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A BUSINESS CASE FOR 5G SERVICES IN AN INDUSTRIAL SEA PORT AREA

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Abstract

5G is a technology that was designed to provide citizens with access to faster and innovative wireless services. While different technical aspects related to 5G have been extensively examined by researchers worldwide, a lack in the existing literature is the economics of 5G in terms of business cases of specific 5G use cases. In this article we analyse the business case for three 5G use cases in an industrial sea port area, the Hamburg port in Germany, over the period 2020-2030. The first use case is enhanced mobile broadband and the results show a payback period lower than one year for all the scenarios analysed. The second use case is automation of container handling in the port's container terminal. It was found that the payback period is also lower than one year with a positive business case net present value in all scenarios studied. The business case of the third case, augmented reality for construction projects in the port's area, is challenging as the payback period was 5 years for the baseline case. Moreover, when performing the sensitivity analysis, it was found that in several scenarios there was a negative return on investment, and it was not possible to recover the investment over the time period studied. It can be concluded that mobile network operators will need to be careful as not all new 5G service offerings may have a positive business case. Future research work should focus on studying other 5G use cases in the port area, and on examining other industrial areas beyond ports such as airports, science parks and manufacturing facilities.

Keywords: 5G, business case, use cases, costs, revenues

1 Introduction

5G is a wireless technology that has the potential to provide citizens with access to better and innovative wireless services. Different countries and regions all over the world are already engaged in the deployment of 5G wireless networks. There are two enablers that permit operators to make this deployment a reality. The first enabler is the availability of spectrum. With the 5G spectrum auctions that have already taken place in several countries and that will take place eventually in all regions, network operators have access to the frequency bands which will be employed for 5G-related signals (European 5G Observatory, 2020). The second enabler is the availability of 5G new radio (NR) equipment. An important stepping stone in this sense was the publication in 2018 of 3GPP Release 15, the first full set of 5G standards, which permits the manufacturing of standardised 5G handsets, 5G radio access network (RAN) and core equipment (3GPP, 2018). Later 3GPP Release 16 expanded in 2020 the 5G-standards (3GPP, 2020). Even though these two technical enablers – the availability of 5G spectrum and the publication of 5G standards - permit the rollout of 5G networks, the motivation of mobile network operators (MNOs) for a broad 5G rollout is based fundamentally on the potential financial benefits that can be achieved. For this reason, the analysis of the business case of a 5G network is a task that needs to be addressed.

When 5G was initially proposed, different 5G use cases were addressed and proposed (NGMN, 2015; Lema et al., 2017). 5G use cases have been divided into three categories: enhanced Mobile Broadband (eMBB), massive Machine-Type Communications (mMTC) and Ultra-Reliable and Low-Latency Communications (URLLC) (ITU, 2018). However, it is still unclear for mobile operators how all these 5G use cases will be monetised. Based on an inspection of the initial 5G commercial plans of mobile operators, it can be deduced that mobile operators will handle 5G over the first years as an evolution of the 4G LTE network. The initial 5G networks deployed provide an improved broadband capacity by offering eMBB services (British Telecom 2020). What is not yet clear is what are the potential business benefits of other 5G use cases such as vehicle-to-everything (V2X), augmented reality (AR), drones, etc. (Lehr, Queder, and Haucap, 2021) made a qualitative analysis of the potential effect of 5G on the business models of MNOS. (Webb, 2016) pointed out the potential difficulties of MNOs to monetise the different 5G use cases. The ability to monetise 5G requires the analysis of a 5G business case that considers the 5G revenues, which are derived from the provisioning of specific 5G use cases, and also the 5G deployment costs. A business case will vary depending on the scenario and so requires a study area to be selected and analysed in detail on a case-by-case basis.

After examining the published literature about the business case for 5G, it can be stated that very few studies about this topic have been published so far. (Rendon Schneir et al., 2019) analyses the business case for 5G broadband provisioning when employing eMBB in three boroughs of central London, United Kingdom (UK). It was shown that over the time period 2020-2030 the business case is positive, but some risks were identified in the later years of this time period. The sensitivity analysis conducted leads to the conclusion that the return on investment (ROI) becomes negative if costs and traffic follow high end forecasts and if revenues are not as large as in the baseline forecast. (METIS-II D1.2, 2017) investigates the economic viability of various technical possibilities and 5G rollout strategies for eMBB and mMTC services in a dense urban area. It was shown that in nearly all the conducted simulations the cost-benefit study will be financially profitable for an MNO. A sensitivity analysis regarding traffic, revenue and cost was conducted. Even with a 30% decrease in revenues the business case is positive over the time period 2020-2030. (Real Wireless, 2020) studied the business case of a neutral host 5G network that provides wholesale connectivity services to MNOs looking to improve coverage on both road and rail transport routes in the United Kingdom. The neutral host 5G network operates in a complementary way to the MNOs network and it fundamentally employs small cell equipment. It is shown that for the case of roads there can be a positive business case after 5 years. The business case for the railway environment remains challenging because of the nature of the wireless connectivity. For the case of large railway networks, which cross remote or rural areas, MNOs do not have a strong financial motivation to improve network performance in these areas.

With regard to the two main pillars that are the input data for the preparation of a business case, the revenues and the costs, it was found that there is some material available in the published literature. Different reports and articles describe the features of the potential 5G use cases. (NGMN, 2015) describes the use cases that could be provided by the rollout of 5G networks. (ITU, 2018) explains the three main uses that can be provided with 5G: eMBB, mMTC, and URLLC. Different business aspects of 5G low latency applications are described in (Lema et al., 2017). Manufacturers of telecommunications equipment have been enthusiastic about the different 5G use cases that could be employed (Ericsson, 2020; Nokia, 2020).

These studies have made a qualitative assessment of the potential 5G use cases that can be provided. However, few studies have quantified so far the demand in terms of revenues, i.e., the monetary incomes that an operator could get by the provisioning of 5G use cases. (Rendon Schneir et al., 2019) calculated the revenues that can be obtained for 5G eMBB services in central London, UK. (5G PPP Automotive Working Group, 2019) assessed the revenues that could be derived when provisioning 5G for V2X services. (Maeng, Kim, and Shin, 2020) studied the consumers' delay related to the adoption of 5G services. (METIS-II D1.2, 2017) analysed the revenues related to a 5G eMBB and mMTC rollout of an existing mobile operator in a dense urban area.

There are a few published studies about the costs of a 5G rollout. (Oughton and Frias, 2018) estimated the overall cost of deploying 5G infrastructure in Britain. (Smail and Weijia, 2017) calculated the cost of a 5G mobile network in a city. (Rendon Schneir et al., 2020) calculated the cost of a multi-tenancy 5G network in a dense urban area. (Wisely, Wang and Tafazolli, 2018) analysed the costs of 5G networks in a dense urban area. (Oughton et al., 2019) developed a tool for the calculation of 5G costs. (Giglio and Pagano, 2019) studied the cost of fronthaul in 5G networks.

Even though there are hundreds of technical articles about 5G and a few articles about strategic and regulatory issues regarding 5G (Rendon et al., 2018), there is a gap in the available literature on the preparation of 5G business cases. In this article we study the case of a mobile operator that will provide users with a few 5G use cases in a sea port environment. Different activities conducted in a port can benefit from the rollout of a 5G wireless network. The research question addressed is as follows: *What is the business case of a mobile operator that provides 5G use cases in an industrial sea port area?*

To answer this question a 5G business case was elaborated that considers as input data 5G revenues and 5G costs. We have analysed the business case related to the provisioning of 5G services in an industrial sea port area. The study area is the Port of Hamburg, Germany, which is Europe’s third largest port. The study area was selected to quantify the commercial potential of the innovations demonstrated in a trial in Hamburg port for the case of this trial being scaled up to a full commercial deployment. Our study was carried out as part of the European Union (EU) funded 5G Public Private Partnership (5G PPP) project 5G-MoNArch, where different aspects of a virtualised 5G network were evaluated (5G-MoNArch, 2020). The revenues for the following three 5G use cases were quantified: eMBB, automation of container handling (ACH) in the port’s container terminals, and augmented reality for construction projects. A cost model that derives the costs in terms of capital expenditures (CAPEX) and operational expenditures (OPEX) of the necessary infrastructure needed to provide the 5G services in the industrial sea port area was developed. A 5G business case was later elaborated and a sensitivity analysis for a range of parameters was prepared.

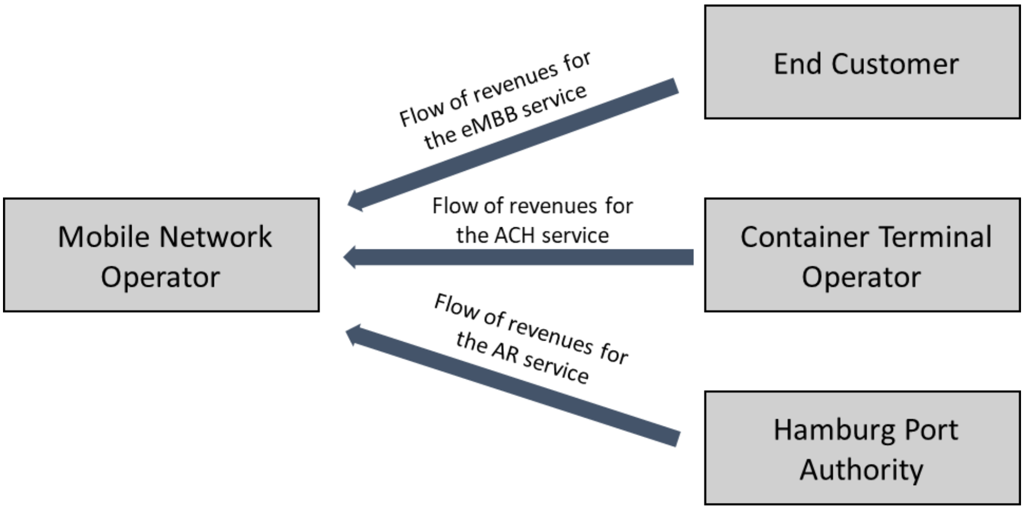
The rest of this article is in the following sections: Section 2 describes the approach for the analysis, the study area, and the 5G definition assumed. Section 3 addresses the 5G revenue calculation. The network implementation of 5G is described in section 4. Section 5 presents the cost analyses. Section 6 shows the results of the business case and of the sensitivity analysis conducted. Section 7 addresses an assessment of the results, the strategic implications and the limitations of the article. Finally, Section 8 presents the conclusions.

2 Approach for the analysis

2.1 Overall approach

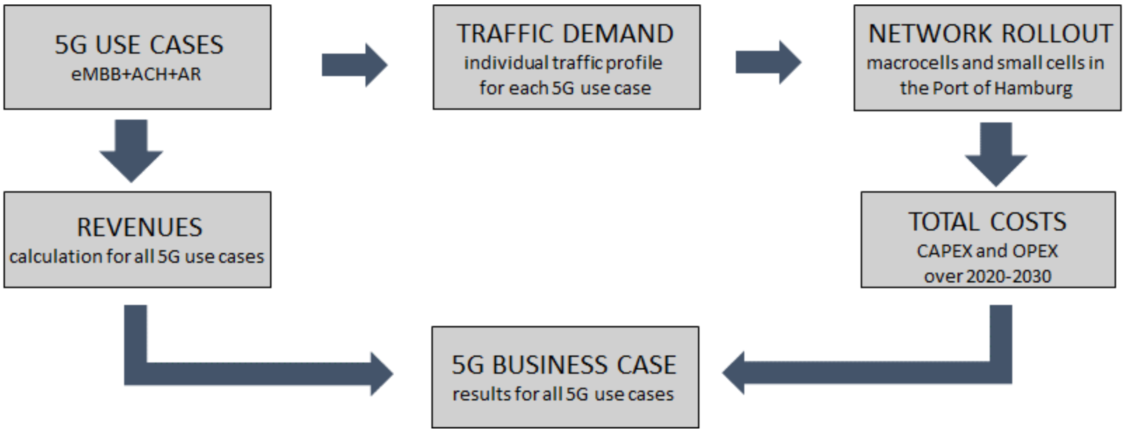
For the analysis conducted in this article a number of assumptions were made (5G-MoNArch D6.3, 2019). It was assumed that a mobile network operator provides 5G services to the Hamburg Port Authority (HPA) and to the end users in the Hamburg port in Germany; the study area is described in Section 2.2. Three types of 5G use cases are provided, which are described in Sections 2.3 and 3: eMBB, automation of container handling in the port's container terminals, and augmented reality for construction projects and maintenance. Fig. 1 shows the flow of revenues related to the services that will be provided. The eMBB service is provided by the mobile network operator direct to consumers in the same way as on today's mobile networks. The eMBB service corresponds to the "business as usual" scenario for the mobile network in Hamburg. Additionally, the analysis considers the MNO receiving revenues for the ACH service coming direct from container terminal operators with revenues for AR services from the HPA. In order to provide these uses cases, the MNO will construct a 5G network infrastructure, which is described in Section 4.

Fig. 1. Flow of revenues.



For the elaboration of the business case several steps were followed, which are depicted in Fig. 2. The first step consists in the definition of the 5G use cases to be provided: eMBB, ACH, and AR. The mobile broadband service includes legacy broadband and enhanced Mobile Broadband. A traffic demand for all the 5G use cases for the period 2020-2030 was forecasted. Based on this traffic demand a 5G network architecture, which consists of macrocell sites and small cells, was engineered. In our study, the 5G network is not a greenfield deployment but is based on the evolution of the existing mobile infrastructure and sites in Hamburg. Later the costs, CAPEX and OPEX, were calculated and the 5G revenues generated by the three use cases were derived. The business case was then calculated based on the total costs and revenues over the time period considered. Afterwards, because of the uncertainties related to the 5G traffic demand and evolution of revenues, a sensitivity analysis was performed regarding traffic and revenue variation.

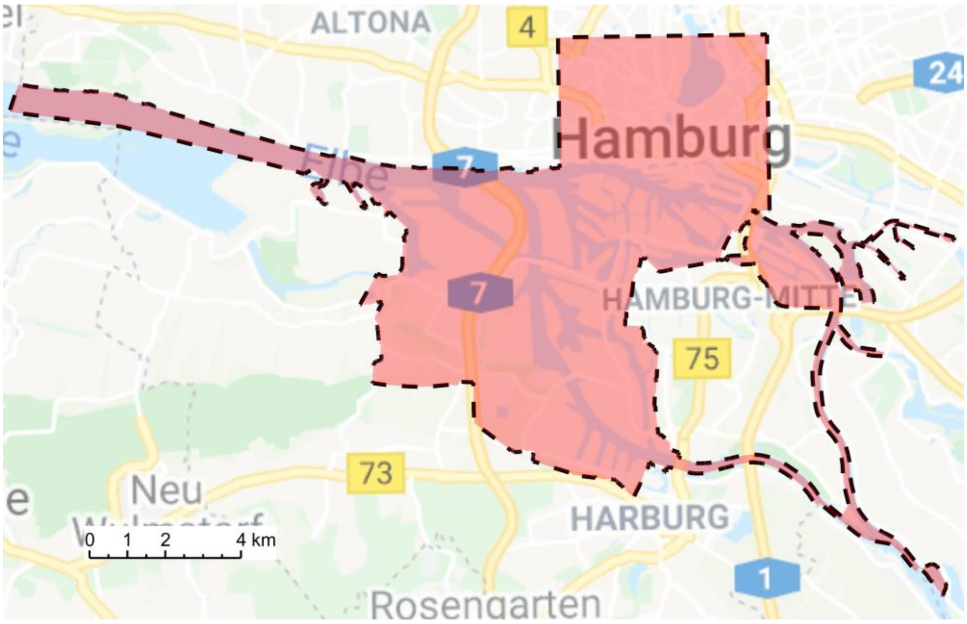
Fig. 2. Approach for the elaboration of the business case.



2.2 Study area

The implications of providing 5G mobile services to an environment that contains a mixed economic context are evaluated in this article. The selected setting encompasses the needs of both consumer and industrial users in the port area of Hamburg and some of the surrounding city centre (see Fig. 3). The city centre to the north of the river Elbe is 21 km^2 and has a residential population of approximately 160,000 residents (Statistikamt Nord, 2020). The city area under study includes zones that are popular for tourists which results in additional wireless coverage and capacity requirements. In contrast, the port area to the south of the river is 71 km^2, with a residential population of around 3,000 residents (Statistikamt Nord, 2020). The port however consists of large areas that require wireless coverage for industrial processes such as freight handling on water and land as well as facilities for arrival and departure of tourists.

Fig. 3. The study area in Hamburg, Germany.



2.3 Defining 5G in the study area

While 5G includes a range of technology advancements, this article focuses on the impact of network slicing and the ability to deliver bespoke mobile services with guaranteed service levels from a 5G network. The emphasis is placed on the newer networking and architectural paradigms in 5G, namely deployment in standalone mode using a 5G core network and a service-based architecture. We consider the mobile infrastructure that was already deployed in the study area in 2018 and that has been providing legacy mobile broadband (MBB) services. We simulate the evolution of this network ensuring it keeps pace with forecast MBB traffic demand until 2020. From 2020 onwards 5G is assumed to be deployed and the analysis anticipates the network evolution needed from 2020 to 2030 to support "business as usual" eMBB services to consumer portable devices with higher throughputs than prior to 2020. The introduction of 5G in 2020 and beyond enables the introduction of network slicing. The eMBB infrastructure set can be reused and enhanced to deliver higher grade wireless connectivity to industrial users in the port area. In total, three services are provided: eMBB and two industrial services. The two industrial services were selected in collaboration with the Hamburg Port Authority. Services were identified based on the operational needs that were most likely to give the highest benefits to the port's operations. The three services considered were as follows:

- *Enhanced mobile broadband*: This is the continuation of providing mobile broadband services to consumer devices in an enhanced form and expected to remain the main driver for operator deployed and operated mobile networks. MBB services will be improved due to the introduction of 5G and its evolution, hence the term enhanced MBB. Improvements from 5G will mean that higher throughputs become available from 2020, with the network dimensioned to ensure at least 10 Mbps single user throughputs at the cell edge.

- *Automation of container handling in the port's container terminals*: This wireless service is delivered to the operators of the container terminals in the port to provide connectivity to the straddle carriers or automated guided vehicles (AGVs) transferring containers from the ship to shore cranes to the loading yards. In addition, we consider providing connectivity and signalling to the stackers moving containers around the loading yards. The provision of highly reliable connectivity between the control room and port equipment in the container terminals enables automation, and thus realises greater operational efficiency and terminal capacity benefits.
- *Augmented reality for construction projects and maintenance*: This wireless service provides high bandwidth connectivity to augmented reality devices that would be used by the port authority at their many construction sites distributed around the port area. Construction projects tend to go beyond budget and over run. The view of the operations experts at the port is some errors leading to overruns could be avoided if inspections on construction sites were improved via better visualisation of plans on site. The inspections can be achieved by visualising plans to the construction workers in their physical setting by using augmented reality.

