these possibilities even further. As obsolete machines can be retrofitted with intelligent control, the technology can bring the benefits of continuous performance and efficiency improvements and market agility to almost every factory.

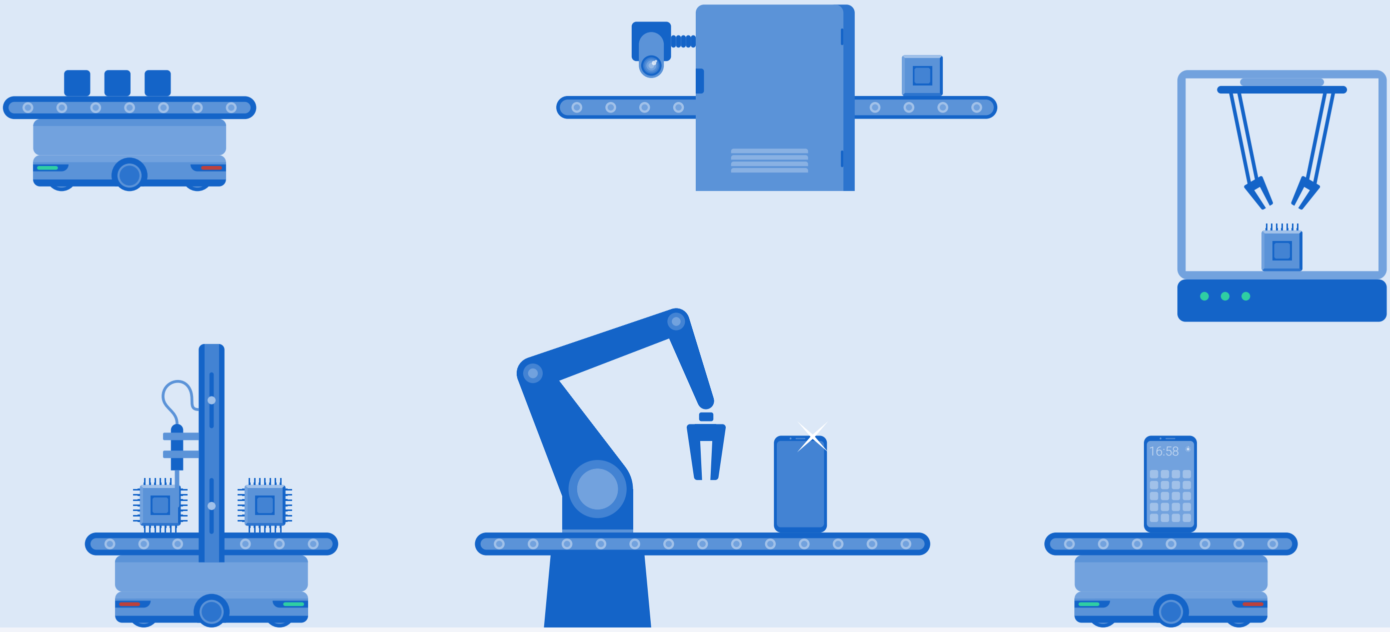
The market potential is huge. According to Statistics Netherlands (CBS), the Dutch industry annually invests 10 billion euros in new production equipment. In Europe and the US, investments in industrial machinery amounted to 250 billion euros and even 1 trillion euros, respectively, in 2020. With their large concentration of costly machinery and their ability to quickly implement new technology concepts, the high-tech, automotive and machinery sectors are expected to be the first to benefit.

Wireless control

The digital factory is envisioned to combine all kinds of machines into all kinds of configurations to create products of all shapes and (batch) sizes. Automated guided vehicles are freely moving across the floor to transport materials, components and subsystems from one station to the next, even continuing the assembly process on the go. Such a highly flexible setup calls for a sophisticated communication infrastructure to make sure that everything stays on track at all times.

> *Our vision is to be completely wireless, all the way to the sensors and actuators*

In this digital factory, it would require many, many kilometers of space-consuming wiring to flexibly connect the stationary production cells, with extensive shielding to prevent electromagnetic interference from affecting the electronics and the necessary redundancy to avoid single points of failure. Running cables to the moving stations poses an even bigger challenge. The obvious solution is to go wireless.



