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Addressing Efficiency and Sustainability in the Port of the Future with 5G: The Experience of the Livorno Port. A Methodological Insight to Measure Innovation Technologies' Benefits on Port Operations

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Abstract: Relying on the international 2030 Agenda and specifically applying sustainable development's triple bottom line to port operations, innovation technologies enabled by 5G transformation have shown to serve as a junction point between the UN Sustainable Development Goals (SDGs) and the port's Key Performance Indicators (KPIs). In order to measure economic, social and financial benefits deriving from 5G networks and digital transformation, a piloted technology model has been shaped with the final aim of designing new models of port management and operational planning, and of implementing sustainable port growth policies. Such an assessment finally represents a crucial means to enhance technological advancements on port competitiveness and efficiency, and to boost sustainability performance by supporting public policies and business decisions, finally leading to the development of the port of the future.

Keywords: 5G; AI; IoT; digitalization; sustainable development; SDG; ports; Livorno

1. Introduction

Industries are facing a new and unprecedented worldwide challenge to adapt their operational decisions to a more responsible and sustainable framework. Ports are not an exception, since they are fundamental economic ecosystems whose practices significantly impact the surrounding environment and community.

Therefore, it is increasingly important to pursue sustainable development in ports within the economic, social and environmental dimensions of sustainability. This requires to always bear in mind the objective of generating economic, social and financial benefits.

In fact, these economic hubs have to be considered as infrastructure assets that are able to foster economic growth and development as well as to be key gateways to international trade. This means that ports are crucial economic actors when it comes to creating employment, wealth, contribute to increase the national Gross Domestic Product

(GDP) and promote urban and industrial agglomerations. This also implies that ports generate significant spillovers with respect to the aforementioned three pillars, especially concerning climate-change-related impacts. These effects can be illustrated by analyzing the individual impacts on economics, society and the environment [1].

Starting with economics, ports are widely recognized as important factors of economic growth in countries, and this is justified by several implications that can be attributed to their development process. First of all, this process of development enables to interconnect cities and regions across the world, thus favoring the progress of international trade. This observation is supported by data and analysis that show how ports are involved in 80% of world trade movements, meaning that they are critical points for sustaining globalization thanks to their ability to ensure the functioning of global supply chains [1,2]. Second, ports are crucial hubs that can promote regional development through the export of local goods and logistic services. Third, they are able to accelerate the integration of a country's domestic economy in the international one and to become key factors in attracting new industries [2]. Therefore, a large part of the literature on this theme has recognized how the development of seaport infrastructures can boost countries' economies, given that they lead to greater trade activity, greater foreign reserves, increased supply, and even more economic benefits [3].

Their impact on society is also something important to be taken into consideration. The development of ports leads to generate employment opportunities thanks to all the activities that are related to them and their logistic activities. In addition, the development of ports contributes to enhancing people's quality of life by improving the social stability of the surrounding areas and by creating new opportunities, not only in terms of new jobs but also in terms of education for the employees and the communities connected to it [4]. From a different perspective, ports can also reduce people's quality of life, especially that of the citizens living immediately next to them, due to their contribution to generating water, air, and noise pollution. It is also important to point out that one great social benefit of seaports is that they stimulate trade and competitiveness within and between countries and this, in turn, results in lower prices for domestic commodities [3].

With regard to Climate Change, seaports are both driving it and exposed to its detrimental effects. On the one hand, ports directly contribute to shipping emissions through their activities, which different studies have estimated to be around 2–3% of total GHG emissions [5]. On the other hand, port operations, supply chain, as well as infrastructures, are highly vulnerable to some of the side effects stemming from climate-related events. Rising sea levels, wind waves, water temperature, precipitation, heatwaves, droughts are concrete threats to port activities and their ability to be resilient. In fact, extreme climatic events materialize both in significant economic costs—damages to ports facilities, supply chains, infrastructures and superstructures—and indirect costs, such as the loss of workplaces and raising taxes for taxpayers, as well as many other intangible side effects, including pollution in estuaries and the lowering quality of life for the people living in the surroundings of the port [6].

Understanding the strategic role of ports in the global trading system, also as emitters, and the potential side effects of climate change implies acknowledging the crucial importance of reducing their contribution to CO₂ emissions and enhancing the climate resilience of ports, not just as a matter of strategic economic importance but also as a matter of sustainability. Without well-functioning, climate-resilient, and low-carbon ports, it would be significantly more complicated to achieve many of the goals set by the *2030 Agenda for Sustainable Development* (2030 Agenda) and other international agreements, given their interlinkages with so many human activities [1].

To help ports moving the path towards the "Ports of the Future", digital connectivity and further technological applications are expected to play a major role in driving the change. The telecom sector, in particular, and the related technologies are considered key players to help building sustainable, resilient, and quality infrastructures that can speed up the progress of attaining the 2030 Agenda [7]. From this point of view, the 5G

technology is going to be essential to increase the advancements of ports in competitiveness, efficiency, and growth. In fact, the new features of this innovative technology are expected to provide better reliability, high speed, energy efficiency, and fast response [8]. Accordingly, 5G communication networks will enable the users to benefit from crucial innovations, as instant cloud services, Internet of Things, robot/drone communication, Vehicle-to-Everything, and tactile internet [9,10]. These last are some of many new potential uses of a technology that can help to orient many human activities towards a sustainable path. 5G can thereby play a strategic role in helping us to move in the direction of a sustainable “Port of the Future”. According to Palazzo and Siano [8], the explored features of 5G should help individuals, organizations, and governments to achieve sustainable development in different areas. More specifically, part of the literature advocates that the innovations introduced by this technology and the related new multimedia service should be useful to help different actors in attaining the 17 SDGs included in the Agenda 2030. For instance, thanks to 5G, it is possible to effectively use virtual technologies or the Internet of Things, which can positively impact several SDGs, such as quality education (SDG 3), Industry Innovation and infrastructures (SDG 9), as well as many others [8]. Therefore, it is evident how 5G might be able to play a strategic role in helping us to move in the direction of a sustainable “Port of the Future” [8].

Traditionally, these benefits would be measured via Key Performance Indicators (KPIs). First, they are used to improve port operations. Second, they provide a crucial basis for planning any future port development [11]. Part of the literature identifies and divides these indicators according to their relevance for the three pillars of sustainable development—economy, society, and the environment. In this sense, the most considered economic indicator is “Foreign Direct Investments” while the most identified environmental indicators are “Water pollution management”, “Air pollution management”, “Noise pollution”, and “Energy and resource usage”. Finally, about the social dimension, the indicators generally used are “Job generation and security”, “Social image”, “Quality of living environment”, “Social participation”, “Job training”, “Public relations”, “Gender equality”, and “Health and safety” [4]. Hence, KPIs can be essential to measure technological advancements in ports, also connecting them with the 17 Sustainable Development Goals (SDGs).

