5G-PPP Technology Board

Innovation Trends in I4.0 enabled by 5G and Beyond Networks

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Executive Summary

The *Industrie 4.0* (I4.0) concept was introduced as a revolution related to the way that quality, productivity, customization, and safety processes -among others- are designed, deployed, executed, and automated in manufacturing environments.

I4.0 (Industry 4.0) has developed over a similar timeline to that of 5G (Fifth Generation) technology. As a matter of fact, I4.0 and 5G have had and keep having a major influence on each other: 5G technology is regarded as a key enabler for supporting the communication needs demanded by the I4.0 vision while I4.0 is the most renowned and rapidly growing vertical sector for 5G deployments.

For more than 10 years now, numerous experiences, projects and publications have identified and addressed the opportunities arising at the intersection of I4.0 and 5G, so readers of this new whitepaper on the subject may wonder about the strong motivation and expected added value behind it. This report covers the following four main aspects.

First of all, this whitepaper provides a 360-degree perspective on I4.0 design principles, drivers and trends – most of them supported or even directly enabled by 5G-, that stems directly from the sustained and tight cooperation of major I4.0 leaders with key industrial and academic contributors to 5G development across a handful of research and innovation projects backed specifically by the EU 5G-PPP (5G-Public Private Partnership) programme.

Secondly, a further step into segmenting, staging and assessing the applicability of 5G and beyond technologies for the short and mid-term challenges of I4.0 is taken, by giving directly the voice to the I4.0 stakeholders engaged in these 5G-PPP projects and, then, extracting from their inputs collective highlights that could serve as a compass for focusing new ecosystem-based initiatives and for drawing new research policies in the field. The survey (see Annex II) conducted by this joint initiative has polled on the competitive advantages, applications and areas of interest for the adoption of 5G in their plans, the expected adoption and transition timelines, the identification of critical 5G network services for their applications, the importance of human-machine collaboration, the investment model that best matches their industry needs, the key requirements and expectations for non-public 5G networks, and the requirements for security and privacy, having been answered by eleven distinct responders holding key responsibility in the I4.0 roadmap within their organizations.

Thirdly, a glimpse into some key evolving and new disruptive technological aspects around 5G evolution to 6G (Sixth Generation), such as Deterministic Networking, Non-Public Networks and Digital Twining, that are already being addressed by -among other EU 6G IA (Industry Association) SNS (Smart Network and Services) projects- Predict6G project is included, with the ambition of stretching the line of sight of this report into longer term synergies between I4.0 with 5G.

Finally, the report also tries to derive from the experience and learnings about the influence of ecosystem dynamics, regulation, exploitation and sustainability of results, and public research policies and programmes, an outlook into the future on the expected evolution in such aspects along with a few suggestions and recommendations that could facilitate the successful completion of the journey of adoption of 5G for I4.0.

Altogether, hopefully new insight on I4.0 synergies with 5G gathered by the lead researchers of 5G-PPP Phase III projects[1] 5G-Induce, 5G-Smart, 5Growth, 5G EVE, Vital-5G, Evolved-5G, 6G-BRAINS, and 5G-Era, and 6G SNS[2] project Predict-6G, is provided by this whitepaper. The journey is starting from a framework for analysis of I4.0-5G dependencies, then sharing the results of a complete survey to I4.0 stakeholders involved in large-scale 5G-PPP projects, and finally closing with an outlook into new technology drivers and key ecosystem factors to consider around 5G evolution to 6G with a potential major impact on I4.0 longer term evolution.

1. Introduction and Background

While the introduction of steam power, the assembly line and early automation characterized the first three industrial revolutions, **the fourth industrial revolution is expected to leverage the digital transformation of manufacturing environments towards intelligently connected production information systems** [1] in order to deliver fundamental improvements to the industrial processes involved in manufacturing, engineering, material usage and supply chain and life cycle management.

For referring to this fourth industrial revolution **the term *Industrie 4.0* (I4.0) was first used and coined in 2011. Ever since then, exponential technologies such as IoT (Internet of Things), Big Data, VR (Virtual Reality), AR (Augmented Reality), ML/AI (Machine Learning/Artificial Intelligence), Cloud and 5G, have developed and reached a maturity stage** that may very well provide many Industry sectors with a solid foundation to build upon for tackling the implementations of their vision and interpretation of I4.0. Even more importantly, such technology advancements in the ICT space have concurred with intense exploration and innovation across many and varied Industry sectors and processes, materializing into the execution of more and more trials and pilot of concrete I4.0 use cases.

According to ABI research on the implementation and ROI (Return of Investment) of Industry 4.0 [2] the adoption of cellular-enabled I4.0 use cases can generate an 8.5% improvement in Operational Cost Savings, which equates to US$200 to US$600 per sqm per year for a factory or industrial site. That translates, for a single Tier 1 automotive manufacturer, to US$500 million for a period of 5 years. Those estimates shape a potential global market for I4.0 of a most considerable size.

In such a context **new and strong incentives, attracting more and more players and talent from various disciplines to collaborate for realising the vision of I4.0, have emerged**, for the benefit of all parties involved, the industry sectors at large and the (European) economy, as a whole. Indeed, either in the form of individual or bilateral projects promoted by Industry players, or, more commonly, through I4.0 focused research and innovation consortia of Industry leaders, large technology companies, specialised SMEs (Small and Medium Enterprises) and Research Centres/Universities, **with the support of EU H2020 and Horizon Europe programmes, I4.0 *is* accelerating**.

[1] https://5g-ppp.eu/5g-ppp-phase-3-projects/
[2] https://smart-networks.europa.eu/sns-phase-1/

A great deal of new knowledge and innovation is created as a result, along with the acquisition of new and multi-domain skills. That consolidates a level of readiness of the innovation ecosystem that, leveraging the fast and **broad adoption of key technology drivers of I4.0 like 5G, Cloud, AR, VR and ML**, creates a **momentum for I4.0 take-off at a large scale**. At this inflection point for I4.0, this report surveys and analyses drivers, facts, and new trends around I4.0, with special focus on the synergies with 5G and its evolution.

1.1 Why is 5G so critical for I4.0?

Before proceeding to the detailed analysis presented in the core sections of this report, we think it is important to address, now and open-mindedly, a general but valid question: ***Why is 5G so critical for I4.0?***

The I4.0 vision aspires to superior levels of flexibility for data-driven Industrial processes. In practical terms a proliferation of new I4.0 applications shall demand seamless access to the devices flexibly operating in the environment (manufacturing plants, warehouses, logistic centres, etc.) for both consuming the operational data that they generate and steering their behaviour to improve productivity.

So, **the most fundamental requirement of I4.0 is connectivity**. Traditionally, manufacturing plants have relied on wired connections, but that is not a suitable approach when moving into the I4.0 world due to two critical downsides:

- Very high costs and long lead times for cabling new equipment. This is a road blocker for the practical integration of the number of devices that I4.0 scenarios demand (at least one order of magnitude greater than previously).
- Reduced flexibility for the location of the devices to be connected, since they have to remain static, attached to a fixed connection point. This is a limitation that, in general, jeopardizes the promise of flexibility of I4.0, and, in particular, is simply not compatible at all with AMR (Autonomous Mobile Robot) and alike solutions for which mobility support is a must.

It is in such context where LTE (Long Term Evolution) and 5G get on stage for I4.0, for becoming the technologies of choice providing I4.0 solutions with wireless connectivity that enables mobility, reliability, and security. Additionally, and equally important, being LTE and 5G standards-based technologies meant for global deployment, relevant economies of scale can be leveraged for accessing network services, on the one hand, and for adopting connectivity devices and modules available in large volumes and very cost-effectively, on the other hand.

Actually, LTE, mainly in the form of Private LTE solutions, has been successfully integrated and it is in operation in, for instance, Industrial Logistics and Transport environments for supporting certain I4.0 scenarios. But it is 5G, given its superior performance levels in speed, latency, and reliability, along with its high flexibility to adapt to heterogeneous needs and environments, the cellular technology in the spotlight for adoption by I4.0.

So, over the paper, the first question seems to be answered already and positively since **there seems to be a perfect match of I4.0 needs with the features and advantages 5G, especially for what we could call *I4.0-native* or I4.0 greenfield projects**.

However, the experience across many initiatives and projects makes it evident the that, when considering not only the addition of 5G to greenfield I4.0 use cases but also the replacement of previous fixed connections by wireless connections, one outstanding issue is top of mind for I4.0 technology managers: network performance. Indeed, when aspiring to base the connectivity of, for instance, a whole factory on mobile technology, having as a mental reference that of the performance and reliability levels of previously deployed fixed connectivity solutions, the bar is set very high. So, in the transition from fixed to mobile connectivity there are evident upsides but also concerns and potential risks to be carefully assessed.

1.2 What type of I4.0-focused activities have been run at 5G-PPP Phase III Projects?

The background scenario described above has been recurrent across most 5G-PPP research and innovation projects focused on I4.0, and it has triggered **intense and fruitful interaction of I4.0 partners with ICT (Information and Communication Technologies) partners, Universities/Research Centres and specialized SMEs towards a thorough and systematic validation of the performance levels that 5G, in many of its various flavours, can deliver versus the implicit and explicit expectations of I4.0 managers**. The analysis of 5G as enabler of I4.0 in 5G-PPP Phase III projects, has always revolved around validating, to start with, very high connectivity speed levels, and low latencies for the communications involved in a broad range of I4.0 use cases. By understanding and accurately quantifying the actual performance delivered by 5G -as well as the actual demands of I4.0 use cases of all types-, and after having validated their match in the large majority of cases across 5G-PPP projects, then the major concern on the risks perceived by I4.0 technology managers when evaluating the transition from fixed connectivity to cellular connectivity explained above has been effectively addressed**. It has been, then, possible to transit from *whether* 5G could be used to *how* 5G can be best used, for I4.0**. The contribution of 5G-PPP projects focused on I4.0 contexts for facilitating this paradigm and mindset shift for all parties involved can probably be regarded as one of its major collective achievements.

Further on, and all along this report, concepts, learnings, insights, and viewpoints from partners of **representative I4.0-focused 5G-PPP Phase III projects (5G EVE, 5Growth, 5G-Smart, 5G-Era, 5G-Induce, 6G BRAINS, Evolved-5G and Vital-5G)** shall be fully leveraged. So, at this introductory level now a quick overview of their focus and insight follows with the intention to start landing some of the concepts introduced and to be further dealt with in the report. For a more complete and detailed understanding of the I4.0 cases, challenges, approaches, and outcomes of each of these projects you can follow the links provided to their web pages and selected key deliverables in Annex I.

The spectrum of I4.0 use cases dealt with at 5G-PPP projects is very broad, covering **innovative scenarios of AGVs (Autonomous Guided Vehicles), UAVs (Unmanned Aerial Vehicles), Digital Twins, Collaborative Robots, AR/VR applications for remote monitoring and actuation of industrial devices, Immersive Training, Condition-based Monitoring, Asset Tracking, High-Precision Metrology, Zero-Defect Manufacturing, Critical Infrastructures Surveillance, Predictive Maintenance, etc.** The application of many use cases is not restricted to Manufacturing industrial sector but also extends, naturally, to Logistics and, further on, to automation and digitalization scenarios of Energy and Transportation, among other. **Major vertical stakeholders of the selected 5G-PPP**

Phase III projects include -among other Industry leaders- ABB AB, ASTI Mobile Robotics SA, Robert Bosch GmbH, COMAU SpA, DHL Exel Supply Chain SL, Diakinisis AE, EFACEC Energia SA, Ford España SL, GMI Aero SAS, HAL Robotics LTD, Innovalia, Public Power Corporation Greece (PPC), Whirlpool Management EMEA SRL, … also leveraging the high specialization of SMEs in concrete technologies, like Fivecomm SL, Fogus Innovations & Services PC, Immersion, Infolysis PC, InQbit Innovations SRL, Nextworks SRL, Oculavis GmbH, Telcaria Ideas SL, Yerba Buena VR Europe SL, Wings ICT Solutions & Technologies, …. Obviously, these projects have heavily relied on the tight interaction with CSPs (Communication Service Providers) such as Altice Labs SA, Deutsche Telekom AG, Telefónica Investigación y Desarrollo SA, Telecom Italia SpA, Orange SA, OTE AE, Wind Tre SpA, …, and with leading 5G vendors Ericsson and Nokia. Also, in the ecosystems for these projects, fundamental contributions are made by leading European Universities and Research Institutions: Consorzio Nazionale Interuniversitario per le Telecomunicazioni (CNIT), Centre Tecnològic de Telecomunicacions de Catalunya (CTTC), Eurescom GmbH, Fraunhofer IIS, Lunds Universitet, National Center for Scientific Research "Demokritos", University Carlos III of Madrid (UC3M), Universitat Politècnica de València (UPV), University of Patras (UoP), University of the West of Scotland (UWS), ….

As it was commented, **measuring the performance that 5G technology, as part of the end-to-end testing and validation of vertical use cases** (being I4.0 a frequently focused vertical), delivers **has been the core activity at 5G-PPP projects, for allowing to extract fact-based learnings and conclusions on the actual feasibility of 5G enablement for vertical applications**. Started in 2018, ICT-17 projects[3] like 5G EVE developed not only advanced infrastructures for execution of vertical use cases (including I4.0 use cases) at a variety of locations and offering several 5G solutions and configurations, but also a set of structured processes, methods, tools making up a whole platform for monitoring and analysing both vertical use cases behaviour and the performance levels of the underlying 5G network. 5G-PPP Phase III projects have shared the same definitions of KPIs and the same or comparable methods for measuring performance in real-world scenarios, obtaining, and presenting quantitative results in a uniform way, thanks to **5G-PPP cross-project coordination in the fundamental subject of testing and validation of vertical applications embracing 5G**. That alignment **has been instrumental for carrying out a comprehensive evaluation of I4.0-5G synergies** since the experience and results on the Use Cases analysed within each and every 5G-PPP project can be unambiguously interpreted and leveraged from one project to another. Moreover, **all the results of 5G-PPP experimentation are publicly available (see Annex II), constituting a large bank of information on I4.0 use cases, their performance and that of the crafted 5G solutions to support them, that can be used for consultation by any firm engaged in I4.0 initiatives**, help accelerating their learning curve in their journey.

