5G technology application in manufacturing systems

Cimini C.*, Cavalieri S.*

** Department of Management, Information and Production Engineering, University of Bergamo, Viale Marconi 5, 24044 – Dalmine – Italy (chiara.cimini@unibg.it, sergio.cavalieri@unibg.it)*

Abstract: The fifth generation of Mobile Wireless Communication, the so-called 5G, is expected to introduce relevant changes in many aspects of the people's lifestyle, as well as new possibilities for the economic and social environment. eMBB (enhanced Mobile Broadband), MTC (Machine-Type Communications) and URLLC (Ultra-Reliable Low Latency) are the core aspects of the 5G, ensuring mobile communications to be smarter, faster, and more efficient than previously. In the manufacturing sectors, 5G could support applications in several fields, from the maintenance and quality to logistics, enhancing the utilisation of augmented and virtual reality, cloud robotics and artificial intelligence. The aim of this paper is to present the current 5G technological context, trying to clarify some fundamental aspects of 5G's applications, advantages and disadvantages, focusing mainly on manufacturing and supply chain. 5G's characteristics and services have been thoroughly analysed in order to highlight the potentialities offered by the implementation of such technology and some real industrial applications, collected by interviews in four Italian manufacturing companies, are described. In the face of numerous expected benefits, such as improved monitoring and service level, several barriers emerge, mainly concerning infrastructure costs and cybersecurity.

Keywords: 5G, Mobile Wireless Communication, Smart Manufacturing

1. Introduction

Mobile Wireless Communication (MWC) networks have experienced remarkable changes during the last decades, showing that this sector is one of the most active globally. Indeed, from when 1G technology was implemented in the 1980s, a new generation has been introduced roughly every ten years (Lopa and Vora 2015). Nowadays, we are witnessing the adoption of a new paradigm, 5G, representing the fifth generation of MWC.

5G is going to be from one side an evolution from the previous generations while, from the other side, it will bring a disruption in the mobile communication, catalysing, among others, a widespread implementation of interconnected IIoT (Industrial Internet of Tings) systems, remotisation of maintenance and control services of machines, diffusion of autonomous vehicles, thus affecting many industrial sectors and more widely the way we live (Rao and Prasad 2018). 5G is not a novel technology since it has been already conceived since the late 2010s; its main features are high speed increased network capacity, latency of 1ms and large broadcasting of data, allowing extremely fast and highly effective transmission of information. Compared to the previous generations, 5G characteristics enable a user data-rate greater than 1 Gbps, thousands of times higher mobile data, hundreds of times more connected devices, more battery life, reduced latency, more than 1000 times higher mobile data volume per geographical area, and a higher access in low populated density areas (Gopal and Kuppusamy 2015).

The main features of 5G, namely eMBB (enhanced Mobile Broadband), MTC (Machine-Type Communications) and URLLC (Ultra-Reliable Low Latency), open many opportunities to improve both economic and industrial sectors (Attaran 2021), as well as changing the people's lifestyle and social environment.

This paper aims at presenting an overview of the 5G technology, in order to discuss potential applications in the industrial sector, focusing mainly on manufacturing and logistics. Particularly, 5G's characteristics and services have been thoroughly analysed starting from a review of the academic and industrial literature, also including whitepapers, consultancy and commercial documentation available online. Then, in the paper, four potential 5G applications in manufacturing companies are described, thanks to the information collected during interviews conducted with the companies.

The paper is structured as follows. Section 2 describes the main features of 5G. In Section 3, potential applications of 5G in several manufacturing areas are described, while Section 4 presents four applications of 5G technology in manufacturing systems. In Section 5 challenges to the 5G introduction are discussed and future development research paths are portrayed.

2. Main technical characteristics of 5G

A mobile wireless Generation (G) generally refers to a change in the system's nature, speed, technology, frequency, data capacity, and latency. Each generation is faster and has better features compared to the previous one (Lopa and Vora 2015). Although the introduction of 4G technology, in the past, significantly improved MWC, evident limitations needed to be addressed. The principal one is the operating area since, in many countries, rural areas and also buildings in metropolitan areas are not served well by existing wireless networks (UKEssays 2017).