The technical requirements of the above-mentioned services are given in more detail in Section 4. However, they are distinct from existing MBB consumer focused services on today's mobile networks in that they will require a stable throughput and latency, in the case of the AR service, and/or a high reliability level, in the case of the container terminal automation services.

3 Revenue calculation

3.1 Approach for the revenue calculation

Our business case analysis considers potential revenues over the 2020-2030 time period to a mobile network operator for the services and scenarios considered. The approach to calculating these revenues is described in this section. Three categories of services are considered: eMBB, ACH and AR.

For MBB related services for consumer portable devices, there is already historical data available on how much mobile subscribers are willing to pay for their monthly mobile subscription. Looking towards 5G and the premium that consumers might be willing to pay for eMBB services with better data rates and lower latency, there are surveys available where consumers have been asked about how much extra they would pay for 5G. Additionally, prices paid by households for fixed broadband subscriptions give some indication on the limit of current consumers' willingness to pay for higher data rates. Therefore, for revenues related to "business as usual" eMBB related services, we draw on these existing related sources on willingness to pay.

For the new industrial services to be delivered from the 5G network considered in our analysis, a different approach to revenue assessment had to be taken compared with eMBB services. A different approach was needed because the new industrial services considered, ACH and AR for construction, have not traditionally been offered by MNOs and so little, if any, data already exists on willingness to pay for the wireless component of such services. We, therefore, have based our revenues for ACH and AR for construction on first quantifying the operational benefits that such services bring to the companies making use of them. We then assess willingness to pay for the wireless component of ACH and AR based on these benefits via the following four steps:

- **Step 1:** Determining the net benefit that the industrial user expects. In this step, the calculated benefits are reduced by system implementation costs that fall with the industrial users. For AR for construction services, this is limited to the AR headsets and associated software development. However, for ACH, a significant investment in replacing straddle carriers and stackers with automated versions of this heavy machinery will be required and borne by the container terminal operators.
- **Step 2:** Applying a discount rate to the net benefits over time to reflect the level of uncertainty associated with the benefits from these new industrial services. A discount rate of 20% is applied for ACH and AR for construction, compared with 10% for more established eMBB services. The higher discount rate applied to ACH and AR reflects the fact that these are new wireless services with a higher uncertainty around the returns that they will bring compared with other more established services like eMBB. Note that the discount rate applied in this step represents the uncertainty around the forecast benefits and risk that they may not materialise for the industrial user. This uncertainty will impact the willingness to pay. The discounting applied in this step is separate to the discount rate applied later in section 6 when the MNO’s business case and discounted cashflow is forecast.
- **Step 3:** Considering how much of the discounted net operational benefit, obtained from steps 1 and 2, an end user might be willing to spend on the wireless component of the system. We assume that this is up to 15%.
- **Step 4:** Considering how strong a position the 5G MNO would have in negotiations with industrial users when agreeing the price for providing ACH and AR services that meet the conditions of specific service level agreements (SLAs). Strength of negotiating position is a highly subjective area which we have attempted to quantify by scoring a 5G offering for each service in terms of:
    - The importance of specific 5G architectural features to delivering these services.
    - How challenging the requirements on throughput and latency are for the service.
    - Whether industrial grade reliability is required.
    - The degree of participation of the MNO in service development.
    - The competitive environment and availability of alternative systems.
    - The tangibility of the operational benefits realised by the service.

As detailed in (5G-MoNArch D6.3, 2019), a scoring between 0 and 3 was given against each of the above aspects based on using 5G to deliver port automation or AR in construction. This scoring was applied subjectively and reviewed with consortium partners who worked on the project that led to the elaboration of the document (5G-MoNArch D6.3, 2019). In the cases of both ACH and AR for construction, the 5G offering scored 67% out of the maximum possible score across these criteria. Finally, we apply this 67% weighting to the result of steps 1-3 to translate operational benefits to potential MNO revenues.

3.2 eMBB services

We forecast revenues for “business as usual” eMBB and MBB services to consumer devices in the study area. The revenues shown represent the revenue that an MNO might expect to obtain from subscribers in the study area over a 2020 to 2030 time period, assuming that the network is repurposed to support 5G. As it will take time for subscribers to migrate to 5G plans, we consider revenue from both:

1. eMBB services: Consumer broadband beyond today’s MBB services and provided via the 5G network.
2. Legacy MBB services: Mobile broadband that subscribers consume today using 4G long-term evolution (LTE), 3G universal mobile telecommunications system (UMTS) and 2G general packet radio service (GPRS) services.

We apply the following four steps to forecast revenues for these “business as usual” services in the study area and scenarios considered over the 2020-2030 time period:

1. Set out the assumed eMBB price plans offered and the expected segmentation of the eMBB market across these.
2. Develop a forecast of the number of users in the study area taking up each eMBB price plan over time.
3. Develop annual revenue per user (ARPU) assumptions for each eMBB price plan as well as for legacy MBB. We abstract from specific 5G pricing strategies which will evolve over time and focus on revenues instead.
4. Combine steps 2 and 3 to calculate revenues across all eMBB price plans per year from 2020 to 2030.

3.2.1 Price plans, uptake and ARPU

We assume that price plans for 5G eMBB services will be offered in three broad categories:

- Basic Needs: The minimum eMBB service necessary to be able to participate and communicate online in society, with high quality video and AR not being required. Customers are very price sensitive.

- Standard: It provides good quality connectivity and coverage for everyday online uses, including social media, good quality video and basic AR experiences.
- High Performance: It provides high quality streaming video-on-demand (SVOD) and AR, and/or high quality gaming.

In our baseline scenario, we assume that the population will be distributed across these price plans as shown in Table 1. The distribution in Table 1 is based on laggards and early adopters from a classic diffusion of innovation curve being the “basic needs” and “high performance” subscribers, respectively (Rogers, 1962). The remaining early and late majority fall into the “standard” price plan. Table 1 also shows our assumed ARPU per price plan in our baseline scenario. For ARPUs we have defined low, baseline and high scenarios, which are employed in Section 5.2 in the sensitivity analysis. The weighted average of the low scenario eMBB ARPUs reflects the 2017 4G ARPU for Germany overall (BNetzA, 2017). The weighted average ARPU of this low scenario is also used to set the ARPU for legacy MBB services with a compound annual growth rate (CAGR) of -2% applied as derived from historic ARPUs for Germany between 2012 and 2019 (Statista, 2020). This results in an ARPU as at 2020 of €13.98 for MBB. The high scenario assumes some willingness amongst “high performance” subscribers to pay more for their 5G service based on studies reported in (RCRWireless News, 2019; Bitkom, 2019). Our baseline ARPUs reported in Table 1 are based on an average between these low and high scenarios per price plan.

Table 1. Baseline scenario: Assumed distribution of eMBB subscribers across price plans (Rogers, 1962), and eMBB ARPUs per price plan.

Price plan	Percentage of subscribers in this price plan category	Monthly ARPU in 2020 (€)
Basic needs	16%	7
Standard	68%	18
High performance	16%	22.5

3.2.2 Forecast revenues for baseline scenario

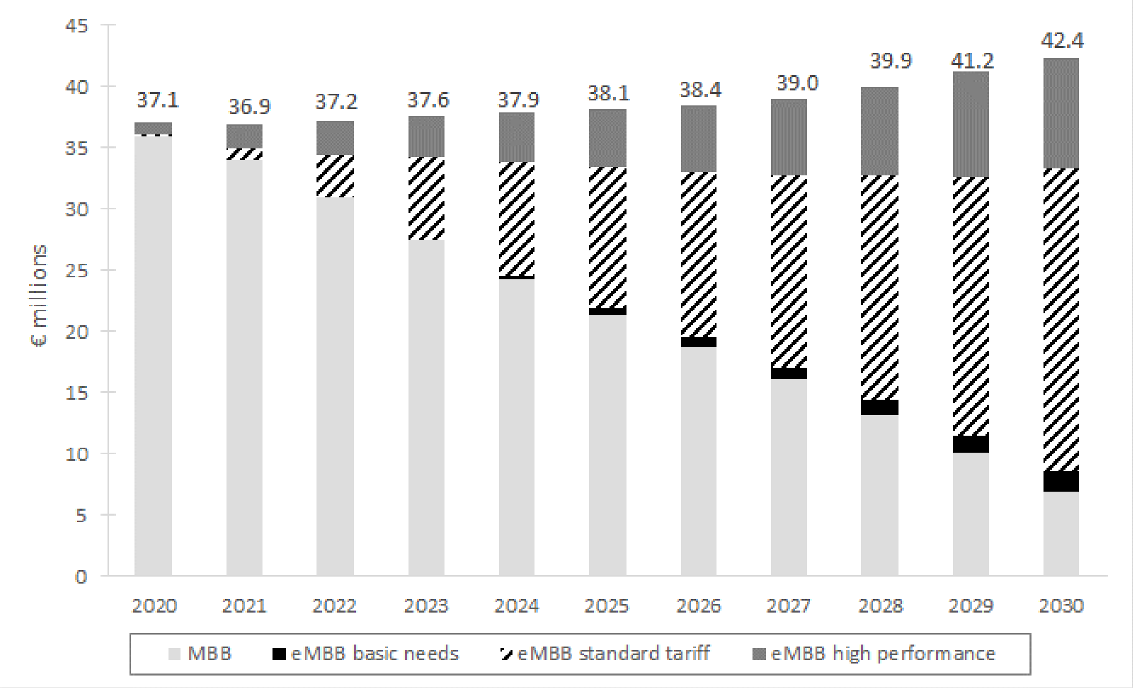
Based on the market segmentation and ARPUs given in Section 3.2.1 and the population of the study area in Hamburg, which is approximately 164,000 residents (Statistikamt Nord, 2020), Table 2 then calculates the anticipated revenues for MBB across all operators for the study area over time. It was assumed an uptake of 5G services by the mainstream “standard” price plan users that begins from 2020 and grows over time in line with the uptake trends already seen for 4G (GSMA, 2015). For the high performance and basic needs price plans, this uptake curve is accelerated by 2 years and delayed by 2 years, respectively. It is further assumed that the maximum proportion of mobile users that will eventually transition across to each of the 5G price plans follows the diffusion of innovations with basic needs users mapped to the late majority (16%), the high performance users mapped to the early majority (16%), and standard users mapping to the remainder (68%) (Rogers, 1962).

Table 2. Baseline scenario: MBB and eMBB calculated revenues over time.

	2020	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**Source**
eMBB revenues over time (€ millions)												
MBB	35.03	33.98	30.88	27.42	24.27	21.31	18.73	16.02	13.16	10.05	6.94	Calculated based on subscriber volumes and ARPUs detailed in Annex A
Basic needs	-	-	0.03	0.09	0.32	0.62	0.85	1.06	1.23	1.44	1.67	
Standard	0.16	0.96	3.53	6.74	9.30	11.55	13.47	15.72	18.29	21.17	24.70	
High perform.	1.04	1.98	2.74	3.40	3.96	4.62	5.38	6.23	7.27	8.49	9.06	
Total revenue	**37.1**	**36.9**	**37.2**	**37.6**	**37.9**	**38.1**	**38.4**	**39.0**	**39.9**	**41.2**	**42.4**	-
33% market share revenue	**12.2**	**12.2**	**12.3**	**12.4**	**12.5**	**12.6**	**12.7**	**12.9**	**13.2**	**13.6**	**14.0**	-

Fig. 4 shows the resulting MBB and eMBB revenues calculated for the study area over time for all mobile network operators. These results show limited scope for growth in MBB and eMBB revenues over time due to limits on willingness to pay amongst consumers coupled with competition in the German mobile market. There are three main MNOs in the German mobile market and an MVNO aiming to launch a 5G network in 2021. Table 2, therefore, shows also the revenue forecast for a single MNO assuming an even distribution of market share, i.e., 33% each.

Fig. 4. Baseline scenario: MBB and eMBB revenues over time for all operators.



3.3 Automated container handling

The handling of containerised cargo is a key function of the Port of Hamburg. It handles the third largest volume of containerised cargo of any port in Europe, behind only Antwerp and Rotterdam. Containerised cargo is handled across the four container terminals in the port. Each container terminal has two main areas:

- Container yards: These include the berths for the container ships arriving at the terminals and a number of quayside cranes for offloading the containers from the vessels. Straddle carriers operate in these areas to transport containers from the quayside cranes into the block storage area.
- Block storage areas: These include large stacker cranes, which move up and down aisles of containers and stack containers arriving from the container yard into the right aisle and location. Containers are then transferred from the block storage areas to trucks or trains for onward travel.

As reported in (McKinsey & Company, 2018), expenditure on automating the equipment used at container terminals is increasing worldwide. This growing trend towards automation of container handling is driven by:

- A steady increase in containerised cargo, which increased worldwide at an annual growth rate (AGR) of 5.1% over the last 7 years (UNCTAD, 2018). At this growth rate, volumes of containerised cargo will have nearly doubled by 2030. Automated container handling equipment can stack containers more accurately and hence higher than manually operated equipment: 6 containers high as opposed to 2 or 3. The resulting impact is to effectively double the capacity of the main parts of the block storage area.

- An increase in the size of container vessels and the need for ports to be able to service ultra large container vessels (ULCVs) to remain competitive with other ports. Servicing such large vessels includes having adequate storage and throughput at container terminals to process these large volumes of cargo in a timely manner. Automation of equipment can assist with both of these.
- A reported reduction in operating costs of 15–25% when terminals are automated, according to (McKinsey & Company, 2018).

Existing systems for automating container terminal equipment can already use wireless fidelity (Wi-Fi) connectivity for passing control messaging between the equipment in the operating areas and remote operators located elsewhere on the container terminal site. However, as Wi-Fi operates in licence exempt spectrum, the reliability of this connection is difficult to guarantee. This is particularly true in the outdoor environment of a container terminal and there have been examples of interference causing automated container terminals to come to a halt (5G-MoNArch D6.3, 2019). Via network slicing, 5G networks have the opportunity to provide a wireless connection at the high level of reliability required by a container terminal.

In our revenue forecasts for the Port of Hamburg, we analyse the value that 5G connectivity might bring to a container terminal by facilitating automation and how this translates to willingness to pay for such connectivity services. Given that only 1% of ports worldwide have fully automated to date (McKinsey & Company, 2018), there is little data on existing spend on the connectivity elements of container terminal automation systems. As highlighted in Section 3.1, we ground our ACH revenue forecast on a quantification of the operational benefits of port automation.

3.3.1 Basis for assessing net benefit

We consider the net benefit of automation in container terminals to the container terminal operators to have two elements: Storage block automation benefits via protected market share and revenues; and yard automation benefits via operational savings.

3.3.1.1 Storage block automation benefits

A port’s market share of containerised traffic can fluctuate significantly in any one year. For example, in 2018 the Port of Rotterdam gained a 1.5% market share whereas in 2017 Hamburg lost 1.3% (HHLA, 2017; HLLA, 2018). Such a reduction in Hamburg’s market share translates to a 6.6% decrease in the volume of containerised traffic handled by the port and hence related revenue. This illustrates the importance of investing in facilities to remain competitive with other ports and protect market share.

In our analysis of the benefits of storage block automation, we assume that automation expands the capacity of the storage block area to the extent that the current growth rate in container volumes can be accommodated and market share protected. We assume that this added capacity allows the volume of containers handled, and hence revenues, to grow at an AGR of 5.1% over the period 2020 to 2030. A 5.1% AGR is in line with current growth rates reported at the beginning of section 3.3. Added complications are mentioned in the following:

- One of the four container terminals, Altenwerder, is already largely automated and the Burchardkai terminal is already partially automated. To allow for this, we only consider the benefits of protected revenues in proportion to the volume of containerised cargo handled by each of Hamburg's terminals and the amount of automation yet to be done at each terminal (5G-MoNArch D6.3, 2019). Table 3 shows the volume of containerised cargo in terms of throughput per terminal. Based on the proportion of cargo handled by the container terminals yet to complete automation, the maximum benefit of further storage block automation in the port is to protect a 30% improvement in revenues compared with the expected 65% growth across all of Hamburg's terminals by 2030.
- It takes time to implement automation solutions. We assume three years for storage block automation based on (McKinsey & Company, 2018). Benefits are, therefore, realised over this period.
- Not all terminals will automate at the same time. We have assumed the automation dates shown in Table 3. Note these are hypothetical dates for the purpose of analysis and do not reflect any current plans for the port, which are commercially sensitive and could not be used. Based on these automation dates and the time taken for automation to be implemented, even with automation, there would remain an overall reduction in market share of 7% between 2020 and 2030.
- The terminal operator will not get the full value of the protected revenue growth that automation brings as these increased revenues, due to increased container volumes, will also have associated operational costs. We assume that operational costs are 70% of gross revenues (HHLA, 2017).
- The cost of automating the heavy machinery at container terminals is high. Based on the cost of automating the Altenwerder terminal and costs at other ports reported in (McKinsey & Company, 2018), we assume that automation requires a €168m investment in equipment per terminal. We convert this to annualised amounts based on amortisation over an assumed 25-year lifetime for heavy machinery with a 10% discount rate.

Table 3: Scale of operation at Hamburg's container terminals.

Terminal	Estimated container throughput in 2018 (million TEU[1])[2]	Our assumed date of automation[3]
Altenwerder	3.3	2002
Burchardkai	2.5	2017 - 2023
Tollerort	1.4	2025
Eurogate	1.5	2022
Total	8.7	-

Notes: [1] Twenty-foot equivalent unit (TEU) is a standard measure of cargo capacity for containerised goods.

[2] Container throughputs for Altenwerder, Burchardkai and Tollerort have been estimated based on truck and rail capacity within Hamburg port's terminals.

[3] These are hypothetical dates for automation to allow benefits and cost assessment for the purposes of this project and do not reflect actual plans of specific container terminals.

3.3.1.2 Yard automation benefits

We assume that the benefits of yard automation are to reduce operating costs. We calculate the benefit as follows:

- Assume that operational costs are 70% of revenues based on previously published financial reports of HHLA (HHLA, 2017).
- Assume that automation reduces operational costs by 25%, i.e., the mid-point of the 15-35% range reported by publications on the benefits of port automation (McKinsey & Company, 2018).
- Attribute operational cost reductions only to terminals still requiring automation in proportion to the existing level of automation and volume of traffic handled by each terminal, as was done for storage block automation.
- Assume that it takes time for the transformations that yard automation brings to translate to operational benefits. Benefits are, therefore, assumed to grow linearly over a 4-year period from when automation starts. As automation of a container terminal is a large undertaking, i.e., it requires replacement of heavy machinery, redeployment of staff, etc., we assume that it would not be practical to automate any of the terminals before 2022. The corresponding dates are shown in Table 3.
- Allowing for investment in equipment costs on the part of the terminal operator in calculating the net benefit of automation. These equipment costs are converted to annualised amounts based on amortisation over an assumed 25-year lifetime for heavy machinery with a 10% discount rate. We assume that yard automation requires a €181m investment in equipment per terminal (McKinsey & Company, 2018).