"At KPN, we've been using (private) 5G and on-premise edge computing for critical production applications in factories and plants. Our commercial offering called KPN Campus is a combination of (private) 5G, on-premise computing and indoor localization for mission and business-critical applications," says Cobben. "(Private) 5G already can connect to IT and OT systems of a factory. With 6G research we focus on how 6G wireless network can be implemented inside machines and directly connect to the machine's sensors and actuator, which we expect will improve uptime of machines even further, by centralizing all machine, sensor and actuator logic to the on-premise edge servers."

Complete wireless control inside a machine, however, is a new domain for cellular technology. Also, for one specific area of machine control, high speed motion applications, 5G Advanced and possibly 6G technology is needed to address the specific requirements of high-speed motion applications. "Motion applications require a much lower latency, a much higher bandwidth and a much higher reliability than other machine application domains. We're going to need at least a ten times better performance, maybe even a hundred times for high-speed motion," illustrates Klaas Wijbenga, automation sales engineer at Weidmüller. "Quality of service is paramount in an industrial setting. We can't have boxes dropping off a conveyor belt because the communication can't keep up." The 6G research of FNS will specifically focus on this highly demanding domain of high-speed motion application in production environments, in order to get the specification of the 6G standard ready to address this stringent application domain.

And the vision doesn't stop there. "6G also is expected to give us the latency, bandwidth and reliability to cluster all the distributed intelligence in one central brain and control everything from there," philosophizes Benno Beuting of Cordis. "In today's machines, there's software deployed everywhere: in every sensor, every actuator and every local controller. A lot of it is handcrafted legacy code. All these different pieces of information processing and logic are almost impossible to maintain, let alone improve. By bringing the software together in a robust and scalable edge computing environment centrally located on the factory premises, we can leverage the power of low-code modeling, data analytics and artificial intelligence to optimize the development and maintenance efforts. "All machine data is automatically stored on the edge, where it's continuously analyzed by AI models for intelligent decision-making," Beuting elaborates. "Operators can seamlessly interact with the systems by asking real-time questions, for example about erroneous behavior. Based on the stored data, the artificial intelligence then gives almost instant answers, providing machine insights on demand. Down the line, the AI will even be able to anticipate failures and enable proactive interventions, ensuring uninterrupted operations and continuous efficiency gains."

Open architecture

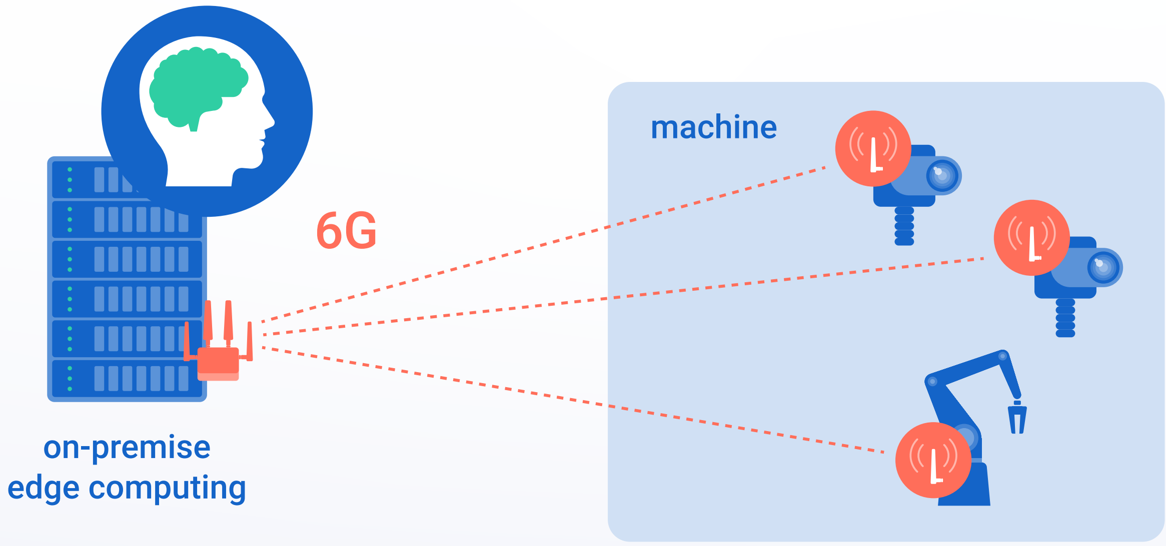
At the Brainport Digital Factory testbed, the consortium partners have embarked on their journey to see where their vision takes them. Their starting point is a modular production line, hooked up to a private 5G network that connects via 5G communication to the so-called programmable logic controllers (PLCs, ie the local brains) and to the remote input/output (I/O) interface module. Behind this I/O module there are wired connections to the sensors and actuators of the machines (the eyes and hands).