Beyond the detailed exploration on multiple architectures, scenarios, and configurations of standards-based 5G systems for meeting performance expectations

[3] https://5g-ppp.eu/5g-ppp-phase-3-1-projects/

of I4.0, the **5G-PPP projects have also pursued and delivered innovations for enhancing the management, flexibility, automation, usability, security, and other aspects of end-to-end solutions, that hold an influence on the adoption of 5G by I4.0**. That has been a central subject for ICT-19[4] projects started in 2019. Two representative projects of the ICT-19 family, which fully concentrated in research and innovation on I4.0, and carrying it out over final industrial facilities, are 5Growth and 5G-Smart. On its side, 5Growth evaluated the feasibility and benefits of multiple innovations applicable across complete trials of I4.0, Energy Management and Transportation, executed on targeted vertical premises, and, remarkably, **5Growth integrated and tested novel Non-Public Network approaches for supporting Industry scenarios (see Section 4.2)**. In parallel, **5G-Smart explored, among other, I4.0 use cases with stringent demands on a new dimension of performance, latency predictability, opening new paths for innovation in deterministic networking**.

The journey along this selection of 5G-PPP Phase III projects takes us now to ICT-41[5] Innovation Action projects **5G-Era, 5G-Induce, Evolved-5G and Vital-5G**, started in 2021 and still in execution, at the time of writing this report. These projects are strongly devoted to concrete I4.0 field trials for the sectors of Manufacturing, Logistics and Transport. They **leverage latest 5G standards commercially available, such as Rel-16, apply advanced architectural patterns for smart integration and orchestration of I4.0 applications at Edge environments, and address central technological and ecosystem aspects for allowing effective and sustainable growth, combination, and reuse of I4.0 Apps**, pitching for a market-place dynamics to be established for such purpose.

1.3 And why is I4.0 so relevant for 5G?

Having completed this basic introduction to key aspects covered in the projects contributing to this report, now we may address the reciprocal question on the synergy of I4.0 and 5G: ***Why is I4.0 so relevant for 5G?***

Considering the rapid and global scale of ongoing deployment of 5G networks, accounting for 1 billion 5G subscriptions in June 2023, according to Ericsson Mobility Report [3], that is indeed a most valid question. Putting things in context, public 5G networks' deployments grow at large scale, with full leverage on a broad customer base of LTE mobile subscriptions worldwide (market potential) and on the major capacity enhancements and cost-effectiveness of 5G over LTE (key business case factor for CSPs deciding to deploy 5G over growing 4G networks). The priority focus of global 5G build-out is on mid-bands (Sub 6 GHz spectrum), starting with dominance of NSA (Non-Stand Alone) architectures although already moving to SA (Stand Alone). On their side, **5G deployments for I4.0 support, instead, are handled case-by-case, demanding 5G SA architectures, and private network services, and normally basing on mid-bands spectrum, although for some specific applications mmWave spectrum is required**.

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[4] https://5g-ppp.eu/5g-ppp-phase-3-3-projects/

[5] https://5g-ppp.eu/5g-ppp-phase-3-6-projects/

From the ICT point of view, I4.0 can be seen as a developing vertical segment for 5G, that, although very specific in needs and context, is extremely important for 5G for two reasons:

1. 5G technology has demonstrated its potential to serve multiple I4.0 scenarios with high performing and reliable mobile connectivity. **The I4.0 phenomenon happens at global scale and may reach, according to [4], up to 1 million factories worldwide**. So, despite the heterogeneity and specificality of I4.0 environments and requirements, collectively I4.0 is a great opportunity for 5G business growth, becoming a reference market segment always leveraging the most advanced features of 5G. That is basically the answer to the question for the short and mid-term.
2. I4.0 stringent demands on 5G and its evolution are major drivers for the continued research, standardization and development of new advanced features and performance enhancements for 5G and towards 6G**. I4.0 vision has a long-term potential that will keep influencing 5G standards in the direction of pursuing major performance, reliability, and flexibility improvements**. Those improvements shall become part of the baseline for Advanced 5G and 6G, and so, expanding its applicability to other developing vertical sectors with also increasing demands expressed on mobile connectivity services. That is the answer to the question considering the long term.

In simpler terms we can summarize, at this introductory level, that **I4.0 is a front-runner agent for advanced 5G technology adoption**, showing the path, through multiple and varied Use Cases, for possibilities to exploit the broad and high potential of 5G and its evolution to its maximum. Obviously, being a front-runner in technology adoption and its induced transformation also has the implications of first-time exposure to complex challenges at several levels (technology, regulation, ecosystem, business transformation, …). I4.0 pioneers are actually exposed to the double challenge of implementing new –most times, disruptive- ways of running their key business/operational processes à-là-I4.0, while integrating, for that purpose, a range of technologies like 5G, Edge, ML and AR/VR, some of them for the first time.
This report is considering that broad landscape around I4.0 but concentrating on I4.0-5G synergies, at both general and very specific aspects, and their expected evolution over time.

2. Spotting the key 5G enablers for Industry 4.0

With the objective of identifying those aspects of 5G that may become enablers for I4.0, and reaching general conclusions that should be applicable across I4.0 Use Cases, in this section a reference framework for I4.0 Design principles is introduced and applied as a tool for spotting major technology trends and their level of influence on I4.0, and then segmenting that analysis for concrete 5G aspects over a timeline covering short and mid-term horizons.

2.1 Industry 4.0: From concept to development

Now, let's do an **attempt to demystify I4.0**, trying to become concrete on differentiating aspects defining this new paradigm, and also going through some illustrative real examples and needs of I4.0.

When approaching the I4.0 concept, researchers and practitioners can be first amazed by the heterogeneity of use cases *labelled* as I4.0 use cases, and then simply overwhelmed when looking into the details of architectural and implementation specifics behind them, that also differ from one concrete project to another. **The lack of common definitions and standards for I4.0, at conceptual, functional and implementation levels is normally inducing a fragmented understanding of the I4.0 phenomenon**, and thus leading to an ineffective dynamic based on case-by-case approaches.

Since our objective is to extract useful conclusions on the status, key levers, and on potential road-blockers for I4.0 realization and evolution, from a 360-degree perspective, **the bias that could be introduced by the consideration of only a few selected use cases and specific technologies has to be mitigated**. So, for analysis purpose going forward in this report, and given the large number and extreme variety of I4.0, **a segmentation of I4.0 is proposed here, into four clusters of I4.0 complementary Design Principles**, derived from the early research work performed in [5], and being updated and assessed over the evolution of I4.0 and the considered in the period from 2016 to 2023.

The four I4.0 clusters (or Design Principles) considered are *Interconnection*, *Information Fusion*, *Human-Machine Collaboration* and *Flexible Decision Making*. An introduction to each of them follows:

- ***Interconnection***: I4.0 scenarios are characterized by the generalized interconnection of machines, sensors, systems, processes, and people. Such interaction is based on communication standards, with Wireless communication technologies playing a prominent role in the increasing interactions as they allow for ubiquitous Internet access and higher flexibility for the foreseen dynamicity of Industry environments.
- ***Information Fusion***: The fusion of intertwined information from both the physical and the virtual worlds constitutes a common base of information for supporting Industry processes in many I4.0 use cases. Such fusion is facilitated by advancements in information systems and sensors, real-time communication technologies and, finally, its essential visualization is highly supported by VR and AR technologies.
- ***Human-Machine Collaboration****:* I4.0 emphasizes Human-Machine Collaboration, promoting that repetitive and, especially, unsafe tasks, are delegated to (smarter) machines, which implies that a new role for the workers evolving to planning, supervision, decision making and collaboration with the machines is instrumented. Remarkably, this collaboration may very well go beyond the boundaries of the factory environment, extending across the value chain. Such a new model for delegation, coordination and collaboration in industrial tasks must be supported by ubiquitous communication technologies, advanced robotics and sensing technologies, intuitive visualization and actuation devices like smartphones and tablets and evolving to AR and VR tools and wearables. Additionally, the increased level of processing and

intelligence required on the machines taking on more and more complex tasks calls for the support of ML/AI technologies.

- ***Flexible Decision Making***: Across multiple I4.0 use cases Flexible Decision Making is pursued, envisaging scenarios where people and, especially, machines may have the possibility to either take decentralized decisions or surrogate to centralized decisions, as ways to respond to the demands of better decision making for increased global productivity. Such flexibility is enabled by interconnection, thus relying on communication standards, and realized to its full potential with the CPS (involving distributed systems approaches and autonomous systems), leveraging embedded systems, cloud-edge paradigm, and ML/AI.

Table 1 - Landscape of key influencing ICT technologies on I4.0

	Key ICT Enabling Technologies for I4.0			
I4.0 Design Principles	**IoT / 5G**	**Cloud&Edge**	**AR&VR**	**ML/AI**
Interconnection	Critical	Significant	Minor	Minor
Information Fusion	Critical	Critical	Significant	Significant
H-M Collaboration	Critical	Significant	Critical	Significant
Flexible Decision Making	Critical	Critical	Minor	Critical

In order to summarize and understand the relative level of influence of the key ICT technology enablers for I4.0 (namely IoT&5G, Cloud&Edge, VR&AR and ML/AI) onto each of the complementary I4.0 Design Principles, Table 1 is provided. As can be seen, **the influence of IoT&5G technologies is critical to the realization of *all* I4.0 design principles**, and the influence of Cloud-Edge continuum paradigm and the associated technologies is, at least, significant for the fulfilment of all I4.0 design principles. On their side, AR, VR and ML/AI are, respectively, critical technologies for supporting the fulfilment of Human-Machine Collaboration and Flexible Decision Making I4.0 design principles.

So, now we have a use case – agnostic framework for I4.0, and a general map of dependencies with major I4.0 technology enablers, clearly indicating – in particular- the expectation and dependency of I4.0 with 5G. How can we use this framework, going forward, in practice?

First, just by mapping a given I4.0 use case -for instance, at inception time- to one, two or even more of these I4.0 design principles, on the one hand, potential differentiation aspects can be identified over the initial use case in consideration. On the other hand, general technological implications can be clearly spotted and assessed. That is a general recommendation to practitioners that may help improve the robustness of their analysis of novel I4.0 use cases.

Also, for the purpose of our analysis **the top-down approach initiated may now be iterated, segmenting this time on the 5G domain, for delimiting the influence and potential impact of each specific aspect of 5G on each of these I4.0 design principles**, thus with a very good granularity level. Please refer to section 2.2 on this aspect.

Finally, the framework itself constitutes the basis for the elaboration of the questions in the survey prepared for, and answered by, the I4.0 stakeholders of representative

5G-PPP projects. That shall enable a fact-based research exercise over a structured framework for analysis. Please refer to section 3 for this exercise.

2.2 5G and beyond networks: What's in it for I4.0?

The top-down approach to the I4.0 phenomenon followed in section 2.1, has already highlighted the high level of influence of IoT/5G and Edge on advanced I4.0 scenarios.

IoT communications have been a horizontal enabler for I4.0 from its very inception, and more so in particular IoT over wireless networks, for meeting both common mobility support I4.0 requirements of machines and people and flexibility demands for planning new processes that should not be fixed to the floors or walls of a floor shop or warehouse anymore.

5G technology (with worldwide, generalized, and rapid adoption) provides with the key underlying technology for IoT connectivity over both public and non-public (private) mobile networks. Still, referring to 5G in general may not be sufficient for arriving to specific conclusions, so, as anticipated, a segmentation on the 5G technology domain is proposed. Just for convenience a very high-level summary of most relevant aspects and features of 5G is included here, to be followed by the assessment of its expected relative support and influence on I4.0 design principles, over a basic timeline, as presented in the subsequent section.

Services and performance

5G standards, since 3GPP (Third Generation Partnership Project) release 15 (Rel-15), diversified its offering into specific types of services defined as:

- Enhanced Mobile Broadband (eMBB), with "human-centric use cases for access to multi-media content, services, and data",
- Ultra-reliable Low-Latency Communications (URLLC) -also frequently referred to as Critical IoT-, with "stringent requirements for capabilities such as throughput, latency and availability", and
- Massive Machine-Type Communications (mMTC) -also sometimes referred to as Massive IoT, with the specificity to address "a very large number of connected devices typically transmitting a relatively low volume of non-delay sensitive data", with low cost and long battery life devices.

Following that disruptive approach, the same mobile communication standard can provide, to distinct mobile users and applications, the so-called *network slices* so as to deliver the performance that best adapts to their distinct needs, which normally fall into one of the three categories of the services featured.

ITU also specifies the operation of 5G New Radio (NR) over distinct frequency ranges, with the intent to support scenarios for, respectively, wider range and higher capacities. The bandwidth available within these frequency ranges is broader than that assigned to LTE, which makes it possible to deliver higher speed (throughput) for both Uplink and Downlink communications over 5G.

Flexibility

5G standards incorporate the adoption of a number of advanced features and mechanisms that provide CSPs with greater levels of flexibility than those of previous generations of mobile communication standards. Among all of them it is worth covering, at least, the following:

- NFV (Network Function Virtualization):

All 5G Network Functions are virtualized, thus allowing for multiple options of cloud-like deployments of 5G. NFV transforms the way in which networks will be designed and built by allowing to consolidate many network equipment types onto industry-standard high-volume servers, switches, and storage, which could be located in data centres, network nodes, end-user premises, etc. This is particularly interesting for benefitting from cloud economics of scale, as well as for reducing the footprint of 5G deployments for non-public dedicated networks, for instance.

- Control-User Plane separation (CUPS):
  5G network topology and connectivity between the different network elements are implemented in a way that the CP (Control Plane) and UP (User Plane) follow different paths. Even though anticipated as an optional LTE feature, CUPS is generalized and stretched to its full potential with 5G. A major benefit of CUPS is to bring the UP node closer to the UE, in order to reduce latency of the service and to offload the backhaul. More generally CUPS allows for flexibly distributing CP and UP functions all along the cloud-edge continuum, from the central office DC (Data Centre) of a CSP down to the far edge, as close as needed to the UE.
- Edge Computing:
  Generally referred to as a distributed computing paradigm where computation is largely or completely performed on distributed low-power device nodes located closer to the users, as opposed to a centralized cloud environment: edge computing pushes applications, data, and computing power (services) away from centralized points to the logical extremes (closer to end-user) of a network. The benefits of this kind of paradigm may be summarized as Latency reduction (since the time needed by data to travel from source device to the place where they are elaborated is shorter) and bandwidth demand reduction (as the more localized elaboration of big amounts of data, may provide a significant reduction of the data otherwise moved all across the whole network). 5G, by embracing NFV and CUPS, is perfectly fitted to support multiple options of Edge Computing, for optimizing performance and resources for both network functions and virtualized verticals applications.
- Network slicing:
  5G includes native support of such feature. It allows to set up multiple virtual slices of the RAN, core and transport networks to meet specific service requirements, e.g., radio access technology, bandwidth, end-to-end latency, reliability, guaranteed / non-guaranteed QoS (Quality of Service), security level. With Network Slicing, over the same physical core and radio-access networks, different slices can run as, for example, one supporting mobile broadband application in full mobility, as provided by the legacy LTE system, and another slice delivering as, e.g., non-mobile, latency-critical industry-automation application. In other words, despite such slices are running on the same physical network, from the end-user point of view they appear as independent networks and each of them may provide different network capabilities.
- 5G NR:
  First, 5G supports, as already introduced, several frequency ranges that can help meet the specific demands of coverage range, penetration, and capacity (from lower bands to higher bands). On top of that, densification of access

networks in mid and high bands allows for providing both high capacity and customized range, for, e.g., enterprise or industrial indoor deployments.