1.1. Context and Background: COREALIS in the Port of Livorno

Situated in the upper Tyrrhenian Sea in northern Tuscany, the Port of Livorno is one of the biggest and most significant Italian seaports [12]. With a yearly traffic limit of around 31.7 million tons of freight and more than 700,000 TEUs recorded in 2020, the port is a multipurpose point, receiving any sort of vessel and handling any kind of traffic.

Since 2015, the Port Authority of Livorno collaborates with the National Inter-University Consortium for Telecommunications (CNIT) by using the Port as a natural testbed to deploy and evaluate new technological solutions [13]. The partnership has conceived a computerized plan towards a technology-driven, smarter framework. In this context, digitalization has become a key component for port management because of the improvement of information assortment, the increment of data unwavering quality, and the quicker information trade. During these years, many activities have been carried on, placing Livorno among one of the most progressive ports in the Mediterranean for innovation and advancement improvements [14].

Reengineering and digitalizing port tasks with 5G and IoT started in 2016, when the Italian branch of Ericsson distinguished Livorno as an optimal testing ground for the “Port of the Future”. While conveying new advancements into traditional ambiances, port specialists and partners need to cooperate in their general execution as far as intensity, viability and manageability are concerned. However, the aim of deploying new technologies in real environments is that of increasing competitiveness, efficiency and sustainability to transform existing business processes.

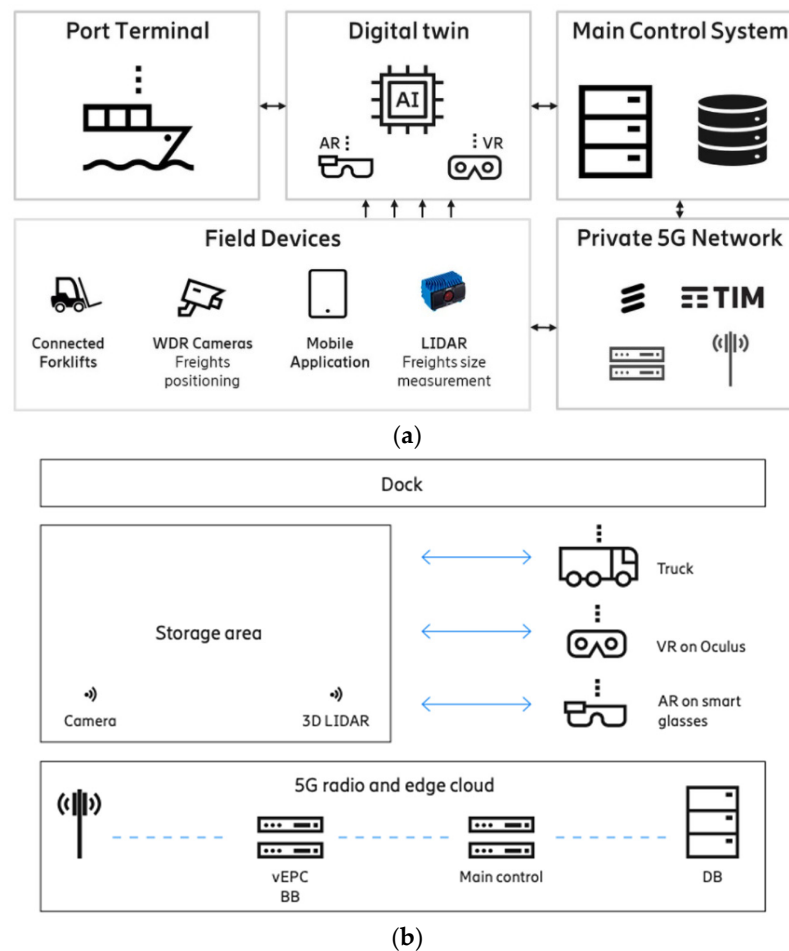
These activities are part of a EU Horizon 2020 program intended to explore advancements, named COREALIS—Capacity with a pOsitive enviRonmEntal and societAL footprInt: portS in the future era (under grant agreement No. 768994) [15].

As 5G gives adaptability, high data transfer capacity and low latency, it is a key empowering innovation for the advancement of compartment terminal activities. The COREALIS project preliminary includes a 5G-based control module, namely RTPORT—Model Driven Real-Time Module [16], designed to coordinate and support general cargo management operations in real-time, collecting data via yard operators and implanted sensors and taking operating decisions based on real-time analytical processing.

Through 5G connectivity (based on 3GPP R15 specifications [17], a huge amount of data is collected from the on-field IoT devices such as 3D LIDARs, Wide Dynamic Range (WDR) cameras, mobile applications (running on tablets) and tracking devices installed on forklifts. Based on this data, the Main Control System, using AI algorithms, determines the sequence of logistic tasks and activities to be performed by container terminal operators including handling, positioning, and tracking of the vehicles as well as of the freights. Finally, the data collected through a private and prototyping 5G network feeds a digital twin engine, which elaborates a virtual representation of the considered port area by allowing on-field operators to virtually navigate inside this virtual environment (Scheme 1a).

The RTPORT module focuses on both unloading (from the truck) and loading (on the vessel) operative phases of the general cargo management process. This includes the following operative steps:

- Once the cargo is unloaded from the truck, a 3D LIDAR device is used to identify the freight by registering all related information (e.g., unique identifier, length, width, height, etc.) into the Main Control System.
- A proper forklift is automatically identified on the yard (based on its status and the distance from the considered cargo) and then it transfers the freight to the storage area. As soon as the WDR camera detects the forklift, the freight and yard vehicles tracking operations begin. The cargo is tracked by a WDR camera until reaching its destination.
- Using Augmented Reality (AR), the forklift's driver is guided to the storage area so that the cargo can be unloaded and properly stored. When the freight is positioned, WDR cameras are used to crosscheck the final position of the cargo and this information is registered by the Main Control System accordingly. Any further repositioning of the cargo during handling operations is also tracked with WDR cameras.
- Finally, during loading operations on the vessel, forklifts are identified and sent to the storage area to move freights in front of the correct crane. While approaching this area, the forklift driver is supported by the Main Control System using AR information related to the position of the specific freight to be moved, also by navigating inside the digital twin model by means of Virtual Reality (VR). During this final procedure, the operations are still monitored and controlled by means through WDR cameras (Scheme 1b).



Scheme 1. (a) G-enabled devices of the control module for cargo operations. (b) 5G-enabled processes of the control module for cargo operations (Authors' elaboration).

