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Abstract

Teleoperated transport, or the use of remotely controlled vehicles and vessels for transportation, has the potential to offer cost savings and efficiency improvements. However, the technical and economic feasibility of this approach must be carefully evaluated. In this study, a techno-economic analysis (TEA) methodology was developed to assess the feasibility of using 5G technology to provide teleoperated transport, particularly in a cross-border setting. The methodology involved identifying deployment scenarios, conducting a business case viability study, and performing sensitivity analysis. Reference scenarios were defined to narrow the scope of the teleoperated transport scenarios, and five deployment scenarios were selected for detailed analysis. Overall, the TEA provided a comprehensive understanding of the feasibility and potential impacts of using 5G technology for teleoperated transport.

Keywords: 5G network, Teleoperation transport, Techno-economic analysis (TEA), cost model, sensitivity analysis.

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CI	Classified, information as referred to in Commission Decision 2001/844/EC	
CO	Confidential to 5G-Blueprint project and Commission Services	

* R: Document, report (excluding the periodic and final reports)
  DEM: Demonstrator, pilot, prototype, plan designs
  DEC: Websites, patents filing, press & media actions, videos, etc.
  OTHER: Software, technical diagram, etc

EXECUTIVE SUMMARY

Techno-economic analysis (TEA) is a method of evaluating the technical and economic feasibility of a project or technology. In the context of teleoperated transport, this analysis involves examining the costs and benefits of using teleoperated vehicles for transportation in a 5G scenario, as well as the technical requirements of and recommendations for this approach. This includes factors such as the cost of implementing teleoperation technology, the potential for cost savings through the use of different deployment options for both 5G network and teleoperation center. Overall, techno-economic analysis of teleoperated transport can help to provide a comprehensive understanding of the feasibility and potential impacts of this technology and the rationale for having teleoperation deployed using 5G network technology. As such it can support the decision-making process around its adoption, implementation scenarios, and economic viability.

Our focus in **this study is on evaluating the feasibility of using 5G technology to provide teleoperated transportation, particularly in a cross-border setting**. To do this, we have developed a **three-step methodology:**

1. **Network deployment scenario identification:** We consider various options for 5G connectivity and different business models for providing teleoperated transportation. By combining these different options, potential deployment scenarios are identified.
2. **Business case viability study:** We conduct a cost-benefit analysis to assess the viability of the selected deployment scenarios. We have developed a Total Cost of Ownership (TCO) model to calculate the cost of deploying 5G connectivity, a teleoperation center, and equipping teleoperated vehicles (such as barges, cranes, and trucks). We also use the average revenue per user (ARPU) to estimate revenue potential.
3. **Sensitivity analysis:** We analyze the impact of uncertain input on our model's output and study how variations in identified cost drivers affect our results. This helps us understand the range of potential outcomes and identify potential risks.

To narrow down the scope of our teleoperated transport scenarios from a business and governance perspective, we have defined a **set of teleoperated transport reference scenarios**. By making assumptions about the deployment scenarios, we can progressively analyze the cost-benefit of providing teleoperated transportation at different scales. Our reference scenarios are classified based on the geographical coverage of the teleoperated transport operation:

1. **Scenario 1: geographically limited area with numerous (short distance) transports**, such as a port or industrial zone with interconnected supply chains.
2. **Scenario 2: major 'national' transport axis with significant transport flows**. Teleoperated transport can be offered on roads or waterways with high levels of traffic, such as a canal between two ports in the same country.
3. **Scenario 3: public road or waterway across national borders.** This scenario extends the coverage of the previous ones to include cross-border roads or waterways.

We have identified a range of potential **deployment scenarios by combining our teleoperated transport reference scenarios with various options for 5G connectivity and teleoperation center deployment** to support different use cases and enabling functions. Based on a scoring system where consortium partners ranked their preferences for the different deployment scenarios, **we have selected five deployment scenarios** involving a mix of project-defined Use Cases to be analyzed in detail, being:

1. Deployment scenario 1: in limited port area, supporting terminal-related UC4.1a, UC4.2b and UC4.4
2. Deployment scenario 2: in port area, terminals including short trips on public roads supporting UC4.1a, UC4.1b, UC4.2a, UC4.2b, UC4.3 and UC4.4
3. Deployment scenario 3: major national transport axis – significant transport flows via water supporting UC4.1a

4. Deployment scenarios 4: major national transport axis – significant transport flows via road supporting UC4.2a, UC4.3 and UC4.4
5. Deployment scenarios 5: major international transport axis – significant transport flows via road and water: cross-border area supporting UC4.1a, UC4.3 and UC4.4

With UC4.1a.1 :Automated Barge Control: Navigating a river and a canal in a national waterway; UC4.1a.2: Automated Barge Control: Navigating a river and a canal in a cross-border waterway; UC4.1b: Automated Barge Control: Navigating, Docking and Unloading in a (busy) port; UC4.2a: Automated Driver-in-Loop Docking; UC4.2b: Teleoperated Mobile Harbour Crane; UC4.3: Cooperative Adaptive Cruise Control (CACC) based platooning, and UC4.4: Remote Take Over.

The developed TEA methodology was applied to the five selected deployment scenarios, and **key findings and recommendations** were identified for each scenario. These findings and recommendations are summarized as follows:

The Techno-economic analysis of the **deployment scenario 1**, which focuses on providing the 5G-based **TO services** in a really limited area within the port namely **terminals only**, showed that:

- For 5G network deployment:
  - The **5G coverage on demand is the most cost-effective deployment option** under the mentioned assumptions and circumstances.
  - If we compare the average TCO per terminal over 10 years deployment to the cost of the early deployment in the two terminals DPW and MPET situated in Antwerp, we see a cost reduction in the TCO of 47.5% for the pessimistic TO adoption and 43.5% for the optimistic scenario. This gives an indication for both connectivity providers and TO service providers in the port terminals about the good moment of adopting the 5G-based TO technology.
  - **OPEX is the dominant cost element** which represents 63% of the TCO.
  - Changing the network strategy by adding one additional macro cell to substitute few small cells (up to 5) will introduce more deployment cost. Yet, it seems more cost efficient to **substitute 8 small cells by one macro cell for the 5G network slicing connectivity option.** This results in a 16-18% cost reduction of the TCO, what would **turn the 5G network slicing option becoming more cost-effective than the 5G coverage on demand option** in the two network deployment strategies considered. This cost reduction overall results in a 7-8% cost reduction in the final average cost per unit (ACPU) for the connectivity service.
- For TO center deployment:
  - Deploying the TO center with a **gradual addition of the control setups following the TO uptake is more cost-effective** than buying all the control setups at the start of the deployment with a 10% cost reduction. The cost saving is around 25%.
  - The **main cost component of the TCO is OPEX**, which represents 89% of the total cost.
  - The **operator wage is the dominant cost element** which represents 93% of the total OPEX and the rest 7% are distributed among office space renting, Internet subscription and energy cost.
  - **Deploying own TO center is less expensive** than renting pre-equipped TO rooms from other TO service providers; cost reduction is around 25%.
- From the business case evaluation:
  - The ACPU in the optimistic scenario is less than the one in the pessimistic scenario, due to the higher number of different types of connected vehicles supported.
  - For the pessimistic TO adoption, the **BEP (Break Even Point**) is reached around year 5 for the two profit margin assumptions being 15% and 30%. Yet, the BEP **is around 5 and 8 years** in an optimistic scenario, with values 30% and 15% respectively.
  - Focusing on only few use cases, for example only skid steers in the terminals to serve TO barges will result in a higher ACPU at the end.
  - Serving skid steers only turns out to be 18% more expensive on the 5G connectivity

level and 29-40% more expensive on the TO service level.
    - Therefore, to ensure that the deployment of TO services is as cost-effective as possible, **it is important to support as many use cases as possible right from the start**. By connecting a higher number of vehicles, the costs of deployment can be shared among a larger group of users/ vehicles, resulting in a lower ACPU.

The Techno-economic analysis of the **deployment scenario 2**, which focuses on providing the 5G-based **TO services** in the port area including **terminals and short trips on public roads**, showed that:

- For 5G network deployment:
    - The **5G coverage on demand is the most cost-effective deployment option** under the mentioned assumptions and circumstances.
    - The **network slicing with providing a separate slice for each service is the costliest option**, this is due to several reasons among which we list the low demand of the studied non-TO slices (namely the eMBB and IoT slices) on the UL (Up Link) capacity which makes the TO slice bearing the significant part of the deployment costs.
    - **OPEX is the dominant cost element** which represents 63% of the TCO.
    - Sensitivity analysis show the **decrease of the TCO with the increase of the number of trucks per platoon** which is explained by the fact that if we have more trucks per platoon a smaller number of TO sessions will be required for the total number of vehicles.
- For TO center deployment:
    - Deploying the TO center with a **gradual addition of the control setups following the TO uptake is more cost-effective** than buying all the control setups at the start of the deployment with a 10% cost reduction. The cost saving is around 31%.
    - The cost of deploying a TO center assuming an optimistic adoption is more expensive than the deployment in a pessimistic uptake scenario.
    - The **main cost component of the TCO is OPEX**, which represents 91% of the total cost.
    - A cost breakdown of OPEX shows that **operator wage is the dominant cost element** which represents 98% of the total OPEX and the rest 2% are distributed among office space renting, Internet subscription and energy cost.
- From the business case evaluation:
    - The **ACPU** in the optimistic scenario is less than the one in the pessimistic scenario, due to the higher number of the different types of connected vehicles, being **€ 86 vs € 101.**
    - For the pessimistic TO adoption, the BEP is reached around year 9 for the two profit margin assumptions being 15% and 30%. Yet, the **BEP is around 9 and 10 years** in an optimistic scenario with values 30% and 15% respectively.

The Techno-economic analysis of the **deployment scenario 3**, which focuses on providing the 5G-based **TO services on a major cross-border transport axis** – significant transport flows **via water**, showed that:

- The **most cost-effective deployment option** for providing (only navigation) services to TO barges in the river is **5G network slicing with a separate slice for each service**. However, for providing a **wider range of use cases and covering the two terminals next to the entrance**, 5G **coverage on demand would be the most cost-effective** option.
- When only UC4.1a (automated barge control) is supported, the cumulative total cost of ownership (TCO) per square kilometer is as follows: €156,070 for 5G network slicing with a separate slice for each service, €233,635 for 5G network slicing with regular traffic, and €320,727 for 5G coverage on demand.
- When a wider range of use cases is provided, e.g., including UC4.1a.1, UC4.1b, UC4.2b,

and UC4.4, the cumulative TCO per square kilometer would go up to €388,509 for 5G network slicing with a separate slice for each service, €332,734 for 5G network slicing with regular traffic, and €320,727 in a 5G coverage on demand scenario. Providing such a **wider range of use cases therefore can be up to 51% more expensive compared to a clear focus on barge navigation operations** (UC4.1a).

The Techno-economic analysis of the **deployment scenario 4,** which focuses on providing the 5G-based **TO services on a major transport axis –** significant transport flows **via road**, showed that:

- For the **pessimistic scenario**, the **network slicing with providing a separate slice for each service is the most cost-effective** option with 45% and 29% as cost reduction comparing to the 5G coverage on demand and 5G network slicing with regular traffic respectively.
- Yet in the optimistic scenario, this connectivity option namely the 5G network slicing becomes the costliest one due to the increase in the number of connected vehicles which implies the increase in the UL capacity requested from the network. The **cost-effective solution in an optimistic scenario would be 5G network slicing with considering the non-TO services under the regular traffic**.
- Changing the type of RAN hardware to provide only 8 beams to solve the over dimensioning of the network leads to a cost saving of 13% for the coverage on demand connectivity option, yet it will not make it the most cost-effective solution – as this still would remain 5G network slicing with a slice for each service and with considering regular traffic, considering 16 beams RAN hardware.

The Techno-economic analysis of the **deployment scenario 5**, which focuses on providing the 5G-based **TO services on a major transport axis –** significant cross-border transport flows via **road and water**, showed that:

- For the **pessimistic scenario**, the **network slicing with providing a separate slice for each service is the most cost-effective** option.
- Yet in the optimistic scenario, the 5G network slicing becomes the costliest one due to the increase in the number of connected vehicles to be served which implies the increase in the UL capacity requested from the network. This calls for a deployment of more small cells (4 versus 1 in a pessimistic scenario). As a result, the total cost of ownership (TCO) for the deployment increases, but the cost sharing coefficient for the TO slice also increases (82% in the optimistic scenario versus 79% in the pessimistic scenario). This means that the TO slice bears the incremental cost of the deployment.
- On the other hand, the increase in uplink capacity for the **coverage on demand in the optimistic scenario** is not requiring any additional infrastructure, because the same deployment (2 macro cells) could support the increased capacity. Therefore, the cost of the deployment remained the same in both scenarios.
- Sensitivity analysis showed that deploying 5G network slicing to provide the minimum UCs UL capacity requirements resulted in 26%-40% of TCO cost reduction comparing to the worst-case studied where the maximum requirements were considered.