Moreover, today's mobile users' requirements focus on faster data speeds and more reliable services. To

overcome these issues, 5G is going to be as much as 100 times faster than 4G. Another relevant difference between 4G and 5G is the latency, which is defined as the time that elapses between sending and receiving a piece of information. (Just Ask Thales 2018). Several latency critical services, concerning factory automation applications, intelligent transportation, robotics and so on, requiring latency <1 ms, could not be handled by 4G, while can be effectively supported by 5G (Parvez et al. 2018). The introduction of 5G will allow quick and easy files downloading and uploading since 5G is able to fix bandwidth issues.

Considering the network aspects, 4G uses a monolithic network entity, while 5G can be integrated with various technologies, such as 2G, 3G, 4G, LTE-A, and its network is designed in order to support different applications of these technologies. In addition, 5G architecture is opened to third parties (i.e., developers, providers, and partners) via APIs (application programming interfaces). This architecture is going to offer a greater network flexibility and adaptability that allows it to respond to real-time requirements, it also provides more distributed intelligence capabilities at the edge of the network (Taleb et al. 2017).

While the architecture defines the structure of the 5G networks, its services have to be analysed to understand better the potentials of its introduction. The International Telecommunication Union (ITU) - the United Nations specialized agency for information and communication technologies - has identified three essential types of use of the 5G services, i.e. eMBB, MTC and URLLC (Slalmi et al. 2020):

- eMBB represents the possibility of having high data rates and low latency communication, improving the Quality of Service (QoS) offered. This service is strictly connected to the possibility to improve spectral efficiency (Siddiqi et al. 2019).
- MTC can be described as a mechanism by which machines, sensors, actuators, physical objects, embedded controllers and other devices are able to communicate over a wired or wireless network to exchange information and, at the same time, take actions without the need for any human intervention, thus reducing errors and therefore costs. (Ström et al. 2015). There are two main types of MTC: uMTC and mMTC (Bockelmann et al. 2016). uMTC provides ultra-reliable links with low latency, while mMTC offers the possibility to support billions of connected devices.
- URLLC meets two essential needs: low latency that, according to 3GPP (Third-Generation Partnership Project), should be less than 0.5 ms on average, and ultra-high reliability, which should be at least 99.9999% per 1ms. These requirements are essential for the implementation of real-time applications (Siddiqi et al. 2019).

The combination of the 5G architecture and these three main services will allow an extremely high-level service offer for specific applications. This will be possible through the use of network slicing, which refers to the capability of virtually dividing a software network into so-called slices, i.e., end-to-end virtual networks at the service of a class of applications. In this way, slices can be flexibly and quickly defined and setup, to support diversified vertical services (Foukas et al. 2017). Ji et al. (2018) showed how the three main 5G services support different applications (Figure 1).

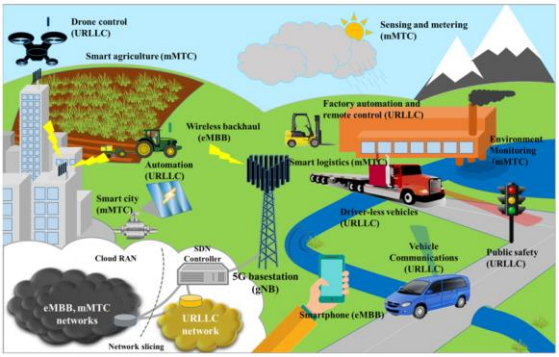

Figure 1: 5G services applications (Ji et al, 2018)

3. The adoption of 5G in manufacturing

The objective of this paper is to point out the possible implementations of 5G in the manufacturing world. In the following, the processes that could be mostly impacted by the 5G adoption are discussed.