1.2. The 2030 Agenda and the Sustainable Development Goals

Adopted in 2015, the 17 Sustainable Development Goals (SDGs) and 169 targets of the 2030 Agenda constitute the United Nations framework for sustainable development until 2030 [18]. This framework encompasses 17 objectives (the SDGs) that can be straightforwardly or by implication connected to port activities. These incorporate environmental protection, the circular economy, sustainable urban areas and communities, high standards of good corporate administration, information sharing and partnership building. With a timetable extending to 2030, port specialists have the opportunity, as well as the time and ability, to contribute to the 2030 Agenda.

From this perspective, some studies have already analyzed how the SDGs might be impacted by the development of sustainable ports. For instance, Schipper [19] has connected the SDGs to Key Port Performance Indicators in order to assess how the implementation of some port masterplans, which are intended to develop sustainable port infrastructures, might impact some of the SDGs. He found out that, going towards the direction of sustainable seaports as in the masterplans taken into consideration for the analysis, positively affects some SDG targets, such as the 4.4 (By 2030, substantially increase the number of youth and adults who have relevant skills, including technical and vocational skills, for employment, decent jobs and entrepreneurship), 6.3 (By 2030, improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally.), 8.9 (By 2030,

devise and implement policies to promote sustainable tourism that creates jobs and promotes local culture and products), or 17.11.1 (By 2020, significantly increase the exports of developing countries, in particular with a view to doubling the least developed countries' share of global exports) [19]. This illustrates the strategic importance of developing more sustainable and resilient ports to achieve the targets set in the 2030 Agenda.

However, accomplishing the SDGs is not an easy task and requires public and private collaborations, in line with Goal 17 (Partnership for the Goals). Only through such a similar arrangement, port authorities have the opportunity to become motors for change, being not only operational specialists in the field, but also points of exchange with metropolitan partners and port urban communities.

2. Methodological Insight

The Port of Livorno, Ericsson Telecommunications (Ericsson), Fondazione Eni Enrico Mattei (FEEM) and the National Inter-University Consortium for Telecommunications (CNIT) have developed an ad hoc methodology for technology assessment, with the aim of increasing port competitiveness, efficiency, and sustainability. The result of the partnership is a comprehensive model to evaluate the contribution to the SDGs and the economic benefits of introducing the 5G technology in port activities.

The methodology includes four different steps (Scheme 2). First, it requires to clearly define the technological, functional, temporal, and impact scope of the assessment. Indeed, when considering whether or not a new technology should be invested in, port actors should identify the exact technology or group of technologies to be analyzed and their reciprocal interactions. They should also identify the specific port processes where such technologies are introduced and the timeframe of the assessment, as larger investments might require longer payback periods or provide long-term benefits or detriments. Last, the SDGs most affected by the port processes should be identified to clearly delimit the impact of introducing new technology. Such demarcations are crucial to focus the assessment where it's most needed. Next, during the application of the model, the first and second tie consequences of implementing new technology are mapped and estimated. Third, these results are analyzed to assess their impact on the selected SDGs. Last, once a comprehensive overview of the introduction of new technology is obtained, a final decision on the investment is taken [20]. For its explorative nature, this study employed the abovementioned methodology to identify relevant port processes (Step 2) and SDGs (Step 1) affected by the deployment of the crucial 5G technology (Step 3). Moreover, to benefit the most from the expertise of the partners involved, the methodology was adapted giving more weight to experts' opinions in the resemblance of a Delphi approach [21].

This is a structured communication technique that has the general purpose of forecasting the outcomes of a phenomenon. It requires knowledgeable and expert contributors responding to questions and submitting their answers to a central coordinator. He processes the contributions, looking for central and extreme tendencies, and their rationales. The results are then sent back to the respondents, who are asked to resubmit their views, assisted by the input provided by the coordinator. This process continues until the coordinator sees that there is a consensus among the experts. The method aims at removing the bias that can exist when diverse groups of experts meet [22]. This technique can be useful to explore the issue under scrutiny in this paper since, according to Buckley [23], as it is particularly effective when the issue under investigation is not clearly suitable to be analyzed by any technique but can benefit greatly from subjective judgments on a collective basis. In fact, this paper has pooled together the knowledge of several experts with regard to the 2030 Agenda, the 5G technology, and the dynamics of one specific Italian port. All these specialists have given their contribution, through their expertise and opinions, in order to identify the most relevant SDGs involved in ports operations and the type of impact that different port activities can have on the 17 Goals.

The choice of adopting such a flexible approach is motivated by the critical necessity of involving all the concerned stakeholders, working smoothly, and, above all, demonstrating the validity of the concept covered, without aiming at concrete results at this stage. This last point is in turn justified by the fact that this must be considered, first of all, an exploratory study.



Scheme 2. Model for the evaluation of disruptive technologies and their impact on port activities (Authors' elaboration).

2.1. Step 1: Identification of the Relevant Sustainable Development Goals

The Italian think tank Fondazione Eni Enrico Mattei, specialized in sustainability applied research, provided the expertise to identify the SDGs most relevant for the introduction of 5G in port operations.

No similar attempt could be found in the literature. Nonetheless, studies concerned with evaluating only the impact of ports or only with the impact of communication technologies were identified and retrieved. As an example from the first category, Schipper [19] combined the Green Port Policy (GPP) approach with the SDGs, linking them with suitable performance indicators to SDGs. This SDG-GPP approach for sustainable port development was applied to the masterplans of 10 selected ports. The results of this analysis are presented in the following sections of this paper to support the empirical evidence from the Port of Livorno.

From the second category, a 2021 report carried out by the Global System for Mobile Communications Association (GSMA) [7] developed a 4-step methodology to understand which SDGs targets are impacted by the deployment of communication technologies, including 5G. The first step consists in reviewing empirical and qualitative evidence on how digital technology has impacted sustainable development. The second step is about identifying the drivers through which mobile technologies impact SDGs. The next step aims at identifying the necessary metrics to quantify the drivers and measure the industry's contribution to sustainable development in its three dimensions. The last step is intended to calculate the industry impact scores for each of the 17 goals. In the report this is done by gathering data for all the 193 countries that have adopted the Agenda 2030. The SDG impact scores show the mobile industry's contribution to the SDGs relatively to a theoretical maximum. The final calculation in the study is obtained by taking the average of the underlying metric scores, aggregating them globally, by region and development level, and weighting the country scores by population in each region and development group. Finally, each goal is assigned an "impact score" on a 100 point scale, where a score of 0 means that the industry is not having an impact and a score of 100 means that it is doing anything possible to contribute to the specific SDG under scrutiny.

Both sources significantly influenced the design of this study and were employed to validate its key findings. However, as previously stated, a Delphi approach was preferred and characterized also the identification of the SDGs. Considering the content of the 2030 Agenda, the SDGs were qualitatively inspected and, after consensus was reached, sorted into three groups: (1) not relevant for the Port Authority; (2) of little relevance for the Port Authority; and (3) very relevant for the Port Authority.