"The original production line had the classic setup where every machine has a separate control cabinet that combines the PLC and the accompanying I/O modules in one rack. From this external cabinet runs a thick bundle of multi-conductor cables connecting each I/O to the corresponding input or output device on the machine," Weidmüller's Wijbenga explains. "We started by introducing a remote I/O solution. With this solution, it's still possible to put the PLC and I/O modules next to each other, like in the classic situation, but we can also replace the PLC with a network interface, a so-called head station, that connects the I/O to a PLC that's located elsewhere. That's what we did."

> *The machine control server will coordinate the different machines in the production line and communicate with other factory automation systems*

By placing the remote I/O close to the sensors and actuators, these can be hooked up using much shorter and simpler wires, obviating the need for a long and bulky multi-conductor cable running across the factory. Instead, there's just a simple network cable connecting the PLC and the remote I/O through a standard industrial Ethernet protocol. This network connection can be easily made wireless, which is what the consortium partners did next. "We've put in a general-purpose controller from Weidmüller, replacing the PLC, and connected it to the remote I/O using private 5G by adding a 5G modem to the controller and the remote I/O unit," clarifies KPN's Cobben. "This is how we connect the machines to the private 5G network."

The general-purpose or edge controller from Weidmüller has the added benefit of providing an open software environment. "Many PLCs come with a



proprietary or closed operating system, creating vendor lock-in. Our edge controller, however, uses u-OS, our open and flexible Linux-based operating system for industrial IoT and automation," notes Wijbenga. "On top of u-OS, we can run all kinds of programs as apps, including soft PLCs."

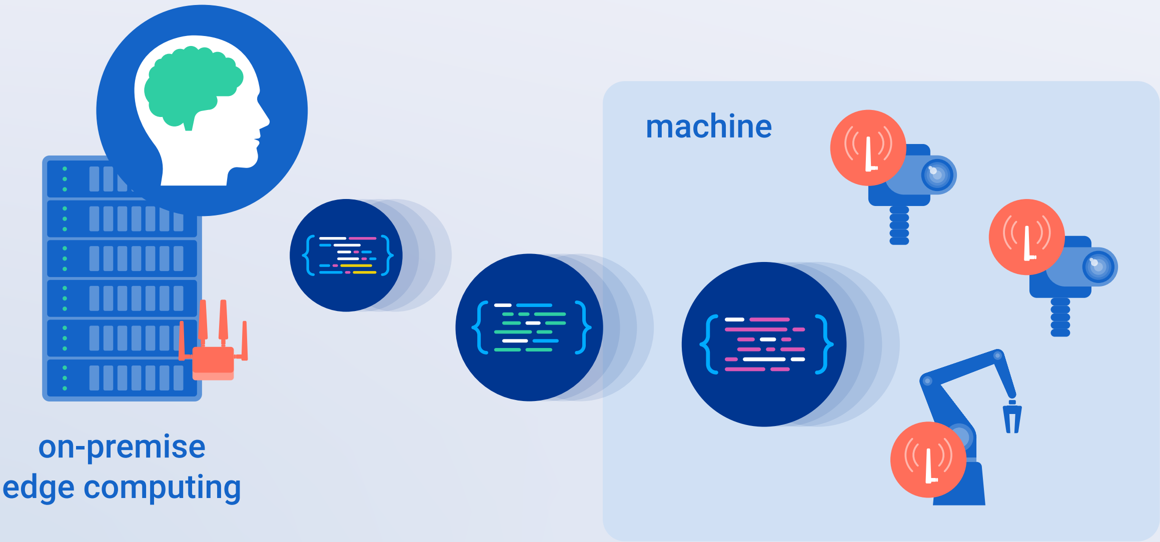
"Our next big endeavor is centralizing all the software at the factory level," adds Beuting of Cordis. "For the Brainport Digital Factory testbed, we'll basically have a machine control server running on an on-premise edge computing environment from KPN, which is centrally located on the BIC and connected via private 5G to the edge controllers on the machines. Ultimately, the soft PLCs and the I/O interfacing will also move to this central edge computing environment, with the remote I/O modules being replaced by a set of sensor and actuator apps that have direct 6G links to the physical input and output devices. The machine control server will coordinate the different machines in the production line and communicate with other factory automation systems, like the MES, and additional tooling, providing the input for data analytics or Hololens applications, for example."