3.1 Factory automation

5G, with its low latency, the ability to handle big data sets, and a reliable connectivity, is the potential future communication platform in factories (O'Connell et al. 2020). As previously described, MTC enables machine to machine communication, i.e., closed-loop communications between machines to optimize manufacturing processes. A critical advantage of 5G will be eliminating wiring, which enables a flexible production line configuration.

Brown (2018) shows how 5G can support factory automation in three steps: i) enabling real-time processes; ii) supporting non-time-critical processes; iii) improving enterprise communication.

In fact, 5G can support the wide spread adoption of IIoT, in order to facilitate real-time data acquisition and communication for factory monitoring (Attaran 2021). Indeed, product and process data, acquired by sensors installed everywhere in the factory, can be used in real-time to monitor equipment conditions, with a twofold objective: keeping under control both the production processes and the products' quality. According to the Industry 4.0 paradigm, cyber-physical production systems will work with precision control in near real-time, from virtually anywhere in the world. Cyber-physical production systems also automatically use data acquired by the physical field to perform diagnosis, self-adaptation and self-healing (see also Section 3.3).

Other real-time applications of 5G deal with the ability to remotely operate equipment e.g., production line robotics on the factory floor. Video-driven machine-human interaction, through the use of augmented and virtual reality, can be applied in several processes, such as welding, painting and assembly.

The huge quantity of data that can be transferred from the factory level to the enterprise information systems can be further used for non-real-time applications that are devoted to optimising the management of production facilities, such as artificial intelligence and data analytics application or simulations (Sultan and Ali 2017).

Finally, intra- and inter-enterprise communication are enhanced by 5G. In particular, the post-production tracking of goods can be achieved. Also, monitoring of the assets distributed in broader geographical areas across the value chain will be enhanced, enabling new and improved service management.

3.2 Logistics

In recent years, it emerged that, to conduct efficient logistics processes, it is essential to achieve logistics dynamic information acquisition and goods information real-time sharing. To support this, the potential of 5G in logistics is strongly related to the applications of the IoT, since logistics companies need to manage a massive quantity of data, coming from different functions carried out by employees, vehicles related to delivery, equipment adopted for material handling, and facility control systems, which need lightning-fast connections with low latencies and very high uptime.

With the introduction of 5G, a significant number of individual devices, also in the logistics sector, will improve their internet connections and firms will be enabled not only to share and send considerably higher quantities of data in comparison with the past, but also to elaborate data closer to the source that originates them, compared to dialogue with servers located remotely. Lean distributed cloud network to link logistical operations together could be developed. Indeed, there will be the possibility of creating a network of automated and connected sensors, with better control of the facilities, conveyors, and better management of the material handling equipment, such as AGVs. 5G uRLLC service will allow improved automation in distribution, transportation and sorting, enhancing the efficiency of logistics processes and the flexibility of warehouses (Shi et al. 2019).

According to the DHL report about 5G applications for logistics service providers, this technology can positively affect logistics in six ways (DHL 2019):

- *Digitalization.* 5G can connect a higher number of users at the same moment and, thanks to faster speeds, lower lag times, more extensive areas of coverage and comparatively smaller power needs, logistics smart devices will be able to communicate faster with one another at speeds that are even closer to real-time. This will catalyse time-sensitive IoT device applications and open up opportunities for new use-cases in the logistics field. Data-driven analytics and decision making with big data and artificial intelligence can be facilitated.
- *Minimizing supply chain risk.* Control and reduction of the supply chain risks are recognised as relevant for maintaining a high level quality of the offered services. This involves the possibility to have proper visibility and traceability for goods transit, which is one of the major challenges for logistics and shipment companies. The 5G technology could prove useful to support portable IoT connected trackers to monitor in real-time the location and condition of the goods throughout the entire supply chain. Thanks to low-energy requirements of 5G, geographical position, temperature, humidity, light, shock, and other vital metrics can be monitored with smart devices including battery-operated tracking securely attached to containers, trucks, and boxes.
- *Autonomous trucks on public roads.* Self-driving systems will have the potential to revolutionize freight transport. Taking advantage of 5G's low-latency, data will be transmitted with a lag time of only one millisecond. Thus, for an autonomous truck to decide, there will be a far lower time, which means safer roads, and more reliable deliveries. 5G-powered trucks have been already engineered by Ericsson, Einride, and Telia and have been tested into a logistics facility in Jönköping, Sweden in order to support a sustainable and safe transport system.
- *Augmented reality (AR) applications.* 5G network will significantly enhance the use of arising AR applications used in logistics, such as vision picking and HoloLens, and improve the AR applications' user experience, mainly to decrease the chance for errors and boosts the efficiency of the staff managing warehouse operations.
- *Cloud Supply Chain.* Real-time data and zero latency ensured by 5G can support the implementation of cloud across the supply chain. This will fundamentally change the operations and management of supply chain processes.