3.3.2 Net benefit and willingness to pay results

Table 4 summarises the results of applying each of the four steps - outline in section 3.1 - of determining the net benefit of ACH services and translating this to pay. Further details of the calculations behind these results are given in Annex B but in brief each step consists of the following method and assumptions:

- **Step 1:** Calculating the net benefit due to automation. This applies the assumptions and methodology outlined in Section 3.3.1 to calculate the potential:
  - Reduction in lost revenues due to the extra capacity of storage block automation
  - Reduction in operational costs due to yard automation

  These operational benefits are then reduced by the cost of automating the terminals to give the net benefit expected in these two categories.
- **Step 2:** Apply a discount rate to the maximum willingness to pay level that reflects the risk level of the investment from the verticals perspective. We applied a 20% discount rate to reflect the relatively high-risk rate due to the high investment in equipment needed on the part of the vertical and long-term nature of benefits.
- **Step 3:** Consider how much of the operational benefit a vertical might be willing to spend to achieve that benefit. We assume a willingness to pay up to a maximum of 15% of the anticipated net benefit for a solution to deliver these benefits.
- **Step 4:** Assume a proportion of this maximum willingness to pay as potential revenue for a wireless service provider based on the strength of negotiation positions between the vertical and wireless service provider. This is based, among other factors, on the availability of substitute technologies.

Note that for steps 3 and 4 only the total is shown rather than applying the calculation to each individual year. This is because willingness to pay needs to be considered based on the accrued benefit and risk over the entire investment period rather than short term changes in cashflow.

Table 4. Potential operational benefits, willingness to pay and aggregate MNO revenues arising from Port Automation.

	2020	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**Total**	**Source**
Step 1: Net benefit of ACH													
Storage block automation (€ millions)													
Avoided net revenue loss	0	0	3	10	19	31	45	60	76	94	113	**451**	Calculation detailed in Annex B
Automation costs	0	0	6	19	31	49	56	56	62	56	56	**389**	
Changes in cashflow	0	0	-3	-8	-12	-18	-11	4	14	38	58	**62**	
Yard automation (€ millions)													
Savings in OPEX	0	0	7	27	48	78	103	115	129	135	142	**784**	Calculation detailed in Annex B
Automation costs	0	0	20	40	40	60	60	60	60	60	60	**460**	
Changes in cashflow	0	0	-13	-13	8	18	43	56	69	76	82	**326**	
Results of Step 1: Net benefit of ACH (€ millions)													
Total undiscounted net benefit for ACH	0	0	-16	-21	-4	0	32	60	83	114	140	**388**	
Step 2: Apply 20% discount rate to reflect risk (€ millions)													
Step 2	0.0	0.0	-9.4	-10.2	-1.7	-0.1	9.0	14.0	16.1	18.5	18.8	**55.1**	Calculation detailed in Annex B
Step 3: Apply 15% limit on maximum willingness to pay (€ millions)													
Step 3	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	**8.3**	Calculation detailed in Annex B
Step 4: Apply 67% scoring to reflect competitive advantage of 5G (€ millions)													
Step 4	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	**5.5**	Calculation detailed in Annex B
Distributed revenues for ACH (€ millions)													
Revenues per year	0.0	0.0	0.4	1.1	1.1	1.4	1.4	1.4	1.4	1.4	1.4	**5.5**	Calculation detailed in Annex B

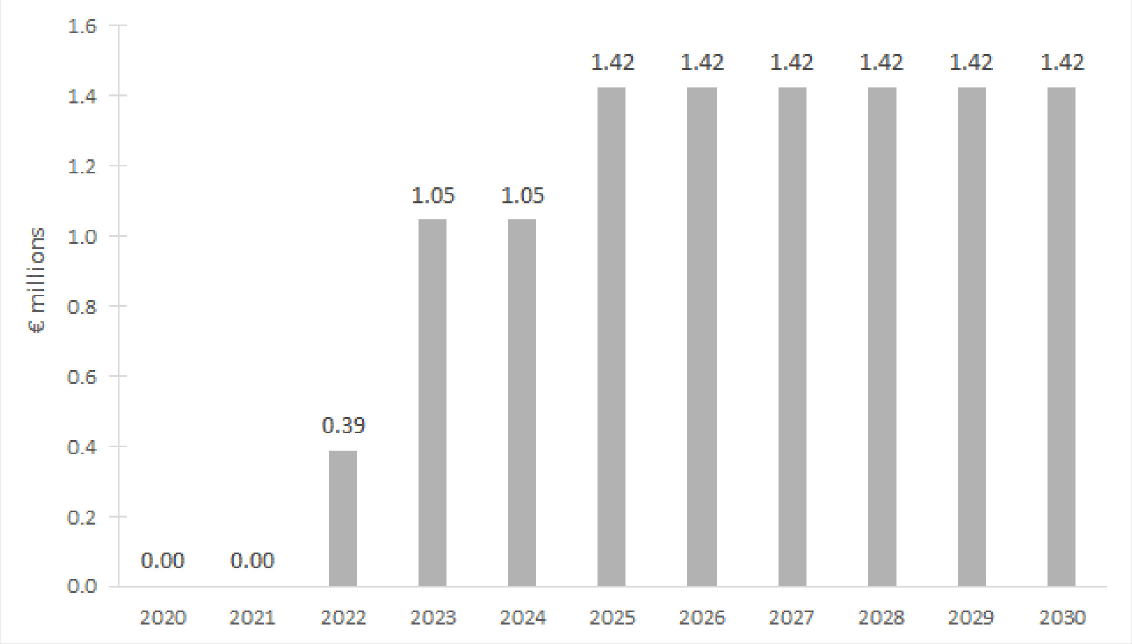
The results of step 1 on Table 4 show that the net benefit of automation is initially negative due to the high level of investment in new equipment needed on the part of the container terminal operator. This highlights some short-term risk in this strategy for the container terminal operator, which is the vertical for the ACH case, for longer term benefits. By 2030, the total undiscounted net benefit for this year is €140m and likely to continue to grow beyond 2030.

3.3.3 Revenue results

The MNO revenue expectation of €5.5 million over the total time period, calculated in the previous section, is distributed based on the proportion of cargo automated in any given year, with more being paid for connectivity over time as the volume of cargo automated increases (see Annex B). This results in the distribution of revenues over time given in Fig. 5.

The revenues shown in Fig. 5 increase initially as each of the three target container terminals are assumed to automate at different years (see Table 3). The revenues stop growing after 2025 as the assumed growth in the container freight market is balanced out by the discount rate at this point.

Fig. 5. Forecast MNO revenues from ACH over time.



3.4 AR for construction and maintenance

A major innovation in the construction industry currently is the adoption of building information modelling (BIM) techniques. BIM involves the capture and representation of construction drawings in 3D spatial form allowing plans to be more readily visualised. The HPA is responsible for the construction and maintenance of infrastructure around the port area. Large projects undertaken include the refurbishment of the St. Pauli Elbe Tunnel. During 2016, €217 million was invested in infrastructure projects and this was increased to €242 million in 2017 (5G-MoNArch D6.3, 2019).

Support for AR services outdoors on construction sites around the port would give HPA engineers the opportunity to inspect building plans on location and easily compare them with the actual build. The benefits of this are that deviations from plans or physical obstructions not previously considered can be identified more quickly and mitigated. The result is a reduction in the time taken and hence cost of construction projects. Providing a 5G slice to support AR services, would ensure the consist bandwidth and latency of connection required to ensure a good user experience for engineers making use of AR on construction sites.

As was the case for automating container terminals, there are no existing pricing benchmarks for providing connectivity to support AR for construction services. Our revenue forecast for an MNO providing a slice for this AR service is, therefore, based on first understanding the operational benefits of AR to HPA's construction projects, and then translating this to willingness to pay and revenues.

3.4.1 Basis for assessing net benefits

The calculation of each of the following aspects of assessing the net benefit to HPA of the proposed AR for construction service is shown in Annex C:

- The investment in infrastructure construction projects by HPA each year.
- Typical overruns on constructions projects and how these translate to costs.
- Time overrun savings that use of AR and BIM might deliver.
- Cost to HPA of equipping their team to use AR on construction sites.

As highlighted above, HPA spent €217 million and €242 million on infrastructure projects during 2016 and 2017. The maintenance and development of facilities at the port is an ongoing process, with planned developments including wharf expansion and development of Steinwerder-Sud. We therefore have assumed that HPA's spend on construction projects will continue at their 2017 level. Additionally, HPA is considering construction of a new Köhlbrand crossing, which would be a significant additional investment in infrastructure from HPA. Based on similar major bridge construction projects, we assume this project will cost €500m spread evenly over the period 2022 to 2025.

Next, we consider the level of overrun that is typical on construction projects. McKinsey has undertaken a survey of major construction projects from across the world (McKinsey & Company, 2018). Their analysis finds that large projects, such as new hospitals, schools, roads, offices, etc., typically overrun by 20% in time and 80% in cost. As not all HPA projects might be considered in this large projects' category, we assume a maximum bound on cost savings from preventing overrun and other issues on construction projects of 50%.

We also looked for evidence of how the use of BIM and AR could reduce some of these potential cost overruns in construction projects. (PWC, 2018) studied the benefits of BIM in construction projects. From the case studies reviewed, they estimated that by using BIM for so-called "clash detection", a mismatch between plans and the physical construction site, cost savings of 10%

were feasible. For our AR in construction case, we make the conservative assumption that this service might lead to a 5% reduction in potential overruns and related costs (see Annex C).

Finally, we considered the cost to HPA of utilising the AR in construction service in their operations. Besides the connectivity cost paid to the MNO, HPA would need to equip their engineers with AR headsets. As a reference point, we have looked at the cost of Microsoft Hololens 2 and Magic Leap One devices which are around €3,010 and €1,970 respectively giving an average cost per device of €2,500. We assume that it takes five years to roll out the service and devices to all of HPA's construction sites and ramp up benefits over time in proportion to this. Hence the savings are less than 5% up to 2023. In addition to these device costs, we assume the following aspects:

- Each of HPA's 100 civil engineers would need to be trained with the new device and applications at a cost of €1,000 per user.
- HPA would need to engage a 3rd party to develop the AR system platform and related software. We assume an initial development cost of €100k with on-going annual costs for software upgrades of €10k.

Table 5 summarises the results of these calculations in Annex C to determine the net benefit attributed to AR in construction.

Table 5. Summary of net benefits calculated for AR in Construction.

	2020	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**Total**	**Source**
Anticipated reduction in overrun costs due to the roll out of AR	1.2	2.4	5.5	7.3	9.2	9.2	6.1	6.1	6.1	6.1	6.1	65	Calculation detailed in Annex C
Cost of AR devices	0.11	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.3	
Undiscounted net benefit of AR in construction	1.1	2.4	5.5	7.3	9.2	9.2	6.0	6.0	6.0	6.0	6.0	64.8	

3.4.2 Net benefits and willingness to pay results

Table 6 takes the undiscounted net benefits, from section 3.4.1, and applies steps 2-4, described in section 3.1, regarding the calculation of willingness to pay and MNO revenue expectations for AR in construction services. Steps 2-4 for this AR in construction service are applied as follows:

- **Step 2:** Apply a discount rate to the maximum willingness to pay level that reflects the risk level of the investment from the verticals perspective. We applied a 20% discount rate to reflect the relative immaturity of BIM and AR in construction and consequential low number of case studies from which to reference potential impact and benefits.
- **Step 3:** Consider how much of the operational benefit the HPA, which is the vertical for the AR case, might be willing to spend to achieve that benefit. We assume a willingness to pay up to a maximum of 15% of the anticipated net benefit for a solution to deliver these benefits.
- **Step 4:** Assume a proportion of this maximum willingness to pay as potential revenue for a wireless service provider based on the strength of negotiation positions between the vertical and wireless service provider. Strength of negotiating position is based, among other aspects, on the availability of substitute technologies.

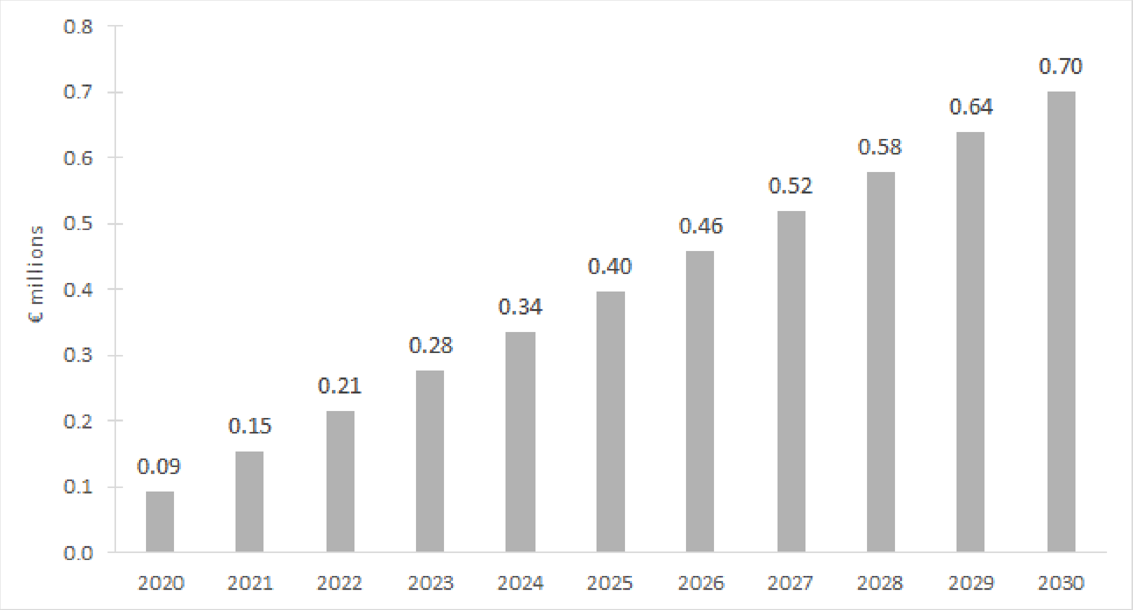
Table 6. Potential operational benefits, willingness to pay and aggregate MNO revenues arising from AR in construction

	2020	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**Total**	**Source**
Step 1: Total undiscounted net benefit for AR in construction (€ millions)													Calculation detailed in Annex C
	1.1	2.4	5.5	7.3	9.2	9.2	6.0	6.0	6.0	6.0	6.0	**64.8**	
Step 2: Apply 20% discount rate to reflect risk (€ millions)													
	0.9	1.7	3.2	3.5	3.7	3.1	1.7	1.4	1.2	1.0	0.8	**22.1**	
Step 3: Apply 15% limit on maximum willingness to pay (€ millions)													
	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	**3.3**	
Step 4: Apply 67% scoring to reflect competitive advantage of 5G (€ millions)													
	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	**2.2**	
Distribution of total revenues over time (€ millions)													
Revenues per year	0.09	0.15	0.22	0.28	0.34	0.40	0.46	0.52	0.58	0.64	0.70	2.2	

3.4.3 Revenue results

Finally, we assume that the cumulative revenue for a mobile service of €2.2 million over this 2020 to 2030 time period is collected proportionate to the cumulative number of active devices deployed across the HPA construction team in each year (see Annex C). The resulting revenue forecast is shown in Fig. 6.

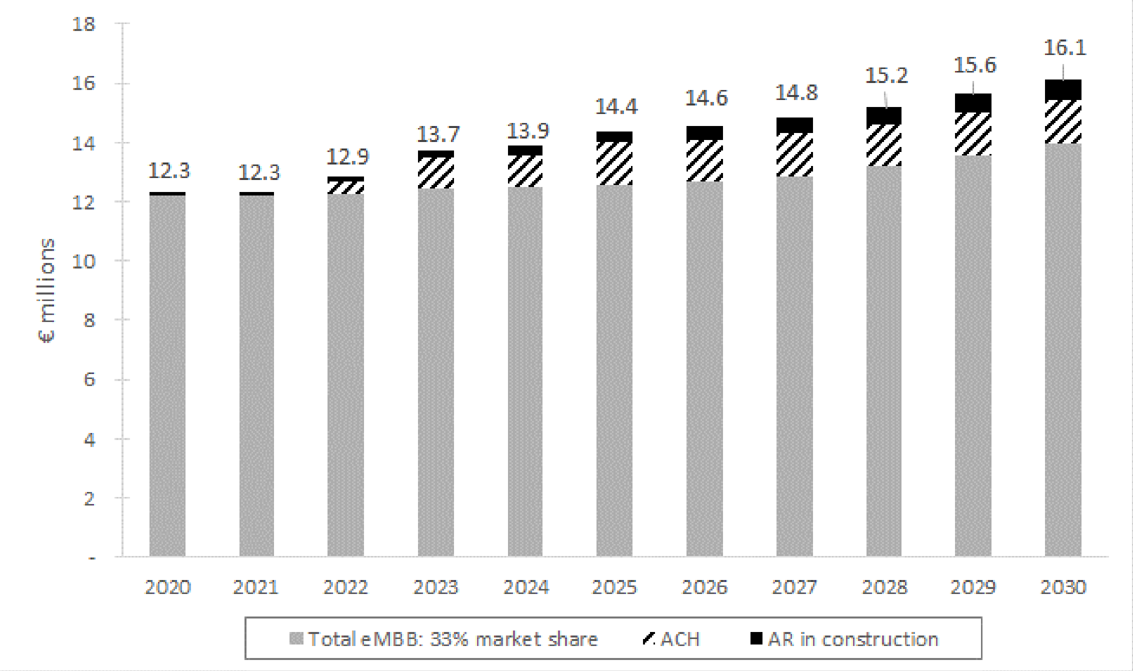
Fig. 6. Forecast revenues from AR in construction over time.



3.5 Overall revenues

Finally, we combine the revenues from the two port services analysed and compare these with the study area revenues forecast for eMBB services. The revenues are shown in Fig. 7. It is shown that revenues from port services, ACH and AR, in the analysed scenario would be €2.1 million per year by 2030. The ACH and AR revenues correspond to a 15% increase in comparison with the expected eMBB revenues by 2030. However, we can see that in initial years it will take time for the uptake of these new port services to grow indicating some short-term risk.

Fig. 7. Estimation of annual MNO revenues from eMBB, ACH and AR services in the Port of Hamburg.



4 Network Implementation of 5G

4.1 Technical requirements

Table 7 summarises the key technical requirements of the different services considered for the mobile network dimensioned for the Hamburg study area. These were derived from stakeholder discussions and industry experience across the members of the consortium that took part on the project that led to the preparation of the document (5G-MoNArch D6.3, 2019).

Table 7. Requirements of the mobile services considered.