Low-code

With all the software easily accessible in one place, it becomes much easier to maintain. Using robust central edge computing, it's also much easier to extend. "Embedded systems, in general, have limited hardware resources, typically a low-end CPU and a small amount of memory. As a result, the software running on them has to be highly efficient. There's virtually no room for additional functionality," Beuting points out. "A central on-premise edge computing environment doesn't have these limitations. If we want to extend the software there, we can just do so, adding more resources if necessary."

Development and maintenance will be further streamlined by transforming the software into low-code models. "Using the Cordis Suite platform, we can create UML-like diagrams of the complete machine control. From these low-code models, we can then automatically generate the control software and deploy it to the Cordis Suite app on the central on-premise edge computing environment," Beuting goes on to explain. "The app, a so-called runtime, will execute the generated C#.NET code that controls the soft PLCs. This is bringing PLC code development into the modern age of software engineering."

The move to low-code models makes it much easier to give the control software the update it so desperately needs. Because of all the handcrafted legacy code, typically decades old, factories prefer not to touch the PLC programming. As the original programmers are usually no longer available and the documentation is mostly lacking, all the knowledge is in the code. "The code is the only truth they've got, which is why they're so very reluctant to lay a finger on it," says Beuting. "Transforming the control software into low-code models creates a new source of truth, one that can be kept up-to-date with minimal effort. It also allows for easy integrations, for example with tools that automatically update the documentation upon each model change and AI models that enable intelligent decision-making and self-optimization."



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Model checking

For factories to adopt AI-driven updates to their low-code models and accept the resulting software in their machines, they need assurance that the resulting system behavior won't take a turn for the worse. That's where Eindhoven University of Technology (TU/e) comes in. "When software updates are deployed automatically, you want to be absolutely sure that they don't contain an error that causes your production line to break down. You want your software to keep meeting the requirements, especially those relating to safety, at all times. That's what we're looking at in this collaboration," states Jeroen Keiren, assistant professor at TU/e, focusing on the verification of industrial control systems.

"We're working on formalizing the system requirements so that we then can automatically verify whether the software exhibits the required behavior," summarizes Keiren. "We've already shown that we can do that for small systems specified in Cordis low-code models, like a robot arm that takes an object from a conveyor belt and puts it down somewhere else. Up in the air, it has a lot of room to move, but close to the surface, its motion is physically bounded by a bracket it should stay clear of. For such a system, we can prove that the software makes it do what it's supposed to do. In the 6G wireless factory project, we aim to extend our formal verification approach to a complete production line."

The approach has two main ingredients: showing that the models are consistent with the requirements and validating that they're consistent with the code. For the first ingredient, the Cordis models are transformed into formal models that are then mathematically verified. Both the transformation and the verification are done using mCRL2, a model-checking tool developed within Keiren's group at TU/e. "In this project, we're looking to scale the application of mCRL2 to more complex control systems through the use of more advanced model-checking techniques."

To validate that the models are consistent with the code, Keiren outlines two avenues of attack. "One way is to take the error scenarios found by mCRL2 and simulate them on the controller. If this causes the same faulty behavior, we can be reasonably certain about the models and the code being consistent. The other way is model-based testing, where we generate test cases directly from our formal models, covering an exhaustive set of input-output combinations, and run them against the code. If the tests pass, it means that the models and the code exhibit identical behavior."