As emerged in the first phase of the project, the main Goals related to port operations resulted in the following: Goal 4 (Quality Education), Goal 8 (Decent Work and Economic Growth), Goal 9 (Industry, Innovation and Infrastructure), Goal 11 (Sustainable Cities and Communities), Goal 12 (Responsible Consumption and Production), Goal 13 (Climate Change), Goal 14 (Life below Water), and Goal 17 (Partnership for the Goals) (Figure 1). These findings are also supported by the already mentioned literature. The paper written

by Schipper [19], in which he uses the GPP-SDG approach to evaluate the link between the UN goals and green port policies, finds that progressing towards sustainability in ports implies an impact to the following goals: Goal 4 (Quality Education), Goal 6 (Clean Water and Sanitation), Goal 7 (Affordable and Clean Energy), Goal 8 (Decent Work and Economic Growth), Goal 9 (Industry, Innovation and Infrastructure), Goal 11 (Sustainable Cities and Communities), Goal 12 (Responsible Consumption and Production), Goal 13, (Climate Change), Goal 14 (Life below Water), and Goal 17, (Partnership for the Goals). The only difference is that this study also finds a link between goal 6 and 7 that the present study has not identified.



Figure 1. SDGs most related to port operations (Authors' elaboration of UN SDGs [1]).

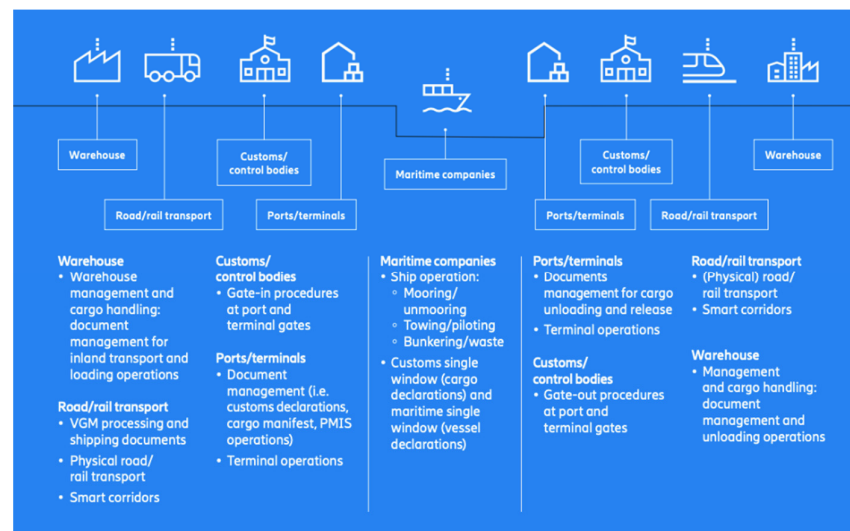
2.2. Step 2: Analysis of Port Processes

The port's processes potentially advantaged by the transformative impact of new digital technology need to be mapped. Employing the lens of value-added services, Ericsson and CNIT identified the port and logistic processes directly affected by the introduction of innovative technology. This set includes warehousing, land transportation, customary and control activities, terminal and port operations, and maritime transportation (Scheme 3).

In application of the Delphi approach, the analysis relied on the authors' own experience of port processes in the port of Livorno as well as on the framework of the COREALIS project [15]. Accordingly, it displays the additional benefit of being tailored to the specific features and needs of the Port of Livorno, thus avoiding "one size fits all" approaches [24].

Additionally, the processes in Scheme III were selected according to two key criteria, and namely representativity and saliency. Concerning the first point, despite more processes such as services to ships (piloting, tugging, mooring and so on) might have also been included, it's worth noticing that those here selected constitute typical containerized processes of an average gateway port with rail and road connections (but not waterborne) to the hinterland. Accordingly, they are relevant to all ports and operations.

On the other hand, the processes presented in Scheme III are connected with unloading and loading of containerized cargo, its shipment to inland nodes (or, its arrival from the hinterland) and can be carried out in parallel. Hence, physical, digital, or documentary steps could be performed by different operators at the same time to ensure faster handling of freight. Therefore, enhancing these synchro-modal operations represents a key priority for improving the efficiency of ports and deserves being the first testbed for new technologies [25].



Scheme 3. Map of the selected port and logistics processes (Authors' elaboration).

2.3. Step 3: Technology Assessment

Among many emerging technologies [7], for their unique benefits [8] 5G networks were chosen by the Port of Livorno, Ericsson, FEEM and CNIT for this experimentation. Indeed, a 5G network has been tested in the Port of Livorno to foster its efficiency, sustainability and safety, as well as to expand the degree of information sharing among stakeholders engaged in terminal activities (see Step 1).

In fact, 5G networks are crucial for the transition to Logistics 4.0 [26], thanks to continuous information collection and analysis, as well as automation. The outcome is better coordination between people, machines and devices. In the case of seaports, these include cameras, forklifts, trucks, and sensors.

The port of the future will be able to make use of always-connected sensors and applications that control and make decisions in real-time, to provide intelligent insights into the port's condition and operations, and creating room for further optimization.

Comparatively, a fixed cable network is only able to support applications for static devices rather than for the typical transportation and movement in port areas. Scaling of connected logistic operations is not feasible either, as cables are costly to install and maintain. Moreover, the need for connectivity goes beyond the standard Wi-Fi connection. Therefore, robust communication for mobile-based IoT business-critical applications are required, to reliably meet time-critical communication through secure networks with carrier-grade data encryption and identity authentication [26].

Thus, cellular technology (5G) is an excellent match because the port of the future will have a myriad of IoT devices deployed, which will have different connectivity demands.

Key cellular capabilities include:

- Low and predictable latencies, even with a heavy load and many users;
- Quality of service to guarantee low latency and bit rates;
- More deployment flexibility for sparse and dense options;
- Mobility capabilities to ensure a smooth handover between base stations;
- Flexible scaling of network capacity, depending on demand;
- Reliability of device interoperability [8].

3. Projection of Results

Before offering some preliminary estimations of some environmental and economic benefits of introducing 5G networks in the Port of Livorno, results from the comprehensive qualitative assessments described in the previous section are presented (Table 1).

During the analysis, experts from the four partners have examined and identified several direct and indirect 5G-empowered solutions benefitting from the unique features of 5G. Most prominently, IoT, augmented reality/virtual reality (AR/VR) and Artificial Intelligence-based frameworks [7]. According to the authors' experience, these technological solutions collectively deliver benefits to the selected port process, here described.