Comparing all deployment scenarios investigated, (summary depicted in Figure 1) we found that providing **more TO use cases generally leads to a more costly 5G network** deployment. If we consider the ACPU for the deployment scenarios considered, we see that offering more use cases implying a higher number of connected vehicles will lead to a **lower ACPU**. For example, the ACPU in deployment Scenario 1 is 18 times higher than in deployment Scenario 2, at €687 versus €38 for 5G connectivity and 8 times higher for TO center deployment.

Based on these results, **we recommend starting the deployment of TO services in a**

geographically limited area, including short trips on public roads, and providing as many use cases as possible in parallel in order to have a higher number of connected vehicles. As such the cost of deployment can be shared what makes each service more affordable. **When significant TO adoption has been reached, the deployment can be scaled up and expanded** to also cover major national and even international transport routes.

The results of the TEA showed that it is **not possible to identify a single network deployment approach that is the most cost-effective approach for all possible deployment scenarios**. 5G coverage on demand was the most cost-effective deployment option for providing teleoperated services in a limited port area. Yet, 5G network slicing with a separate slice for each service will be more cost-effective as long as a good network deployment strategy is adopted. In a port area with terminals and short public roads, 5G coverage on demand was the most cost-effective option. For major national transport axes with significant transport flows via water or road, 5G network slicing with regular traffic was found to be the most cost-effective deployment option in our analysis. For a major international transport axis with significant transport flows via water and road in a cross-border area, 5G coverage on demand was the most cost-effective option when considering the maximum uplink capacity of use cases. However, if the use case requirements can be minimized, 5G network slicing may become a more cost-effective deployment option.

We therefore **recommend reducing use case requirements for the uplink capacity in order to save (connectivity) costs.** For example, using good video compression and network status prediction algorithms can lead to a 26%-40% reduction in total cost of ownership (TCO) compared to the worst-case scenario, in which the maximum requirements were considered. Of course, the additional cost for such development/ implementation needs to be balanced, but benefits of scale can be expected.

In addition, **smart deployment of small cells in addition to macro cells can be an effective strategy for enhancing uplink capacity in a network deployment, but it is not without limitations**. Deploying a large number of small cells (more than 8) can be more costly than adding one more macro cell due to the use of MIMO within the macro cell RAN hardware. This is because the cost of deploying many small cells may outweigh the benefits of the additional uplink capacity they provide.

Finally, **adopting one or more cost saving strategies for the network deployment such as passive and active network sharing** may significantly help reducing the network overall deployment cost.

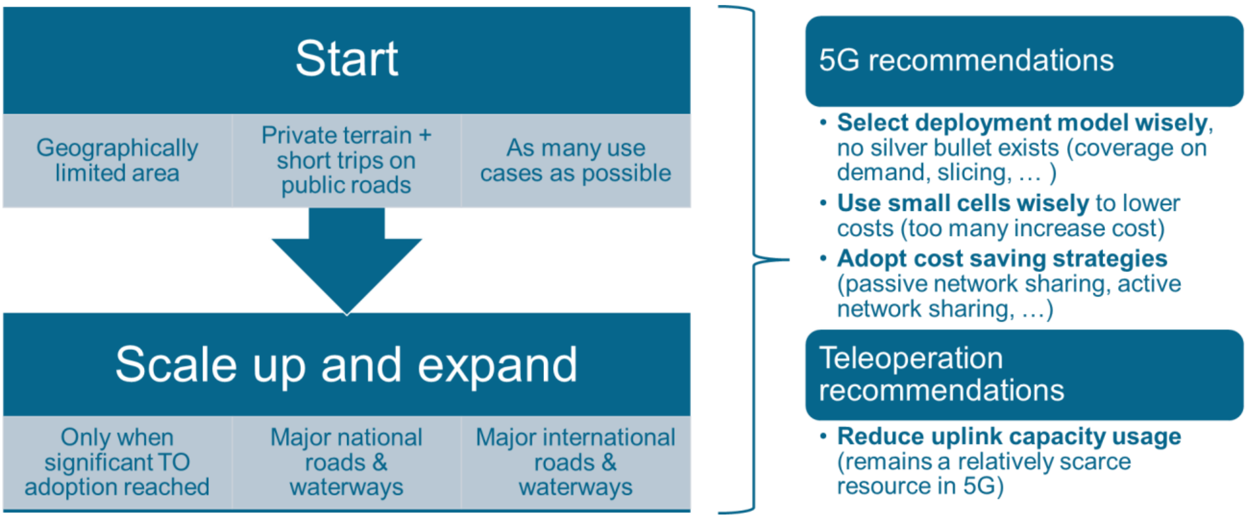

Figure 1: Summary of findings and recommendations

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ABBREVIATIONS

ACPU	Average Cost Per User
ARPU	Average Revenue Per User
BEP	Break Even Point
BM	Business model
CAPEX	Capital Expenditures
CACC	Cooperative Adaptive Cruise Control
CCAM	Connected, Cooperative and Automated Mobility
CS	Control Set-up aka 'TO operator desk'
eMBB	enhanced Mobile Broadband
IoT	Internet of Things
KPI	Key Performance Indicator
MNO	Mobile Network Operator
NH	Neutral Host
NPN	Non-Public Network
OPEX	Operational Expenditures
QoS	Quality of Service
RAN	Radio Access Network
ROI	Return On Investment
SA/NSA	Standalone/non Standalone 5G deployment option
SLA	Service Level Agreement
TCO	Total Cost of Ownership
TEA	Techno-economic Analysis/assessment
TO	Teleoperation
TOC	Teleoperation Center
UL	Up Link
V2X	Vehicle-to-everything
VNF	Virtual Network Function