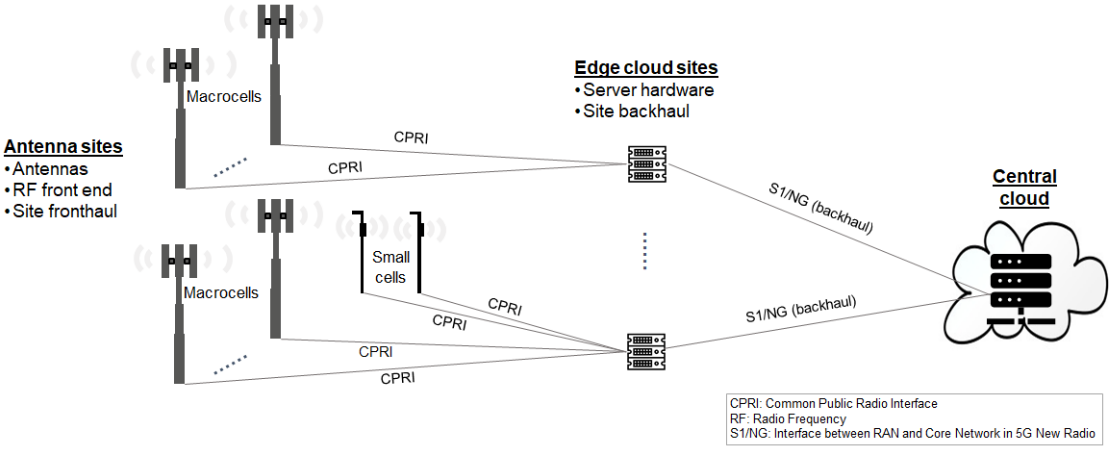
Service	**Key Performance Indicators**			
	Throughput	**End-to-end latency**	**Reliability**	**Coverage confidence**
eMBB	up to 10 Mbps	100 ms	99.9%	95%
Port automation	0.5 Mbps	<10 ms	99.999%	99.9%
Augmented reality	10 Mbps	<10 ms	99.9%	95%

4.2 Network architecture

We have determined that the eMBB service that is sufficient for consumers' portable devices and that most MNOs will target in their initial 5G deployments does not achieve the key performance indicators (KPIs) that are necessary for industrial services required by the port users. It has also been established that augmenting an eMBB focused mobile network with Narrowband Internet of Things (NB-IoT), as is possible under 4G networks, would not achieve the requirements either. In fact, under 4G, these industrial services would likely only be realised via dedicated standalone private network deployments that are completely isolated from the existing public network infrastructure, and which can be specifically designed to meet the operational requirements. In this article, we consider the appropriateness of a virtualised 5G network capable of network slicing that could be optimally dimensioned to support more challenging industrial services such as the ones required here. We assume that this 5G network utilises a single public mobile network that is also capable of delivering consumer grade services.

The analysis presented considers the deployment of a virtualised network that employs a service-based architecture and network slicing capabilities (5G-MoNArch D2.1, 2017). One of the features of such an architecture is that the macrocell and small cell sites are assumed to employ remote radio heads with baseband processing for multiple antenna sites being performed at local edge cloud sites as shown in Fig. 8. The radio heads contain the antennas and the radio frequency (RF) front end. The edge cloud site contains the baseband unit (BBU).

Fig. 8. Network architecture assumed.



The network dimensioning uses existing antenna site locations in Hamburg. Four edge cloud sites in the vicinity of the network are selected from locations where existing fixed telecommunications exchanges are deployed. Their current functionality as a telecommunications exchange provides a natural connectivity and supporting infrastructure for a cost-efficient upgrade to cloud capability. The maximum distance between any antenna site and the edge cloud site that it is connected to is well within the requirements of the common public radio interface (CPRI) (CPRI, 2017). The user plane processing, in terms of general purpose processor (GPP) cores, services and cabinets required at each edge cloud site, is explicitly dimensioned and considered in our cost calculations as are the transport links between sites. The link between the edge cloud sites and the central cloud employs the S1/NG interface. Core network and management and orchestration functions have not been explicitly modelled. Nonetheless, we apply an adjustment parameter to the calculated antenna site and edge cloud site costs in the business case analysis, which is described in Section 5.1, to allow for these architectural elements of the network.

This article examines the case for using network slicing to deliver bespoke industrial wireless services by reusing and extending the existing public mobile radio infrastructure in a given area. To this end, our analysis assumes the “business as usual” scenario for mobile infrastructure in the area initially. This means that the evolution of existing mobile infrastructure in the area over the study timeline is considered against the growth in demand for eMBB services. This represents how the business case for MNOs would evolve in the study area without the provision of other services. It is next assumed that this baseline infrastructure is upgraded and extended where necessary to provide the more industrial focused services of ACH and AR via network slicing. The change in cashflows over time or incremental business case for each of these two services is examined relative to the eMBB “business as usual” baseline.

4.3 5G network dimensioning

4.3.1 Network dimensioning approach

In our simulated evolution of the network, we commence with a baseline "business as usual" network. The "business as usual" network is dimensioned to deliver a 10 Mbps eMBB service at the cell edge taking into account the required coverage and signal levels. The network is also dimensioned to supply sufficient capacity such that the network can support historic and anticipated growth in consumption of eMBB services by German consumers from a traffic demand perspective. Section 4 describes this assumption in more detail. The demand evolution of the three port services, eMBB, automation of container handling and augmented reality, over the 2020 to 2030 analysis period, is then established against the anticipated "business as usual" eMBB demand in the area. Network dimensioning and evolution of the network over time is established against these demand profiles to calculate the volume of network elements deployed and accumulated costs. For the network dimensioning we employed a network and cost modelling tool which is described in Section 5.1

As networks evolve towards 5G they will become more flexible in the efficient delivery of eMBB as well as supporting more specialised capabilities such as mMTC and URLLC. For the purposes of the port network, we focussed the building of the network on the essential feature set required for the services. Enhanced reliability and coverage confidence were key targets to secure the quality of service required for industrial services. The following two features have been included in the network dimensioning (5G-MoNArch D3.2, 2019):

- *Multi-connectivity*: Multi-connectivity involves transmitting duplicate data from sites in areas where the signal to interference plus noise ratio (SINR) may be poor, but diversity of connectivity can be achieved to a minimum of two antenna sites to increase the probability of successful reception of the data. Applying this technique will improve coverage confidence if there is sufficient overlap in the coverage of existing sites in the areas where services requiring higher coverage confidence are being consumed. The result is that this technique reduces the need to always densify the network to deliver higher reliability connectivity. Hence the cost of supporting such services is reduced.
- *Tele cloud reliability*: Tele cloud reliability involves dimensioning the processing at the edge cloud sites to include some redundant processing, which is necessary to achieve the level of reliability required by the service.

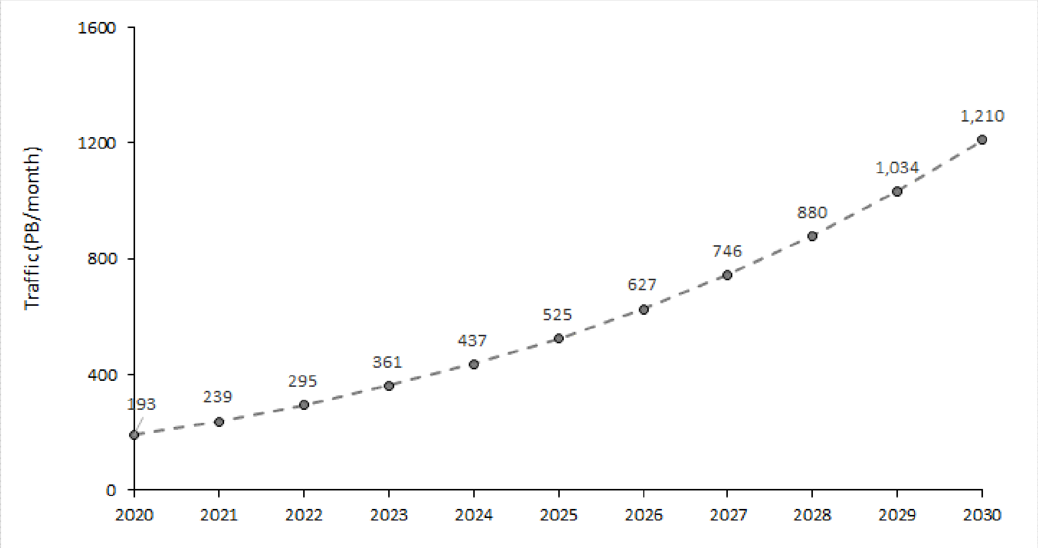
The availability of spectrum is also considered in the model. The 2G and 3G bands are initially excluded from available spectrum for the network until these bands are likely to have been re-farmed for 5G. It is assumed that the network would continue to make use of existing 4G spectrum and equipment and that a migration towards 5G NR would occur over time. Thus, the total spectrum available for the simulated network evolution and network dimensioning includes both 4G and 5G spectrum. To simulate the adoption of different technologies into the network over time, different spectral efficiencies are applied to different spectrum bands at appropriate times in the life of the network. Hence, the refarming of spectrum and transition to new air interfaces over time is emulated. The theoretically achieved spectral efficiency of the different wireless technologies takes into account the antenna configuration deployed on each antenna site at any point in time. Configurations up to 32 port active antennas are considered and are viable from a deployment and cost perspective within the timeframe of this project. Depending on the year and frequency band considered, different antenna configurations are applied. Further details on spectrum, spectrum efficiency and antenna configuration assumptions are given in (5G-MoNArch D6.3, 2019).

A network dimensioning exercise has been carried out to determine the number of sites and equipment required on each site to deliver the services in the study area over the 2020 to 2030 time period considered. The network dimensioning applied considers a virtualised 5G network using network slicing to provide the range of services considered as outlined in Section 3. These site and equipment volumes can then be translated into anticipated CAPEX and OPEX, which in turn are combined with revenues to give cashflows and return on investment in Section 6.

The cost analysis has used the following steps:

1. *Traffic demand*: For each of the three services considered in our analysis, we have developed a forecast of anticipated demand in the study area over the 2020-2030 time period.
    a. *eMBB*: As growth of mobile data consumption by consumer portable devices is inherently uncertain, we consider low, medium and high scenarios for eMBB demand in the study area. All three scenarios are aligned in 2017 with the mobile data consumption reported for Germany at that time by Cisco visual networking index (VNI) (Cisco, 2018). For the high scenario, we follow the Cisco VNI forecast where available and then apply a 30% growth rate that reduces over time, in line with Cisco VNI trends. For the low scenario, we apply a more conservative initial year on year growth rate of 20% which slowly declines over time. The medium scenario, which in our study corresponds to the baseline case, takes the average growth rate of the low and high scenarios. The traffic values for the baseline case are depicted in Fig. 9. These national demand forecasts are then translated to the study area based on the daytime population of the study area. An uplift to the residential population for visitors and commuters was assumed. The demand is further distributed, as described in (5G-MoNArch D6.3, 2019), between indoors and outdoors, over different days of the week and hours of the day, and spatially, so that points of interest in the study area attract more demand.

Fig. 9. Traffic demand for eMBB in the study area, baseline case.



b. *ACH:* The demand for ACH services is based on maintaining a constant throughput of 0.5 Mbps to all cranes, automated guided vehicles and stackers in the container terminals assumed to become automated. Hamburg contains four container terminals with one of these, Altenwerder, already automated. Therefore, we only consider automation of the remaining three terminals of Eurogate, Burchardkai and Tollerort with hypothetical automation dates of 2022, 2023 and 2025, respectively. ACH demand is localised to the relevant container terminal, which means that coverage is not required for these services across the entire port area.

c. *AR for construction:* Demand from AR devices supporting on-site inspections by HPA’s construction teams is based on delivering a 10Mbps continuous streaming service to up to 30 active devices at any one time. We assume that a low number of devices is initially deployed in 2020, and that this grows to 30 active devices by 2025. Furthermore, it will take time to equip all construction teams with such devices.

2. *Assessment of coverage and capacity:* Depending on the scenario being modelled and costed, the coverage requirements, in terms of coverage confidence, geographic area to be covered and throughput of each service is considered. The existing Hamburg network, as described in Section 2, is evolved. Network evolution is modelled by upgrading new sites with additional bandwidth or antennas or by deploying new macrocells or small cells to meet the coverage requirements for each year over the 2020 to 2030 time period. In the case of services requiring a 99.9% coverage confidence, we consider multi-connectivity as a mechanism for improving coverage confidence where sufficient overlap occurs between cell areas. The network dimensioning also considers the demand generated by the mix of services and devices in the study area in any year, and constantly evolves the network to accommodate this growing demand. In both cases, the most cost-effective network evolution option is selected based on

assessing the cost of additional equipment and site transmission required for each option that would meet the coverage or capacity shortfall.

3. *Network elements:* Having determined the volume and configuration of the antenna and edge cloud sites required in the study area for the combination of services being considered in any given year, this is next translated into an inventory of network elements. The network inventory includes the volume of antenna and edge cloud sites required and the supporting equipment and site transmission required on each of these. In the case of edge cloud sites, this includes translating the processing of the radio protocol stack, traditionally done in a basestation at the antenna site, into volumes of GPPs, servers and cabinets required.
4. *Cost calculation:* The inventory of network elements for each year in step 3 is finally combined with the CAPEX and OPEX per network element to give the network cost per year.

4.3.2 Calculation of virtualized network elements

As described in section 4.2, our analysis assumes a virtualised network architecture supporting network slicing. With this in mind, the network dimensioning tool must consider, not only more traditional RAN elements, such as the construction of antenna site structures, antennas and radio units, but also the cost associated with deploying servers in edge cloud sites to carry out the processing which in more traditional architectures would be done in base station equipment at the antenna site.

In dimensioning the edge cloud sites, we assume that existing data centre locations in the form of fixed telecoms exchanges are already available in the area. This is in line with feedback from mobile operators operating in the Hamburg area. We assume that space can be rented in these data centres and that the rent charged is proportional to the area that the edge cloud equipment occupies. To determine the area occupied in the data centre, a dimensioning exercise is performed on the number of cores required to do the processing for the antenna sites connected to the edge cloud site as described in (5G NORMA D2.3, 2017). This is then translated to the number of processors and hence the number of server blades that would be needed. We then assume that a cabinet can accommodate a maximum of 16 server blades to determine how many cabinets would be required at each edge cloud site in the network.

The footprint of the number of cabinets with associated air conditioning is then used to determine the site rental for the edge cloud sites. Utility costs are also assumed to be proportional to the number of cabinets installed. Site transmission costs between the edge cloud site and core network are also dimensioned in line with the bandwidth of connection required to support the volume of data expected from the number of antenna sites using each edge cloud site.

In dimensioning the number of cores required, we follow the methodology set out in (5G NORMA D2.3, 2017). This method has been reviewed and validated against more recent publications and benchmarking on the processing required for layers 1 to 3 of the 5G NR protocol stack in (5G MoNArch D4.2, 2019). We assume that the number of cores required at edge cloud sites is dominated by user plane processing and, in particular, layers 1 to 3 of the user plane.

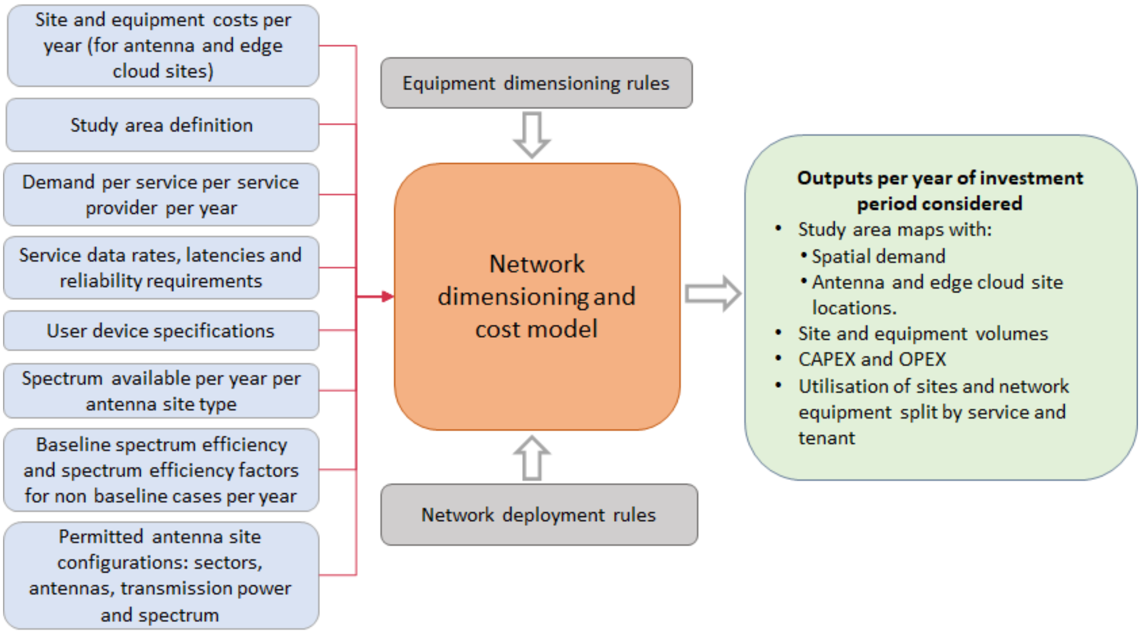
The above method for dimensioning the number of cores draws upon benchmarking of processing requirements as presented in (Nikaein, 2015). This is combined with the frequency of usage of different modulation and coding schemes in mobile networks in urban environments as presented in (Bhaumik et al., 2012), which will vary with SINR quality observed by the user equipment distributed across each cell. Combining these two sources leads to a dimensioning assumption that on average 1.37 high-end x86 processing cores would be required to process layers 1 to 3 of a 20MHz single input single output (SISO) channel. This baseline assumption can then be scaled depending on the bandwidth and multiple input multiple output (MIMO) order being used by the antenna sites connected to the edge cloud site being considered. A further aggregation margin of 25% is applied to provide additional processing beyond that required to carry the average expected network load and allow for peak conditions as per (5G NORMA D2.3, 2017).

5 Cost Analysis

5.1 Costing methodology

The above RAN dimensioning and cost analysis steps have been implemented in a MATLAB based tool, CAPisce. CAPisce was initially developed to understand the implications of regulatory decisions on the timing of releasing new spectrum bands for the UK regulator Ofcom (Real Wireless, 2012). Under the EU 5G PPP phase 1 5G NORMA project, this tool was then evolved to dimension and cost antenna sites, edge cloud sites and site transmission between these for virtualised 5G networks (5G NORMA D2.3, 2017). Under the EU 5G PPP phase 2 5G-MoNArch project, this tool was further enhanced to consider industrial services requiring higher levels of reliability. The requirement for higher reliability is considered in the network dimensioning in the tool in terms of coverage confidence, which was enhanced via multi-connectivity, and telco-cloud availability, which was enhanced via additional dimensioning of redundant processing at edge cloud sites. Finally, the framework for network costs in virtualised networks developed under 5G NORMA and 5G-MoNArch is being further used and developed under the EU 5G PPP phase 3 5G-TOURS project (5G-TOURS, 2020). Fig. 10 shows the input and output data of the network dimensioning and cost modelling tool, CAPisce.