First, during warehousing, they might faster freight localization, guarantee better and closer control of cargo conditions, and improve the detection of movements and eventual damages. Second, during rail or road transportation, the same technologies are expected to foster coordination between transport modes, allow remote controlling, and enable automation and autonomous driving in private areas. Third, customs and control activities could benefit from remotely managed operations and digitalizing their dispatches. Fourth, ports and terminals might enhance their automated operations and create digital twins; ensure oversight on freights and reduce internal movements. Last, shipping operations are expected to benefit from these 5G-enabled technologies in vessel-assisted navigation and automation.

These improvements are expected to positively impact a number of SDGs. On the one hand, SDG 8 (Decent Work and Economic Growth), SDG 9 (Industry, Innovation and Infrastructure), SDG 11 (Sustainable Cities and Communities), and SDG 12 (Responsible Consumption and Production) are directly influenced by the 5G-enabled transformation thanks to the benefits for the logistics value chain, the port infrastructure, and the investments in innovation. On the other hand, SDG 4 (Quality Education), SDG 13 (Climate Action) and SDG 14 (Life Below Water), are also positively influenced by this transition despite not being its main focus, and particularly thanks to the reduced environmental pollution, the saving of energy and CO₂ and the need for more qualified workers. As part of the port's role in protecting the marine and coastal ecosystems. Last, the public-private partnerships necessary to leverage diverse ideas, know-how and contributions for the adoption of highly transformative technologies—embodied in the partnership behind this collective endeavor—constitute a crucial step towards the actualization of SDG 17 (Partnerships for the Goals). These findings are also supported by the existing literature [7,19].

Table 1. Results from the qualitative analysis (Authors' elaboration).

Port Process	Focus Area	Enabled Transformation by 5G	Enabled Benefits by 5G	Contributions to UN SDGs
Container Terminal Operations	Automation	Remotely controlled quay cranes. (URLLC, mMTC)	Lower vessel completion time, improved personnel safety, less human mistakes, less operational inefficiencies, working profile upgrade.	4, 8, 9, 11, 12, 13, 17
	Transport & Logistic	Connected/smart ship with augmented navigation info, predictive maintenance	Improved security/safety during the navigation, new business models,	4, 8, 9, 11, 12, 13, 17

		for on-field machineries (cranes, forklifts, stackers, trucks). (URLLC, mMTC, Network Slicing)	increased number of the stakeholders involved into data exchange, CO2 and maintenance costs reduction, less power consumption.	
	Environmental Sustainability and Personnel Safety	Personnel and environmental monitoring with potential critical and dangerous situations identification. (URLLC, mMTC, Network Slicing)	Less exposure to polluting agents for on-field personnel, CO2 and environmental impact reduction, new job opportunities, shorter intervention time for specialized personnel.	4, 8, 9, 11–13, 17
	Cybersecurity	Unmanned Aerial Vehicles for potential real-time threats detection. (eMBB)	Improved security for sensible data transmission, better capacity to identify potential threats, improved data reliability, new professional figures.	4, 8, 9, 11–13, 14, 17
Verified Gross Mass Management	Automation	Automated systems for the container weighing. (URLLC, eMBB)	Reduced weighing times, lower environmental impact, higher number of weighing per time unit.	9, 11, 17
	Transport & Logistics	Secured documental VGM practices. (URLLC, eMBB)	Improved data integrity, faster data elaboration, better stowage-planning, reduction of the trucks waiting time.	8, 9, 11–13, 17
Warehouse Management	Automation	Remote and automated cargo handling, monitoring and tracking systems. (URLLC, mMTC, Network Slicing, eMBB)	Lower time to find a cargo, reduced accidents, less operational inefficiencies, less human mistakes, lower handling time per cargo unit, reduction of the economic costs, improved competitiveness.	8, 9, 11–13, 17
	Transport & Logistic	Smart and autonomous vehicles for cargo handling and monitoring. (URLLC,	Lower time to find a cargo, reduced accidents, less operational inefficiencies, less	4, 8, 9, 11–13, 17

		mMTC, Network Slicing, eMBB)	human mistakes, lower handling time per cargo unit, reduction of the economic costs, improved competitiveness.	
Ship practices (Loading/unloading Trailer/Piloting)	Transport & Logistic	Remote assistance and monitoring of ship practices through use of distributed sensors and cameras communicating in real time to the mIoT system and with AR/VR assistance for drivers. (URLLC—mMTC—Network Slicing)	Reduction of risks of accidents and economic losses, lower time for maneuvers, operation optimization, greater safety, positive consequences for updating education programs, on-the-job and continuous training.	4, 8, 9, 11, 12, 14, 17
	Environmental Sustainability and Personnel Safety	Monitoring of seabed, terminals and other port infrastructures with a distributed sensor system and mIoT cameras. (mMTC—URLLC—eMBB)	Major safety through the 5G-enabled MIOT sensors, reduction of accidents.	4, 8, 9, 11–14, 17
Controlled corridors	Transport & Logistic	Cargo Tracking Truck Appointment System with a massive IoT network distributed over the entire area connected with RSU, AR, control centers and other trucks. (URLLC—mMTC—Network Slicing—eMBB)	Reduction of traffic congestion, decrease in pollution; Increased visibility of the load and road safety; Positive consequences in terms of updating education programs, on-the-job and continuous training.	4, 8, 9, 11–13, 17
	City/Port Relations	Smart Corridors for real-time monitoring/control and infomobility services for passengers in the concept of Smart City. (URLLC—eMBB)	Improved mobility, reduction of environmental impacts, greater control over processes, positive consequences in terms of updating education programs, on-the-job and continuous training.	4, 8, 9, 11–13, 17

Of the several processes presented in Table 1, those more relevant for the Port of Livorno are here described more in detail. Container terminal operations can be better automated through 5G technologies, since the closer spotting, the lower latency and the

thus faster communication lead to improved functioning of all automated activities. Automation, per se, is not a value, but it indirectly benefits the environment, security, safety and overall working conditions. However, automation is not just a matter of equipping vehicles and facilities with adequate devices, but rather requires reengineering processes and services entirely. In the Port of Livorno, the most significant application today relates to remotely controlled quay cranes and transport and logistics activities. The remote operations of quay cranes is enabled by 5G led technologies, since the accuracy that yard movements require can be fostered by 5G services. Moreover, reduced latency allows greater productivity and faster operations. Benefits are closely linked to reduced idle time, hence reducing the time spent for handling cargo. Of course, as later displayed in this article, this results in a reduced carbon footprint. Transport and logistics can also benefit from connected vessel services and improved assistance to ships and other transport operations. This upgrade has both environmental and economic benefits, as a consequence of reduced idle times, better exploitation of productivity factors and enhanced safety conditions.