1 INTRODUCTION

1.1 Scope of the deliverable

The goal of the work undertaken is to judge necessary investment costs for enabling 5G-based Teleoperation considering use cases and enabling functions in the operational environments of the 5G-Blueprint project on a short-term, and public and commercial value creation over longer periods of time. In this deliverable, initial investment costs and operational costs are presented and allocated to pre-defined use cases and enabling functions in specific geographical deployment areas including different 5G-connectivity scenarios and multiple teleoperation center deployment scenarios. The specific geographical areas are (1) a geographically limited area (with numerous short distance transports) such as a port area or industrial zone, (2) major 'national' transport axis with significant flows via road or water and (3) cross-border public roads or waterways. The 5G-connectivity scenarios investigated relate to 5G-coverage on-demand, 5G private network and 5G network slice. And, the deployment of teleoperation centres is divided into specifically owned teleoperation centres by a public or private organisation or rented TO centres by a third party. All in all, the outcomes of the techno-economic analysis allow to cater to first and still ongoing economic and business considerations about the actual implementation of 5G teleoperation in (cross-border) port environments as a primary example. Current logistical operations and their initial and operational costs are determined and compared with adopting and upscaling towards 5G teleoperation solutions. This, logically, from the perspective of the selected study area of the 5G-Blueprint project (i.e., Flemish-Dutch border) and with the assistance of input from the project beneficiaries.

The importance of the work of deliverable 3.3 is the construction of a factual basis from a techno-economic point of view. The constructive basis serves, in line with the outcomes of the deliverables 3.1 and 3.2, the validation of viable business model configurations to be reported in Task/ Deliverable 3.4 'Business model validation' and will contribute to the constitution of a 'roadmap for deployment and governance' (Deliverable 3.5).

The combination of technical necessities and financial conditions reveal respectively thresholds on the capabilities of 5G-network deployment and the minimum finance needed to establish 5G teleoperation for logistic services and Connected Automated Mobility (CAM). In compliance with the process of the project, the techno-economic analysis builds in essence on the deliverables 3.1 and 3.2 where potential viable business models in relation to stakeholders have been discussed and identified. In fact, the added value of the techno-economic analysis is to investigate and review under which economic and technical conditions 5G teleoperation could be adopted and scaled towards more existing (cross-border) port areas within the European Union for example. In order to ensure the credibility of what is proposed, the temporal technical and economical outcomes of the analysis's are verified and validated by the beneficiaries. In the upcoming Task 3.4 the defined business models, including costs and benefits, are to be presented for feedback to and validation by the consortium, and the wider community .The goal of this task will be to validate the emerged business models and, interactively, find out whether they shape technical, economic and organisational viability for the beneficiaries of this project and future public and private organisations.

Hence, the importance of the present analysis (and Deliverable) is to provide an elaborated techno-economic analysis that directly supports the validation and co-creation process to come aiming at defining deliberate, desirable and innovative business models. Further on in time, this provides the necessary input for the roadmap. In the first place, the expected needed technical and financial proportions provided a constructive basis for further rollout of 5G-teleoperation services also beyond the geographical scope of port and industrial areas and purely logistic services. With this in mind, next phases for 5G-teleoperation can be (re)designed, iterated and determined based on the factual outcomes of the techno-economic analysis. From an inductive point of stand, follow-up projects can learn and include the generated and disseminated technical and economical knowledge in their appraisal to innovative 5G-based teleoperation solutions. With the added inclusion of the stakeholders (i.e., the beneficiaries of this project) and their positive attitude towards specific business models, valid arguments can be formulated for the incorporation of technical, economical, and organizational accents in a roadmap that forms advancement and risk over time.

1.2 Relation with other tasks and work packages

This deliverable builds on the **Initial Business Case identification** (T3.1) reported in [1] which aimed to determine the interest of various ecosystem players in the proposed solution and the potential benefits it would generate, as well as the interactions needed to achieve these benefits. It also incorporates the different technological/business options from the business models identified in **Business Models Identification** (T3.2) [2] and conducts a cost-benefit analysis of these options (**Techno-economic analysis**). This analysis will inform the **Business Models Validation & Assessment** (T3.4) and provide insight into the **Deployment Requirements** and the **Governance Models** identification (T3.5). Additionally, this deliverable takes into account the 5G-based design solution developed in WP5, as well as the technical network requirements for each use case and enabling function. The results of 5G measurements from the pilot sites (WP7) are used to validate the technical requirements used in the analysis, as illustrated in Figure 2 that follows.

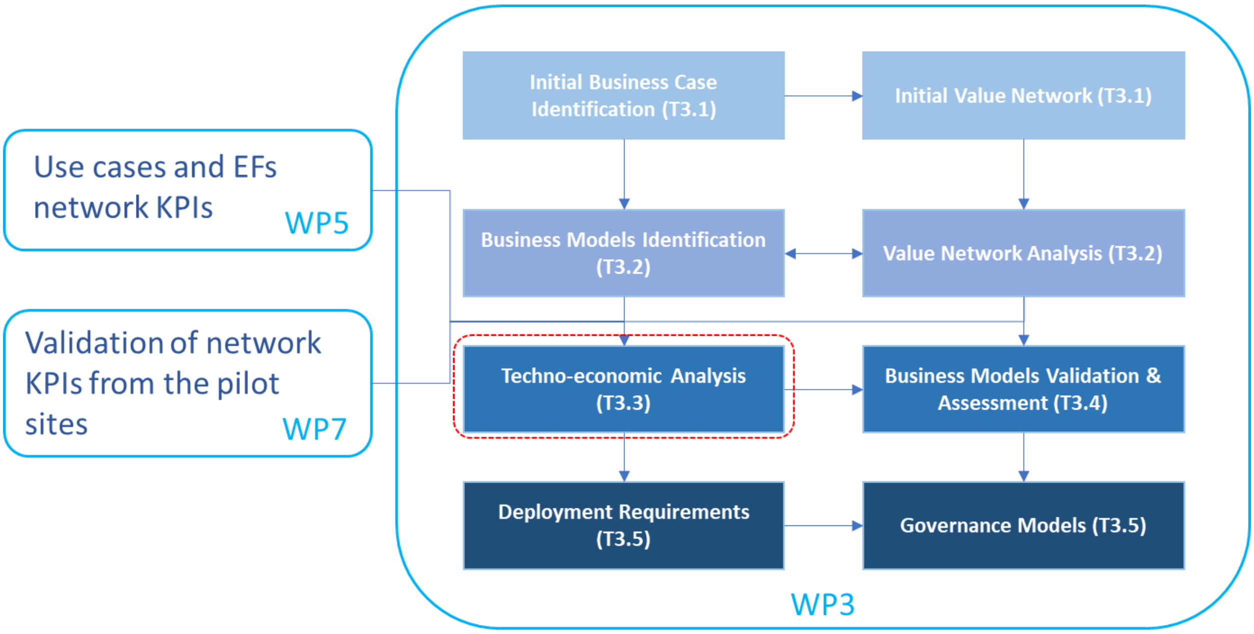


Figure 2 T3.3 interdependencies with other WP3 tasks and WPs

1.3 Flow of the deliverable

The deliverable consists of different parts:

a. A literature review of the techno-economic analysis tools used to analyse the economic impact of the 5G networks rollout and assessing the provision of the Connected and Automated Mobility (CAM) 5G-based services is presented in Chapter 2.
b. An overview of the developed TEA methodology to be used in the analysis is provided in Chapter 3, as well as a description of the different models developed. Concepts and terminology are explained in this section as well.

c. In Chapter 4 , 5G-Blueprint settings i.e., reference scenarios, use cases and enabling functions, 5G connectivity provision options and TOC deployment options are discussed.
d. Chapter 5 details the application of the developed TEA methodology to the specific 5G-Blueprint deployment scenarios that were identified Chapter 4.
e. Finally, Chapter 6 summarizes the key findings of the deliverable, mainly focusing on recommendations of the economic impact of adopting teleoperation transport using 5G networks.

2 STATE OF THE ART

2.1 Techno-economic analysis of 5G network deployment

Techno-economic assessment is a fundamental technique engineers use for evaluating new communications technologies. By reviewing the state-of-the-art of the TEA (Techno-economic Analysis/Assessment), commonly used techniques and evaluation tools for studying the 5G network roll-out can be identified.

Authors in [3] reviewed 150 papers studying the TEA of the 5G deployment. The survey discusses emerging trends from the 5G techno-economic literature and makes five key recommendations for the design and standardization of Next Generation 6G wireless technologies. These proposals reflect modelling uncertainties, metric usefulness, the increasing use of virtualization, the open science agenda, and a call for greater multi-disciplinary collaboration as part of the 6G R&D and standardization process. Authors highlighted that: i) TCO model is the most used TEA tool; ii) OPEX is sometimes not in the evaluation; iii) 4 main 5G technology areas have received a reasonable amount of attention: network densification, millimetre wave, mMIMO and network virtualization; iv) QoS has a dramatic effect on TEA findings. The study recommends to explicitly state any QoS assumptions; to include both CAPEX and OPEX in financial analyses; to include sensitivity analysis with the model since every model is an approximation of reality and to share input data, code and results openly with the research community. In particular, other papers have studied the TEA of private 5G networks or Non-Public Networks (NPN) by industry.

Authors in [4] conducted a detailed techno-economic analysis on 5G NPN deployment. The study formulated a technoeconomic model that focuses on; (i) Cost savings in support of ROI achieved by enabling Network Function Virtualization (NFV) technology and Neutral Host (NH) concept; (ii) The trade-off study between enterprise goals (cost vs deployment technologies) with a multi-objective sensitive analysis; And (iii) the trends of 5G NPN adoption worldwide. Analytical results confirm savings of up to 53% in Total Cost of Ownership (TCO) reflecting a significant reduction in Capital and Operation Expenditures (CAPEX and OPEX). Simulation analysis identifies a ranking order of deployment parameters, which prioritise the use of Cost saving strategies and Deployment type. And finally, it offers a prediction of a starting annual average worldwide adoption rate of 82.2% with an expected height by 2026.

2.2 Techno-economic analysis of 5G-based CCAM projects

Several research papers and projects in recent years have focused on the cost of deploying 5G networks to support connected and automated mobility (CCAM) services.

One study examined the costs, coverage, and rollout of 5G networks in Britain, using 4G LTE and LTE-Advanced characteristics as a reference [5]. The study found that 90% of the population could be covered by 5G by 2027, but the final 10% may be difficult to reach due to increasing costs. The study also looked at the impact of factors such as capital intensity, infrastructure sharing, and end-user speed on the deployment of 5G networks, and found that these factors can significantly influence the time it takes to reach the 90% coverage threshold, especially in rural areas.

Another study [6] explored the concept of "digitalized highways" for CCAM, considering the costs and potential returns on investment of 5G deployment in a V2N highway environment. The study also analyzed the potential for partnerships between the private and public sectors to accelerate the deployment of 5G networks and reduce costs. Overall, these studies provide valuable insights into the challenges and uncertainties of deploying 5G networks for CCAM services.

A study by [7] analyzed the potential for a return on investment in a 5G-digitalized highway, considering factors such as investment costs, user fees, and the number of users. The study found that a positive business case is likely, particularly when network infrastructure is shared among different operators. The study also predicted that partnerships between the private and public sectors in the early phase of 5G deployment could accelerate the rollout of these networks and make CAM services more accessible to users at lower costs, ultimately leading to safer roads and more efficient transportation.

A joint study involving three cross-border projects, referred to as the meta-study [8], analyzed the cost of providing connected and automated mobility (CCAM) services in European corridors using 5G networks. The study reviewed and compared the findings of three different deployment studies and found that they provided important insights into the costs of 5G deployment for CCAM in these corridors. The study found that key factors influencing deployment costs included geographic location, existing infrastructure, and topography. It also identified several "gaps" in knowledge that future studies should address, including the demand for 5G from connected automated vehicles (CAVs) and the costs associated with cross-border interference and data storage. The study also emphasized the importance of identifying and involving key stakeholders in the deployment process and exploring ways to recover deployment costs through business models. Overall, the study found that cooperation among stakeholders is crucial for efficient deployment strategies and that further research is needed to fully understand the challenges and opportunities of deploying 5G for CCAM in cross-border corridors.

Another European project, 5G-NORMA [9], examined the potential use cases for 5G technical innovations and conducted a socio-economic assessment of these cases. The project focused on network dimensioning, cost, revenue, and social benefits in three evaluation cases, including single tenant and multi-tenancy, in a central London scenario over the period from 2020 to 2030. The study analyzed the costs and revenues associated with 5G NORMA infrastructure and the potential social benefits of these networks. It also explored the possibility of public-private partnerships and the importance of creating a supportive regulatory environment to encourage industry investment in these networks, even in cases where the commercial business case may be uncertain or involve short-term risks.