Fig. 10: Overview of inputs and outputs of the network and cost dimensioning tool.



For each year, the tool considers the forecast demand for the wireless services being analysed and distributes it over the study area both spatially and for each hour of the day. The demand is then mapped to the existing antenna sites considering the spectrum bands, antenna configurations and air interfaces supported on each site for that particular year. The mapping of demand to sites is done in terms of coverage, via link budget calculations against the target service requirements, and capacity, based on spectrum efficiency per band, bandwidth per band and number of sectors. Table 8a shows the assumed number of macrocells and small cells in the network in 2020, which are further assumed to have been incorporated into the virtualised 5G network of the operator by 2020. The modelled 2020 network was based on available site databases for Hamburg evolved to meet the anticipated eMBB demand by 2020.

If the existing network is unable to meet the coverage or capacity requirements in any given year, the tool selects the most cost-effective option, from a 10-year total cost of ownership perspective, for evolving the network to meet this shortfall. Network evolution includes considering upgrades to existing sites, in terms of more bandwidth, frequency bands or antennas, or building new sites, which can be macrocells or small cells. The process is repeated from 2020 to 2030 giving as an output the list of sites and their corresponding equipment sets required to meet demand over this time period. The bill of materials can then be readily translated into costs.

Both CAPEX and OPEX are considered in the model in line with the cost elements outlined in Table 8b. Note the CAPEX labour cost is the cost associated with installation of radio equipment on the site and separate to the civil works cost which covers the cost of constructing the structure for mounting equipment on the mobile site as well as supporting cabinets, air-conditioning, etc. The transport CAPEX covers the installation of a fibre connection to the site that has been dimensioned for the fronthaul or backhaul requirements of the site. An example of site costs is given in Table 8c. The sum of OPEX and CAPEX then gives the total cost of ownership (TCO). These costs are based on those used under the 5G NORMA project which were then reviewed and evolved to be representative of costs in Hamburg (5G NORMA D2.3, 2017). These are average costs based on a collection of industry feedback and do not represent any one consortium partner's view. Network dimensioning and subsequent costs also include a replacement cycle of equipment in the network: macrocell antenna sites have a 10-year lifecycle; small cells a 5-year lifecycle; and servers on edge cloud sites a 4-year lifecycle, as based on commercial off the shelf (COTS) equipment with relatively short lifecycles.

The network dimensioning and cost analysis focuses on user plane processing requirements and the RAN elements of the network. When combining costs with revenues in the business case, as is described in Section 5 later, a 10% uplift is applied to this for control plane and core network costs, and a further 30% on top of this for administrative costs in line with (5G NORMA D2.3, 2017; 5G-MoNArch D6.3, 2019).

Table 8. a) Main assumptions, b) RAN cost elements, c) Relevant RAN unit costs.

a)

Item	MNO
Number of macrocell sites, start of 2020	90
Number of small cell sites, start of 2020	5
Number of edge cloud sites	4
Market penetration for eMBB to consumer portable devices	33%

b)

	Macrocell	Small cell	Edge cloud
CAPEX	Civil works and acquisition	Civil works and acquisition	Processing servers
	Antennas/feeder	Antennas/feeder	Cabinets
	RF front end and baseband	RF front end and baseband	-
	Labour for equipment installation	Labour for equipment installation	Labour for equipment installation
	Transport (fronthaul)	Transport (fronthaul)	Transport (backhaul)
OPEX	Site Rental	Site Rental	Site Rental
	Power costs	Power costs	Power costs
	Licensing and maintenance	Licensing and maintenance	Licensing and maintenance
	Transport	Transport	Transport
	Site visits and on-site maintenance	-	Site visits and on-site maintenance

c)

Item	€k
CAPEX macrocell antenna site with (low band, 2x4, 20 MHz)	80
OPEX macrocell antenna site with (low band, 2x4, 20 MHz)	20 per annum
CAPEX small cell site with (low band, 2x4, 20 MHz)	27

OPEX small cell site with (low band, 2x4, 20 MHz)	2 per annum
CAPEX edge cloud site example upgrade cost[1]	51
OPEX edge cloud site example running cost[2]	52 per annum

[1] In 2025 a typical edge cloud site adds 3 working + 1 spare server and refreshes 4 working servers.

[2] In 2025 a typical edge cloud site has 26 working + 3 spare servers.

5.2 Cost Results

In line with the three services discussed in Section 2.3, we present in this section the results of the network dimensioning and cost modelling in the Hamburg study area for the following three scenarios:

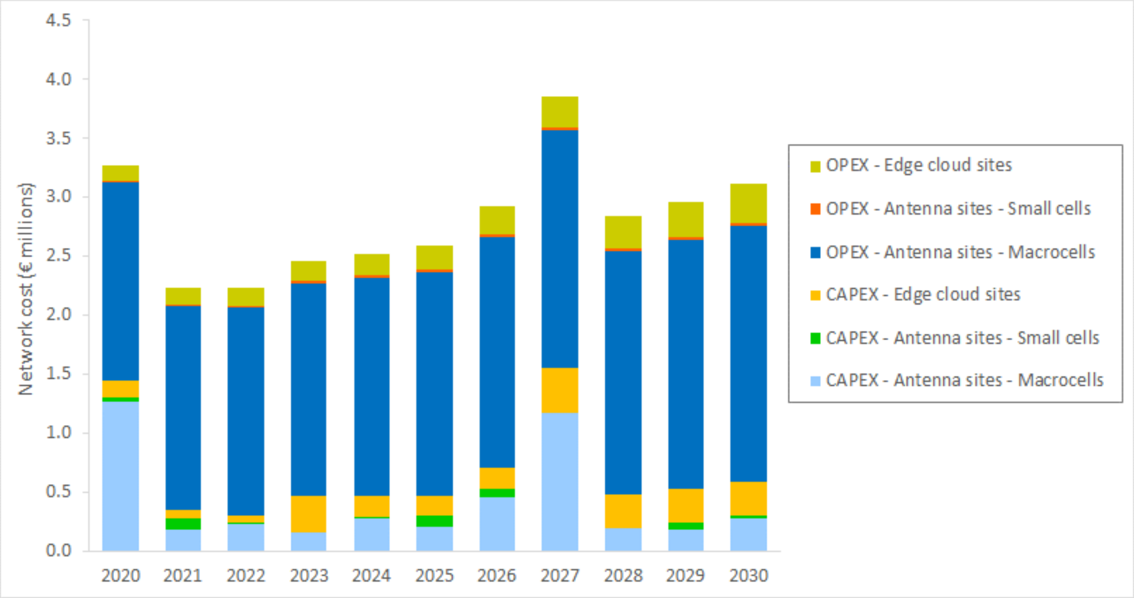
- *Baseline eMBB only*: It is "business as usual" eMBB provision to consumer portable devices across the entire study area, representing the anticipated 5G roll-out of a single MNO in the area without the inclusion of industrial services.
- *eMBB with ACH*: It provides reliable wireless connectivity to the container terminals in the port area to support automation in addition to the baseline eMBB services.
- *eMBB with AR:* It provides an AR service to the HPA across the port area in addition to baseline eMBB services.

All results are presented over a 2020 to 2030 timeframe with the split between CAPEX and OPEX and different site types shown in each case.

5.2.1 Costs of providing eMBB to the study area

Fig. 11 shows the resulting CAPEX and OPEX of the RAN elements of the mobile network of a single network operator obtained from the cost model when considering solely eMBB demand in the Hamburg study area. The costs are split between antenna sites, with both macrocells and small cells, and edge cloud site costs. The antenna sites contain the antennas, the RF front end and the site fronthaul, whereas the edge cloud sites contain the baseband unit. As expected, OPEX is greater than CAPEX in all years and grows gradually over time as more or upgraded sites are added to the network to deal with the growing eMBB demand. The network CAPEX is large in 2020 as the network gets repurposed in this year for eMBB targeting 10Mbps cell edge data rates. In subsequent years, a consistent amount of CAPEX is spent each year to cover the cost of new equipment on upgraded sites, or on building new sites to keep pace with demand. There is a particularly high CAPEX in 2027 as a large number of existing macrocell sites were due for renewal in this year. It was assumed that macrocells have a 10-year life span.

Fig. 11. Cost composition, eMBB: CAPEX and OPEX over time.

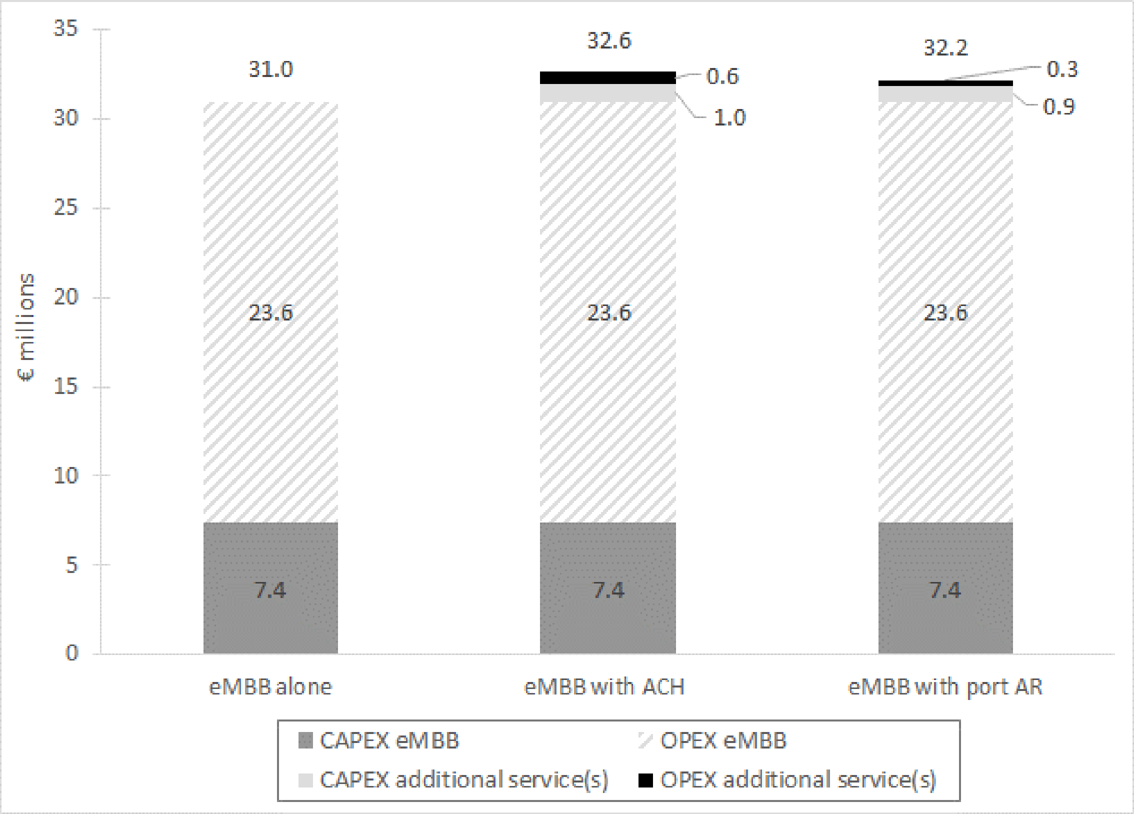


5.2.2 Costs of automating the container terminals and providing port wide augmented reality

Fig. 12 shows the total cost of the RAN summed from 2020 to 2030 for the three scenarios of providing:

- The baseline eMBB network, as per Section 5.2.1.
- Both eMBB services and ACH services to the container terminals in Hamburg Port. As discussed in Section 3.3, ACH services consider automation of three terminals of Eurogate, Burchardkai and Tollerort with hypothetical automation dates of 2022, 2023 and 2025 respectively.
- Both eMBB services and AR services to the Hamburg Port Authority. In contrast to the ACH services which are only required at the container terminals, these AR services are to be provided across the entire port area.

Fig. 12. RAN costs of providing the ACH and AR services over the time period 2020-2030.



In the case of adding ACH, the results show an additional cost of €1.6m over the total time period for changing the eMBB network rollout to accommodate more reliable ACH services as well. This is a 5.2% increase over eMBB alone. The observed relatively small increase in costs, despite the high reliability requirement, is because the coverage area for ACH is localised to the container terminals.

Though port AR has higher demand levels and a wider coverage area than required for ACH, it has a lower reliability requirement. The 2020-30 cumulative network cost of providing these AR services amounts to €1.2m more than the cost of providing eMBB alone, which corresponds to a 3.9% increase on eMBB alone.

Overall, in the case of adding support for either ACH or AR services to the existing eMBB network, the extra cost is relatively modest. This is because the volume of industrial users and hence the volume of mobile demand created by these services is relatively low compared to eMBB demand across the study area. Additionally, in the case of ACH, although higher reliability is required, the coverage area is very localised.

6 Results of the business case

6.1 Baseline case

6.1.1 Approach for the business case calculation

In this section the results of the business case for the baseline case are presented. The following financial measures were employed: the business case net present value of cash flows (CFs), which corresponds to the discounted cumulative cash flow (DCCF) (ECOSYS D9, 2005); the payback period and the undiscounted return on investment. A commercial discount rate for MNOs of 10% was used (5G-MoNArch D6.3, 2019).

The business case NPV was calculated as follows:

$$\mathrm{NPV} = -\,\mathrm{CF}_0 + \sum_{i=1}^{n} \frac{CF_i}{(1+rate)^i}$$

where i is the time of the cash flow, n is the total time period studied, CF_i is the net cash flow at time i, and CF_0 is the capital outlay at the beginning of the investment at time t = 0.

The ROI was calculated according to the following formula by employing a high-level estimate:

$$ROI = \frac{(Total\ revenues - Total\ Costs)_{2020-2030}}{Total\ Costs_{2020-2030}}$$

6.1.2 The business case for broadband (eMBB)

In Table 9 we combine revenues and costs to give the baseline business case for consumer focused broadband services, eMBB, in the Hamburg study area. Table 9 reflects the business case for an MNO with a 33% market share. A 10% discount rate is applied in the cumulative discounted cashflow calculation (DCF). The return on investment over the 2020-2030 time period is 189% for this case. Note that this ROI represents the eMBB business case in the study area alone and not nationally for Germany. Moreover, it is very positive due to the favourable density of subscribers in urban environments like central Hamburg. While the cost and revenue figures in Table 9 are not discounted by the operator's cost of capital, the cumulative DCF reflects the discounted cost and revenue figures. The payback period is less than one year. These results are also illustrated in Fig. 13.

Fig. 14 shows the NPV of the three use cases analysed: eMBB, ACH and AR. These results show that eMBB remains the dominant source of cashflow in this scenario, but that this is improved marginally by the additional of AR and to a greater extent by the addition of ACH services. The business case for each of these is examined in more detail in Sections 5.1.3 and 5.1.4.

Table 9. Cost, revenue and business case results, baseline scenario for eMBB, Hamburg study area, single operator with 33% market share.

(€ millions)	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**Total**
Total revenues	12.2	12.2	12.3	12.4	12.5	12.6	12.7	12.9	13.2	13.6	14.0	140.5
Total RAN costs	3.3	2.2	2.2	2.5	2.5	2.6	2.9	3.9	2.8	3.0	3.1	31.0
Total costs (incl. core and overheads)	5.1	3.5	3.5	3.9	4.0	4.1	4.6	6.1	4.5	4.7	4.9	48.7
Undiscounted cashflow	7.1	8.7	8.8	8.6	8.5	8.5	8.1	6.8	8.7	8.9	9.1	91.8
Discounted cashflow	6.5	7.2	6.6	5.8	5.3	4.8	4.2	3.2	3.7	3.4	3.2	-
Cumulative discounted cashflow	6.5	13.6	20.2	26.1	31.4	36.2	40.3	43.5	47.2	50.6	53.8	-

Fig. 13. eMBB, baseline case: Revenues and Business Case NPV.

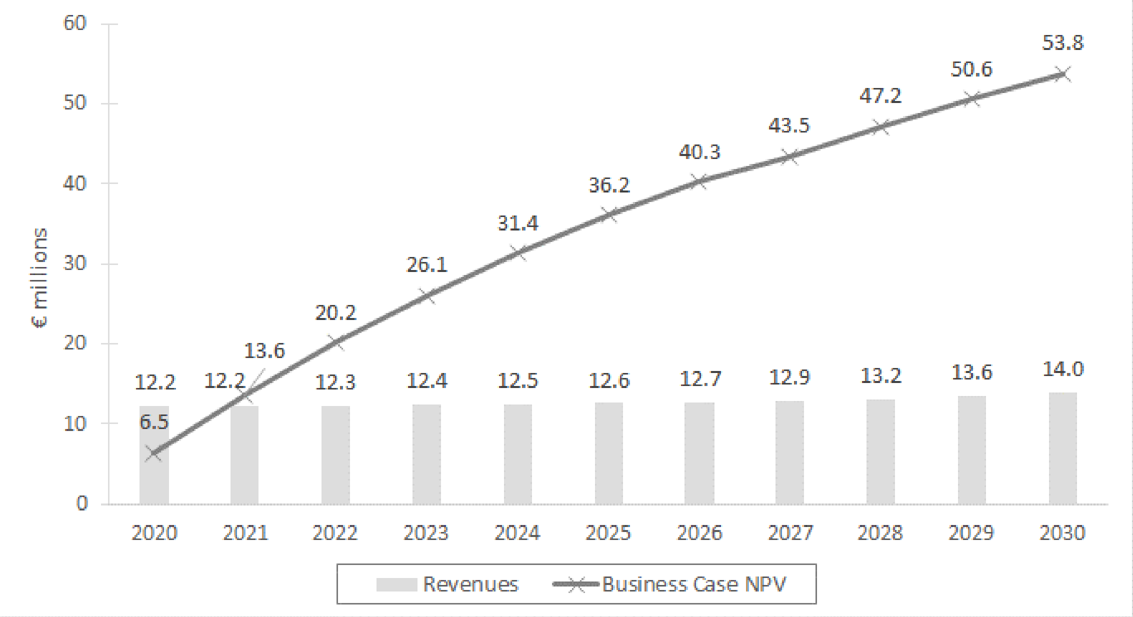
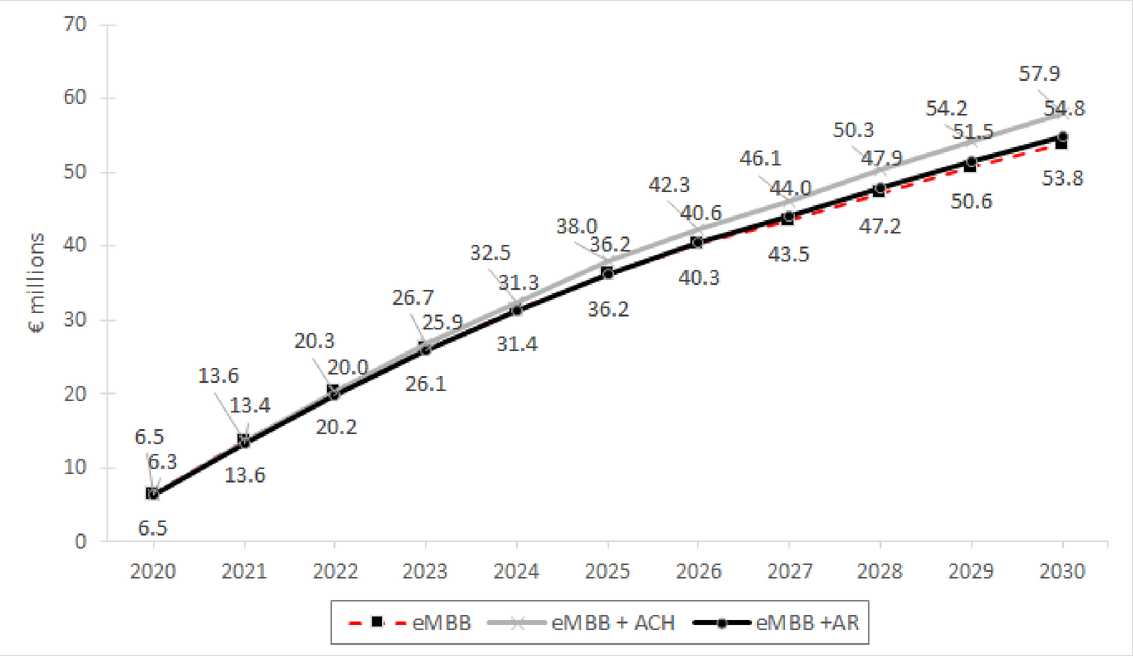


Fig. 14. Baseline case, Business Case NPV of the three use cases: eMBB, eMBB + ACH and eMBB + AR.