Therefore, 5G technology has high potentials for the improvement of logistics information management, contributing to the creation of a real-time collection, visualization, and intelligence in logistics and supply chain management (Que et al. 2017).

3.3 Maintenance and Service provision

Maintenance is essential for any production system and the application of 5G technology can strongly support predictive maintenance operations, enabling timely fault detection. Indeed, 5G provides the ability to transfer high volume data with low latency, which in turns enable real-time data analysis of equipment. Consequently, real-time data analysis can provide information about the equipment current status and detect complex correlations utilizing big data analytics. (Lundgren et al. 2017). This can be used to support operations and maintenance, increase flexibility, efficiency, and technical availability.

Thus, 5G implementation in manufacturing systems can contribute to the development of data-driven decision support systems for improving maintenance strategies with positive effects in production output, process robustness, and reduced total maintenance downtime (Åkerman et al. 2018).

Moreover, 5G enables the use of augmented reality to support maintenance and service provision. Maintenance operators can be supported remotely in the execution of procedural tasks in maintenance and repair activities, with potential savings in the costs currently deriving from on-site maintenance interventions (O'Connell et al. 2020).

4. Case applications in industrial companies

Through this section, four potential and preliminary applications of 5G in industrial companies are analyzed (Table 1). The case enterprises are all large companies located in the north of Italy and have been chosen covering different sectors (i.e., manufacturers, technology provider, service provider) through a selection among the participants to a survey promoted in collaboration with the local Industrial Association and the Digital Innovation Hub, since they were the most advanced in the planning and development of 5G projects. Interviews with the main involved stakeholders, such as IT and R&D managers, have been conducted in order to identify the objectives of the 5G implementation, pointing out at the same time potential benefits and expected or experienced challenges.

4.1 Private 5G networks for the factory

Company A is a multinational company that produces cement, ready-mix concrete, and construction aggregates. The company is part of a multinational group that is a world's leading player in the vertically integrated supply of building materials and is extremely active in targeted investments in new technologies that would bring excellent benefits to the cement production processes.

Table 1: Potential of 5G applications in the interviewed companies

Company	Interviewee	Scope	Description	Application area
A	IT manager	Private 5G Network	Optimization of signal in vast factories, and more precise control in concrete sites	Factory automation, Logistics
B	R&D manager	Teleoperated platform	Remote control of autonomous robots	Factory automation
C	Maintenance manager	Network automation and control of assets	Real-time maintenance	Maintenance
D	R&D manager	Enable and support Agriculture 4.0	Real-time data, close loops at the cloud level, tractor-to-tractor communication	Maintenance and Service

During the interview, the responsible for the IT department explained three specific projects. He suggested that, through an optimal bandwidth guarantee and more excellent coverage, better production benefits are going to be obtained, despite the current 4G LTE and optical fiber implementation already underway.

More in detail, the company is now going to introduce a new private 5G network useful for signal optimization in factories. Indeed, they have invested resources to buy three mixed reality technology HoloLens produced by Microsoft for augmented reality. This kind of investment is related to AR, one of the main fields in which 5G will be applied. The operator who needs assistance for a faulty equipment is remotely assisted by a second worker projected in front of him through a hologram. The remote operator is in his office but still manages to see the machine as if he was physically in front of it. He can then interact by indicating objects in space visible in the hologram near the physical operator.