2.3 Mobile network deployment: cost saving strategies

Different cost saving strategies were identified in literature and can be analysed in our case to assess their impact on the TCO of providing TO use cases as well. They are summarized as follow:

- Passive and Active network sharing: using network sharing models results in different cost savings **[10]**. Passive infrastructure sharing could save from 16% to 35% CAPEX and 16% to 35% OPEX. Active infrastructure sharing excluding spectrum could result in savings from 33% to 35% CAPEX and 25% to 33% OPEX. Yet savings in the active sharing including spectrum sharing model would range from 33% to 45% CAPEX and 30% to 33% OPEX.
- Neutral host: The concept of Neutral Host supports deeper levels of infrastructure sharing. This can be beneficial for deploying 5G network, given the ROI challenges associated with wireless network deployments. According to **[4]**, a 50% network sharing can be achieved by adopting a Neutral Host deployment; Neutral Host has continued to gain traction following the 5G styled service-based architecture (SBA). The SBA design enables Neutral Host to leverage 5G services to offer customised and differentiated services with reduces outlay.
- Network Function Virtualization (NFV): a 40% energy savings from NFV has been arrived at based on research literature. The conclusion in several studies corroborates the current research opinions, which suggest that reduction in energy consumption can be on the order of 40 percent when Network Function Virtualization/Software Defined Networking technology is deployed **[4]**.

3 TECNO-ECONOMIC ANALYSIS METHODOLOGY

3.1 General methodology

With a clear focus on studying the viability of providing 5G-based teleoperated transportation and especially in a cross-border environment, we developed a general methodology that consists of three main steps (illustrated in):

1. Network deployment scenario identification: based on different possible 5G connectivity options and different business models related to the provision of teleoperated transportation, several deployment scenarios can be identified.
2. Business case viability study: using a cost-benefit analysis for the selected deployment scenarios, their viabilities can be judged. A Total Cost of Ownership (TCO) model has been developed to derive i) the cost of 5G connectivity options deployment, ii) the cost of deploying a teleoperation (TO) center and iii) the cost of making TO-capable barges/cranes/trucks etc. For the revenue part, the use of the average revenue per user (ARPU) is used to assess the viability of the business cases.
3. Sensitivity analysis is elaborated to i) assess the impact of uncertain input on the model outputs and ii) to study the degree of variation of the model results given certain variation of cost drivers that are identified using a cost breakdown.

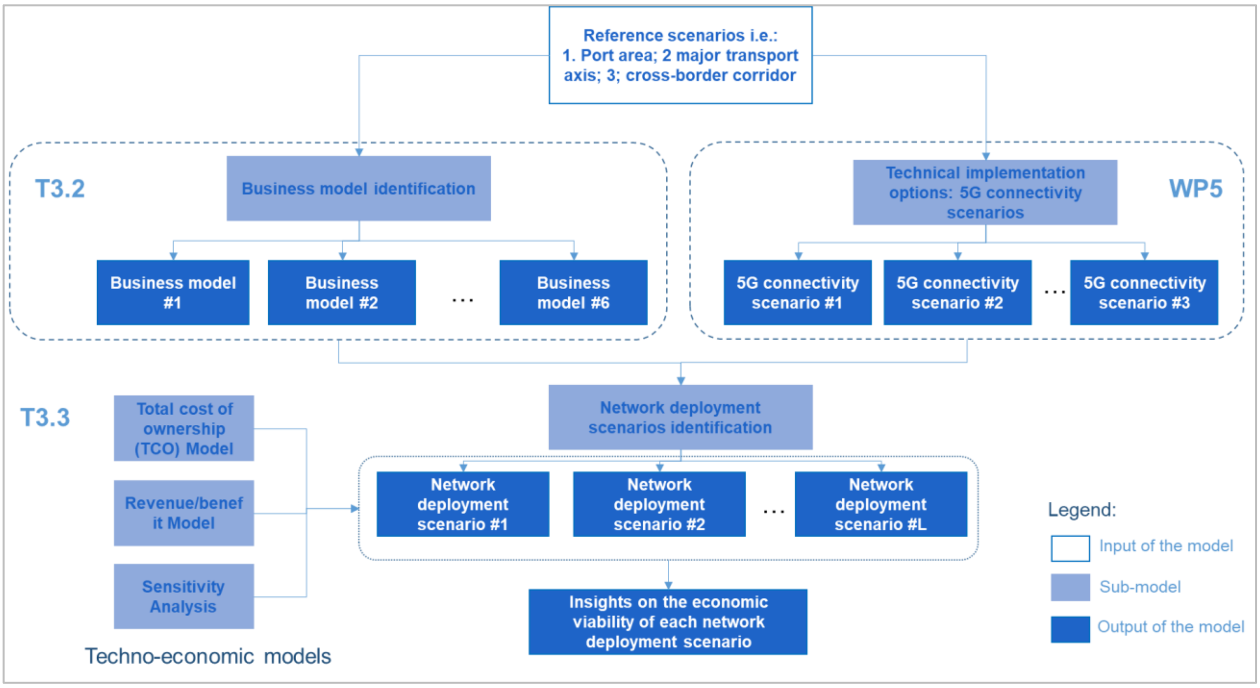


Figure 3 Techno-economic methodology

Several modelling techniques used in assessing the techno-economic implications of 5G technologies, among which the scenario analysis, the total cost of ownership and the sensitivity analysis are popular ones [3]. These key techniques are used in the developed methodology as mentioned above and are described in more detail in the following sections.

3.2 Scenario analysis:

We adopt the definition of scenario analysis of [3], where a scenario analysis is a technique used in strategic planning to examine the potential outcomes of different sets of defined input parameters on a quantitative model. This can provide valuable insights for decision making, particularly when there is limited scientific information available to accurately predict future outcomes. In the context of cellular technology, such as 5G, scenario analyses can be useful for assessing the demand for networks and informing deployment decisions. In 3GPP literature, scenarios often refer to different deployment situations, such as urban or rural areas, and are used to evaluate various 5G deployment options. In the specific case mentioned, various deployment scenarios have been defined to consider different combinations of 5G deployment and teleoperation center deployment options. The identification of these scenarios is further described in section 4.6.