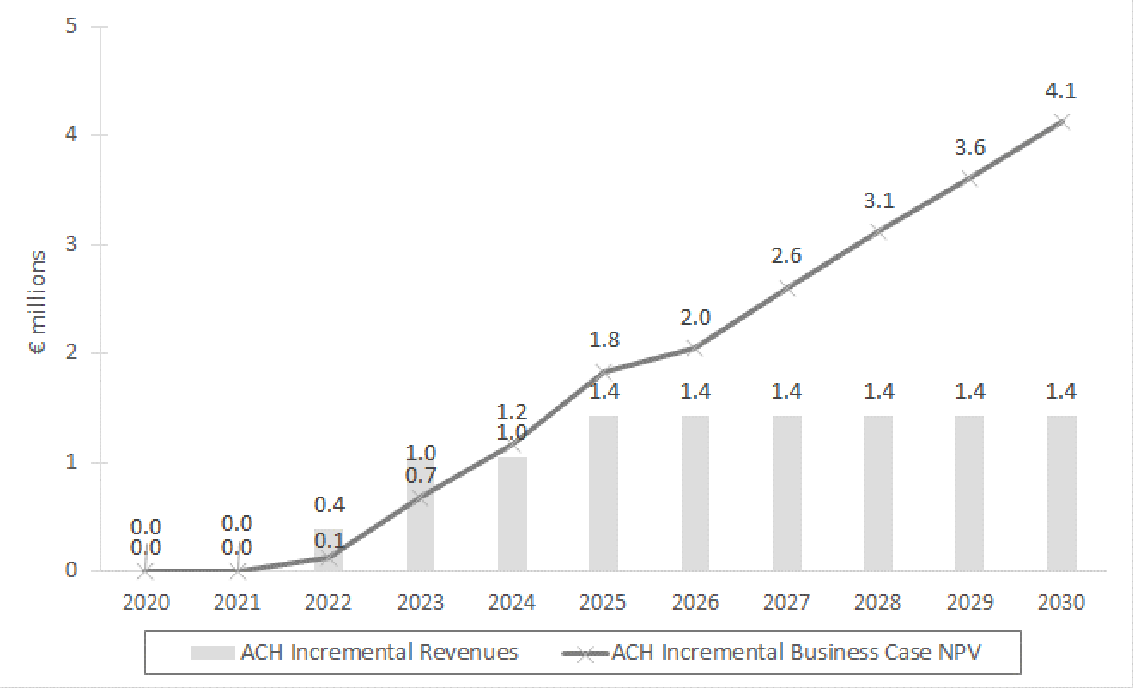
6.1.3 The business case for ACH

The ACH service is provided on top on the eMBB service. In this section we show the delta or change in revenue and costs, compared with the eMBB only case, for the case when ACH is also provided. These incremental revenues and costs for ACH, beyond the eMBB only case, are shown in Table 10. The discounted cashflow over time for ACH is calculated and shown in Table 10 and Fig. 15. The results highlight that ACH has a positive impact on cashflow throughout the investment period, adding €4.1m to the cumulative DCF by 2030. The cashflow impact of adding the ACH service to the eMBB network is positive from the initial year of investment, which is year 2022. The ROI for adding ACH is 378%.

Table 10. Cost, revenue and business case results, baseline scenario for delta ACH, Hamburg study area, single operator with 33% market share.

(€ millions)	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	Total
Total revenues	-	-	0.4	1.0	1.0	1.4	1.4	1.4	1.4	1.4	1.4	11.0
Total RAN costs	-	-	0.1	0.2	0.2	0.2	0.6	0.1	0.1	0.1	-0.0	1.6
Total costs (incl. core and overheads)	-	-	0.2	0.2	0.2	0.3	1.0	0.2	0.2	0.2	-0.1	2.5
Undiscounted cashflow	-	-	0.2	0.8	0.8	1.2	0.4	1.2	1.2	1.3	1.5	8.5
Discounted cashflow	-	-	0.1	0.5	0.5	0.7	0.2	0.6	0.5	0.5	0.5	-
Cumulative discounted cashflow	-	-	0.1	0.7	1.2	1.8	2.0	2.6	3.1	3.6	4.1	-

Fig. 15. Baseline case, Delta case for ACH: Revenues and Business Case NPV



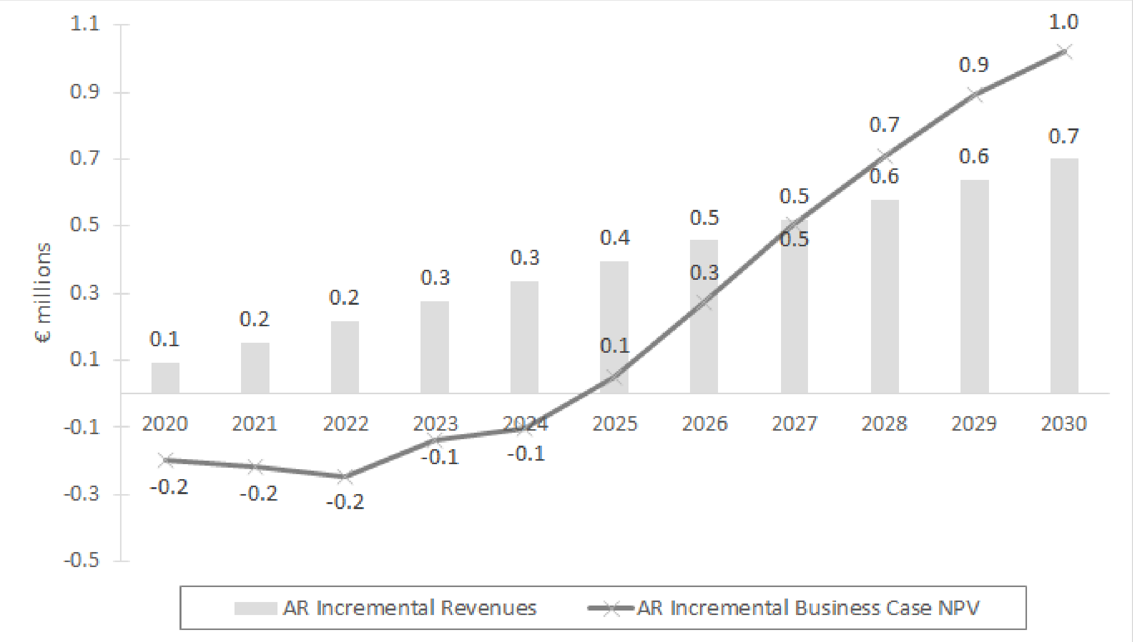
6.1.4 The business case for AR

The AR service is provided in addition to the eMBB service. In this section we show the revenue and costs for the delta AR case or the change in revenues and costs when delivering AR compared to delivering eMBB alone. Table 11 shows the incremental revenues and costs associated with providing AR services in the study area. The DCF over time is also calculated and shown in Table 11 and Fig. 16. In contrast to ACH, providing the AR service in this scenario has a minor but negative impact on cashflow over the first 5 years. By 2030, AR adds €1m to the DCF compared with eMBB alone. This represents an ROI of 130% compared to the investment required to support AR services. However, the payback period for AR is 5 years and much longer than for the other services analysed in this article. The observed longer payback period represents risk over the first 5 years of investment that will only be rewarded in the longer term and to a much more marginal extent than the other services considered.

Table 11. Cost, revenue and business case results, baseline scenario for delta AR, Hamburg study area, single operator with 33% market share.

(€ millions)	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	Total
Total revenues	0.1	0.2	0.2	0.3	0.3	0.4	0.5	0.5	0.6	0.6	0.7	4.4
Total RAN costs	0.2	0.1	0.2	0.1	0.2	0.1	0.0	0.0	0.1	0.1	0.2	1.2
Total costs (incl. core and overheads)	0.3	0.2	0.3	0.1	0.3	0.1	0.0	0.0	0.1	0.2	0.3	1.9
Undiscounted cashflow	-0.2	-0.0	-0.0	0.2	0.1	0.3	0.4	0.5	0.5	0.5	0.4	2.5
Discounted cashflow	-0.2	-0.0	-0.0	0.1	0.0	0.2	0.2	0.2	0.2	0.2	0.1	-
Cumulative discounted cashflow	-0.2	-0.2	-0.2	-0.1	-0.1	0.1	0.3	0.5	0.7	0.9	1.0	-

Fig. 16. Baseline case, Delta case for AR: Revenues and Business Case NPV.



6.2 Sensitivity Analysis

6.2.1 Scenarios

A sensitivity analysis was also performed against the baseline results, presented in Section 5.1. The sensitivity analysis aimed to test the sensitivity of our results to assumptions on:

- eMBB traffic growth over time: baseline and traffic high.
- Revenues per service or price plan: (eMBB: -15%, -30%; ACH: -15%, -30% and AR: -15%, -30%).

A summary of the cases applied in our sensitivity analysis are shown in Table 12 and include:

- Baseline case: Baseline eMBB demand and revenues per service, as presented earlier.

- The impact of mobile traffic forecast assumptions:
  - Case 2: Higher eMBB data consumption than in the baseline scenario, requiring more network capacity.
- The impact of revenue assumptions:
  - Case 1: Baseline eMBB traffic demand but flexing revenues per service by -15% and -30%.
  - Case 3: High eMBB traffic demand but flexing revenues per service by -15% and -30%.

Table 12. Scenarios for the sensitivity analysis.

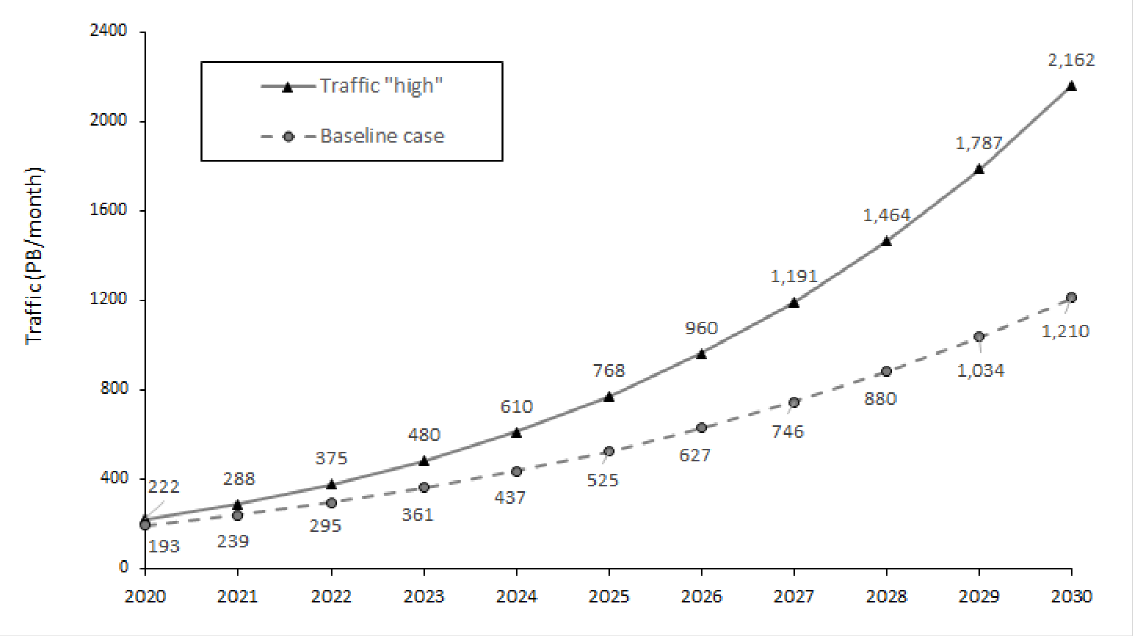
	Revenues: baseline	**Revenues (modification of baseline)**
Cost: baseline **(Baseline traffic)**	**Baseline Case** baseline traffic & baseline revenues	**Case 1:** baseline traffic & values to be applied to the baseline Revenues: -15%, -30%
Costs: high **(Traffic high)**	**Case 2:** traffic high, baseline revenues	**Case 3:** traffic high & values to be applied to the baseline Revenues: -15%, -30%

6.2.2 Results of the sensitivity analysis

6.2.2.1 Sensitivity of eMBB only business case

Fig. 17 shows the traffic forecast employed to calculate the case of traffic “high”. The traffic “high” case is different from our baseline eMBB traffic forecast in that it follows more aggressive industry forecasts on the CAGR for mobile traffic. As described in Section 4.3.1, our baseline and high scenarios are both aligned in 2017 with the mobile data consumption reported for Germany at that time by Cisco VNI (Cisco, 2018). For the high scenario, we follow the Cisco VNI forecast for the years available in this forecast. We then apply a 30% growth rate that reduces over time, in line with Cisco VNI trends, for the remaining years out to 2030.

Fig. 17. Traffic forecast: baseline case and case of traffic “high”.



Applying the high demand scenario to our cost model for the Hamburg port area, generates the cost results shown in Fig. 18 compared with our baseline cost results. Fig. 18 shows that to accommodate the additional demand, additional sites and higher capacity sites are required in the high demand case over the 2020-2030 timescale examined. Notably, from 2028 onwards the high demand scenario has consistently much higher costs than the baseline demand scenario. This is because by this time the capacity upgrade options that can be applied to existing sites, i.e., the employment of more frequency bands, bandwidth or higher orders of MIMO antennas, become exhausted and, therefore, a costly densification of the network is required.

Fig. 18. CAPEX and OPEX: baseline case and case of traffic “high”.

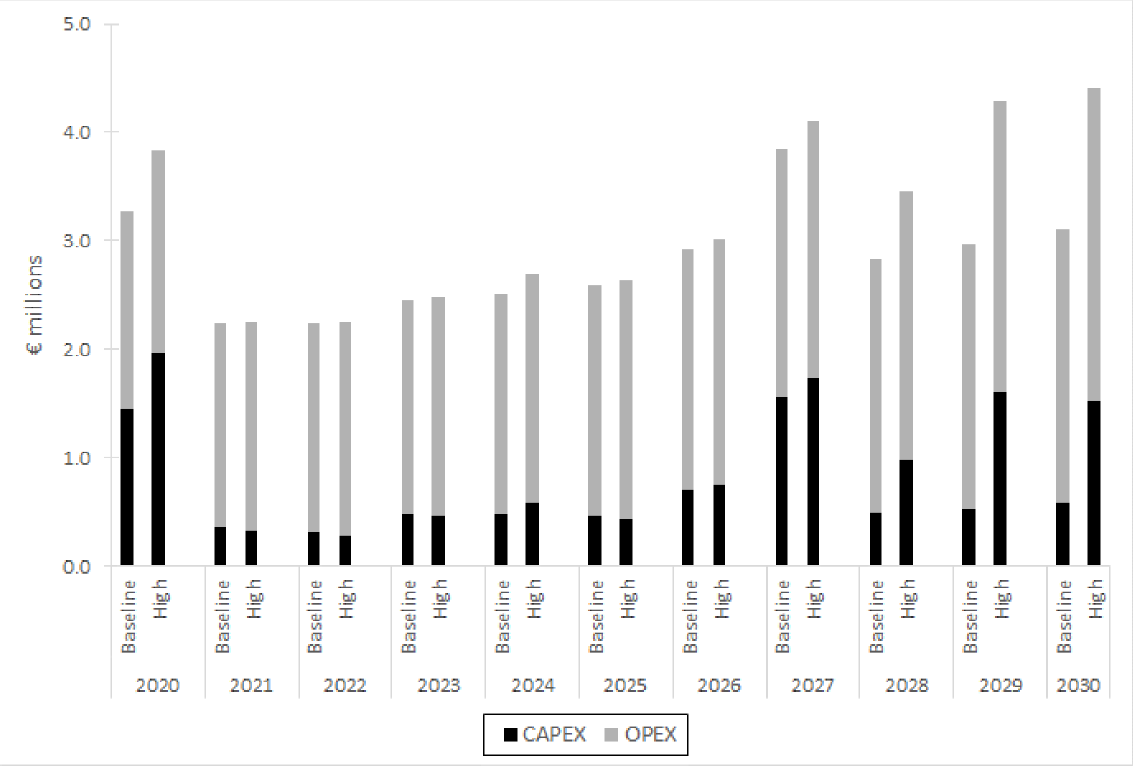
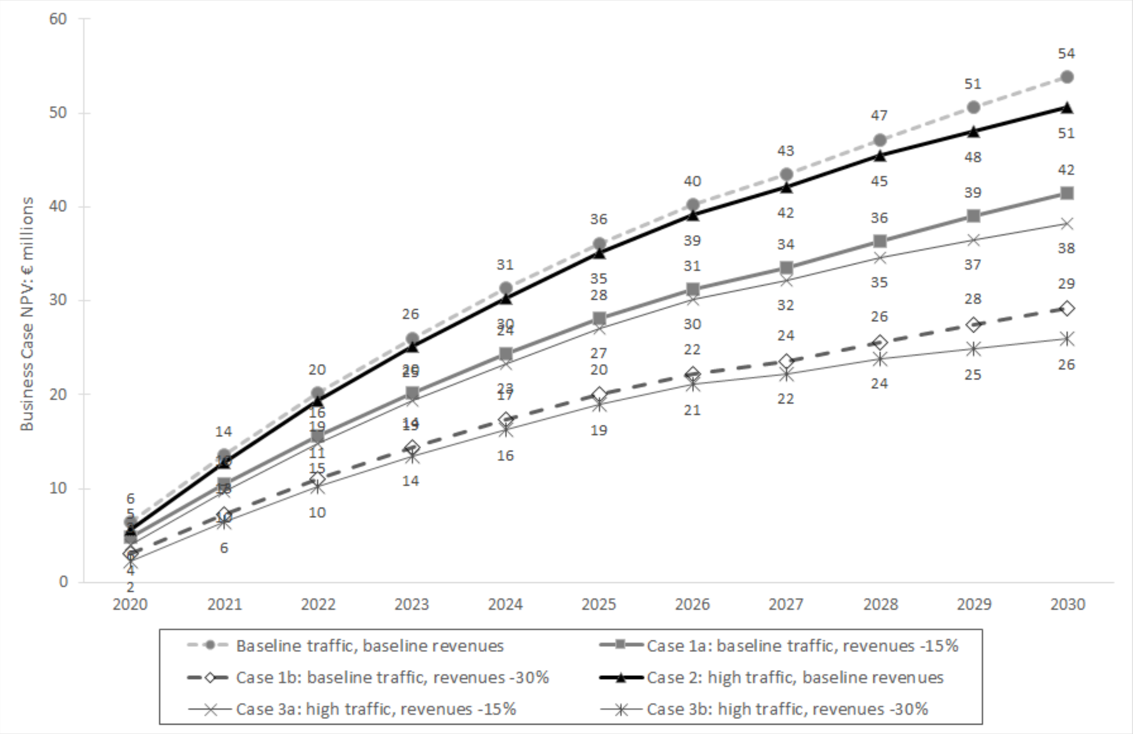


Fig. 19 shows the impact that the increase in eMBB traffic scenario has on the overall eMBB business case. Assuming the baseline eMBB price plan uptake and ARPUs, and a high demand scenario, which is case 2, the cumulative DCF is reduced by €3.4 million by 2030 or 6%.