- Architecture Options:
  5G specifies several architecture options, which can be summarized for simplicity as legacy architectures (full compatibility with LTE), NSA architecture option (CP is anchored to a supporting LTE network, while UP communications fully leverage 5G-NR) and SA architecture option (with full independence of 5G from LTE legacy networks). SA option is a natural choice for non-public networks since it can be smoothly deployed, independently of LTE networks.
- 5G RAN Configuration Options:
  5G also allows to select a variety of configurations for the modulation, beam forming, MIMO (Multiple In, Multiple Out) layers, TDD/FDD (Time Division Duplex/Frequency Division Duplex) patterns, among other aspects of 5G-NR numerology that go beyond the scope of this report. This flexibility can be helpful in various scenarios, e.g., for prioritizing uplink communications throughput, or for improving capacity or coverage.
- 5G Bandwidth flexibility:
  The bandwidth used within the frequency ranges assigned to 5G can be increased, or adapted in general, by using features such as carrier aggregation and dynamic spectrum sharing (DSS), to meet the actual needs of speed (throughput) of the use cases supported.

2.3 Top-down assessment of I4.0-5G synergies for the present and towards the near future

Having reviewed the key concepts, status, and trends for I4.0 and 5G, now we can complete a side-by-side analysis at their intersection, trying to identify major synergies for the present moment and for the near future, and highlight some opportunities and challenges associated.

Following the methodological framework of I4.0 Design Principles, and leveraging on the key 5G concepts (or enablers) above explained, the relevance of each key 5G enabler on each I4.0 design principle has been assessed for the present and the near future, and reflected in Table 2.

Table 2 - Assessed relevance of key 5G enablers on I4.0, for the Present and near Future

	5G Services			5G Spectrum			5G Architecture					
I4.0 Design Principles	**eMBB**	**URLLC**	**mMTC**	**Low Bands**	**Mid Bands**	**High Bands**	**NFV**	**CUPS**	**Edge**	**Slicing**	**NSA**	**SA**
Interconnection	P+F	P+F	F	F	P+F	F	P+F	P+F	P+F	F	P	P+F
Information Fusion	P+F	F	F	F	P+F	F	P+F	P+F	P+F	F	P	P+F
H-M Collaboration	P+F	F	F	F	P+F	F	P+F	P+F	P+F	P+F	P	P+F
Flexible Decision Making	F	F	F	F	P+F	F	F	F	P+F	F	P	P+F

The cells in the matrix related to 5G enablers estimated to having a major influence on an I4.0 design principle, but *only on its present*, are shown in blue and labelled as 'P'. Then, the cells in the matrix related to 5G enablers estimated to having a major influence on an I4.0 design principle, *both on its present and near future*, are presented in green and labelled as 'P+F'. Finally, the cells in the matrix related to 5G enablers estimated to having a potential influence on an I4.0 design principle, but *only in the near future*, are shown in yellow and labelled as 'P+F'.

Some insights that can be extracted from this matrix follow.

- Analysis of 'P alone' matches (blue cells):
  Very few cells (only 4 out of 48) in the table show a match for *just* the present, alone. It is the case for the role of NSA for I4.0 (and it would have also been the case for legacy LTE, if it had been analysed and included in the table). That reflects the fact that NSA has been used for some early 5G trials and pilots of I4.0, as 5G SA was maturing, and until 5G SA CPE manufacturers are fully activated to serve new devices to the market, **but the future of 5G for I4.0 will talk SA, unlocking increased performance levels (URLLC) and other flexible 5G features such as slicing and flexible edge computing support**. Therefore, the recommendation for new 5G-enabled I4.0 initiatives is going for investments on 5G SA architecture option from scratch.
- Analysis of 'P+F' matches (green cells):
  A large number of cells (23 out of 48) in the table indicates a match of 5G and I4.0 for both present and future. This is the case for, among others, these **5G Key enablers: eMBB, mid bands frequency for 5G-NR, NFV, CUPS, Edge and SA**. It illustrates the **current feasibility, along with the future/sustained potential, of such 5G enablers for realizing I4.0**. Those 5G enablers can be regarded as the "safe bets" of investment (through knowledge build, to technology integration, validation and exploitation) for actors engaged in I4.0 5G-enabled endeavours now and in the near future. Even if the entry barrier can seem high due to the involvement of several technologies and the potential complexity of integration, the investments are likely to pay off over time through evolution and reuse of the associated knowledge and technology base.
- Analysis of 'F alone' matches (yellow cells):
  A large share of cells (21 out of 48) in the table indicates matches of 5G and I4.0 expected to be materialized in the near future (i.e., not yet in the Present). That can be seen as a fair illustration of the **high potential that 5G technology status and regulation hold for the future**, as well as of the still long innovation journey ahead of I4.0 revolution. As remarkable cases of 5G enablers falling into this category **URLLC, mmWave, Slicing and (potentially) low bands** can be clearly spotted. A rushed conclusion out of this situation could be that technology and strategic investment for learning/deploying/integrating/using these 5G enablers should be put on hold, but a more careful analysis considering the viewpoints of both I4.0 and 5G may lead to another conclusion: these matches for the near future indeed represent a **huge opportunity for differentiation and increased competitiveness through timely research and innovation** on the identified intersections. So, the recommendation could be, instead, to start new cycles of knowledge build and collaborative projects aiming at properly exploring them. As an additional and final observation, it can also be seen that the row **for I4.0 Design principle "Flexible Decision** Making" is particularly dense on 'F' matches (8 out

of 12) also suggesting that **the potential for innovation yet to be unlocked in this field can be extremely high**.

A synthesis of this analysis, and the derived recommendations could be visualized as a most likely (and desired) scenario for the I4.0-5G ecosystem: coexistence of large-scale I4.0 pilots (around the 'P+F' matches) safely moving to both business exploitation and evolved with further innovation cycles, with brand-new research activities exploring and road-mapping forward-looking opportunities (around the 'F' matches). The challenges to overcome for reaching that sweet spot scenario are not negligible though. There is the need for ramping up teams of engineers with the skills and talent required for this ecosystem, managing the transformation of industrial processes triggered by I4.0 advancements and establishing effective business models and supply chains for 5G services. Moreover, it requires the integration with other key technologies, to be smoothly delivered to, and widely used by, I4.0 solutions. If the associated challenges are overcome, then the establishment of such type of ecosystem dynamics would represent the inflection point for I4.0 take off, and the start of its promise being delivered.

3. Strategic Approaches for embracing and leveraging 5G and beyond networks in I4.0

A comprehensive survey (see Annex II) has been elaborated and distributed to I4.0 vertical stakeholders of representative 5G-PPP projects dealing with I4.0-5G challenges. **The aim of this survey is to collect information that reflects the verticals' point of view on I4.0 motivations, trends, challenges as well as on the role and considerations on 5G as enabler for I4.0 evolution**. The questions were designed to motivate that the vertical stakeholders are not only considering the specific scope of the use cases they are involved in, but providing, more generally, their firm's viewpoint on the general subjects of analysis.

The survey consists of eleven questions, allowing the vertical stakeholders answering them for both providing free textual answers and explanations questions, and providing inputs to tabulated questions for the selection and scoring of factors over multiple-choice boxes (being its aggregated analysis fully documented in Annex III). The next two sections of this report reflect, respectively, these two types of inputs, exactly as they were provided by the participants in the survey.

3.1 General Perspectives on I4.0, 5G and its synergies, expressed by I4.0 stakeholders of 5G-PPP projects

A broad sample of the complementary perspectives of the participants in this survey (see Annex II), derived directly from their free-text answers and comments to the open questions included in the survey -more concretely questions Q2, Q4, Q6, Q9, Q10 and Q11- is provided here.

ABB Corporate Research Centre (Sweden)
With regards to the envisaged I4.0 5G-enabled applications for the near future ABB considers that the adoption of 5G technology is key for:

- Industrial equipment and products that have to enjoy freedom of movement, like mobile robots, mining trucks, drones, etc. to accomplish their tasks, thus requiring both mobility support and high-performance wireless connectivity.
- smart manufacturing applications with time-critical requirements, highlighting the importance of URLLC and Edge Computing.

ABB estimates that the generalized adoption of 5G in their industry sector is to come within the period 2025 to 2029, indicating the following key milestones in that process:

- Further evolution and consolidation of the 5G ecosystem
- Increased availability of industrial type 5G UEs/CPEs (User Equipment/Customer Premises Equipment), including specific integration aspects to be developed, like native support of Ethernet PDUs (Packet Data Units)
- New features in 5G standards for the support of more time critical I4,0 applications (beyond Rel-16)

With regards to the options on deployment models, the main scenarios being considered by ABB are local on-prem Data Centre (far Edge) and near-Edge.
In this regards ABB indicates that having applications and data stored on-prem is the preference of most of its customers.

On the analysis of Non-Public Networks (NPNs), ABB states the priority that the networks need to be secure and reliable, and shares that deploying and managing the networks need to evolve to become "IT friendly" so no additional expertise in-house is demanded. According to ABB the biggest hurdle today is on the costs for owning and managing dedicated 5G solutions.

Regarding security and privacy, ABB has identified and shared the following considerations:

- Security provided by 5G is perceived as good for I4.0 requirements.
- Taking a holistic view on security is very important, especially as I4.0 drives the merge of IT and OT.

ASTI -now ABB Autonomous Mobile Robots (Spain)

ASTI considers that especially the following I4.0 use cases do leverage 5G technologies:

- Remote control and remote maintenance of AGVs
- Remote commissioning
- Virtualization, and deployment of hardware controllers as MEC (Multi-access Edge Computing) applications
- Wireless industrial field communications
- Safe collaboration between cells with robotic arms and AGV’s

ASTI estimates that the generalized adoption of 5G for I4.0 will take place in the period 2025 to 2029, and shares that their key milestones in the process are the following:

- Development of software and hardware adaptions in the AGVs to enable the deployment of AGV and fleet management services as Edge applications (some relevant advances have been carried out in research projects).
- Experimental validation of software and hardware adaptions in laboratory and test networks (some relevant advancements have been carried out in research projects).
- Deployment of 5G networks in non-public networks providing 5G services to their customers.
- Pilot tests in end user facilities progressing from involving a small number of AGVs to a large number of AGVs.
- Long-term validation in end users' facilities in production, verifying 99% reliability reached.

With regards to deployment models, in ASTI's view, near edge deployments are considered for virtualization of hardware controllers currently embedded in the AGVs and other machines, such as PLCs (Programmable Logic Controller) and industrial PCs and implementing AGV fleet management systems. These applications require low latency and high reliability, therefore 5G-URLLC would be beneficial. On the other hand, central offices and hyper-scalers are more suitable options for monitoring AGVs working in plants located in separated geographic areas, store information, analyse statistical trends, and apply machine learning techniques and forecast failures and future performance.

When addressing security and privacy requirements, ASTI comments that the internal data produced by the AGVs can provide very valuable information about how the production lines are working in real time. Moreover, the unauthorized access to the AGVs could cause stops of the production line and huge profit losses. Thus, security and privacy are two key aspects to enable AGV-based Industry 4.0 applications. The key security requirements indicated by ASTI are:

- All information transmission must be encrypted.
- Any unauthorized access to the AGVs must be blocked.
- It must be ensured that information flows between two systems cannot be manipulated.
- It must be possible to guarantee the authorship of all information flows.

  The current plan to address this issue is to include specific communication devices and small embedded systems to incorporate encryption and security in all AGV communications.

CIM4.0 (Italy)

With regards to the envisaged I4.0 5G-enabled applications for the near future CIM4.0 enumerates the following:

- Flexible and reconfigurable production lines thanks to the wireless connectivity also at OT (Operational Technology) level.
- Integration of OT level with edge cloud solutions.
- Security at the shopfloor. OT level devices could communicate and control wireless other moving components such as AMR based on current production status.
- XR (Extended Reality) video streaming in real-time and augmentation of the experience with AI-based application.

CIM4.0 estimates that the generalized adoption of 5G in their industry sector is to come within the period 2025 to 2029, indicating the following as key milestones in that process:

- Integration of the OT level with Edge Cloud Solutions.
- Integration of 5G to manage security aspects within production facilities.
- Implementation of XR-based solutions enabled by 5G technology.
- Availability of reconfigurable production lines.

With regards to the options on I4.0 applications deployment models, the main scenarios being considered by CIM4.0 are Near Edge and Hyperscalers.

Regarding security and privacy, CIM4.0 has identified and shared the following key aspects and requirements of their I4.0 initiatives:

- Security aspects integrating edge cloud and OT level.
- Access to the network management systems (e.g., VLAN management).
- Dynamic configuration of network QoS.

FORD (Spain)

With regards to the potential that 5G can unlock for new I4.0 applications and use cases, Ford stresses the importance of these 3 factors:

- Increased bandwidth for 5G: It enables considerably bigger data flows between machines and servers than earlier networks.
- Very low delay of communications: The very low delay (or latency) of 5G communications allows the company to use remote processing servers and rely less on local or embedded computing as it was conventionally done.
- Outdoor and Indoor coverage: 5G enables smoother transition of outdoor-indoor communication between machines, systems, and the network. That can open wide areas of applicability for AGV applications and traceability of asset parts.

Ford remarks that, above all, 5G is a wireless technology that removes the painful dependency of industry equipment to wired infrastructure (not flexible and very expensive, if available at all at the location). Then, 5G can also guarantee the levels of high reliability (for securing smooth synchronization of control processes within their set time-outs), and optimized UL (Uplink) date rates (to allow concurrent streaming of video from machines in the factory, such as AGVs) that I4.0 applications of many types of demand.

Ford indicates that an especially relevant example of application of 5G to I4.0 is the E-BEAT project developed at Final Assembly plant, focused on battery and headlight traceability using 5G.

Ford foresees that the generalized adoption of 5G for I4.0 in their industry will take place between 2025 and 2029.

With regards to the deployment models considered, Ford focuses on Edge Computing (both Near and Far Edge computing options) and Hybrid Cloud models, as they could best adapt to the diverse requirements in performance, flexibility, security and costs of different I4.0 use cases.