Verified Gross Mass (VGM) is another key operation that can be positively affected by 5G technologies. It deals with containers before they are loaded onto the ship, basically for safety reasons and proper storing of cargo. If not fully digitalized, this process may represent a challenge for medium-large container ports. Fewer queues at port gates are a clear environmental and social benefit in terms of air and noise pollution often affecting citizens living nearby. It is also possible to improve the security and reliability of data on shipments, thus enabling traceability of weighted cargo and facilitating the control of lorries arriving at port gates. These solutions foster the efficiency of the entire logistic chain, improving performances also in inland nodes and facilities. Of course, all these improvements require specific investments in information and communication technologies and smart mobility applications which are not possible if the connectivity is not upgraded through 5G coverage. Since VGM is linked both to safety and security of navigation, as well as smoothness of the logistic chains, the enhanced transformation leads to safer dispatching and sharing of information as well as to early detection of threats thanks to the improved communications between stakeholders. This results in enhanced operations (i.e., less idle time) and guarantees data integrity, thus allowing greater interworking and potentially new services based on blockchain.

Since VGM is still in its early stage, we focused our analysis of the port of Livorno on the more operational and yard-based benefits. However, it deserves to mention that broader benefits along the logistic chain are possible if some solutions (such as VGM) move fully digital and interoperable made interoperable thanks to 5G. Table 1 attempts to provide a comprehensive overview of what might be achieved in the medium-long term.

For the limited resource available and its explorative nature, the following subsections narrow the focus of this study to two major benefits expected to follow the deployment of a 5G network in the Port of Livorno: a reduction in the emission of CO₂ and a reduction of economic costs. Please, note that these estimations are entirely preliminary and hypothetical as, for the limited time since the rollout of 5G in the Port of Livorno, empirical data are not available yet.

3.1. Environmental Benefit Analysis

The reduction in CO₂ emissions was estimated by considering the time needed to accomplish each terminal operation and the average fuel consumption of machines/vehicles. When 5G technologies facilitate the exchange of real-time information among actors in the terminal, it leads to reducing movements in cargo handling. This optimizes the process and lowers fuel consumption and associated CO₂ emissions (Tables 2 and 3). Despite other emission reductions likely taking place, it was decided to focus only on this aspect for reasons of efficiency and simplicity.

Data shown in Tables 2 and 3 are not based on literature sources, but on the authors' working experience in the collaboration between the terminal and the Port Authority.

Table 2. Results from the intra-terminal operations process, enabled by 5G. (Authors' elaboration).

Activity	Machines	Measurement in 2019 (before 5G)			COREALIS Project (with 5G)		
		Hours Activity/Year	Diesel/Year (m ³)	CO ₂ /Year (ton)	Hours Activity/Year	Diesel/Year (m ³)	CO ₂ /Year (ton)
Vessel loading/unloading	Tower crane	26,717	419	1106	26,717	419	1106
Yard movements	Reach Stackers	40,093	595	1571	34,480	512	1351
Total		-	1015	2678	-	931	2458 (-8.21%)

Table 3. Results from the intra-terminal operations process, enabled by 5G. (Authors' elaboration).

Operation	KPI (Average Value)	KPI Baseline	KPI Corealis Target	What Improved	Benefitted Stakeholder	Environmental Analysis	
						CO ₂ Saving	What Improved
Vessels' berthing time	Vessel operation completion time	18 h	16 h	Increase of operations speed rate	Shipping company	-	
	Vessel idle time at berth	36 h	34 h			-	
Cargo Release	Loading (on ship)/Unloading (from a single truck) operations completion time	18 h/40 min	16 h/30 min	Increase of operations speed rate	Haulers	8.2% CO ₂ saving	Fuel reduction
	Time to find a pallet on the yard	8 min	7 min				Fuel reduction
Quays and yards operations	Cargoes registration completion time	3 min	2 min	Reduction of operational costs	Terminal Operator		Fuel reduction
	Percentage of cargoes physical characteristics info registered electronically	0.9	0.95				Fuel reduction
	Forklift operation execution time	8 min	7 min				Fuel reduction
	Occupied space during	5000 m ²	4500 m ²				-

the storage phase				
Percentage time of activity/inactivity of the forklift	60%/40%	65%/35%	-	-
Total number of movements per cargo unit	4	3	-	-

On the other hand, the heterogeneity of the processes assessed prohibits presenting in this paper a common method of analysis and calculation. Accordingly, an exemplifying description of the CO₂ reduction resulting from the more limited use of reach stackers is here provided.

Typically, tower cranes work for 12 h a day loading and unloading cargo from ships, while supporting vehicles, such as reach stackers, work for 14 h a day. This difference is due to the time required to locate a container or a cargo in the yard and the related handling time. These activities can be optimized with 5G reducing the working time from 14 to 12 h (14% of the time) for the same amount of cargo, thus matching the working hours of tower cranes.

Towers cranes worked 26,717 h in 2019. Reach stackers worked 40,093 h (Table 4). If processes were optimized, reducing actual working hours by 14% (5613 h) the annual working hours of reach stackers would drop to 34,480 (equivalent to a 0.86 reduction factor).

Table 4. Real working hours for the year 2019 (Authors' elaboration of data provided by the terminal).

Machines	Hours per Year	Machines	Hours per Year
Reach Stacker 1	2513	RTG 2	2469
Reach Stacker 2	1989	RTG 3	3029
Reach Stacker 3	2501	RTG 4	2926
Reach Stacker 4	2928	RTG 5	1526
Reach Stacker 5	3233	RTG 6	1157
Reach Stacker 6	3845	RTG 7	2239
Reach Stacker 7	4375	RTG 8	1729
Reach Stacker 8	3712	RTG 9	1683
Reach Stacker 9	4337	RTG 10	1683
Reach Stacker 10	4947	RTG 11	1066
Reach Stacker 11	5713	RTG 12	1189

From there, the fuel reduction is calculated as the sum of the product of the hourly consumption of every single vehicle, the number of working hours per year and the reduction coefficient of working hours (0.86) according to the formula:

$$Fuel = \sum (M_i \times F_i \times T_i \times F_t)$$

where:

- M_i = machine i-th;
- F_i = hourly fuel consumption of the machine i-th;
- T_i = annual working hours of the machine i-th;
- F_t = coefficient of working hours = $\frac{Original\ hours - Reduced\ hours}{Original\ hours} = 0.86$.

The reduction of CO₂ emissions in this scenario is calculated with the formula:

$$CO_2 = Fuel \times C_{CO_2}$$

where:

- C_{CO_2} = CO₂ is the emission coefficient supplied by ISPRA [27].

Under the assumption that reach stackers' operating hours are reduced from 14 to 12 per day, the annual fuel consumption saving is estimated to be 83 m³. This means that CO₂ emissions associated with yard movements are reduced by 14%. Based on this, it is estimated that, due to the 5G technologies introduced in the Port of Livorno, CO₂ emissions for one terminal operation would decrease by 8.2% as a result of improved yard movements. This figure indicates a potential improvement in the environmental sustainability of the port and more specifically in a contribution to SDG 13 (Climate Action).