However, while mobile demand trends are inherently difficult to predict, there is also considerable uncertainty around the willingness of consumers to pay for mobile services. The current outbreak of COVID-19 has had wide reaching economic consequences worldwide and will likely reduce the income that consumers have available for services such as mobile connectivity. To understand the impact of this and subsequent risk to the eMBB baseline business plan, we flex eMBB revenues by -15% and -30% in our sensitivity analysis and couple this with the baseline cost and high cost scenarios. Results for these scenarios are also shown in Fig. 19 with the worst case analysed of high cost and revenues -30%, case 3b, showing a reduction of ROI over the 2020 to 2030 time period to 77% compared with 189% in the baseline case. For case 3b, in comparison with the baseline case, there is a reduction of the cumulative DCF of €27.8 million or 52% by 2030.

Fig. 19. Sensitivity analysis of business case NPV for eMBB: baseline case and Cases 1, 2 and 3.



6.2.2.2 Sensitivity of ACH service

We next examine the sensitivity of the incremental business case for ACH to revenue forecast assumptions for this new industry focused mobile service. Being a new category of mobile service without historical ARPUs, the willingness of industrial users to pay for such a service will have some uncertainty. As was the case for the eMBB business case sensitivity analysis, this willingness to pay might again be impacted by the economic implications of the current COVID-19 pandemic.

Fig. 20. shows the impact of reducing the ACH revenue forecasts by 15% and 30%. In all cases, the addition of the ACH service to the eMBB network still has a positive impact on the incremental cashflow due to ACH in all years. The payback period for repurposing the network to accommodate ACH remains less than 1 year, i.e., from 2022 onwards when ACH is first introduced.

Fig. 20. Sensitivity analysis of business case NPV, delta case for ACH: baseline case and Cases 1, 2 and 3.

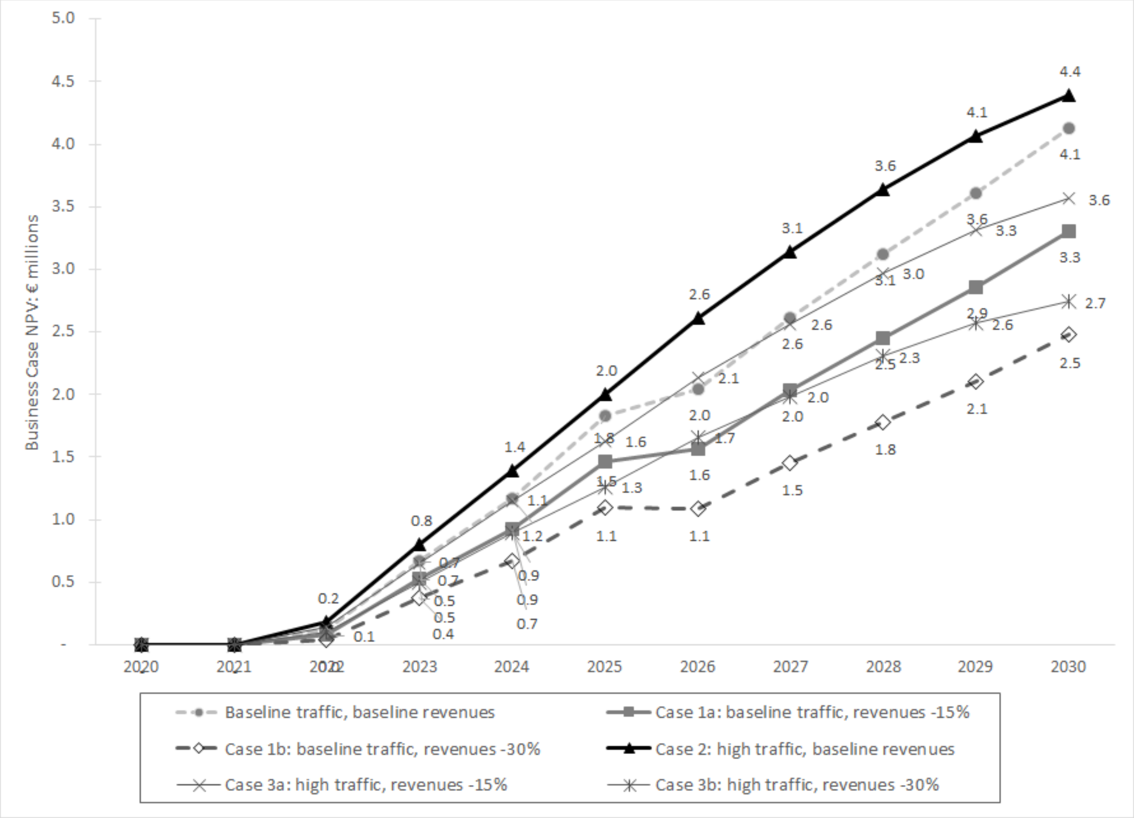


Table 13. Additional RAN costs necessary to provide the ACH and AR services for the case of traffic "high".

(€ millions)	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	Total
ACH	0.0	0.0	0.1	0.1	0.1	0.2	0.1	0.2	0.2	0.2	0.3	1.5
AR	0.2	0.5	0.3	0.9	0.3	0.9	1.2	0.7	0.9	0.6	1.5	8.0

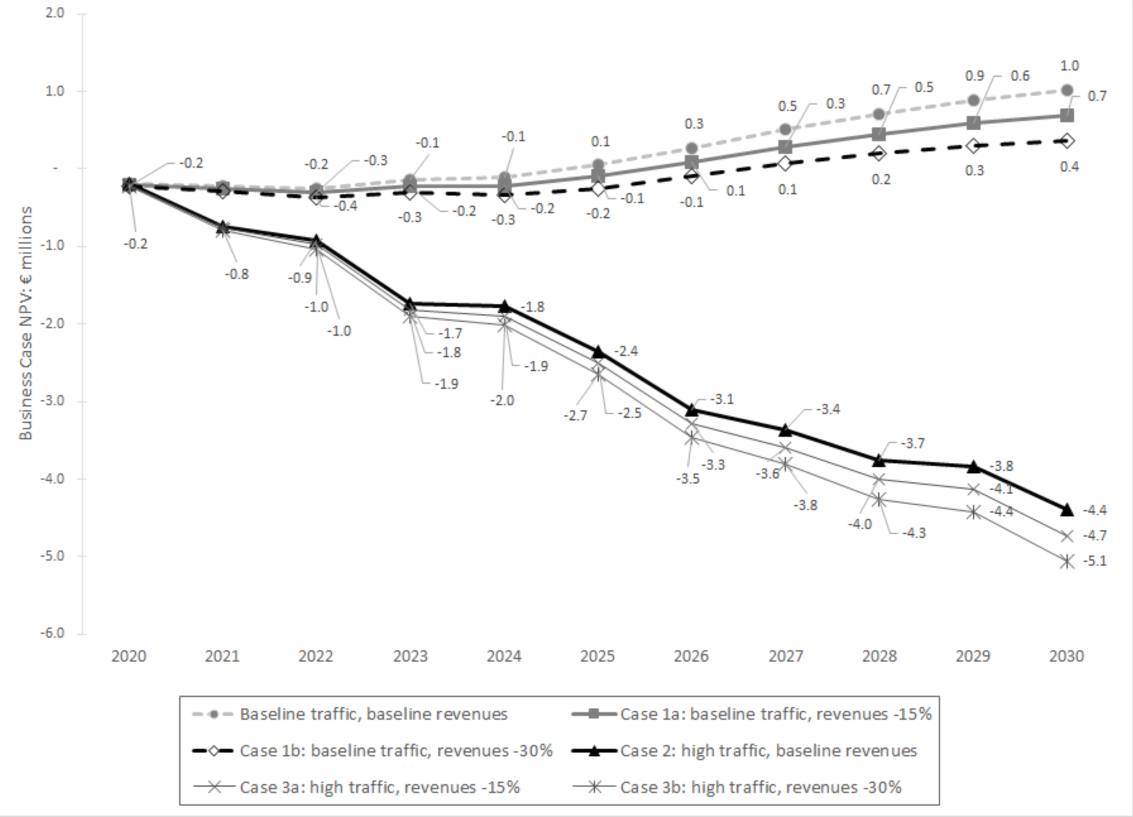
The capacity provided for eMBB in the high demand scenario helps to provide more capacity and this capacity can also be employed by other services, such as ACH. In our analysis, in the high demand scenario it was found that there is enough eMBB-related capacity than can be employed for the ACH case. The total RAN incremental cost of supporting ACH is slightly lower, €1.5m from Table 13, compared with €1.6m for the baseline scenario, which is shown in Fig. 12. This occurs because in the high demand scenario, the eMBB network is densified earlier in the time period modelled. The network densification driven by eMBB is beneficial for improving the reliability of the mobile signal in the container terminals required for ACH and means that less additional infrastructure is required to support ACH in the high demand scenario than in the eMBB baseline traffic scenario.

6.2.2.3 Sensitivity of AR service

In the sensitivity analysis for port AR services, we also examine the incremental cost of supporting port AR on an eMBB network rolled out to cope with the high demand scenario. Table 13 shows the resulting incremental cost for AR. These values are now much higher than was the case in the baseline demand scenario shown on Fig.10, i.e., €8.0m vs. €1.2m, respectively. In contrast to the ACH service, the port AR service is a high bandwidth service required over a large coverage area. Initially, in 2020, the cost of accommodating the AR traffic is the same in both the baseline and high demand eMBB cases. However, from 2021 onwards accommodating the extra traffic from port AR becomes more costly in the high eMBB demand case than in the baseline case. This is because, in the high demand scenario, it is more likely that less costly upgrades to existing RAN sites, such as adding carriers, increasing MIMO order, etc., will already have been applied to accommodate the high eMBB demand. Therefore, the extra capacity required for AR is more likely to require new sites, and hence incur higher costs, than was the case in the baseline demand scenario. Fig. 21 shows a much more negative business case for AR in the high demand scenario due to these higher costs.

Fig. 21 also shows the impact of reducing AR revenue forecasts by 15% and 30%. These results show that each 15% reduction in revenues from AR can delay the payback period by a further year. Fig. 21 shows that the incremental DCF does not go positive until 2026 and 2027 for the -15% and -30% AR revenue cases, respectively. However, in the baseline revenue case the incremental DCF is positive by 2025.

Fig. 21. Sensitivity analysis of business case NPV, delta case for AR: baseline case and Cases 1, 2 and 3.



6.2.2.4 Summary of results

Table 14 summarises the outcome of the financial indicators related to all the scenarios studied.

Table 14. Main economic indicators.

Service	Scenario	Business case NPV: € millions	ROI	Payback period	Evolution of NPV of business case
eMBB	eMBB, baseline case	53.8	189%	within 1st year	upwards trend
	eMBB, Case 1a: baseline traffic and revenues lower (-15%)	41.5	145%	within 1st year	upwards trend
	eMBB, Case 1b: baseline traffic and revenues lower (-30%)	29.2	102%	within 1st year	upwards trend
	eMBB, Case 2: Traffic high and baseline revenues	50.6	153%	within 1st year	upwards trend
	eMBB, Case 3a: traffic high and revenues lower (-15%)	38.3	115%	within 1st year	upwards trend
	eMBB, Case 3b: traffic high and revenues lower (-30%)	26.0	77%	within 1st year	upwards trend

ACH	Delta ACH, baseline case	4.1	342%	within 1st year	upwards trend
	Delta ACH, Case 1a: baseline traffic and revenues lower (-15%)	3.3	275%	less than 1 year	upwards trend
	Delta ACH, Case 1b: baseline traffic and revenues lower (-30%)	2.5	209%	within 1st year	upwards trend
	Delta ACH, Case 2: Traffic high and baseline revenues	4.4	378%	within 1st year	upwards trend
	Delta ACH, Case 3a: traffic high and revenues lower (-15%)	3.6	306%	within 1st year	upwards trend
	Delta ACH, Case 3b: traffic high and revenues lower (-30%)	2.7	235%	within 1st year	upwards trend
AR	Delta AR, baseline case	1.0	130%	5 years	upwards trend
	Delta AR, Case 1a: baseline traffic and revenues lower (-15%)	0.7	95%	6 years	upwards trend
	Delta AR, Case 1b: baseline traffic and revenues lower (-30%)	0.4	61%	7 years	upwards trend
	Delta AR, Case 2: Traffic high and baseline revenues	-4.4	-65%	negative business case in all years	downwards trend
	Delta AR, Case 3a: traffic high and revenues lower (-15%)	-4.7	-70%	negative business case in all years	downwards trend
	Delta AR, Case 3b: traffic high and revenues lower (-30%)	-5.1	-76%	negative business case in all years	downwards trend

7 Assessment of the results

In this section, we summarise the key findings from across the business case results previously presented in this article and make recommendations based on these.

7.1 Overall assessment of the results

The analysis of the eMBB baseline business case in Section 6.1.2, shows that in large city environments, like Hamburg, eMBB will continue to provide an important source of income and return on investment for MNOs up to 2030. For the baseline eMBB scenario examined, NPV grew to €53.8m by 2030 representing a return on investment over the period 2020 to 2030 of 189%. The payback period was less than one year.

The sensitivity analysis for eMBB described in Section 6.2.2.1 shows that the eMBB business case is more sensitive to revenue assumptions than traffic forecasts. Higher eMBB demand will require more network infrastructure and hence increase network costs. However, for the high traffic forecast modelled, this only reduced the NPV for eMBB to €50.6m by 2030 and reduced

ROI by 36% to 153%. The worst-case scenario examined for eMBB of high traffic and revenues 30% lower led to a NPV of €26m by 2030 and reduced ROI to 77%. For all the cases studied the payback period was less than one year and the NPV showed a positive development over the time period 2020-2030. The positive business case that was found for the eMBB case in this article is aligned with the results for the eMBB business case that were analysed in (Rendon Schneir et al., 2019). In (Rendon Schneir et al., 2019) it was found that for the majority of eMBB cases study the business case was positive.

This article has also presented results on the business case for MNOs to broaden the range of end users that they deliver services to and provide connectivity at higher KPI levels for industrial users via network slicing. The business cases for automated container handling and augmented reality have been studied as delta cases which work on top of the eMBB business case.

The baseline analysis of offering ACH services to the container terminals around Hamburg port in addition to satisfying the baseline eMBB traffic levels, shows that ACH could add a further €4.1m to the eMBB baseline business case NPV of €53.8m by 2030. Compared to providing eMBB alone, this is a modest improvement in NPV. However, it is worth noting that the ratio of increased revenues due to ACH, compared with the extra costs required to deliver ACH, is very high. The incremental ROI for ACH is 342% in the baseline case examined. In the case of ACH, the payback period was less than one year. The sensitivity analysis has shown that this incremental ROI for offering ACH remains high even in the worst-case scenario of ACH revenues being 30% less than forecast. In this case, the incremental NPV fell to €2.5m with an incremental ROI of 209%.

Finally, the business case analysis of offering AR services to the port authority’s construction engineers, in addition to satisfying the eMBB traffic levels in the study area, showed a much weaker incremental business case for AR than was the case for ACH. In the baseline case, AR services only added €1m to the €53.8m NPV of eMBB alone of by 2030. The incremental ROI is 130% for AR, which is much less than in the ACH case. The incremental cashflow for AR also shows that it would take 5 years in the baseline case before the initial network investments to support AR would be returned in the form of cumulative revenues. The sensitivity analysis for AR shows that in the case of having to keep pace with high traffic demand on the eMBB network, the business case for offering AR becomes negative in all years. The ROI drops to between -65% and -76% for the high traffic cases analysed. This highlights further the level of risk associated with offering this type of service at the revenue levels forecast in our analysis.

Overall, our analysis shows that when choosing industrial services to invest in MNOs need to be cautious as not all new service offerings may have a strong business case. The eMBB results show that MNOs should continue to prioritise the eMBB market as this is likely to provide the main source of revenue and return on investment for their networks going forwards. In the case of services like ACH, there are very clear tangible benefits and the willingness to pay, and hence the potential revenues, for delivering the high reliability but localised connectivity required, should be high in comparison with the corresponding costs. In the case of providing AR services across the entire port area, the network investment required to meet required KPIs and mitigate any impact on existing eMBB services will be over a much wider area. However, the benefits of such services such as reductions in overspend in construction projects are less well proven as yet, and as such the willingness to pay and forecast revenues remain relatively modest compared with the level of additional investment needed.