The second active project concerns a better remote control of concrete sites. Through the adoption of specific cameras, the operator supervises the correct loading of concrete in the trucks' mixers. Once the concrete mixer is positioned, the driver has to wait for the remote operator to press the activation button. About a couple of seconds are currently required between the action from the button and the released material. This time frame becomes unsustainable when problems arise, and an immediate interruption of the flow is necessary.

The last activity concerns the transition to a totally wireless network for the whole company. A centralized room inside large cement plants includes hundreds of sensors that aim to return the status of processes, and currently, most of them are wired.

The company primary efforts have been focused on creating optical-fiber infrastructures allowing to activate a more efficient data collection and backup system at most sites. With the new technology's advent, they expect to have a broader bandwidth to cover their vast cement factories, since with the current technological level, LTE and 4G, the connection often turns out in slowdowns, such as grainy or blocked images that do not allow a clear streaming transmission.

Furthermore, Company A will expect to solve the geographical issues related to most cement production sites located in remote areas where typically even a 4G connection struggles to operate. Through a total wirelessly conversion, they would significantly reduce the costs benefiting the purchase of more performing sensors. In conclusion, it is required that 5G brings a sufficient bandwidth guarantee to allow optimal signal coverage and lower latency for waiting time so that the company could

surely reap many benefits in terms of better service and lower operating costs.

4.2. Teleoperated robotic platform

Company B is a multinational company that develops infrastructure for telecommunication networks for over 80 years. It is now a consolidated point of reference in the market, a key player in the development of first telephony, then telematics, while also making significant contributions in electricity and energy networks. In recent years, the company has continued focusing on its core business, telecommunications, while diversifying its sectors of operation at the same time. In this sector, it has the role of a system integrator. Recently, the company is also increasingly engaged in developing technological suites for energy monitoring and control and constructing high-efficiency charging stations for electric vehicles.

Company B uses 5G for activities essential to its business. During the interview, the head of the R&D department talked about the two uses of new technology in their processes.

Mainly, 5G will be implemented for the remote control of autonomous robots. More specifically, the company takes advantage of several data centers as data collection points. Usually, when problems arise, operators will physically attend to figure them out. Autonomous robots would perform about 80% of the tasks done by a physical operator benefiting the company with greater reactivity avoiding downtimes. In 2018, the first remote control robot was tested. The adopted bandwidth was a *30 Mbps ADSL*, which was insufficient for the correct execution of operations. Indeed, at least twice as much bandwidth would have been needed. The challenge today is to not only improve the connection parameters but to be able to allow the virtual operator to act wherever without concerning the current position.

Furthermore, the second focus of Company B is pushing 5G towards IoT for data monitoring activities. Typically, a series of data is collected regarding the consumption of electricity. The company has several gateways that act as concentrators between the data and various sensors placed at the measurement points. The gateway has the dual function of communicating with the sensors (wired, or in some cases through *LoRa* protocol) and redirecting data to databases relies on 4G technology. Data need to be updated every 15 minutes. It is estimated that about 40 parameters are collected approximately every 10 seconds. The final amount of data generated is hugely significant.

Therefore, the low signal, or complete absence, is one of the current problems that the company B is expected to solve as soon as possible. On the other hand, significant funds are allocated every year to invest in IoT and AI in autonomous robots' context. A better bandwidth with low latency would improve all the data control activities that Company B relies on. It is possible to conclude that, for the moment, the two most significant barriers against the development of its projects, according to Company B, are related to the difficulty of having a proper connection and the need to have a larger bandwidth.

2021 is going to be the year of the new 5G transmitter's purchase. Indeed, both static information such as temperature and humidity, and dynamics like vehicle loads and stresses, are going to affect bridges and some other substantial civil infrastructures. Following market laws, if costs will decrease in 2022, the company could start producing 5G transmitters' embedded systems for optimal data monitoring.