3.2. Economic Benefit Analysis

5G testing and deployment are still in their early stages and it is a quite hard task to estimate the economic impact of 5G in port and logistics operations. 5G will boost automation and the development of autonomous driving in port yards and terminals, speeding up and smoothing operations nowadays mostly operated on-site by personnel.

For assessing the economic benefits from 5G deployment, we decided to focus on three main operational areas. Within port terminals/land operations, these include the use of gantry cranes and quay cranes controlled remotely through 5G telecommunication; the employment of autonomous vehicles for yard handling; and faster freight release through port gates.

As for the maritime side, operations, that can be improved through the deployment of 5G are assisted piloting within port waters, especially in narrow water canals; berthing and mooring of ships; ships information noticing and communication with the Harbormaster.

Both for land and maritime operations, major benefits would emerge from the reduction of operational costs through savings, and the increased speed of operations thanks to improved processes. These benefits would be inevitably distributed to many different players, and namely: shipping companies, in relation to reducing navigational costs and time spent at berth; terminal operators, due to reduced yard costs and increased efficiency of operations; and hauler/transport operators, due to seamless and faster release of documentation and information of freight.

It is also straightforward that benefits can be only achieved if these operators are willing to invest in the enabling technologies unlocked by 5G. These front investments are major obstacles to the deployment of innovative technologies, including 5G, and would require accurate consideration. Accordingly, for its exploratory nature, this study only considered operational costs and gains in productivity, leaving capital costs for dedicated research.

3.2.1. Maritime Operations

Autonomous vessels and no-manning are the long-term objectives. Nonetheless, the deployment of 5G can already boost the development of supporting technologies, like AR/VR, capable of aiding navigations in narrow waters. Please, note that no experimentation with 5G networks in maritime operations is presently undertaken at the Port of Livorno. Accordingly, the following considerations are entirely speculative.

Currently, the largest vessels enter the port of Livorno only with the aid of three tugboats and the help of two pilots on board. Infrastructural improvements are planned but, in the near future, no changes are expected to occur. Accordingly, assisted reality may lead to a reduction of pilots' effort in maneuvering, thus allowing a reduction of costs for this kind of service. This saving could lead to a reduction of up to 1400 euros per service, which currently is 2800 euros for each ship [28]. No further reduction is expected for tug

services from 5G deployment in the early stages. Investment costs for AR/VR are of course not neglectable but can be considered low in comparison to yearly expected savings (Table 5). Of course, not all vessels need to navigate with two pilots on board. Hence, vessels that presently calling the terminal with two pilots can shift to more advanced sailing ways.

Table 5. Expected yearly cost savings from 5G-related technologies (Authors' elaboration).

Operation	Current Costs (EUR)	Costs (EUR) after 5G Related Deployment	No. of Affected Operations (EUR)	Total Savings (EUR)
Piloting of largest vessels	201.600 thousands	100.8 thousands	72	100.8 thousands

3.2.2. Land/Terminal Operations

In relation to terminal operations, 5G can ease and make smoother processes at the quay and in yards, enabling fast telecommunication and remote management (Table 6).

In this respect, the terminal chosen for 5G deployment in the Port of Livorno has 5 quay cranes and 4 RTGs which are presently operated by dockers on-site and in the future could be converted for remote control.

As for RTGs, a single operator will be able of operating all existing machinery in the terminal, instead of having 4 operators per shift on site. This will result in lower staff costs, even if the capital (fixed) cost of placing new equipment should be also duly taken into account. It is prudential, however, to assume that operating costs at yard may be halved and, due to an average staff cost of 65,000 euros, this would lead to 130,000 euros cost savings per year. These data refer to the average yearly cost of staff unit.

The same happens for quay cranes, with operational costs for staff expected to be halved with new technologies. No changes in shifts may occur, but the remote control enables less staff effort on site. This reduction is estimated worth 65,000 euros per year.

In the short term, following the results highlighted by the COREALIS analysis, it is expected that the utilization rate of forklifts would be higher, thus allowing to reduce the equipment deployed by the terminal. More in detail, it is estimated that the reduction of one forklift might reduce operational costs by 20,000 euros per year.

Indeed, automated quay cranes may increase productivity by a 20–25% rate [29], which can be estimated as a reduction of a quarter of the berthing time of vessels. Vessels in 2020 have spent a total of 1500 h at berth in the selected terminal, which leads to a potential reduction of 375 h of global berthing time [30]. These values are impacted by the severe loss of traffic due to the COVID-19 outbreak, which led to reduced activity during 2020. On average, this equals 25 h of berthing time for each container vessel, which can be reduced to 20 h on average. As seen above, the reduction for the general cargo vessel category in the short term could be from 36 h to 34 h, highlighting thus a 5% decrease. This decrease concerns a smaller number of vessels and is, therefore, less significant for the expected savings.

The time saving achievable through improved technology could either bring to more vessels calling at the port or to a reduction of costs due to less time spent for operations. In this analysis, it is assumed that the vessel number would not change as a bigger port throughput would require other interventions (e.g., an increased reach of hinterland markets) as well. On the other hand, vessels would be already saving time. This is estimated to amount to 915,000,000 euros saved each year [31,32].

Furthermore, 5G unlocks also smoother operations and, thanks to more precise detection and freight handling, reduces time lost for mistakes or unnecessary movements. This assessment is even harder to be made, but we can rely on current procedures and evaluation of mistakes that averagely occur.

Past analyses made in the framework of the B2MOS project could be referred to, estimating an average mistake rate of 5% on all transactions [33]. This rate can be reduced to 1% with upgraded procedures. Likewise, the overall time spent for checking cargo

documentation for the release can be lowered from 4 min on average to 0.4 s by avoiding manual handling. In the short run, the expected decrease would be lower with an expected reduction from 3 to 2 min (source: COREALIS project).

For assessing time savings related to quicker release of freight, we have to make the following assumptions:

- We estimated 1.25 TEU for each lorry, entering and getting out of the terminal; this assumption is based also on general consensus in the relevant literature
- We assume a road modal share of 85% of total handling; this value equals the present rail share for containerized cargo in the port of Livorno;
- We, therefore, project a yearly value of 140,000 trucks getting in and out of the terminal, thus leading to 8400 h saved for faster documental release and the exact identification of the location to load/unload the cargo in the long run; in the short term, the impact stands at roughly 5800 h. These values are assumed on current traffic and handling volumes of the port of Livorno.

Economic savings from less idle times at terminals are mostly difficult to assess. Nonetheless, it is deemed that this benefit leads to better use of truck drivers' time and the achievable economic return is mainly based on saving on drivers' hourly costs. According to the *Comité National Routier*, in Italy a driver costs hourly 28.14 euros. This value could result in a yearly saving of 236,000 euros, which is of course a benefit shared by all haulers.