7.2 Strategic implications

This section analyses the strategic implications of the results presented. Firstly, the results of the business case will have an effect on the different parties involved in providing the 5G services. The MNOs will be motivated to continue investing in 5G infrastructure that provides customers with localised eMBB services. This can be done by upgrading the current wireless cellular infrastructure. For the ACH use case there is also a positive business case and it is possible that the MNOs will be motivated to make the corresponding investment on its own and to sell the services to the container terminal operator. As the sensitivity analysis has shown that the risks of having a profitable business case for the augmented reality use case is high, a possible solution might be that to provide customers with the AR service the MNO and the port authority embark on a type of partnership model. By doing this, both parties will share the investment and the risk.

Secondly, there are some implications regarding the economics of network slicing. The analysis in this article has assumed that the MNO providing the ACH or AR services to the port users is doing this by applying network slicing, i.e., by providing bespoke connectivity services based on upgrades to the existing eMBB network rather than developing a separate network. In 5G networks, it is claimed that network slicing will help to improve the business case for MNOs beyond offering eMBB services along. This is based on a) attracting users with much higher willingness to pay than traditional consumers; and b) delivering bespoke services based on limited upgrades to the existing and deployed eMBB network. This is a type of economy of scale and scope effect.

Our analysis has shown that, when carefully selected, delivering bespoke services via network slicing can provide important incremental ROIs as was the case for ACH. However, MNOs need to select these additional services to offer carefully as our analysis also shows that, as in the case of AR, some will have a much higher risk profile than others.

7.3 Limitations of the study

Several aspects could be improved in the future when preparing a 5G business case. Firstly, this study was conducted by using a port as the study area. Other ports or other areas where 5G services could be provided will have different characteristics, such as already deployed infrastructure, number of potential customers, etc. Any business case corresponds to a particular situation in a specific area. In this sense, it cannot be concluded that the results presented in this study are valid for other areas, which will probably have a different mobile network infrastructure and different types of customers. Both aspects, the network infrastructure and the demand, will have a direct effect on the costs and revenues. As a result, the output of the business case might be different in another setting. Secondly, for this study we assumed three types of 5G services: eMBB, ACH and AR. It is possible that in the future other 5G services could be provided. Moreover, the demand evolution of the abovementioned use cases was made based on traffic predictions, which over time could change. Thirdly, the cost of 5G equipment could change over time because of the volume of equipment that could be employed. Moreover, the potential employment in the future of other types of mobile network architectures, such as Open RAN (O-RAN, 2021), could have an effect on the total costs. For our study we have not considered the cost of a network orchestrator, which is an element that helps to control the network slices in a 5G environment.

8 Conclusions

This article has shown the results of a business case for three 5G use cases in an industrial sea port area, which is the Hamburg port, over the period 2020-2030. The first use case is eMBB and the results show an ROI of 189% with a payback period lower than one year. The sensitivity analyses show that the by varying the traffic demand and the revenues the ROI can be reduced to 77%.

The other two use cases studied, automation of container handling and augmented reality, work on top of the eMBB use case. The results of the ACH business case show an ROI of 342% and a payback period lower than one year. The sensitivity analysis shows that the ROI ranges from 209% to 378%. The business case of AR is challenging because for the baseline case the ROI is 130% with a payback period of 5 years. When performing the sensitivity analysis for AR it was found that the worst-case scenario has a negative ROI of -76% with a negative NPV in all years. To sum up, it was shown that when choosing industrial services to invest in MNOs need to be careful as not all new service offerings may have a positive business case. The eMBB results show that MNOs should continue to prioritise the eMBB market. For the ACH case there is also a positive business case. However, the business case of AR remains challenging.

Future research work should focus on studying other 5G use cases in the port area, on analysing the ecosystem of businesses in the port area, and on examining any economy of scale and scope generated by the provisioning of multiple industrial services on top of existing eMBB services.

Furthermore, other industrial areas beyond ports such as airports, science parks and manufacturing facilities could be studied.

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Annex A. Revenues for eMBB services

Table A.1 shows the assumed market segmentation for eMBB subscribers across price plans in the baseline scenario. This means that once all subscribers have migrated to eMBB price plans, they will be distributed across the price plans as in this table. It was assumed that laggards and early adopters map to "basic needs" and "high performance" subscribers, respectively (Rogers, 1962). The remaining early and late majority fall into the "standard" price plan. Table A.2 shows the evolution of the monthly MBB ARPU over time. A CAGR of -2% is used as derived from historic ARPUs for Germany between 2012 and 2019 (Statista, 2020).

Table A.1. Baseline scenario: Assumed market segmentation of eMBB subscribers across price plans (Rogers, 1962), and eMBB and MBB ARPUs.

Price plan	**Percentage of subscribers in this price plan category**	**Monthly ARPU in 2020 (€)**
eMBB: Basic needs	16%	7
eMBB: Standard	68%	18
eMBB: High performance	16%	22.50
MBB	-	13.98

Table A.2. Monthly ARPU over time for the MBB service.

	2020	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**Source**
MBB Monthly ARPU	13.98	13.70	13.43	13.16	12.90	12.64	12.39	12.14	11.90	11.66	11.43	An ACGR value of -2% is employed

However, the transition to eMBB services will not be immediate, and instead there will be a mix of MBB and eMBB subscribers over time. A further complication is that not all types of subscribers will migrate to eMBB price plans and services at the same rate. This is considered in Table A.3, which shows the assumed uptake or market penetration curves for each eMBB market segment. This is based on the historic uptake of 4G services (GSMA, 2015). Each eMBB market segment uptake profile is based on the 4G uptake trend delayed by 2 years, unaltered and accelerated by 2 years for basic, standard and high, respectively. Here a 100% uptake indicates that all potential subscribers in that market segment having moved from MBB to eMBB services.

Table A.3. Uptake within eMBB market segments assumed over time.

	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	Source
Uptake within eMBB market segments assumed over time												
Basic needs	0%	0%	1%	3%	11%	21%	29%	36%	42%	49%	57%	Based on the historic uptake of 4G services delayed by 2 years, unaltered and accelerated by 2 years for basic, standard and high, respectively (GSMA, 2015)
Standard	1%	3%	11%	21%	29%	36%	42%	49%	57%	66%	77%	
High perform.	11%	21%	29%	36%	42%	49%	57%	66%	77%	90%	96%	

Table A.4 multiplies the percentage of subscribers expected in each price plan at 100% uptake from Table A.1 with the uptake over time in each eMBB price plan from Table A.3. In each year the remaining percentage of subscribers not on one of the three eMBB price plans is assumed to be on an MBB service plan. This percentage of mobile subscribers in each price plan over time is then multiplied by the population of the study area, which is approximately 164,000 residents, and by the assumed number of mobile devices per head of population of 1.33 (World Bank, 2020) to get the number of subscribers in each price plan over time.

Table A.4. Proportion of mobile subscribers in each price plan over time and number of subscribers.

	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	Source
Proportion of mobile subscribers in each price plan over time												
MBB	98%	95%	88%	79%	72%	64%	58%	50%	42%	33%	23%	Remaining portion of non-5G users
Basic needs	0%	0%	0%	0%	2%	3%	5%	6%	7%	8%	9%	Above uptake applied to a maximum market segment of 16%, 68% and 16% for basic, standard and high performance, respectively (Rogers, 1962)
Standard	0%	2%	7%	14%	20%	24%	29%	33%	39%	45%	52%	
High perform.	2%	3%	5%	6%	7%	8%	9%	11%	12%	14%	15%	
Population (thousands) and devices per head of population												
Population	164.23	164.23	164.23	164.23	164.23	164.23	164.23	164.23	164.23	164.23	164.23	(Statistikamt Nord, 2020)
Devices per person	1.33	1.33	1.33	1.33	1.33	1.33	1.33	1.33	1.33	1.33	1.33	Devices per head of population (World Bank, 2020)
Number of subscriptions in each price plan over time (thousands)												

MBB	213.8	206.6	191.6	173.6	156.8	140.5	126.0	110.0	92.2	71.8	50.6	Calculated from population, proportion of subscribers and mobile devices per head of population
Basic needs	-	-	0.3	1.0	3.8	7.3	10.1	12.6	14.7	17.1	19.9	
Standard	0.7	4.5	16.3	31.2	43.1	53.5	62.4	72.8	84.7	98.0	114.4	
High perform.	3.8	7.3	10.1	12.6	14.7	17.1	19.9	23.1	26.9	31.5	33.6	

Finally, the number of subscribers over time is multiplied by the relevant ARPU from Tables A.1 and A.2 to generate the revenues for mobile broadband given in Table A.5.

Table A.5. Mobile broadband revenues over time.

	2020	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**Source**
eMBB revenues over time (€ millions)												
MBB	35.88	33.98	30.88	27.42	24.27	21.31	18.73	16.02	13.16	10.05	6.94	Calculated based on subscriber volumes in Table A.3 and ARPUs given in Table A.1
Basic needs	-	-	0.03	0.09	0.32	0.62	0.85	1.06	1.23	1.44	1.67	
Standard	0.16	0.96	3.53	6.74	9.30	11.55	13.47	15.72	18.29	21.17	24.70	
High perform.	1.04	1.98	2.74	3.40	3.96	4.62	5.38	6.23	7.27	8.49	9.06	
Total revenue	**37.1**	**36.9**	**37.2**	**37.6**	**37.9**	**38.1**	**38.4**	**39.0**	**39.9**	**41.2**	**42.4**	-
33% market share revenue	**12.2**	**12.2**	**12.3**	**12.4**	**12.5**	**12.6**	**12.7**	**12.9**	**13.2**	**13.6**	**14.0**	-

Annex B. Revenues for ACH services

The revenue calculation for ACH services follows the four steps outlined in section 3.1. Step 1 of this calculates the net benefit of automating the container terminals based on the assumptions and method outline in section 3.3.1. Further detail on the results of step 1 and how these are formed is given in Table B.1.

Table B.1. Further detail on step 1 of calculating the net benefits of ACH.

	2020	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**Total**	**Source**
Storage block automation (€ millions)													
Lost revenues without automation	59	93	131	172	217	267	320	379	443	512	587	3181	Based on historic revenues and 5.1% assumed growth in containerised cargo per year (HHLA, 2017; HLLA, 2018), volumes of containerised cargo and existing automation levels per terminal in Hamburg (Table 3) and an assumed 4 year period to apply automation (McKinsey & Company, 2018).
Lost revenues with automation	59	93	121	138	155	163	171	180	189	199	209	1679	
Reduction in lost revenues with automation	0	0	10	35	62	104	149	199	253	313	378	1502	Calculated based on difference between the two above rows.
Increase in net profits with automation for a 30% margin	0	0	3	10	19	31	45	60	76	94	113	451	Assume operational costs are 70% of revenues (HHLA, 2017; HLLA, 2018)
Cost of automation	0	0	6	19	31	49	56	56	62	56	56	389	Assume a €168m investment in equipment per terminal based on the costs of storage block automation from (McKinsey & Company, 2018). Converted to annualised amounts based on amortisation over an assumed 25-year lifetime with a 10% discount rate.
Net benefit for storage block automation	0	0	-3	-8	-12	-18	-11	4	14	38	58	62	Calculated based on difference between the two above rows.
Yard automation (€ millions)													

Savings in OPEX	0	0	7	27	48	78	103	115	129	135	142	784	Assume operational costs are 70% of revenues (HHLA, 2017; HLLA, 2018), that automation reduces operational cost by 25% (McKinsey & Company, 2018), a 4 year period for automation roll out and benefits accrued in line with volume of freight handled by automated terminal (Table 3).
Automation costs	0	0	20	40	40	60	60	60	60	60	60	460	Assume a €181m investment in equipment per terminal based on the costs of yard automation from (McKinsey & Company, 2018). Converted to annualised amounts based on amortisation over an assumed 25-year lifetime with a 10% discount rate.
Changes in cashflow	0	0	-13	-13	8	18	43	56	69	76	82	326	
Results of Step 1: Net benefit of ACH (€ millions)													
Total undiscounted net benefit for ACH	0	0	-16	-21	-4	0	32	60	83	114	140	388	Sum of net benefit of storage block and yard automation

Table B.2. Calculation of steps 1-4 of willingness to pay assessment for ACH services.

	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	Total	Source
Step 1: Output, Total undiscounted net benefit for ACH (€ millions)	0.0	0.0	-16.3	-21.1	-4.1	-0.3	32.2	60.1	83.3	114.3	139.9	**388.1**	Output of step 1 detailed in Table B.1
Step 2: Apply 20% discount rate to reflect risk (€ millions)	0.0	0.0	-9.4	-10.2	-1.7	-0.1	9.0	14.0	16.1	18.5	18.8	**55.1**	Net present value calculation with 20% discount rate to reflect high risk around ACH benefits
Step 3: Apply 15% limit on willingness to pay (€ millions)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	**8.3**	Assume the vertical is willing to pay up to 15% of the calculated net benefits
Step 4: Apply 67% scoring for competitive advantage (€ millions)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	**5.5**	67% weighting applied to reflect the strength of market position of 5G vs. other wireless (5G-MoNArch D6.3, 2019)

In Table B.3 the first set of rows shows the total amount of cargo per container terminal. The second set of rows shows the cargo benefitting from automation as not all container terminals automate in the same year. This is used to generate the revenue weighting.

Table B.3. Distributing revenues over time, weighted by level of cargo being automated in each year.

	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	NPV	Source
Volume of containerised cargo at each terminal not automated as at 2020 (TEU m)													
Burchardkei	2.8	2.9	3.1	3.2	3.4	3.6	3.7	3.9	4.1	4.3	4.6	N/A	Based on 2018 container throughput from Table 3 and a 5% growth rate per year in line with worldwide containerised cargo growth (5G-MoNArch D6.3, 2019). Altenwerder not considered as already automated
Tollerort	1.6	1.7	1.8	1.8	1.9	2.0	2.1	2.3	2.4	2.5	2.6	N/A	
Eurogate	1.6	1.7	1.8	1.9	2.0	2.1	2.2	2.3	2.4	2.6	2.7	N/A	
Volume of containerised cargo benefitting from automation under scenarios modelled (TEU m)													

Burchardkei	0.0	0.0	0.0	3.2	3.4	3.6	3.7	3.9	4.1	4.3	4.6	N/A	Applying the automation dates of our baseline scenario from Table 3 to the containerised cargo volumes above
Tollerort	0.0	0.0	0.0	0.0	0.0	2.0	2.1	2.3	2.4	2.5	2.6	N/A	
Eurogate	0.0	0.0	1.8	1.9	2.0	2.1	2.2	2.3	2.4	2.6	2.7	N/A	
Revenue weighting in line with proportion of automated cargo per year applied to distribute revenues over time													
Revenue weighting	0.0	0.0	0.3	0.7	0.7	1.0	1.0	1.0	1.0	1.0	1.0	N/A	Weighting based on the proportion of total cargo automated in each year
Revenues	0.0	0.0	0.4	1.1	1.1	1.4	1.4	1.4	1.4	1.4	1.4	5.5	Distributing the total revenues expected over the investment period in line with the above weighting and discounting at a 10% commercial rate

Annex C. Revenues for AR in construction services

Table C.1 describes step 1 which calculates the net operational benefit delivered by AR in construction services. This follows the assumptions and method detailed in section 3.4.1.

Table C.1. Step 1: Calculation of net benefits arising from AR in construction.

	2020	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**Source**
Regular spend on construction projects	242	242	242	242	242	242	242	242	242	242	242	Based on historic spend on construction projects in 2016 and 2017 by HPA (5G-MoNArch D6.3, 2019)
Exceptional upcoming construction costs on new Kohlbrand crossing	0	0	125	125	125	125	0	0	0	0	0	Assume this project will cost €500m spread evenly over the period 2022 to 2025, based on similar major bridge construction projects
Total HPA investment in construction projects	**242**	**242**	**367**	**367**	**367**	**367**	**242**	**242**	**242**	**242**	**242**	Sum of the two previous rows
Expected extra spend due to project overrun (50%)	121	121	184	184	184	184	121	121	121	121	121	Mid point of range given by (McKinsey & Company, 2018)
Reduction in overrun costs due to AR (5%) if all projects equipped	6.1	6.1	9.2	9.2	9.2	9.2	6.1	6.1	6.1	6.1	6.1	Conservative 5% benefit assumed vs. the 10% benefit of AR found in (PWC, 2018)
Proportion of projects using AR	20%	40%	60%	80%	100%	100%	100%	100%	100%	100%	100%	Assume usage of AR ramps up over 5 years to all construction teams
Anticipated reduction in overrun costs due to the roll out of AR	1.2	2.4	5.5	7.3	9.2	9.2	6.1	6.1	6.1	6.1	6.1	Multiple of the two previous rows

Cost of AR devices	0.11	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	Cost to equip HPAs 100 civil engineers in proportion to uptake over time considering: - Device cost of €2,500 each - Training of €1,000 each - AR software development and ongoing costs (5G-MoNArch D6.3, 2019)
Undiscounted net benefit of AR in construction	1.1	2.4	5.5	7.3	9.2	9.2	6.0	6.0	6.0	6.0	6.0	Difference between two previous rows

Table C.2 then applies steps 2-4 to convert the net benefits found in step 1 to a willingness to pay as per the assumptions given in section 3.4.2.

Table C.2. Steps 1-4: Calculation of willingness to pay and revenues.

	2020	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**Total**	**Source**
Step 1 output: Total undiscounted net benefit for AR in construction (€ millions)	1.1	2.4	5.5	7.3	9.2	9.2	6.0	6.0	6.0	6.0	6.0	**64.8**	From step 1 calculation of net benefit
Step 2: Apply 20% discount rate to reflect risk (€ millions)	0.9	1.7	3.2	3.5	3.7	3.1	1.7	1.4	1.2	1.0	0.8	**22.1**	20% discount rate reflects high risk of benefits materialising as new unproven service
Step 3: Apply 15% limit on willingness to pay (€ millions)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	**3.3**	Assume vertical is willing to spend up to 15% of the anticipated net benefits on connectivity services to achieve those benefits
Step 4: Apply 67% scoring for competitive advantage (€ millions)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	**2.2**	67% weighting applied to reflect the strength of market position of 5G vs. other wireless (5G-

													MoNArch D6.3, 2019)

Finally, Table C.3 distributes the total revenues, found on Table C.2, across the investment period in line with the number of active AR devices anticipated in each year. This assumes that a per device revenue model is applied.

Table C.3 Distributing total revenues over the investment period.

	2020	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**Total**	**Source**
Step 4 output: total expected revenue for MNO over investment period	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	2.2	Step 4 output
Cumulative number of AR devices / Revenue weighting	4	7	9	12	14	17	20	22	25	27	30	N/A	Assume start with 4 devices and gradually increase to 30 devices across a team of 100 civil engineers over 10 years
MNO revenues per year	0.09	0.15	0.22	0.28	0.34	0.40	0.46	0.52	0.58	0.64	0.70	2.2	Distributing the total revenues expected over the investment period in line with the above weighting and discounting at a 10% commercial rate