GMI Aero (France)

GMI Aero considers that the specific applications enabled by Industry 4.0 using 5G are related to the creation of Digital / Physical Twins of bonded composite repairs performed on aircraft remotely located. Thanks to the 5G network at the repair area real-time data will be transmitted to the Engineering Centre of aircraft manufacturer / airline / MRO certification authorities (EASA, FAA etc.). This data will be used either to create, in real-time, a “Replica” repair using a second bonding console, identical to the “Source” repair (Physical-Twin), or to use such data for calculation of the DoC applying corresponding material curing equations (Digital Twin).

GMI Aero adds that, overall, the 5G network will be assisting in the reinforcement of the competitiveness and the performance of EU transport manufacturing industries and related services, facilitating the development of next generation of transport means, further exploiting the advantages of light composite structures, while enabling new manufacturing and maintenance techniques for both existing and new composite structures, in order to retain areas of EU leadership in the transport sector. GMI Aero being part of this ecosystem will be directly positively affected by these global advancements and innovations.

GMI Aero estimates that the generalized adoption of 5G in their industry sector is to come within the period 2025 to 2029, indicating the following as key stages in that process, in their business/domain context:

- Development of hardware and software solutions within the frame of R&D projects.
- Development of innovative products, based on R&D achievements, by companies active in the aeronautical sector.
- Presentation of innovative solutions to the aeronautical stakeholders, i.e., aircraft manufacturers, airlines, Maintenance - Repair - Overhaul MROs
- Introduction of solutions to the aeronautical authorities (EASA, FAA etc.) Approval of innovative solutions by the aeronautical authorities and inclusion within aircraft Structural repair Manuals (SRMs).

With regards to the options on deployment models, the main scenario being considered by GMI Aero is local on-prem Data Centre (far Edge).

Regarding security and privacy, GMI Aero has shared the following key aspects and requirements of their I4.0 initiatives:

- Aeronautical stakeholders require very high standards both in terms of security and privacy. Security is directly related to airworthiness of aircraft, so any Industry 4.0 and 5G related operations must fully comply with applicable requirements.
- Privacy has to do with fierce competition among companies, which would not accept sharing of sensitive data related to their fleet condition, aircraft availability, number, and status of repairs etc.

In that sense -GMI Aero adds- security and privacy have to be fully secured before any expansion of Industry 4.0 and 5G solutions is expected in aeronautics.

IMMERSION (France)

With regards to the envisaged I4.0 5G-enabled applications for the near future IMMERSION considers that 5G opens doors for innovative Extended Reality (XR) usages in industrial contexts. Technologies like Augmented Reality have a strong potential for remote collaboration scenarios as a remote expert/helper can guide a worker to perform a given task, like repairing or inspecting a machine. Such use case requires:

- Strong network performances (real-time communications (audio + high-quality video), real-time cooperation on shared 3D virtual objects
- Network services to monitor the network state and prioritize dataflows. For instance, being able to detect when the network state does not match the initial QoS since disturbing the maintenance/repair task could lead to hazardous situations.

IMMERSION estimates that the generalized adoption of 5G in their industry sector is to come within the period 2025 to 2029, indicating the following as key milestones in that process:

- Research projects and first applications in testbeds. Focus on technological aspects of 5G, application to a few targeted use-cases. Limited functionalities. Adoption limited to industrial partners directly involved in these projects. 5G looks interesting but complex to setup and use in concrete scenarios for SMEs and industries.
- Emergence of an ecosystem. The benefits of 5G are demonstrated in key real-scenarios and deployed to a few real factories. Some tools start to exist to either a) buy an all-in-one setup or b) train IT employees to develop & customize their own system.
- Wide adoption, deployment of 5G within many factories. Formation and training tools for both end-users (ex: factory workers) and IT teams are mature.

With regards to the options on deployment models, the main scenarios being considered by IMMERSION are local on-prem Data Centre (far Edge) and Near Edge. IMMERSION adds that this is not only a question of performance, but of the management and life cycle of data (due to concerns about keeping data from the factory near the factory).

Regarding security and privacy, IMMERSION has identified and shared the following key aspects and requirements of their I4.0 initiatives:

- User identification.
- Ability to encrypt communications.
- Respect of GDPR (General Data Protection Regulation) regulations (personal & behavioural data).

Public Power Corporation - PPC (Greece)

With regards to the envisaged I4.0 5G-enabled applications for the near future PPC considers that the adoption of 5G networks enables the deployment of applications with stringent requirements. The strict timing determinism and low latencies, the high bandwidth and the massive machine to machine communications provide the necessary means to make the deployment of these application feasible. Examples of such applications are Factory automation processes within ms., and Real-Time high-quality video streaming accompanied with AR/VR.

PPC estimates that the generalized adoption of 5G in their industry sector is to come within the period 2025 to 2029, indicating the following as key milestones in that process:

- Adoption of new technologies (AI, big data analytics)
- Hardware support (AI processors)
- Innovative solutions on data exploitation (Digital Twin)

With regards to the options on deployment models, the main scenarios being considered are the local on-prem Data Centre (far Edge) and the Central Office (Telco cloud). A more elaborated analysis of deployment options follows:

- The on-premises Data Centre that can satisfy the needs for process automation and monitoring and can operate securely in an isolated environment.
- The Central office can provide the cloud capabilities needed to support the applications.
- Near edge can become feasible in more advanced use cases for example in the case of distributed energy resources regarding the energy sector.
- Hyper-scalers' services should be considered as a next step considering the needs for more storage and computation capabilities.

On the analysis of Non-Public Networks (NPNs), PPC gives special attention to both their security and reliability capabilities. For PPC, reliable communications in critical processes and the protected environment of a non-public network can enable seamless operation under an isolated environment.

Regarding security and privacy, PPC has identified and shared the following key aspects and requirements of their I4.0 initiatives:

- Reliable communications in critical infrastructure's processes.
- Integrity and confidentiality in all the communications.
- Authentication mechanisms and access control mechanisms.
- Intrusion detection system (e.g., DoS attack detection).
- Privacy preserving approaches for user sensitive information that can be derived from tracing or monitoring the activities and location.
- GDPR and company's policies compliance
  And finally, in relation to them, PPC states their belief that by adopting 5G technologies along with implementing disruptive technologies (such as AI) many of the above introduced requirements are expected to be satisfied.

WHIRLPOOL (Italy)

In Whirlpool's view, 5G technology, applied to I4.0 solutions may enable new applications not possible until today, mainly boosted by the possibility to achieve improved performance in terms of higher throughput and faster E2E (End to End) response time, while also enabling the possibility of a reliable and cheaper assets' connectivity at the shop floor.

Commenting on the factors motivating the adoption of 5G for I4.0. Whirlpool makes a special remark to the security management that 5G connectivity implies vs. traditional Wi-Fi connectivity.

Whirlpool expects that the generalized adoption of 5G for I4.0 in their industry is to start on year 2025 and, highlighting the following milestones along the journey towards its full adoption:

- Key assets connectivity achievement
- Disruptive technologies piloting (collaborative robotics, AI, big data, ...)
- Massive data analytics for process monitoring at shop floor level (vertical integration)
- Pilots' extension and roll-out
- Predictive analytics with horizontal integration within enterprise
- Prescriptive analytics supporting decision making.

Whirlpool shares on the 5G application of Bosch Rexroth in the Fraunhofer Test Centre Hannover, that it demonstrates the great advantage of 5G solutions in logistics for manufacturing companies, not only for autonomous navigation but also for the horizontal integration with other connected assets (machines, equipment, ...) in the industrial ecosystem.

With regards to deployment model options, for Whirlpool the preferred option for vertical applications deployment remains the local server in protected production network and edge implementation for process monitoring and control. Then, for analytics applications the central office solution with cloud technology is the preferred option. Finally, the hyperscaler option is often considered for Cloud applications to increase computation capabilities, when required.

About their view on NPNs, Whirlpool remarks that all the performance requirements have to be strictly comply with its security and privacy requirements, as a precondition for decisions on deployments.

In the subject of security and privacy challenges, Whirlpool shares that full compliance with internal security and privacy policies is a mandatory condition to proceed in the implementation for confidential and privacy data management and for GDPR compliance. The I4.0 5G solutions currently in the market or in development phase are under evaluation to validate their compliance with targeted requirements and their application limitations. Key requirements for additional security and privacy mechanisms are:

- Logical isolation mechanisms and physical radio layer protections mechanisms (ex. jamming protection). Actually, the current perimeter protection and access control have been widely used to protect the confidentiality of processes, operational data, users, and equipment. While access from outside is strictly controlled, operational data flows to the outside have also been restricted. With 5G, this physical isolation is no longer maintained.
- Encryption and integrity protection mechanisms reinforcement. This is because a 5G telecommunications operator would not be part of the internal trust domain defined within a "closed" organization by the perimeter, the users, equipment, and processes. Third parties are not typically allowed within the perimeter, except for certain remote maintenance tasks that do not impact real-time operations. Further operational boundaries within factories may be used to ensure segregation of operational duties and to protect privacy (need-to-know principle) in accordance with regulatory requirements.

- Regulatory compliance and associated certifications are major business imperatives. Each network configuration change or update needs to ensure continuity of compliance.
- Any 5G security mechanisms to be introduced need to interact and interoperate with legacy systems and processes over a long transition period, since in a production environment equipment and processes have long lifecycles.

3.2 Collective Analysis of the Answers of I4.0 stakeholders of 5G-PPP projects to the Tabulated Questions in the survey

The aggregated inputs provided by the firms participating in the survey, responding to the tabulated questions included in it, are reflected here, along with a basic statistical analysis aiming at extracting the common and highest priority aspects and requirements of the ecosystem of vertical stakeholders of 5G-PPP.
Before proceeding to the review of the results and a basic analysis, a few words on the adopted methodology follow. In the survey distributed some questions allow for providing either selection (Yes/No) or scoring (1 to 5) inputs. The specific answers, from each respondent to these tabulated questions are kept private and not included in this report. Instead, the focus is on the aggregated/statistical analysis of all the answers. For that purpose, the following data is included in the Tabulated Answers Summary, being obtained through these simple procedures:

- For selection (Y/N) check boxes, the percentage of positive answers is obtained and displayed.
- For scoring (1-5) boxes three intervals have been established and are displayed in the report:
  - o Score = 1-3: “Minor”
  - o Score = 4: “Significant”
  - o Score = 5: “Critical”

The results are commented here, question by question.

Q1. What are the main competitive advantages that a company may achieve by adopting Industry 4.0 with 5G?

Q1: ADVANTAGES ADOPTING INDUSTRY 4.0	POSITIVE ANSWERS
OPTIMIZATION OF RESOURCES	80.0%
MAINTENANCE THROUGH VR INTEGRATION	80.0%
EFFICIENT DATA FLOW	80.0%
PRODUCTION TIME REDUCTIONS	70.0%
COST SAVINGS	70.0%
SECURITY	60.0%
OTHERS	

The 80% of vertical stakeholders of 5G-PPP projects participating in the survey believe that the main competitive advantages that a company may achieve by adopting Industry 4.0 are on the Optimization of Resources, on the Maintenance enhanced through VR

Integration and on Efficient Data Flow. Also, very high consensus (70%) is expressed on Production Time Reductions and Cost Savings.

Q3. In what areas of the industrial process do you embrace Industry 4.0 with 5G?

Q3: INDUSTRIAL PROCESS	POSITIVE ANSWERS
FACTORY AUTOMATION	66.7%
MAINTENANCE	66.7%
SUPPLY CHAIN	44.4%
QUALITY CONTROL	44.4%
CUSTOMIZATION	22.2%
PLANNING	11.1%
OTHERS	

About 66.7% of vertical stakeholders of 5G-PPP projects participating in the survey plan to embrace I4.0 with 5G for Factory Automation and Maintenance areas.

Q4. When will Industry 4.0 with 5G have been mostly adopted by your industrial sector?

Q4: ADOPTION BY YOUR INDUSTRIAL SECTOR	POSITIVE ANSWERS
2025-2029	90.0%
2030-2040	10.0%
2022-2024	10.0%

The 90% of vertical stakeholders of 5G-PPP projects participating in the survey estimate that I4.0 enabled by 5G will be generally adopted, for their respective industrial sectors, in the period from year 2025 to year 2029.

Q5. What technologies do you consider critical for the Industry 4.0 transformation?

Q5: CRITICAL TECHNOLOGIES	% MINOR	%SIGNIFICANT	%CRITICAL	%SIGNIFICANT + %CRITICAL
MOBILE ROBOTICS	10.0%	40.0%	50.0%	90.0%
EDGE COMPUTING	10.0%	30.0%	60.0%	90.0%
MACHINE LEARNING	20.0%	10.0%	70.0%	80.0%
IOT/IIOT	30.0%	20.0%	50.0%	70.0%
HYBRID CLOUD	30.0%	50.0%	20.0%	70.0%
COMPUTER VISION	33.3%	22.2%	44.4%	66.7%
3D PRINTING	33.3%	33.3%	33.3%	66.7%
WIFI	40.0%	20.0%	40.0%	60.0%
AR/VR/XR	40.0%	40.0%	20.0%	60.0%
5G URLLC	40.0%	30.0%	30.0%	60.0%
5G mMTC	50.0%	30.0%	20.0%	50.0%

5G eMBB	50.0%	40.0%	10.0%	50.0%
TSN AND DETNET STANDARDS	60.0%	20.0%	20.0%	40.0%
NETWORK SLICING	60.0%	20.0%	20.0%	40.0%
BLOCK CHAIN	66.7%	22.2%	11.1%	33.3%
NETWORK EXPOSURE	77.8%	0.0%	22.2%	22.2%
TACTILE INTERNET	80.0%	20.0%	0.0%	20.0%
PUBLIC CLOUD	80.0%	10.0%	10.0%	20.0%
QUANTUM COMPUTING	100.0%	0.0%	0.0%	0.0%
OTHERS				

Vertical stakeholders of 5G-PPP projects participating in the survey have regarded the following technologies as either Significant or Critical to I4.0 realization:

- Mobile robotics , Edge computing, Machine learning, IoT, IIoT (Industrial IoT), Hybrid cloud, Computer vision , and 3D Printing (above 66% of responses).
- WiFi, AR/VR/XR, 5G URLLC, 5G mMTC, 5G eMBB, TSN (Time Sensitive Networking) and DETNET (Deterministic Networking) Standards, Network Slicing, and Blockchain (33% to 66% of responses).
- Network Exposure, Tactile Internet, Public Cloud, and Quantum Computing (up to 33% of responses).