4.3. Network automation and remote control of assets

Company C is an Italian network service management company active in the distribution of electricity and gas. The company serves as a local distributor for about two hundred Italian municipalities, included in seven regions and has a network of over 20,000 kilometers in length, which can serve over one million end customers. The medium and low voltage electricity network annually produces over 12,000 GWh of electricity. The company also indirectly deals with the distribution of natural gas.

Company C plans to use 5G from an IoT perspective to implement predictive maintenance. The goal is to apply technology to sensors to optimize interventions. Their networks consist of many electrical substations which are usually placed in the most strategic points. Some are positioned, for example, at the ends of the network and are powered by wired connections; others, the most important, are remotely controlled. When a fault is generated, an error signal, "interblock goose," is communicated to the substations. By doing this, it is possible to isolate the faulty section in approximately 70/80ms. Longer times for reporting errors lead to penalties for the company.

Currently, the project described above works only in large cities via optical fiber. Often, they have encountered problems laying fiber cables. Certainly, 5G will help in areas with low fiber implementation (it does not need cabling, unlike optical fiber) improving the service level. Subsequently, 5G will improve logic selectivity, which puts cabins in communication and the carriers' reliability. The latency required should allow faster communications than those already used. Undoubtedly, the company has to ensure guaranteed performances are respected even if in particular conditions. Company C is investing heavily in the digitization of plants to allow real-time monitoring and, the establishment of an intelligent system for more effective business processes interconnections.

4.4. Real-time data for service provision

Company D is a multinational company and is a worldwide leading manufacturer of tractors and agricultural machinery. Currently, the company strategy aims at expanding the sales network into key and emerging markets, as well as testing and developing the most advanced technology. They are specialized in core components and offer an extensive and competitive product range.

Nowadays, the traditional customer has to manage the whole agricultural process. This means that Company D has to provide the vehicle and an adequate infrastructure

with data and sensors, which are getting more critical in the agricultural sector. The gathered data come from drones and satellites; then, they are translated by a map on the tractor that interprets them and sends instructions to the tractor to work accordingly. This allows having greater yield and less environmental impact. This situation map also sends instructions to the vehicle concerning its geographical position. In this way, the tractor itself becomes a kind of numerically controlled machine. In the same way, also the irrigation part is governed. All this data flow needs to be coordinated and organized; the tractor works as a data communication hub. However, there are many variables that it is not possible to control, especially in the rural environment.

Indeed, the R&D responsible for the developing of 5G infrastructure concerns about potential issues in rural regions. Regarding possible 5G applications, Company D has a bunch of cases in mind.

First of all, the possibility to introduce the real-time concept on the tractor. In this way, it will be possible to increase computational capacity, with higher power than a computer, by introducing onboard processing. Linked to this, another project is related to introducing closed loops at the cloud level to obtain data in real-time. The advantages are the real-time upgrade and a reliable structure for sharing information. In this case, the lowest latency possible is essential, while the emerged problems are related to coverage. The third project relates to the improvement of the machine-to-machine communication between tractors to allow that a tractor follows the other one. In this way, it is possible to coordinate the operations of a fleet of tractors. This idea relies on tractors' exploitation as micro weather stations that know precisely when it will rain or snow.

From the interview with Company D, it emerged that the company is already operating in a smart and high-tech way, mainly to accomplish the so-called agriculture 4.0. It implies a reduction of the environmental impact through better management of natural resources, reduction of waste, and sustainable crops development. The company also believes that 5G will be extremely relevant, enabling technology for its future projects. On the other side, the most relevant barriers are the costs and the need to spread the technology also in rural areas.

5. Discussion

From the discussion with the industrial companies, some expected benefits coming from the introduction of 5G communication emerged.

First of all, it has been evident that thanks to its low latency and high reliability, 5G is going to give a substantial boost to all the monitoring activities, concerning both the production, logistics and maintenance field. A better control of the internal equipment can be achieved, since data transferred through the 5G can be instantly accessed and analysed by predictive algorithms to prevent issues. In particular, the 5G potential is evident in AI-based models, algorithms, and practices, in which even few milliseconds of latency can make a difference and data can not be transferred to the cloud, but edge computing is necessary.