3.3 Generic Total Cost of Ownership cost model

The cost model consists of three main parts: cost model for the 5G networks, cost model for the TO center and, cost model for TO-capable vehicles/barges. In the following sections, each of them will be described separately:

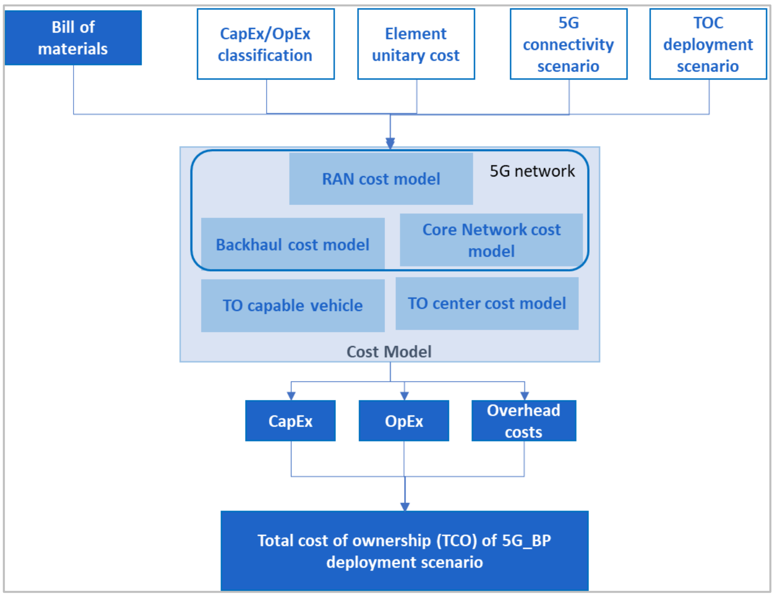


Figure 4 Generic TCO model

3.3.1 Cost model of the 5G network

The 5G network cost model consists of two main components: the network dimensioning process module and the cost model. The network dimensioning process module uses the 5G-Blueprint use cases and enabling functions specification, as well as information about the existing infrastructure in the area being studied, the length of the area, the number of connected devices, and the capacity requirements of the use cases and enabling functions to determine the necessary network infrastructure (in terms of the number of macro/small cells) to meet the defined key performance indicators (KPIs), particularly the UL capacity. The cost model, on the other hand, calculates the total cost of ownership (TCO) by using the bill of materials (BOM) generated by the dimensioning process, element unit costs, and distinctions between capital expenditures (CAPEX) and operational expenditures (OPEX). The BOM includes the cost of the 5G network infrastructure and overhead costs. The TCO can then be derived by summing the CAPEX and OPEX costs.

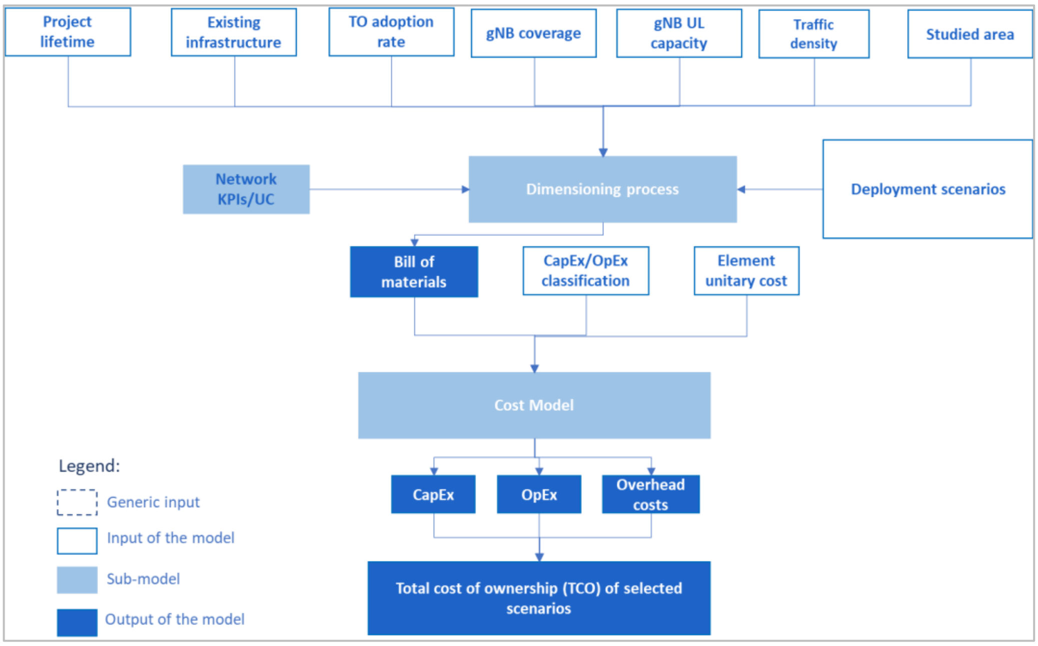


Figure 5 TCO model of the 5G network

3.3.1.1 5G Network dimensioning

The 5G network consists of three main parts namely the RAN, the backhaul network (often called the backbone or transport network), and the core network. If a new use case is supported by the network in most cases only the RAN part gets impacted because this new use case requires radio capacity (translated into spectrum resource), and it is a scarce resource among all the network resources. So, for MNOs to support a new use case in a specific location they need to densify their RAN in that location. Therefore, the network dimensioning to provide teleoperation (TO) use cases translates into the following measures with regard to the three main components of the 5G network:

RAN Network dimensioning

This is the most important part of the network dimensioning that impacts the Bill of Materials (BOM) and hence the cost of the required network. To calculate the needed number of new cells/base stations to deploy to support TO use cases in a specific location, we need to know first the area to cover and second the number of TO-capable barges/trucks to serve simultaneously in that area.

Therefore, the network dimension is a two-steps process:

1. Ensure the full coverage of the studied area:

Derive the number of macro cells to be installed (taking also into account the existing ones) using the inter-site distance.