If the models are consistent with the requirements *and* with the code, it follows that the code is consistent with the requirements. Which is exactly the guarantee factories are looking for. "For all the components in a production line like the one at the Brainport Digital Factory testbed, we want to be able to generate software that can be shown to meet all the requirements, but we also want to be able to automatically check that it still meets the requirements after every update," Keiren concludes. "Our efforts will undoubtedly also result in additional requirements on the design choices for the low-code models. The better the models, the easier they are to verify."

Peeling the onion

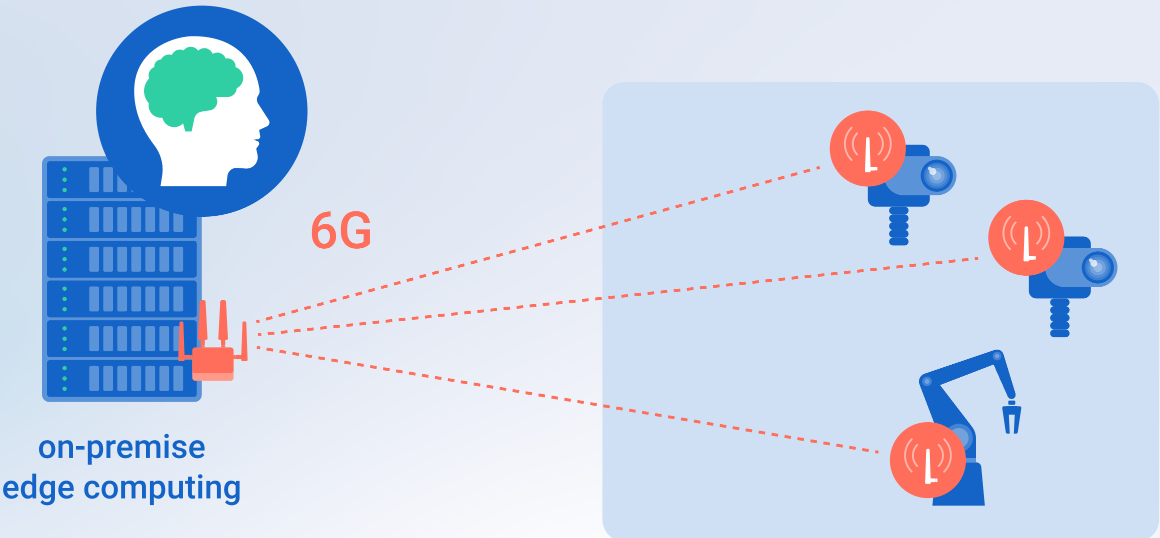
One of the companies that already took some of the legacy software out of factory equipment and replaced it with Cordis low-code models and generated code is consortium partner ASML. "In one of our assembly lines, we have a tool that qualifies modules that go into our lithography machines," says ASML project manager Wim Bor. "The tool was custom-made for us some twenty years ago and now its components are starting to go end of life. As the system hasn't been maintained for quite a while, we have a whole lot of legacy software on our hands that could stop working at any time."

Together with Cordis, Bor has begun to peel this onion, as he puts it. "Layer by layer, we're replacing the legacy software. Based on our current and anticipated requirements, we've set up a completely new machine control architecture and created low-code models, from which we automatically generate substitute software. Thus, we can gradually convert the 270,000 lines of code in a controlled way."

As a result of these efforts, the qualification tool has been revitalized. "It's already better equipped for the job," finds Bor. "For example, the tool can now automatically deal with new module configurations, whereas every little configuration change used to require a software modification, and we've added functionality to manage the tests to perform, which wasn't possible before. We'll keep peeling the onion as long as necessary for the business of ASML."

For the other aspects of the 6G wireless factory, Bor equally sees ample opportunities at the semicon giant. "We also have a massive amount of cables running across our factories already and it would be highly beneficial for us as well if we could unlock additional data sources by simply setting up an extra wireless connection. We're in the project because we're very interested in what 6G can bring us. At the same time, we're seeing some ASML-specific challenges in introducing advanced wireless technology in our factories, which we can help address by participating."