Remote realtime control has several potentialities since it allows companies also to oversee their products through the lifecycle, increasing the service level, for instance for companies that are service providers (e.g. Company C) or enabling new service offerings, such as the optimisation of the products' functioning or the coordination of multiple products (e.g. Company D).

Another interesting benefit of 5G concerns the possibility to enable ecosystem communications. This allows the connection of factories located in different geographical sites (e.g., Company A) and it is particularly useful for logistics and supply chain. Equipment, product, people, transportation systems can communicate realtime and coordination of tasks among all the resources becomes simpler and more efficient.

Nevertheless, the discussion with the interviewed companies highlighted some barriers which are currently obstructing the inception of innovation projects involving the implementation of 5G in the industry.

As the companies suggested, currently, there are several issues concerning the infrastructure needed to support 5G communication. Indeed, companies have to face high investment cost and also need to harmonize 5G with predecessor technologies (wired and wireless) which are already employed in their production and logistics systems. The infrastructure needed to support 5G emcompasses both the network layer (e.g., base stations, access points, industry switch) and the computing resources (e.g., edge server, data centers, cloud server). It has been estimated that for 25% annual data growth, the Total Cost of Ownership of the 5G network will rise about 60% (Grijpink et al. 2018). Moreover, infrastructure issues are even more evident in rural areas (Chiaraviglio et al. 2016).

Striclty connected to the previous one, another barrier is the implementation of adequate practices to ensure the data security. If in the past, manufacturing operations systems were substantially isolated from external networks, nowadays they can be vulnerable to cyber-attacks and need to be properly protected to avoid the loss or alteration of essential data.

As discussed before, the co-existence of different wired and wireless protocols will characterise the situation of industrial networks for a long time to come. For this reason, several regulations and standards are emerging, but concerns about interoperability and communication among different protocols are still open.

Finally, the interviewed companies drew attention on the lack of knowledge for the adoption of new, more powerful technologies as the 5G communication. To this purpose, internal technical competencies need to be developed in order to capitalise on the potentials of 5G.

6. Conclusion

This paper aimed at addressing the topic of 5G potentials in manufacturing application. Since the research is in its

infancy, some insights about benefits and barriers to the implementation were presented by discussing four applications explored in large companies. To overcome the limitation of the current research, further investigation will concern costs and benefits of installing a 5G network in the factory and its interoperability with legacy systems, as well as the estimation of payback times. To do so, a systematic and wider assessment of the diffusion of 5G in the industrial sector will be developed.

References

Åkerman, M., Lundgren, C., Bärring, M., Folkesson, M., Berggren, V., Stahre, J., et al. (2018). Challenges Building a Data Value Chain to Enable Data-Driven Decisions: A Predictive Maintenance Case in 5G-Enabled Manufacturing. *Procedia Manufacturing*, *17*, 411–418.

Attaran, M. (2021). The impact of 5G on the evolution of intelligent automation and industry digitization. *Journal of Ambient Intelligence and Humanized Computing*.

Bockelmann, C., Pratas, N., Nikopour, H., Au, K., Svensson, T., Stefanovic, C., et al. (2016). Massive machine-type communications in 5g: physical and MAC-layer solutions. *IEEE Communications Magazine*, *54*(9), 59–65. Presented at the IEEE Communications Magazine.

Brown, G. (2018). Ultra-Reliable Low-Latency 5G for Industrial Automation, 11.

Chiaraviglio, L., Blefari-Melazzi, N., Liu, W., Gutierrez, J. A., Van De Beek, J., Birke, R., et al. (2016). 5G in rural and low-income areas: Are we ready? In *2016 ITU Kaleidoscope: ICTs for a Sustainable World (ITU WT)* (pp. 1–8). Presented at the 2016 ITU Kaleidoscope: ICTs for a Sustainable World (ITU WT), Bangkok, Thailand: IEEE.