Q7. What benefits can a company get by having human resources and machines cooperating with one another?

Q7: BENEFITS	% MINOR	%SIGNIFICANT	%CRITICAL	%SIGNIFICANT + %CRITICAL
REDUCE THE NUMBER OF EMPLOYEE HOURS DEDICATED TO THE MANAGEMENT OF REPETITIVE PROCESSES	10.0%	40.0%	50.0%	90.0%
INCREASE AUTOMATION OF THE PRODUCTION PROCESS	10.0%	50.0%	40.0%	90.0%
DEDICATE THE WORK EFFORT OF HUMAN RESOURCES TO ACTIVITIES WITH GREATER ADDED VALUE	10.0%	20.0%	70.0%	90.0%
INCREASE PRODUCTION CAPACITY	20.0%	20.0%	60.0%	80.0%
HEALTH AND SAFETY	20.0%	50.0%	30.0%	80.0%
MULTIPLY PRODUCT QUALITY	40.0%	20.0%	40.0%	60.0%

RAISE THE CAPACITY TO INNOVATE IN PRODUCTS AND SERVICES	50.0%	40.0%	10.0%	50.0%
INCREASE FLEXIBILITY	60.0%	20.0%	20.0%	40.0%
INCORPORATE CUSTOMIZATION CAPABILITIES	70.0%	20.0%	10.0%	30.0%

The following benefits expected from the adoption of I4.0 for implementing new models of Human-Machine cooperation have been regarded as either Significant or Critical by 90% of vertical stakeholders of 5G-PPP projects participating in the survey:

- Reduce the number of employee hours dedicated to repetitive tasks.
- Increase automation of the production process.
- Dedicate the work effort of human resources to activities with greater added value.

Additionally, 80% of them concur to regard the adoption of I4.0 as a Significant or Critical factor for being able to increase production capacity, and for health and safety.

Q8. If you are considering engaging in Industry 4.0 with 5G projects, what investment model would you consider?

Q8: INVESTMENT MODEL	% MINOR	%SIGNIFICANT	%CRITICAL	%SIGNIFICANT + %CRITICAL
CO INVESTMENT	20.0%	80.0%	0.0%	80.0%
PUBLIC FUNDING	30.0%	10.0%	60.0%	70.0%
OWN INVESTMENT	60.0%	20.0%	20.0%	40.0%
INVESTING IN EXTERNAL VENTURES	100.0%	0.0%	0.0%	0.0%

The 80% of vertical stakeholders of 5G-PPP projects participating in the survey believe that the Co-investment model is critical for realizing 5G-enabled I4.0 initiatives, while 60% of them regard public funding as critical for taking on I4.0 initiatives.

Q9. What options do you consider for vertical application deployment in the context of Industry 4.0 with 5G?

Q9: DEPLOYMENT OPTIONS	POSITIVE ANSWERS
NEAR EDGE	88.9%
LOCAL DATA CENTER (ON-PREM)	66.7%
HYPERSCALER	55.6%
CENTRAL OFFICE (TELCO)	55.6%

The 88.9% of vertical stakeholders of 5G-PPP projects participating in the survey consider Near Edge option for vertical applications' deployments for supporting I4.0, whilst 66.7% of them additionally consider on-prem application deployment option.

Q10. What are your key requirements and expectations on non-public networks for Industry 4.0 and 5G projects?

Q10: REQUIREMENTS ON NPN	POSITIVE ANSWERS
OPTIMIZE NETWORK RESOURCE UTILIZATION	100.0%
NETWORK PERFORMANCE	100.0%
SECURITY AND PRIVACY	80.0%
CUSTOMIZATION AND FLEXIBILITY	60.0%

The 100% of vertical stakeholders of 5G-PPP projects participating in the survey consider Network performance and Optimized network resource utilization as key requirements on NPN's for supporting I4.0, and 80% of them also regard Security and Privacy as key I4.0 requirement for NPN's.

3.3 What can we learn and remark from this survey?

The answers to the survey have just been presented in sections 3.1 and 3.2 at its full extent. With the best intention of capturing and sharing some insights from them, rather than trying to provide an unnecessary and partial summary of the answers, here follows a basic analysis in search of key aspects of convergence, divergence and complementarity of the answers with the landscape for I4.0 sketched in chapter 1 and chapter 2.

First, the estimated influence of key Technology Enablers reflected in Table 1 can be compared to the analysis of the answers to question *Q5. What technologies do you consider* *<u>critical</u>* *for the Industry 4.0 transformation?* for reaching the following conclusions:

- Very good alignment of the map of influences derived from the theoretical analysis with the collective results of the survey, with IoT/IIoT, Edge Computing, Hybrid Cloud and ML highlighted by above 66% of all responses, whilst AR and several specific (disaggregated aspects of 5G) come next, being highlighted by the 33% to 66% of the responses.
- Interestingly enough, the range of critical enabling technologies for I4.0 is, according to the answers to this question even broader than expected. In addition to the "core" set of IoT/5G, Cloud, Edge, ML and AR/VR technologies that vertebrates this report, over 66% of participants in the survey also highlight the critical role of, specifically, Mobile Robotics and Computer Vision.

Then, concrete 5G enablement factors on I4.0 for a sample of innovative Use Cases can be compiled from the literal free-text inputs provided by participants in the survey to question *Q2: What kind of specific applications and use cases are enabled by Industry 4.0 with 5G that previously were not feasible?* :

- Industrial equipment and products that have to enjoy freedom of movement, like mobile robots, mining trucks, drones, etc. to accomplish their tasks, thus requiring both mobility support and high-performance wireless connectivity.
- Smart manufacturing applications with time-critical requirements, highlighting the importance of URLLC and Edge Computing.
- Remote control and remote maintenance of AGVs
- Remote commissioning

- Virtualization, and deployment of hardware controllers as MEC applications
- Wireless industrial field communications
- Safe collaboration between cells with robotic arms and AGV's
- Flexible and reconfigurable production lines thanks to the wireless connectivity also at OT level.
- Integration of OT level with edge cloud solutions.
- Security at the shopfloor. OT level devices could communicate and control wireless other moving components such as AMR based on current production status.
- XR video streaming in real-time and augmentation of the experience with AI-based application.
- Increased bandwidth for 5G: It enables considerably bigger data flows between machines and servers than earlier networks.
- Very low delay of communications: The very low delay (or latency) of 5G communications allows the company to use remote processing servers and rely less on local or embedded computing as it was conventionally done.
- Outdoor and Indoor coverage: 5G enables smoother transition of outdoor-indoor communication between machines, systems and the network. That can open wide areas of applicability for AGV applications and traceability of asset parts.
- Digital / Physical Twins of bonded composite repairs performed on aircraft remotely located.
- AR-enabled remote collaboration scenarios as a remote expert/helper can guide a worker to perform a given task, like repairing or inspecting a machine.
- Factory automation processes within ms.
- Real-Time high-quality video streaming accompanied with AR/VR.

The number and variety of 5G-enabled I4.0 use cases listed above calls the attention. Being Use Cases clearly anchored to concrete aspects of 5G support, it also reveals that the level of knowledge and direct experience on them are well developed. Also, the spread in nature, covering all four I4.0 Design Principles, may indicate that the scan and promotion of opportunities across all the spectrum of the I4. paradigm is quite intense and balanced.

Next, moving to the segmentation of 5G aspects and features and their influence on I4.0 present and future, reflected in Table 2, the survey can complement it with levels of criticality expressed by the participants, to question *Q5. What technologies do you consider critical for the Industry 4.0 transformation?* From that perspective its's worth observing that:

- The level of criticality highlighted by 50% to 60% participants on eMBB, URLLC and mMTC is almost homogeneous, with a slightly higher scoring for URLLC. The a priori expectation would have been on higher scoring for eMBB, closely followed by URLLC and then by mMTC, if considering the maturity of standards and their level of deployment. But it seems that the logic behind this homogeneous answer is, instead, that all these three flavours of 5G services (Slice types) are not expected to prevail or compete among them but to complement each other in I4.0 environments.
- The level of criticality on Slicing (in general) and TSN was highlighted by a minority of answers (20%), which can be compatible with the top-down

analysis on these features, that suggested that their influence in I4.0 would grow in importance for the long term.

Following, and focusing now on the critical aspect of the Cloud/Edge/Local environments for hosting the necessary Applications supporting the I4.0 Use Cases, the answers to question *Q9. What options do you consider for vertical application deployment in the context of Industry 4.0 with 5G?* show that above two thirds of responses favour Near Edge and Far Edge deployment of applications. But additionally, more than 50% of respondents also express preference for central office and even hyper-scaler location for applications. That is coexistence with the broad potential for Edge for the present and the near future, as derived from the top-down analysis represented in Table 2. And it implies that coexistence of multiple models can shape a new norm, and that, in consequence, a high level of flexibility for cloud/edge options is expected to be supported for I4.0 needs.

Also, on the pace of adoption of I4.0-5G, answers provided to question *Q4. When will Industry 4.0 with 5G have been mostly adopted by your industrial sector?* foresee, almost unanimously, the period for generalized adoption to 2025-2029. Two comments can be added:

- Being survey participants involved in Manufacturing, Logistic, Transport and Energy vertical sectors this implies that I4.0 transformation with 5G shall affect them over a similar timeline. Also, the similarity of the milestones for adoption journey referred to by participants, including ecosystem development and technology evolution aspects indicates that the way such adoption of I4.0-5G is expected to happen may follow a similar pattern across industries.
- When also analysing the answers to question *Q8. If you are considering to engage in Industry 4.0 with 5G projects,* what investment model would you consider? they show a mix of co-investment (80%), public funds supported (70%) and own investment scenarios (40%), that seems very compatible with the type of milestones indicated for the timeline for adoption, to be happening in parallel with further research and innovation, probably induced by the availability of new releases of standards like those of 5G Advanced and towards 6G. This aspect shall be further developed in the final sections of this report.

Then, a dive on the inputs of participants in the survey to questions Q1 What is the main competitive advantages that a company may achieve by adopting Industry 4.0 with 5G and question Q3 In what areas of the industrial process do you embrace Industry 4.0 with 5G? is essential for spotting concrete business motivations for 5G-enabled I4.0. From the answers received Factory Automation, Optimization of Resources, Maintenance, and Efficient Data Flows are the key focus areas that stand out from the rest. So, it is in those areas where exploitation of I4.0 use cases is expected to be prioritized.

Finally, the survey provides more explicit messages on several aspects enquired for like on the requirements on Non-Public Networks (Q10) expressing deep focus on Network Performance and Resource Optimization, and on the perspectives and priorities on Security and Privacy (Q11) which are worth being checked out directly from section 3.1.

4. How could 5G evolution push I4.0 further?

The evolution of adoption and embracement of ICT related technologies in the industrial manufacturing sector is unstoppable. It is commonly agreed that 5G has been and will be a key component of this evolution. While the initial efforts focused on exploring and learning on how the industrial sector could benefit from the adoption of 5G, next steps involve going a step further (also as part of the natural evolution towards 6G) to develop additional features relevant to I4.0. This chapter describes 3 relevant examples: deterministic networking, non-public networks, and digital twinning.

4.1 Deterministic Networking

The current landscape of industrial companies revolves around the transformation towards Digitization and Industry 4.0, aiming to create more efficient and adaptable production factories through data analysis and process intelligence. The concept of a Smart Factory is at the forefront, defining a connected, secure, and scalable environment that caters to the evolving needs of the industry. However, several critical problems persist in this pursuit:

1. Information Silos and Data Management: The transition to a Smart Factory requires comprehensive digitalization, necessitating the connection and integration of all company processes into a unified database. However, this endeavour is hampered by existing information silos, where departments manage data independently. These silos hinder effective data utilization and decision-making.

2. Determinism and Automation: In the realm of automated manufacturing, determinism is paramount. The traditional approach involves a wired connection of components to a PLC. The precise timing and order of signals are crucial for error-free execution. Any deviation in timing can disrupt the entire manufacturing process, leading to inefficiencies and stoppages.

3. Wiring and Flexibility: The current reliance on wired connections for communication introduces rigidity into the manufacturing process. Achieving the flexibility and mobility envisioned by Smart Factories is challenging due to the limitations of wired systems. The intricate wiring setup inhibits the movement of assets and machinery, hampering agility.

4. Wireless Challenges: While wireless connectivity promises flexibility, it struggles to match the determinism, reliability, and latency of wired connections. This limitation hinders the seamless integration of wireless technology into the existing manufacturing framework. As a result, realizing the full potential of wireless solutions remains a challenge.

5. Network Isolation: The deterministic technologies used in industrial settings often operate in isolation from other networks. This isolation prevents industries from capitalizing on external innovations, such as those brought by 5G technology. Consequently, manufacturers are confined to in-house network setups, missing out on the benefits of broader technological advancements.

6. Future Connectivity: The potential breakthroughs expected with 6G technology hold promise for providing deterministic wireless connectivity to cloud-controlled robots. This development could alleviate some of the limitations associated with current wireless solutions, enabling more flexible and adaptable manufacturing processes.

7. Virtualization and Real-time Connection: A potential solution involves virtualizing the PLC, implementing it within a standard PC as a virtual machine hosted in the factory's server room. While this approach could offer real-time connectivity using industrial protocols, challenges remain in ensuring consistent and reliable performance.

To overcome the above problems, **we expect new technologies around the concepts of deterministic networks, with the three main characteristics of predictability, reliability and time sensitiveness appear in the near future**. These technologies will evolve the current set of deterministic technologies towards the multi-technology, multi-domain space, with a major focus on wireless. As an example, IEEE 802.11 is working towards this goal with the newly created IEEE 802.11bn working group, looking at how to enable ultra-reliable communications. The incorporation of time sensitive communications in the 5G core also goes in this direction. The future integration of IEEE 802.11, the evolution of 5G TSC (Time Sensitive Communications) and wired communications, will enable a true multi-technology, multi-domain approach for the Factory of the Future.

Another example of effort in the standardization arena is what the Internet Engineering Task Force (IETF) is doing in the Reliable and Available Wireless (RAW) and Deterministic Networking (DetNet) working groups (WGs), which are about to be merged shortly. Both WGs have as a mission developing layer-3 networking technologies to ensure deterministic, reliable and highly available communications. A recently published RFC (RFC9450) describes several relevant use cases for RAW technologies, being I4.0 one of the key identified ones.

In conclusion, the continued journey towards Smart Factories and Industry 4.0 presents a range of challenges that need to be addressed. From information silos and wired determinism to the limitations of wireless connectivity, industries must navigate these obstacles to truly realize the vision of efficient, flexible, and intelligent manufacturing. Embracing future technological advancements while finding innovative solutions to the existing problems will be crucial for the success of this transformative endeavour.