> *Layer by layer, we're replacing the legacy software*



Wireless communication being less secure is one of the concerns. According to KPN's Cobben, cellular connectivity can actually provide better security to current OT environments. "We see OT environments that aren't optimally secured, especially when these systems are becoming more and more exposed to the Internet. In security scans of such environments, we also observe that passwords of OT network elements and end points aren't regularly changed. Lastly, OT end-point security, in general, is a topic that raises concerns within manufacturing environments. Meanwhile, to date, 4G and 5G networks have never been breached. The exceptionally hardened SIM technology, combined with strong encryption, privacy, authentication and fraud detection, makes these cellular infrastructures extremely secure. This will be no different for 6G."

New ball game

The road to the 6G wireless factory is traveled in a stepwise fashion. "5G is our starting point and from there, we'll add our own pieces to the puzzle, but we'll also benefit from new technology as it becomes available," details Cobben. "Every new modem generation, for example, will bring more performance and more functionality to our Brainport Digital Factory testbed. This will allow us to raise the bar one notch at a time, gradually taking us from 5G to 5G Advanced to 6G."

The partners have already identified a couple of use cases where 6G trumps its predecessors. "There's the ultra-low latency allowing for hard real-time control," Beuting of Cordis illustrates. "6G will also offer a higher level of reliability, including more redundancy, which further optimizes network availability and thereby reduces the risk of factory downtime. It also enables highly accurate indoor positioning and even directionality, opening up a host of new opportunities."

6G is a whole new ball game, Cobben concludes. "Communicating with radio waves inside the steel casing of a machine is mainly uncharted territory. It can introduce all kinds of side effects that you don't want in an extremely conditioned and tightly controlled environment like an ASML wafer stepper. There's still a whole lot of research and development to be done here, but with our efforts, we're contributing to the foundation of 6G and outlining the framework for a successful application on the factory floor."

> *Every new modem generation, for example, will bring more performance and more functionality to our Brainport Digital Factory testbed*

Consortium partners

Cordis SUITE transforms software development for mechatronic systems through a model-driven low-code approach tailored to Operational Technology (OT). It eliminates the complexity of traditional coding by offering a visual, more intuitive, and maintainable way to understand, design, and manage machine behavior.
By leveraging real-time data and AI-driven optimization through its model-centric platform, Cordis makes systems more adaptable, easier to maintain, and capable of continuously improving their behavior. With built-in support for edge computing and integration with digital twins, Cordis enables a new class of intelligent, self-adaptive industrial systems.

Benno Beuting, founder and CEO of Cordis SUITE, envisioned more than 25 years ago a platform approach to simplify software development for Operational Technology (OT) and help engineers control complex mechatronic system behavior—a vision he continues to refine to this day. As the driving force behind the concept of centralized software intelligence and the 'Dreaming Machines' vision, he plays a leading role in shaping the future of self-adaptive industrial systems. Within the 6G Wireless Factory initiative, Benno introduced the foundational idea of shifting machine logic from distributed embedded systems to a centrally managed edge platform. This architecture—treating control as a unified 'machine brain'—has become a cornerstone of the broader initiative, developed in close collaboration with leading network infrastructure partners.

KPN provides enterprise- and campus networks to businesses and organizations, complemented with on-premise edge computing. KPN provides the digital infrastructure for the IT and OT environment of the digital factory, consisting of private 5G, on-premise edge computing and indoor localization. This enables our customers to realize a highly reliable, robust, real-time and security digital infrastructure to redundantly connect devices and applications to service their critical digital business processes.

Paul Cobben, Portfolio Lead for KPN Campus at KPN, has been engaged in Smart Industry and Digital Factory for 10 years and has broad experience in 5G and Edge applications in discrete- and process manufacturing. He shaped the 5G wireless factory approach in 2020 and has founded the vision for the 6G wireless factory in 2023, where 6G is used inside machine and all machine logic is centralized on a on-premise edge server. Paul is currently engaged in implementing (private) 5G networks, indoor location and on-premise edge computing in Healthcare, Manufacturing and Logistics and in expanding the 5G and 6G wireless factory setup at the Brainport Digital Factory in Eindhoven.