DHL. (2019). 5G: Five things it means for logistics. https://lot.dhl.com/5g-five-things-it-means-for-logistics/

Foukas, X., ElmokashfiElmokashfi, A., Patounas, G., & Marina, M. (2017). Network Slicing in 5G: Survey and Challenges. *IEEE Communications Magazine*, *55*(5), 94–100.

Gopal, B. G., & Kuppusamy, P. G. (2015). A Comparative Study on 4G and 5G Technology for Wireless Applications. *IOSR Journal of Electronics and Communication Engineering*, *10*(6), 67–72.

Grijpink, F., Ménard, A., Sigurdsson, H., & Vucevic, N. (2018). The road to 5G: The inevitable growth of infrastructure cost. *McKinsey & Company, Technology, Media & Telecommunications Report*.

Ji, H., Park, S., Yeo, J., Kim, Y., Lee, J., & Shim, B. (2018). Ultra-Reliable and Low-Latency Communications in 5G Downlink: Physical Layer Aspects. *IEEE Wireless Communications*, *25*(3), 124–130.

Just Ask Thales. (2018, March 14). What is the difference between 4G and 5G? *Just Ask Thales EN*. https://justaskthales.com/en/difference-4g-5g/.

Lopa, Ms., & Vora, J. (2015). Evolution of mobile generation technology: 1G to 5G and review of upcoming wireless technology 5G. *International journal of modern trends in engineering and research*, *2*(10), 281–290.

Lundgren, C., Skoogh, A., Johansson, B., Stahre, J., & Friis, M. (2017). *The value of 5G connectivity for maintenance in manufacturing industry* (p. 3975).

O'Connell, E., Moore, D., & Newe, T. (2020). Challenges Associated with Implementing 5G in Manufacturing. *Telecom*, *1*(1), 48–67.

Parvez, I., Rahmati, A., Guvenc, I., Sarwat, A. I., & Dai, H. (2018). A Survey on Low Latency Towards 5G: RAN, Core Network and Caching Solutions. *arXiv:1708.02562 [cs]*. http://arxiv.org/abs/1708.02562.

Que, S., Chen, J., Chen, B., & Jiang, H. (2017). The Application of 5G Technology in Logistics Information Acquisition. *DEStech Transactions on Computer Science and Engineering*, (iceiti).

Rao, S. K., & Prasad, R. (2018). Impact of 5G Technologies on Industry 4.0. *Wireless Personal Communications*, *100*(1), 145–159.

Shi, Y., Han, Q., Shen, W., & Zhang, H. (2019). Potential applications of 5G communication technologies in collaborative intelligent manufacturing. *IET Collaborative Intelligent Manufacturing*, *1*(4), 109–116.

Siddiqi, Yu, & Joung. (2019). 5G Ultra-Reliable Low-Latency Communication Implementation Challenges and Operational Issues with IoT Devices. *Electronics*, *8*(9), 981.

Slalmi, A., Chaibi, H., Saadane, R., Chehri, A., & Jeon, G. (2020). 5G NB-IoT: Efficient network call admission control in cellular networks. *Concurrency and Computation: Practice and Experience*, (e6047).

Ström, E. G., Popovski, P., & Sachs, J. (2015). 5G Ultra-Reliable Vehicular Communication. *arXiv preprint arXiv:1510.01288*. http://arxiv.org/abs/1510.01288.

Sultan, K., & Ali, H. (2017). Where big data meets 5G? In *Proceedings of the Second International Conference on Internet of things, Data and Cloud Computing* (pp. 1–4). New York, NY, USA: Association for Computing Machinery.

Taleb, T., Samdanis, K., Mada, B., Flinck, H., Dutta, S., & Sabella, D. (2017). On Multi-Access Edge Computing: A Survey of the Emerging 5G Network Edge Cloud Architecture and Orchestration. *IEEE Communications Surveys & Tutorials*, *19*(3), 1657–1681.

UKEssays. (2017). The Limitations Of 4G. *UKEssays*. https://www.ukessays.com/essays/information-technology/the-limitations-of-4g-information-technology-essay.php.