4.2 Non-Public Networks

5G standards revolutionized the role of mobile networks with the introduction of Network Slicing capabilities. Network Slicing makes it possible to, over common and standard mobile network technology infrastructure, create a set of distinct and specialized connectivity services which can be delivered to different users. Now we are seeing an increase globally in 5G network deployments, expected to reach more and more varied types of businesses, users, and devices. This will come with a broad range of heterogeneous needs and demands on the network, which is especially the

case for the envisaged scenario of proliferation of Non-Public Networks (NPN) [6] that rely on 5G Public Networks and pervasive application of Network Slicing.
The variety of NPN approaches, addressed by 3GPP specifications [7], and, in particular, **the Public Network Integrated Non-Public Networks (PNI-NPN) model (addressed in 5Growth and 5G-Induce, among other 5G-PPP projects) opens a promising avenue for exploration for generalized I4.0's 5G enablement for the mid-term**.

In essence, the concept is that 5G Public Networks stretch their arms and, thus, their slicing capabilities, into I4.0 locations, for providing them with NPN services, which are felt as private services even though they leverage public 5G infrastructure assets. **The balance between optimal performance delivery to Enterprise Users and maximized resource efficiency seems to be an attractive value proposition to both I4.0 players and CSPs**. The shorter lead times for accessing PNI-NPN services, and the reduced management and operation burden on the Enterprise side are also strong incentives for adoption, along with the possibility to leverage cost-effective subscription-based models. In consequence this model also has the potential to easily expand to all kinds of enterprises involved in I4.0 scenarios, regardless their size and specific requirements, therefore facilitating the launch of I4.0 use cases with the multiple parties involved the value network.

Then, moving from concept and potential to feasibility and realization, considering that this model can be widely adopted by Enterprises demanding NPN services, it becomes evident that **CSPs who will offer and operate PNI-NPN services will have to dramatically expand their Network Slicing capabilities to provide vital tools and services to thousands of enterprises of all sizes**, for safely arriving at a new global scenario of Massive Network Slicing. Clearly, standing before this business scalability and sustainability challenge, **new paradigms will have to emerge for overcoming and managing the intrinsic complexity of Massive Network Slicing in such a fast-growing market** which analyst organization IDC estimates will expand at CAGR (Compound Annual Growth Rate) of 35.7%, from 2022 to 2026 [8].
The main aspects that we deem should concentrate major research and innovation focus include the following:

1. Flexibility: Securing best fit of network performance levels to the demands of the subscribers and an optimal distribution and utilization of network resources.
2. Energy Efficiency: Minimizing the consumption of energy and improving overall sustainability across the full network from the 5G network core through the edge and the RAN and the user equipment.
3. Zero-touch Automation: Implementing Zero-Touch automation approaches for reducing the lead times for launching new NPN services, including automatic connection of the NPN to the public network and edge environment, and self-configuration for meeting expected performance levels.
4. Resiliency: Safeguarding end-to-end Network Resiliency, incorporating mechanisms to detect, predict, and prevent situations of potential network service unavailability or degradation.

4.3 Digital Twining

In the last decades, supply chain environments have been slowly introducing digitization and automation of operations and processes. Industrial environments in particular, generate many repetitive tasks, most of which in hazardous locations creating risks for workers. Introduction of mobile robots and other automated or remotely controlled vehicles has been addressing the problem, while at the same time generating huge amounts of IoT data as of yet unexploited.

One of the main necessities of such a sensitive environment is the ubiquitous connectivity of the machines, which can only be assessed with beyond 5G networks. As already demonstrated in some projects, e.g., iNGENIOUS, 5G networks are a first attempt in ideal networking conditions. However, such ideal conditions are not the norm in real deployments, making the continuous evolution of 5G technologies towards beyond 5G the adequate networks for real-time reliable connectivity.

Such a complex scenario requires of a **centralized overview and control of the whole system, which requires exploiting the value of the generated data. Digital Twins are the perfect tool for this**. Digital twins are virtual representations that serve as the real-time digital counterpart of a physical entity, becoming a paradigm-changer for the industrial management, transforming how products and services are made and delivered, while enabling the creation and sharing of supply chain information. allowing for the full digitalization of industrial elements (e.g., data, sensors, robotics, vehicles, etc).

Thanks to the capabilities of AI/ML, the real-time Digital Twins will be supplied with intelligence, allowing them to be executed in real-time. The solution takes advantage of the data gathered by sensors, machines, robots, and cameras to offer a native experience that will allow design and engineering teams to interact with a virtualized model in real time through a single self-contained device, and without the constraints of a physical connection.

Real-time Digital Twins are a mix of the best of each I4.0 Design Principles, i.e., *Interconnection*, *Information Fusion*, *Human-Machine Collaboration* and *Flexible Decision Making*. This makes Digital Twins a perfect fit for industrial complex environments as they optimize the manufacturing process to reduce costs, increase operational efficiency and quality and sustainability. Digital Twins will help to reduce the time and cost associated with assembling, installing, and validating factory production systems.

That said, it is interesting to also consider Digital Twining from a complementary angle: its application to 5G Networks themselves [9]. This new trend, normally referred to as ***Network* Digital Twin (NDT), is starting to develop and its prospect of application is generating lot of attention**. What could we expect from a Network Digital Twin solution? First of all, it should provide with a replica of the configuration and behaviour of a selected segment of the 5G chain (for instance the RAN segment for a Non-Public Network), for enabling real-time monitoring, analysis, and optimisation of its performance. For achieving so it is necessary to obtain the Network Digital Twins models for a variety (potentially hundreds or even thousands) of real-world NPN configurations. Conceptually, it is a similar process to that of 3D-scanning a physical asset such as prototype of new cars or aircrafts, and it yields the same type of advantage: visualizing, testing and enhancing the system in the digital space, so as to optimize its real performance in the field. Therefore, **the application of Network Digital Twins in the foreseen landscape of proliferating 5G NPNs has the**

potential benefit of ensuring a major contention of cost of planning, reduction in lead and integration times, and robust operation and maintenance maximizing network system uptime and performance levels.

The immediate next challenge -and promising opportunity- envisaged for research in this field arises at the actual intersection of I4.0 scenarios embracing Digital Twins with 5G Network Digital Twins. **That would make it possible to simulate the whole 5G-enabled I4.0 use case in a digital environment, dramatically reducing research, engineering and integration lead times**, by helping to discard/confirming architectures, configurations and solution approaches ahead of costly trials. And besides that, its systematic application to the lifecycle of the systems in actual operation could grant superior levels of performance and optimization of resources in many varied ways. That's a huge potential that we consider it should be proactively explored in new generation I4.0 research projects.

5. Ecosystem aspects influencing I4.0 evolution.

The pace and streams of evolution of I4.0, going forward, shall be conditioned by both business and ecosystem development, which are tightly intertwined. In this chapter an overview of influencing ecosystem dynamics, including standards and regulation is provided, connecting it key considerations on industrialization, exploitation, and sustainability aspects. Also, some suggestions for consideration in new public research policies and programmes to be deployed around the subject of 5G-enabled I4.0 are offered.

5.1 Expected consolidation and industrialization.

5G is being broadly deployed, for providing eMBB experience to a rapidly growing base of subscribers all over the world and complemented with LTE through NSA options. Being eMBB the mainstream for global 5G deployment -for obvious economies of scale-, **5G is also being deployed, more and more often, for supporting enterprise scenarios in non-public networks adopting the SA architecture option**. **On the downside, the ecosystem of 5G CPE manufacturers is still developing, delivering low volumes of functionality-limited devices**, since the major focus (as of the date of writing this report) remains on the manufacturing and supply of 5G smartphones at the very high volumes demanded by the commercial roll-out of 5G public networks. For a detailed analysis and outlook on the needs, features, status, and prospect on Industrial 5G devices please refer to the report of 5G-ACIA on the subject [10].

Regardless of the difficulties and complexity involved, a review of the general status of maturity also reflects that the full potential of performance and flexibility of 5G is already being unlocked in multiple pilots, and also initial exploitations, of a variety of vertical Use Cases across many Industrial sectors.

In order to put these trends in context with concrete and up-to-date figures, we refer to the research conducted by GSA and reported in [11]. In such study, first of all, GSA defines -based on the consensus of its Executive Members- the term private mobile networks as "3GPP-based 4G LTE or 5G networks intended for the sole use of private entities, such as enterprises, industries and governments", and then extracts and organizes information on actual deployments classified into such category, provided by Executive Members of GSA. The outcome of their research outlines that private mobile networks have been deployed (by 2022) in 68 countries and territories and amount to 794 distinct deployments (with 5G being used by 296, or 37% of these customers). Also, **GSA's reported data suggests that the manufacturing sector is a strong adopter of private mobile networks (either LTE or 5G based) in terms of the number of customer deployments, with 140 identified companies involved in known pilots or deployments**.

Finally, the overall picture for the state of maturity of 5G NPN for Industry 4.0 applicability must be necessarily completed with a few considerations on regulatory aspects and plans, at global and national levels, related to the spectrum for the frequency bands considered for 5G NR. In this regards we refer to the up-to-date review on the spectrum for local industries published by Ericsson [4]. Such report not only updates on the diverse spectrum availability models and specific frequency bands enabled for industrial applications in countries all around the globe, but, even more importantly, it highlights the influence of such heterogeneous context on the adoption of Private/NPN 5G by Enterprise -and therefore I4.0- customers. The major requirement of **"access to spectrum must be predictable over a long period of time to support uninterrupted operation and major investments in production processes and industrial facilities"**, calls for the need of well-established national policies about spectrum access allowing for a variety of models, ranging from direct access by the Enterprise itself to SLA-ed access to spectrum of CSPs, in order to flexibly meet the varied needs of Industrial sectors. It is expected that, as the relevant regulation is in place and the adequate business models emerge taking that fundamental requirement of predictability in mind, the adoption of private/NPN 5G by Industry sector shall precipitate towards a scenario where, in the long run, up to 1 million factories in the world could leverage 5G technology for their critical business processes. Then the report also points out the major influence that the diversity of national regulatory frameworks on the selected spectrum bands for Industrial use has on the pace of scaling of the ecosystem of the manufacturers of 5G devices for Industrial applications. Indeed, **the higher the harmonization of spectrum regulation across markets, the faster that 5G device manufacturers can produce and deliver larger volumes of units, therefore securing the levels of supply and the diversity of devices required by Industry customers deciding on large investments associated to I4.0 and 5G**. As a key example of coordinated action addressing the introduced aspects, the report outlines that "the European Commission has identified the demand for mid-band licensed spectrum, … and issued a mandate to CEPT to investigate the shared use and harmonized frequency arrangement of the 3.8-4.2 GHz frequency and for local area connectivity." The work is tasked to finish by March 2024".

5.2 Sustainability of the impacts in the Industrial sector

Beyond the technical and economic feasibility of designing specific I4.0 use cases and integrating the technologies and solutions for implementing them into their business processes, for industrial sectors like Manufacturing, I4.0 does represent a major change of paradigm that induces both evolution and transformation, thus demanding large investments across the full lifecycle of many I4.0 use cases and technology platforms that have to prove sustainable.

In fact, the necessary stage of research and development on I4.0 solutions is just the beginning of a transformation cycle. **I4.0 transformation also implies the adoption of new technology platforms, up-skilling of key staff to master the new**

competencies associated along with onboarding new talent into the firms, the establishment of new business connections to new partners and providers, etc.

Most likely the business case equation for embarking in this type of transformation journey just from the validation of a single successful I4.0 Use Case will prove inconsistent. Luckily that is not the general approach of Industry leaders. From the direct experience in 5G-PPP projects**, I4.0 leaders are collectively analysing sets of complementary I4.0 use cases and road-mapping them for integration in their operations, therefore creating "internal" economies of scale** for procuring and launching new platforms serving multiple purposes, onboarding new critical skills, and transforming processes. That strategic approach to I4.0 ramp-up mitigates risks for a transformation journey that otherwise would be bumpy and much more costly, but the level of complexity and investment can probably only be afforded by large corporations. As highlighted by ABI research on I4.0 implementation and ROI [2], the Cost of Inaction (COI) of delaying the adoption of I4.0 is absolutely not affordable, so large Manufacturing companies and their suppliers are acting in consequence. Therefore, **it is foreseeable that the strong drive of Tier 1 OEM (Original Equipment Manufacturer) for I4.0 adoption shall stimulate the necessary transition from Proofs of Concept to Proofs of Scale**, propagating the wave to their key suppliers (large and small specialized firms) in their established value and supply chains.

In order to complete the path towards sustainable I4.0 transformation, adoption of standards -with their derived global economies of scale- shall be essential. Unfortunately, in this regard, the variety of I4.0 use cases and the logic of first-mover competition, are not making it possible that I4.0 standards – at *foreground* level- are defined and leveraged for efficiency. That remains a major issue for swift I4.0 adoption today that, however, over time, will probably dilute as de facto solutions and best practices are established and spread. One way or another, **it can be estimated that the economies of scale that cannot show up at I4.0 use case *foreground* level should be instead materialized at I4.0 *platform* level, thanks to the adoption of global standards, such as 5G**. That point cannot be overestimated, and as was previously highlighted at the introduction of this report, 5G technologies, based on global single-standard do deliver that advantage, enabling interoperable, cost-competitive and scalable offerings of cellular services and devices worldwide. Should the same trend of formal or de facto standardization of other critical technologies for I4.0 realization be the case then I4.0 leaders could benefit from economies of scale and avoid lock-ins, setting necessary new business connections with providers of advanced equipment and services around 5G, Cloud, Edge, AR/VR and ML. The challenge of multi-technology integration remains but the prospect for sustainable business transformation around I4.0 seems consistent, following the approaches recommended above.

5.3 Research and innovation policies in support of 5G-enabled I4.0

As has been discussed, the level of actual development of the I4.0 vision, with regards to both use case innovation at varied industry sectors and undergoing integration of diverse technologies in countless trials and pilots in execution, is already remarkable. **The proliferation of I4.0 projects and use cases at this stage reflects, equally, the**

determination of all parties involved (private and public) to invest in the area and the necessity of completing learning cycles and fulfilling validation processes before moving onto exploitation and scaling of the developed solutions, given the strong dependency with -and the complexity behind the integration of- advanced and evolving ICT technologies.