Consortium partners

Smart Industrial Connectivity: Electrification, automation, digitalisation, electrical connectivity, electromobility and renewable energies – markets in which **Weidmüller** feels right at home. The family-owned company established in 1850 has production facilities and sales companies in over 80 countries.

As a global player in electric connection technology, Weidmüller achieved a turnover of more than one billion euros in the 2023 financial year with around 6,000 employees worldwide - around 2,000 of whom work at the company's headquarters in Detmold, in the heart of East Westphalia-Lippe, Germany.
What Weidmüller lives by: Diversity with respect.
Technologies and engagement for a liveable future - Weidmüller demonstrates how it approaches the topic of sustainability in its interactive sustainability brochure.

Klaas Wijbenga is Automation Specialist at Weidmüller and is an experienced no-nonsense consultant with a broad knowledge of industrial automation with more than 25 years of experience, who enjoys working as part of a team. Since 2013, he has been responsible for the Weidmüller automation portfolio in the Benelux region and in that capacity works closely with product development and fellow specialists. The combination of broad practical knowledge and a balanced edge-oriented u-OS product portfolio make his advice goal- and future-oriented, fitting into modern industrial 5G solutions.
Weidmüller is a proud member of the Brainport Digital Factory cluster and provides devices and 5G modules to the machines and cooperates in development of the 6G network

Eindhoven University of Technology (TU/e) is a research-driven and design-oriented university with an international outlook, founded in 1956, with 12,000 students and 3,000 staff. It focuses on coherent education, research and knowledge valorisation in the fields of engineering science and technology.

Jeroen Keiren is assistant professor in the Formal System Analysis group (FSA) at TU/e. His research focuses on the development of formal methods for the design and implementation of correct and reliable software, and their application to industrial systems.

ASML is an innovation leader in the semiconductor industry. We provide chipmakers with everything they need – hardware, software and services – to mass produce patterns on silicon through lithography. We believe in pushing technology forward, enabling groundbreaking solutions to some of society's toughest challenges.

Founded in Eindhoven in 1984, we're a global team of more than 42,000 employees (FTE), of 144 nationalities and counting. Our operations are spread across more than 60 locations in Europe, Asia and the Middle East and the US (2023 annual figures) .

Wim Bor Appointed as Platform architect to achieve maintainable multidisciplinary Manufacturing/Calibration-tooling. Platform refers to control-software that can be shared across multiple applications within a specific application domain, and that should enable easy integration of future technologies.

For the Multi-disciplinary tooling domain, ASML uses the Cordis SUITE. They both share the same vision on Operational Technology (OT) and the associated technology roadmap.

NXP Semiconductors N.V. (NASDAQ: NXPI) is the trusted partner for innovative solutions in the automotive, industrial & IoT, mobile, and communications infrastructure markets.

NXP's "Brighter Together" approach combines leading-edge technology with pioneering people to develop system solutions that make the connected world better, safer, and more secure. The company has operations in more than 30 countries and posted revenue of $12.61 billion in 2024.

Find out more at www.nxp.com.

BRAINPORT
Digital Factory

Brainport Digital Factory (BDF) is an open innovation hub located at Brainport Industries Campus (BIC) in Eindhoven, where industry, technology providers, and researchers collaborate to accelerate the adoption of smart manufacturing. BDF provides a large-scale industrial testbed, including a fully operational demonstration line where digital manufacturing solutions are developed, tested, and validated in a real-world production setting. These include low-code machine control, AI-driven optimization, digital twins, real-time analytics, edge computing, private 5G networks, secure industrial connectivity, augmented reality (AR) and collaborative robotics.

Supporting companies across all digital maturity levels—from isolated legacy automation to predictive and adaptive manufacturing—BDF offers a clear and practical roadmap. Companies can validate and integrate innovative technologies under realistic production conditions, ensuring interoperability, scalability, and successful industrial implementation.

By providing both the technological environment and strategic collaboration between industry, technology developers, and research institutions, BDF empowers manufacturers to reduce costs, improve efficiency, enhance production agility, and future-proof their operations in an ever-evolving technological landscape.