Table 6. Land/terminal operations benefits (Authors' elaboration).

Operation	What Improved	Benefited Stakeholder	COREALIS Project, Enhanced Automation	
			Savings per Container Terminal (EUR)	in Port's Processes (EUR)
Vessels' berthing time	Increased operational speed	Shipping companies	126,500	2500
Cargo Release	Increased operational speed	Haulers	164,000	236,000
Terminal operations (throughput speed)	Quays and yards operations	Terminal operators	20,000	195,000
			70,000	-

Overall, the annual benefits from 5G deployment at the very local scale (the selected terminal operator in Livorno), in the aftermath of the introduction of new technologies, can reach 1.346 million euros yearly (2020 prices).

These estimations are the very first attempt to analyze the impact of 5 G-related novelties in port and logistics operations in the Port of Livorno. By all evidence, values should be considered as very provisional and based on rough estimates. Most of the improvements are eventually linked to the introduction of technologies that, in principle, are already available and that we deem will be fostered through the availability of the 5G network. These upgrades will be only possible if private companies are willing to invest and to convert processes. Moreover, it has also been highlighted in the literature that automation is still at its early stages in many ports around the world and that smaller container terminals tend to invest in this upgrade more difficulty [34]. Subsequently, additional issues besides 5G play a role in deciding whether to invest in terminal automation and other technologies that have been outlined in this article. 5G could nonetheless support this transition but requires decision-makers to change present procedures and mindsets. We would like to stress that benefits can spread along the logistic chain, involving many different players. As soon as Logistics 4.0 sets in at the local level, 5G will in this respect build the background infrastructure for such developments.

3.3. Impact on Port Productivity: An Insight

5G-enabled technologies mean a faster port turnaround for vessels and thus cargo handling, which is a key priority for most seaports all over the world. If we look at global figures, we find that the average turnaround time for containerships is presently 0.69 days, showing that middle-sized ports like Livorno are already significantly behind the global average. Generally speaking, dry bulk vessels tend to spend more time in ports, on average 2 days, despite the trend of growing ships' size has led to a reduction of this time [1]. This pattern shows the importance of investing in port productivity and operational tools to speed up ships' operation and cargo release in ports.

Western and Southern European countries, like Italy, report an average performance, while Asian seaports generally perform better. The potential for a reduction, as depicted above, is even larger if we look at other vessel types, such as general cargo ships.

Another point that deserves mention, and has been highlighted also in the relevant literature, is the growing phenomenon of intermediate stops which leads to an increasing role of transshipment in global trade. Indeed, apart from few large hubs located along the main shipping routes or at the heartland of economic powerhouses, most seaports are supplied through a hub and spoke system of a growing number of intermediate calls and handling needs. In fact, the top 939 global seaports generate only 12,748 pair connections, meaning that 97.1% of port pairs are possible only through the transshipment of containers [35].

Accordingly, transshipment is a significant source of operations and hence cost for seaports, thus requiring to improve the productivity of these operations. It requires to invest in 5G-enabled technologies in order to improve the following productivity factors crucial to all ports:

- Berth occupancy;
- Revenue for a ton of cargo;
- CAPEX for a ton of cargo;
- Turnaround time;
- The number of gangs needed for port operations [36].

Besides them, indicators highlighting environmental performance can be also taken into consideration, measuring the impact of port operations on the environment and climate change [4].

As this study has shown, both port efficiency and sustainability are significantly improved thanks to 5G-enabled technologies, and there is consensus that their deployment will continue and expand [37]. Nonetheless, the actual impact of these improvements, both at the terminal and at the port level, largely remains to be assessed.

Last, when investing in these technologies, ports should not only consider projected cost cuts and environmental benefits, but more extensively think of a vision for a new business model. One example is the connected and autonomous vessel, a revolution that is not going just to modify seafarers' world and terminal operations, but rather is going to have a significant impact on sailing schedules, logistics chain fine-tuning and time optimization. It is therefore important that ports and in particular Port Authorities create a cooperative environment where such transformations can occur and can be adopted [16]. In this respect, the Port of Livorno is aiming to enhance a network of collaborative innovation that can set a long-term path involving stakeholders from both the public and the private sector. This paper is the result of one of such crucial partnerships.

4. Conclusions and Policy Recommendations

Ports have a strategic role to play in pursuing sustainable development in all its three dimensions. The potential benefits connected to the "Port of the Future" are of uttermost economic and social importance given the contribution that ports can give to boosting growth, generating employment, improving people's quality of life, and lowering the price of goods. Furthermore, they are key actors with respect to climate change from two viewpoints. First, because of their contribution to global GHG emissions through shipping

operations. Second, they are key global interconnection points that are critically exposed to extreme wheatear events and sea-level rise. Accordingly, they must reduce their emissions and improve their resiliency to not compromise global supply chains.

Therefore, it is evident that actions must be taken to enhance and preserve ports. This goal can be accomplished thanks to innovation. For instance, 5G networks and related new technologies can contribute to smooth and achieve more efficient ports operations. This can result in a crucial improvement in terms of making ports more sustainable and help them play their part, which might be significant, to achieve the 17 goals set by the Agenda 2030. As we have seen, introducing 5G alone can concretely enhance ports efficiency and contribute to sustainability by having a positive impact on several SDGs.

This requires to develop and apply adequate methodologies to assess economic, social, and environmental benefits beyond port KPIs. This can be accomplished by utilizing more extensive sustainability systems like the SDGs, along with traditional economic examination, administration and estimation models. Despite its explorative nature and the use of speculative estimates, this study achieved just that. However, we also acknowledge that there might be limitations related to this work at the present stage.

To begin with, for the purpose of our analysis, it was not been possible to consider the environmental and social externalities stemming from port operations, such as the potential job losses due to technological improvements that might result from using machines instead of human labor for certain port activities; the potential increase in GHG emissions that could stem from using more machines and devices instead of workers; and the impact on the landscape of building several 5G antennas to make this technology work.

Another limitation, which is also related to potential environmental externalities, can be recognized in not having kept into consideration the problem of rebound effects: even if ports might increase their efficiency, they might not reduce their CO₂ emissions but rather increase them, as enhancing the efficiency of these economic hubs could lead to an increase of shipping activities. This would imply more freight traffic and, in turn, lead to a net increase in CO₂ emissions.

Moreover, we have not been able to properly analyze the possible benefits and disadvantages given by the introduction of these technologies on specific stakeholders, such as haulage companies, public authorities, shipping lines, port terminal operators, and citizens. further research is needed to foster our understanding of the “Port of the Future”. Expanding the scope of this work, it could start by exploring the impact of other technologies on ports’ sustainability and efficiency or analyzing the impact of similar innovations on port processes that have not been included in this paper.

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