Going forward, along the second half of this decade, the research and innovation of I4.0 solutions enabled by 5G is going to accommodate two concurrent streams of activities addressing different objectives and time horizons. Firstly, **as the key enabling technologies supporting I4.0 consolidate and become mainstream** -not only for I4.0 but for many other application purposes- **their industrial integration for supporting the actual business processes of I4.0 pioneers will become easier and swift**. Secondly, the continued scan and inception of new value-adding and more demanding I4.0 use cases, along with the paced evolution of the key ICT enabling technologies for I4.0, will propel **new cycles of early investments in research and innovation in collaboration, that are likely to extend to, at least, the end of this decade**.

In such a context of coexisting cycles of technology research, innovation, adoption, and exploitation, **and being I4.0 a major driver of economic development, the support of European and National programs for research and innovation shall be instrumental**.
Considering the two concurrent streams foreseen to coexist until the end of this decade, let's take a look at the major hurdles and impediments they may have to address, for which public research and innovation policies in their support could aid.

For the stream of activities related to the transition from validated 5G-enabled I4.0 solutions to their adoption into actual business exploitation, it can be foreseen that the firms involved in such mission shall have to address **challenges and risks of financial, business, regulatory, legal, and technological nature**. It is not a straightforward transition, involving, among other transformations, the establishment of new and long-term business connections with providers of technology and services, disruptions in core processes (in a sector with a high risk-averse profile), and dealing with new technologies changing often, in very fast cycles, compared to those of the industrial sector. Even more importantly, the business ecosystems to rely on are still being shaped, which introduces a major concern for investments, and it's a known factor delaying the take-off of many I4.0 industrialization initiatives. Putting it all together, I4.0 transformation, in the critical transition from research to exploitation, is not a matter of business case planning and execution over predictable scenarios and stable business assumptions; it's indeed a mission that, for many aspects, goes beyond the sphere of control and influence of I4.0 players. The fact is that such (not uncommon) situation is not a firm-specific and actionable issue but an **ecosystem issue that clearly calls for attention of public policies, that should contemplate sustainability programs, market incentives and lean regulation for securing that the business ecosystem develops at the pace expected**. **This type of policies can be much better focused to the desirable impact if deployed at national level**, for securing the density and tight cooperation of players and business connections in I4.0 in concrete geographical areas, same as has happened over many years with now well-established productive business ecosystems and value chains, for instance, in the manufacturing industry. **This type of public policies should pave the way for**

economic growth derived from technology adoption and transformation, thus returning major benefits for the economies and the society of the countries whose governments deploy them and maximizing the return on investments of long previous stages of research and development, typically at European level.

Now, lest us switch the attention to the stream of activities of further cycles of new research and innovation of I4.0 evolution along with 5G evolution. For this case, as per the predicted potential of innovation and hybridation of a broad range of involved technologies (5G Advanced, Cloud, Edge Computing, AR/VR/XR, ML/AI, …), **collaborative research schemes at European should be the most fruitful approach towards unlocking and achieving significant collective breakthroughs**. The long-term span and fast pace of the evolution of 5G technology into 5G Advanced and towards 6G -expected to first come to life in 2030- are going to be a major influencing factor in the new cycle of research and innovation for I4.0, with each new 3GPP release analysing, triggering, and delivering new synergies of I4.0 and 5G. On their sides, the evolution of Cloud, Edge, XR and ML, with their own respective dynamics, will for sure influence this new research and innovation journey, and therefore Europe also has to double down its efforts on them. So, the most impactful policies for supporting research and innovation in this global matter should probably stem from public-private partnerships at European level, aiming at i) **strengthening the new research ecosystem** required for addressing the new challenges, ii) supporting and even provoking long but **iterative cycles of research for timely influencing and leveraging new waves of standards such as 5G**, and iii) putting special focus on **securing technology sovereignty in all critical areas supporting the future of I4.0** for the benefit of long term competitiveness of Europe in both I4.0 itself and its supporting technologies.

6. Key Takeaways

The readers of this whitepaper shall extract their own takeaways from the information, viewpoints, analysis, and recommendations put forward, being hopefully related and applicable to the specific challenges and opportunities that they are addressing in the I4.0 space. In fact, the main objective of the 5G-PPP TB (Technical Board) and the editorial team for putting this whitepaper together was, as already explained, facilitating a swift knowledge transfer for the experience of 5G-PPP to the audience of this report. The approach of providing perspectives of general applicability but always rooted in concrete cases, facts and trends observed in the universe of research and innovation activities in the field of 5G enablement of I4.0 has, hopefully, delivered on this expectation. That said, some of our own takeaways from the research work performed for this report follow now.

Towards the adoption of cellular technologies for supporting critical operations and processes, sometimes implying the migration from previous wired dedicated networks, what is top of mind for I4.0 technology managers is 100% ensuring the adequate levels of performance and reliability of the new connectivity layer. 5G-PPP Phase III projects have dedicated major attention to this concern and accumulated broad experience in performing systematic and repeatable tests and validations of I4.0 use cases enabled by 5G. For the large majority of cases, the adequate support of 5G performance and resilience levels to addressed I4.0 use cases of all types has been validated, which allows to change the perspective from evaluating whether 5G can support I4.0 to deciding how 5G can be best leveraged for I4.0, thus progressing in the industrialization and exploitation of I4.0 solutions.

I4.0 can display many faces, as many as distinct I4.0 use cases may be designed and crafted by key players of Manufacturing, Transport and Logistics, and other Industrial sectors. That's what first strikes from this new paradigm, on the surface, although on the inside a set of core motivations, requirements, technologies, and solutions can be found. Standards like 5G play a key role on the establishment of platforms on the inside by providing I4.0 with essential features and performance demanded across heterogeneous use cases and bringing economies of scale to be leveraged now and towards the future. It is possible to foresee that those I4.0 leaders who will manage to both diversify in I4.0 use cases (for pursuing operational excellence) and adopt standards-based technology platforms such as 5G (for meeting common requirements while leveraging economies of scale) will gain a major competitive advantage.

Finally, it becomes evident that the full innovation and transformation cycle around I4.0 is already activated. For along the rest of this decade, streams of industrialization of I4.0 use cases will coexist with new streams of research on new use cases and their technology enablers. While industrialization of previous innovation efforts requires large investments and addressing major transformation challenges before delivering the expected ROI, new research activities for unlocking a future wave of I4.0 services with even deeper impact shall demand broad cross-industry collaboration. Ecosystem dynamics, regulation and public research policies will have a major influence, in such a challenging context.

Abbreviations and acronyms

3GPP	3rd Generation Project Partnership
5G-ACIA	5G Alliance for Connected Industries and Automation
5G NR	5G New Radio
5G NSA	5G Non-Stand Alone
5G SA	5G Stand Alone
5G-PPP	The 5G Infrastructure Public Private Partnership
AI	Artificial Intelligence
AMR	Autonomous Mobile Robot
AR	Augmented Reality
BB	Baseband
BBF	Broadband Forum
CBM	Condition-Based Maintenance
CP	Control Plane
COTS	Commercial of the shelf
CPS	Cyber-Physical Systems
CPUs	Central Processing Units
CSPs	Communication Service Providers
CUPS	Control – User Plane Separation
DevOps	Development and Operations
DT	Digital Twin
eMBB	Enhanced Mobile Broadband
Hyperscaler	Refers typically to Amazon Web Services, Microsoft Azure and Google Anthos
I4.0	*Industrie 4.0* (Industry 4.0)
ITU-R	ITU Radiocommunication
MANO	Management and Orchestration
mMTC	Massive Machine Type Communications
mmWave	Millimetre Wave (Spectrum from 30Ghz to 300GHz)
NDT	Network Digital Twin
NFV	Network Function Virtualization
NPN	Non-Public Network
OEM	Original Equipment Manufacturer
OT	Operational Technology. The term refers to the hardware and software that monitors and controls devices, processes, and infrastructure, and is used in industrial settings
OTT	Over The Top
PaaS	Platform as a Service
PLC	Programmable Logic Controller
PLMN	Public Land Mobile Network
PNI-NPN	Public Network Integrated Non-Public Network
ROI	Return On Investment

SDN	Software Defined Networks
SLA	Service Level Agreement
UPF	User Plane Function
URLLC	Ultra-Reliable Low Latency Communication
VR	Virtual Reality
XR	Extended Reality

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ANNEX I: List of relevant project deliverables addressing I4.0 Scenarios.

Representative 5G-PPP Phase III and 6G-IA SNS projects

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List of relevant project deliverables addressing I4.0 Scenarios.

5G-INDUCE (http://5g-induce.eu; https://cordis.europa.eu/project/id/101016941)

- "5G-INDUCE D2.2: Targeted use cases and NetApp related requirements". [Online]. Available at: https://www.5g-induce.eu/index.php/outcomes/

5GROWTH (http://5growth.eu; https://cordis.europa.eu/project/id/856709)

- "5Growth D3.6: Execution report of in-house use cases for Pilots". [Online]. Available at: https://5growth.eu/wp-content/uploads/2019/06/D3.6-Execution_report_of_in-house_use_cases_for_Pilots.pdf
- "5Growth D4.4: Final validation and verification report". [Online]. Available at: https://5growth.eu/wp-content/uploads/2019/06/D4.4-Final_validation_and_verification_report.pdf

5G-SMART (http://5gsmart.eu; https://cordis.europa.eu/project/id/857008)

- "5G-SMART D4.4: Report on validation of the 5G Use Cases in the factory". [Online]. Available at: https://5gsmart.eu/wp-content/uploads/5G-SMART-D4.4-v1.0.pdf

5G EVE (http://5g-eve.eu; https://cordis.europa.eu/project/id/815074)

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- "5G EVE D2.5: Final pilot test and validation". [Online]. Available at: https://zenodo.org/record/5070256

EVOLVED-5G (http://evolved-5g.eu; https://cordis.europa.eu/project/id/101016608)

- "EVOLVED-5G D2.1: Overall Framework Design and Industry 4.0 requirements". [Online]. Available at: https://evolved-5g.eu/wp-content/uploads/2021/11/EVOLVED-5G-D2.1_v1.4.pdf

PREDICT-6G (http://predict-6g.eu;https://cordis.europa.eu/project/id/101095890)

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VITAL-5G (http://vital5g.eu; https://cordis.europa.eu/project/id/101016567)

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5G-ERA (http://5g-era.eu; https://cordis.europa.eu/project/id/101016681)

- "5G-ERA D4.3: Reference Network Apps for 5G-ERA - Initial-version". [Online]. Available at: https://5g-era.eu/wp-content/uploads/2022/07/D4.3-Reference-NetApps-for-5G-ERA-Initial-version.pdf

6G BRAINS (http://6g-brains.eu; https://cordis.europa.eu/project/id/101017226)

- "6G-BRAINS D2.5: Measurement for User Cases and Proof of Concept Performance KPIs". [Online]. Available at: https://zenodo.org/record/5786388

ANNEX II: Survey – Full Questionnaire

Survey on I4.0 and 5G
to 5G-PPP Vertical Stakeholders
–
Full Questionnaire

INSTRUCTIONS

PLEASE READ CAREFULLY

You are invited to fill out this Questionnaire as you have been identified as the appropriate person within your H2020/5GPPP project to provide relevant feedback on I4.0 Trends enabled by 5G.

This Questionnaire comprises 11 questions. To answer each question, please, refer to the following instructions provided for each question.

For all questions, contributors are encouraged to include illustrative diagrams, drawings, pictures, etc.

Question 1: What are the main competitive advantages that a company may achieve by adopting Industry 4.0 with 5G?

[ ] Production time reduction

[ ] Optimization of resources

[ ] Cost savings

[ ] Security

[ ] Efficient data flow

[ ] Maintenance through VR integration

[ ] Others… ____

Question 2: What kind of specific applications and use cases are enabled by Industry 4.0 with 5G that previously were not feasible?

(Suggested min: 700 characters)

Question 3: In what areas of the industrial process do you embrace Industry 4.0 with 5G?

INDUSTRIAL PROCESS	Positive Answers
FACTORY AUTOMATION	
SUPPLY CHAIN	
QUALITY CONTROL	
CUSTOMIZATION	
MAINTENANCE	
PLANNING	
OTHERS (Please specify)	

Please add any details that you may consider relevant:

Question 4: When will Industry 4.0 with 5G have been mostly adopted by your industrial sector?

[ ] 2022-2024

[ ] 2025-2029

[ ] 2030-2040

Please share on relevant milestones that you foresee in the adoption of Industry 4.0:

(Suggested min.: 700 characters)

Question 5: What technologies do you consider critical for the Industry 4.0 transformation?

Indicate your answer from 1 (not relevant) to 5 (most relevant).

COMMUNICATION TECHNOLOGIES	1-5
EDGE COMPUTING	
HYBRID CLOUD	
PUBLIC CLOUD	
5G eMBB	
5G mMTC	
5G URLLC	
IOT/IIOT	
WIFI	
NETWORK SLICING	
NETWORK EXPOSURE	
COMPLEMENTARY TECHNOLOGIES	**1-5**
TSN AND DETNET STANDARS	
AR/VR/XR	
BLOCK CHAIN	
QUANTUM COMPUTING	
COMPUTER VISION	
MOBILE ROBOTICS	
MACHINE LEARNING	
TACTILE INTERNET	
3D PRINTING	
OTHERS (Please specify)	

Question 6: Could you please introduce any Industry 4.0 with 5G initiative out of your company that you consider relevant for the industry overall?

Initiative 1:

Initiative 2:

Initiative 3:

Question 7: The relationship between machine and human work effort is variable. What benefits can a company get by having human resources and machines cooperating with one another?

Indicate your answer from 1 (not relevant) to 5 (most relevant).

BENEFITS	1-5
REDUCE THE NUMBER OF EMPLOYEE HOURS DEDICATED TO THE MANAGEMENT OF REPETITIVE PROCESSES	
INCREASE AUTOMATION OF THE PRODUCTION PROCESS	
INCREASE PRODUCTION CAPACITY	
INCREASE FLEXIBILITY	
MULTIPLY PRODUCT QUALITY	
INCORPORATE CUSTOMIZATION CAPABILITIES	
DEDICATE THE WORK EFFORT OF HUMAN RESOURCES TO ACTIVITIES WITH GREATER ADDED VALUE	
RAISE THE CAPACITY TO INNOVATE IN PRODUCTS AND SERVICES	
HEALTH AND SAFETY	

Question 8: If you are considering engaging in Industry 4.0 with 5G projects, what investment model would you consider?

Indicate your answer from 1 (not considered) to 5 (preferred option).

INVESTMENT MODEL	1-5
OWN INVESTMENT	
CO-INVESTMENT (WITH TECHNOLOGY AND BUSINESS PARTNERS)	
PUBLIC FUNDING PROGRAMS	
INVESTING IN EXTERNAL VENTURES	

Question 9: What options do you consider for vertical application deployment in the context of Industry 4.0 with 5G?

More than one option can be selected.

[ ] Local data centre (on-prem)

[ ] Near Edge

[ ] Central office (Telco)

[ ] Hyperscaler

For what scenarios would you choose the selected options?

(Suggested min: 700 characters)

Question 10: What are your key requirements and expectations on non-public networks for Industry 4.0 and 5G projects?

[ ] Network performance

[ ] Optimize network resource utilization.

[ ] Customization and flexibility

[ ] Security and privacy

Please add any details that you may consider relevant:

(Suggested min: 700 characters)

Question 11: What are your key requirements for additional security and privacy mechanisms for Industry 4.0 and 5G? What is your current approach and plans in this subject?

(Suggested min: 700 characters)

ANNEX III: Answers to Tabulated Questions of the Survey

Survey on I4.0 and 5G to 5G-PPP Vertical Stakeholders – Answers to Tabulated Questions of the Survey

Q1. What are the main competitive advantages that a company may achieve by adopting Industry 4.0 with 5G?

Q1: ADVANTAGES ADOPTING INDUSTRY 4.0	POSITIVE ANSWERS
OPTIMIZATION OF RESOURCES	80.0%
MAINTENANCE THROUGH VR INTEGRATION	80.0%
EFFICIENT DATA FLOW	80.0%
PRODUCTION TIME REDUCTIONS	70.0%
COST SAVINGS	70.0%
SECURITY	60.0%
OTHERS	

Q3. In what areas of the industrial process do you embrace Industry 4.0 with 5G?

Q3: INDUSTRIAL PROCESS	Positive Answers
FACTORY AUTOMATION	66.7%
MAINTENANCE	66.7%
SUPPLY CHAIN	44.4%
QUALITY CONTROL	44.4%
CUSTOMIZATION	22.2%
PLANNING	11.1%
OTHERS	

Q4. When will Industry 4.0 with 5G have been mostly adopted by your industrial sector?

Q4: ADOPTION BY YOUR INDUSTRIAL SECTOR	POSITIVE ANSWERS
2025-2029	90.0%
2030-2040	10.0%
2022-2024	10.0%

Q5. What technologies do you consider critical for the Industry 4.0 transformation?

Q5: CRITICAL TECHNOLOGIES	% MINOR	%SIGNIFICANT	%CRITICAL	%SIGNIFICANT + %CRITICAL
MOBILE ROBOTICS	10.0%	40.0%	50.0%	90.0%
EDGE COMPUTING	10.0%	30.0%	60.0%	90.0%
MACHINE LEARNING	20.0%	10.0%	70.0%	80.0%

IOT/IIOT	30.0%	20.0%	50.0%	70.0%
HYBRID CLOUD	30.0%	50.0%	20.0%	70.0%
COMPUTER VISION	33.3%	22.2%	44.4%	66.7%
3D PRINTING	33.3%	33.3%	33.3%	66.7%
WIFI	40.0%	20.0%	40.0%	60.0%
AR/VR/XR	40.0%	40.0%	20.0%	60.0%
5G URLLC	40.0%	30.0%	30.0%	60.0%
5G mMTC	50.0%	30.0%	20.0%	50.0%
5G eMBB	50.0%	40.0%	10.0%	50.0%
TSN AND DETNET STANDARDS	60.0%	20.0%	20.0%	40.0%
NETWORK SLICING	60.0%	20.0%	20.0%	40.0%
BLOCK CHAIN	66.7%	22.2%	11.1%	33.3%
NETWORK EXPOSURE	77.8%	0.0%	22.2%	22.2%
TACTILE INTERNET	80.0%	20.0%	0.0%	20.0%
PUBLIC CLOUD	80.0%	10.0%	10.0%	20.0%
QUANTUM COMPUTING	100.0%	0.0%	0.0%	0.0%
OTHERS				

Q7. What benefits can a company get by having human resources and machines cooperating with one another?

Q7: BENEFITS	% MINOR	%SIGNIFICANT	%CRITICAL	%SIGNIFICANT + %CRITICAL
REDUCE THE NUMBER OF EMPLOYEE HOURS DEDICATED TO THE MANAGEMENT OF REPETITIVE PROCESSES	10.0%	40.0%	50.0%	90.0%
INCREASE AUTOMATION OF THE PRODUCTION PROCESS	10.0%	50.0%	40.0%	90.0%
DEDICATE THE WORK EFFORT OF HUMAN RESOURCES TO ACTIVITIES WITH GREATER ADDED VALUE	10.0%	20.0%	70.0%	90.0%
INCREASE PRODUCTION CAPACITY	20.0%	20.0%	60.0%	80.0%
HEALTH AND SAFETY	20.0%	50.0%	30.0%	80.0%
MULTIPLY PRODUCT QUALITY	40.0%	20.0%	40.0%	60.0%

RAISE THE CAPACITY TO INNOVATE IN PRODUCTS AND SERVICES	50.0%	40.0%	10.0%	50.0%
INCREASE FLEXIBILITY	60.0%	20.0%	20.0%	40.0%
INCORPORATE CUSTOMIZATION CAPABILITIES	70.0%	20.0%	10.0%	30.0%

Q8. If you are considering engaging in Industry 4.0 with 5G projects, what investment model would you consider?

Q8: INVESTMENT MODEL	% MINOR	%SIGNIFICANT	%CRITICAL	%SIGNIFICANT + %CRITICAL
CO INVESTMENT	20.0%	80.0%	0.0%	80.0%
PUBLIC FUNDING	30.0%	10.0%	60.0%	70.0%
OWN INVESTMENT	60.0%	20.0%	20.0%	40.0%
INVESTING IN EXTERNAL VENTURES	100.0%	0.0%	0.0%	0.0%

Q9. What options do you consider for vertical application deployment in the context of Industry 4.0 with 5G?

Q9: DEPLOYMENT OPTIONS	POSITIVE ANSWERS
NEAR EDGE	88.9%
LOCAL DATA CENTER (ON-PREM)	66.7%
HYPERSCALER	55.6%
CENTRAL OFFICE (TELCO)	55.6%

Q10. What are your key requirements and expectations on non-public networks for Industry 4.0 and 5G projects?

Q10: REQUIREMENTS ON NPN	POSITIVE ANSWERS
OPTIMIZE NETWORK RESOURCE UTILIZATION	100.0%
NETWORK PERFORMANCE	100.0%
SECURITY AND PRIVACY	80.0%
CUSTOMIZATION AND FLEXIBILITY	60.0%

ANNEX IV: List of Firms and Institutions Participating in the Survey

Survey on I4.0 and 5G
to 5G-PPP Vertical Stakeholders
–
List of Firms and Institutions
Participating in the Survey

The editorial team of this whitepaper wants to acknowledge and thank the interest, dedication and contribution of the following firms and institutions participating in this 5G-PPP I4.0 survey:

ABB Corporate Research Center (Sweden)
https://global.abb/group/en/technology/corporate-research-centers/sweden
The ABB Corporate Research Center in Sweden is located in Västerås, about 100 kilometres west of Stockholm. Together with our colleagues in other R&D centres, we develop technologies for future products and services for ABB's core businesses.
Our focus areas include:

- Automation control and optimization
- Automation networks and wireless technologies
- Chemistry and environmental technologies
- Electrical machines and power electronics
- Mechatronics and robot automation
- Nanotechnology and advanced materials technologies
- Power systems and apparatus
- Software architecture and processes

We collaborate with universities around the world, including MIT, Carnegie Mellon, Rensselaer Polytechnic Institute in New York, KTH Royal Institute of Technology in Stockholm, Chalmers University of Technology in Gothenburg, Linköping University, Mälardalens University in Västerås and Uppsala University.

ASTI Mobile Robotics – now ABB Autonomous Mobile Robots (Spain)
https://new.abb.com/products/robotics/robots/autonomous-mobile-robots
Working every day to offer the widest range of solutions across the whole value chain, perfectly meeting the intralogistics needs of the connected industry.

- Reception - Warehouse - Shipment
- Intralogistics and material handling
- Line supply and kitting
- Assembly and sub-assembly lines
- End of line handling – Auxiliary supplies
- Interprocess connection

CIM4.0 - Competence Industry Manufacturing 4.0 (Italy)
https://cim40.com/en/
CIM4.0 Competence Center is the national reference centre for the technologic transfer and the diffusion of competences related to manufacturing and service industries.
CIM4.0 is a network made of Politecnico and University of Turin, together with 22 partner businesses, offering strategic and operational support within Industry 4.0 development context through technological services and advanced training courses.

Ford Motors (Spain)
https://corporate.ford.com/
Ford is a family company, one that spans the globe and has shared ideals. We value service to each other and the world as much as to our customers. Generations have made their memories with us and included us in their hopes and dreams. After 120 years, we're

used to adapting to and leading change. That's why we're evolving to focus on services, experiences and software as well as vehicles.

GMI AERO (France)
https://www.gmi-aero.com/en
GMI Aero SAS has been since its foundation in 1985 a leading innovator and a key provider of solutions and products for advanced process control used in the composite material manufacturing and repair.
As the pioneer in the integrated equipment for advanced process control, GMI Aero evolved to be a key player in the composite repair market and today provides full range of repair equipment and products to best address the ever-increasing technical challenges arising in the aeronautical and wind energy industry.
Deployed with the world's largest Aircraft Manufacturers, MRO's and Airlines, GMI's products deliver the most advanced solutions throughout in all process steps in the repair application and lifecycle.
Our holistic approach and complete suite of products support even the most advanced demands for today's composite repairs.
The company maintains its technological edge by continuously introducing advanced capabilities and extensions of its technology portfolio.
GMI's headquarters are located in Paris, France. The company serves customers worldwide from agents in Singapore, China, Australia, Russia, South and North America.

Immersion (France)
https://www.immersion.fr/en/
Immersion: Reinventing workspaces.
Immersion creates immersive and collaborative workspaces.
Immersion is rethinking the work of tomorrow. Beyond improving the performance, efficacity and efficiency of their solutions, their ambition is to instil pride and the desire to collaborate amongst their client's employees.
A catalyst for innovation, an expert in virtual and augmented reality, and a designer of spaces and interfaces… Above all, Immersion is an architect of solutions capable of shaping and reinventing the work experience. And what is the one thing that these solutions all have in common? They put people back at the heart of technological innovation by focusing on the user experience.
A pioneer in virtual reality since 1994, Immersion now boasts a multidisciplinary team with a wide range of expertise. Immersion selects, invents, patents, and distributes innovative technological products. Immersion integrates immersive and interactive systems, combining headsets, large image walls and collaborative tables. Immersion develops software solutions including "Shariiing," their software solution for presentations and collaborative work. And lastly, Immersion also develops mixed reality applications, participates in national and European research projects, and conducts technical and user studies.
Whatever their size or field of activity, private and public sector players are using their reimagined immersive and collaborative workspaces to make their colleagues proud, generate ideas, work more efficiently, and dream... They are using these workspaces to explore the possibilities of innovation, production, marketing, training, and maintenance.
These immersive and collaborative workspaces include virtual reality rooms, creativity rooms, hybrid training rooms, innovative showrooms, innovation laboratories, factories of the future, …

Infolysis (Greece)
https://infolysis.gr
INFOLYSIS P.C. is an innovative SME company, established in Athens, Greece, specialising on the design and development of chatbots, either as custom-made standalone applications or as subscribed-based services (Chatbot as a Service) via the privately owned chatbot platform. Chatbots are applications that simulate human conversation, based primarily on conversational flows and occasionally enriched with DL/NLP technologies for more sophisticated use-cases. INFOLYSIS provides its chatbot solutions over various popular messaging apps as well as over the web.
INFOLYSIS is committed to driving research results forward by experimenting with novel technologies and infrastructures, such as 5G/6G, IoT, Non-Terrestrial beyond 5G Networks (NTN emulation), SDN/NFV at the network edge and container-based virtualization in IoT areas, IoT vGWs enriched with DPI functionalities, data analysis with ML techniques, network applications, in order to advance the chatbot capabilities and expand its applicability in novel ICT use-cases.
INFOLYSIS team includes highly qualified engineers of multiple ICT background, which have a strong focus on R&D with a long track record in EU- and national-funded research initiatives. INFOLYSIS has actively participated in a number of European funded research projects (H2020 and HE) and its team has authored or co-authored over 100 papers in international refereed journals and conferences.

InQbit Innovations (Romania)
https://inqbit.io/
InQbit Innovations is small medium enterprise (SME) that focuses on the designing, developing, providing to the market ICT solutions and services. It has been founded by an international team that ensures a right balance of entrepreneurship, research and engineering that joined their forces targeting to produce innovation that will serve and satisfy societal and market needs.
The company aspires to build on the latest technologies and develop intelligent technical solutions securing the industries with “future proof” tech, providing its customers and business, stability in the markets.

Public Power Corporation (PPC) / Dimosia Epichirisi Ilektrismou (DEI) (Greece)
https://www.dei.gr/en/ppc-group/ppc/
PPC was founded in 1950 and has been listed on the Athens Stock Exchange since 2001. It is the leading electricity generation and supply company in Greece, with activities in the generation, distribution and sale of electricity to consumers. It is the largest electricity supplier in Greece, serving approximately 5.6 million customers throughout the country. It is the largest power generation company in Greece with a total capacity of 11.1 GW including thermal, hydro and RES power plants. HEDNO S.A., its 51% subsidiary, is the owner and operator of the electricity distribution network of Greece with a Regulated Asset Base of c. € 3 bn.

Whirlpool (Italy)
https://www.whirlpool.com/

Whirlpool Corporation (NYSE: WHR) is the world’s leading kitchen and laundry appliance company, with approximately $19 billion in annual sales, 78,000 employees and 57 manufacturing and technology research centres in 2020. The company markets Whirlpool, KitchenAid, Maytag, Consul, Brastemp, Amana, Bauknecht, JennAir, Indesit and other major brand names in nearly every country throughout the world. Additional information about the company can be found at whirlpoolcorp.com or find us on Twitter at @WhirlpoolCorp.

Whirlpool Management EMEA is the division of Whirlpool corporation which includes all the central functions supporting the EMEA Whirlpool organization. With a European footprint based on 11 production facilities and 35 sales organizations, it produces and distributes more than 20 mln pcs in 140 countries with important brands like Whirlpool, KitchenAid, Hotpoint, Indesit, Bauknecht. Very active in Innovation projects to support the digital transformation through the "test before invest" concept, it has been working in the funded research European programs like Horizon2020 and EIT Manufacturing to boost the technological innovation at process and product level.