Equation 1 $N_{MC} = ceil(\frac{A}{Covrg_{MC}})$

Equation 2 $covrg_{MC} = {(3 \times \sqrt{3} \times R^2)^2}/{2}$

With:

N_{MC}	Number of Macro cells
A	Area to cover
$Covrg_{MC}$	The coverage of 1 Macro Cell
R	The radius of the hexagon which is the half of the site inter-distance

1. Fulfil the capacity requirements (here we consider the UL capacity):derive the number of small cells to add.

$$\text{Equation 3 } N_{SC} = N_{CC} - N_{MC}$$

$$\text{Equation 4 } N_{CC} = ceil(\frac{Total_{Cap}}{Cap_{Cell} \times N_{Beams}})$$

If, an existing Cell will be used, we should consider the free capacity available in that cell, thus:

$$\text{Equation 5 } N_{CC} = ceil(\frac{Total_{Cap} - Cap_{available}}{Cap_{Cell} \times N_{Beams}})$$

With:

N_{MC}	Number of Macro cells
N_{SC}	Number of Small cells
N_{CC}	Number of cells required to provide the total required capacity
$Total_{Cap}$	The total required capacity in the studied area
Cap_{cell}	The capacity provided by one cell
N_{Beams}	Number of beams per cell

With Beamforming in 5G, the same UL capacity can be provided simultaneously in the form of several beams if users are sufficiently spaced.

To calculate the total required capacity in the studied area to support TO use cases; we need to know the expected TO-capable vehicles (barges/trucks) connected to the network at the same time. This depends on the connectivity option adopted i.e., 5G coverage on demand and 5G network slicing:

- 5G coverage on demand: in this option, the densification of the RAN will be done only for the purpose of supporting TO use cases in the studied area, hence the total required capacity is expressed using the following formula:

$$\text{Equation 6 } Total_{Cap} = \sum_{i=1}^{N} N_{TO\_VH_i} \times Cap_{TO_{UC}/EF(i)}$$

- The option of 5G network slicing involves taking into account the capacity requirements of both teleoperation use cases and other types of services when dimensioning the densification of the Radio Access Network (RAN). There are two methods for calculating the non-teleoperation capacity in the studied area: 1) assuming that all services in the area will be delivered using slices, and deriving the total non-teleoperation capacity based on the UL capacity needed for each slice, as expressed in Equation 7; and 2) assuming that only teleoperation services will be supported by slicing and the rest of the services will be included under the umbrella of "regular traffic," with an annual growth rate of 20-25%, and estimating the total non-teleoperation capacity accordingly. In this analysis, both methods were used. It is believed that the latter method may be more appropriate in the early stages of standalone (SA) 5G deployment, while the former may be more relevant in later stages of deployment when all services could potentially be offered using different network slices.

$$\text{Equation 7 } Total_{Cap} = \sum_{i=1}^{n} N_{TO\_VH_i} \times Cap_{TO_{UC}/EF(i)} + \sum_{j=1}^{S} N_j \times Cap_{S_j}$$

With:

$Total_{Cap}$	The total required capacity in the studied area
N_{TO_VH}	Number of TO-capable vehicles (barges/trucks) related to specific use case
$Cap_{TO\_UC/EF}$	Required capacity of use case (i) and its supporting EFs
n	Number of TO use cases

N_j	The number of connected users for Slice S_j
S	Number of slice types
Cap_{Sj}	Required capacity of slice type j

There are two ways to estimate the capacity required for other services/slices (the non-TO services):

1) forecast the type of slices that will be provided in the area, the expected number of users for those slices and the network capacity needed per slice.

2) consider only two slices, one for TO use cases and the other one for regular traffic (without making the differentiation between the served services) and to estimate the required capacity for this regular traffic, MNOs consider an early growth of the traffic in the area between 20% to 25% and add it on top of the current traffic. This is based on MNO's best practices.

Cost allocation model of the RAN part for network slicing

We adopt the network slicing allocation model developed in [11]. The network is made up of three parts: the core network, the transport network, and the radio access network. In order to create an end-to-end (E2E) slice, these three components must be considered. On the core network side, a slice consists of a chain of virtual network functions (VNFs) and physical network functions. On the transport and radio access network parts, the slice can be thought of as a pipe or tunnel with a dedicated bandwidth or throughput reserved for that slice. As such, the cost of an E2E slice should include the cost of all three components of the 5G network (RAN, transport, and core network). So far, the cost modeling has focused on the RAN component for supporting teleoperation slices, enhanced mobile broadband (eMBB), and Internet of Things (IoT). In order to complete the cost modeling, two additional pieces of information are needed:

- Allocate the cost of the RAN part to the three deployed slices
- Model the cost of the transport network + core network (please see the discussion on that in the following section).

In this model we assume that:

- A predefined throughput is reserved per slice.
- Each slice has its own exigence in term of quality of service (QoS), priority level, packet error loss rate, packet delay etc.
- The cost of the QoS requirement is identified by a weighting coefficient.

Equation 8 $$C_{Thps} = C_{RAN} \times Qco_s$$

Equation 9 $$Qco_{Sj} = Cost_{sharC} \times \frac{Thp_{Sj}}{\sum_{i=1}^{N} Thp_{S(i)}} + (1 - Cost_{sharC}) \times \left(1 - \frac{L_{Sj}}{\sum_{i=1}^{N} L_{S(i)}}\right)$$

With:

N	number of slices running
C_{BS}	cost of the base station
L_S	Latency of the slice S
Qco	weighting coefficient according to throughput and the QoS level of the slice (defined in the next section).
C_{Thps}	cost of throughput of slice s
$Cost_{sharC}$	Cost sharing coefficient

Backhaul network dimensioning

Usually, the deployed backhaul of any mobile network is over-dimensioned to support new use cases on top of the existing ones, and hence, in most of the cases, there is enough capacity on that part of the network (i.e., backhaul) to support TO use cases. Therefore, in this case, no need to count for additional cost implication related to supporting TO use cases. However, if we consider the entire network status on a national scale, in some cases, the transport network needs an upgrade to support TO use cases among other 5G use cases. This upgrade cost of the transport network should be shared among the different supported use cases so that a fast ROI can be achieved for MNOs. Hence, multiple options exist:

1. Assume that this cost is marginal and neglect it in the cost model.
2. Define cost allocation model to distribute the cost of the transport network between the running services/use cases, for example based on the required TO capacity from the overall provided capacity by the backhaul network.
3. Assume that the cost needed to upgrade the transport network (together with the core network cost) is a percentage on top of the cost of the RAN deployed to support TO use cases like 10 % used in [12].

After discussing the different options with MNOs involved in the project, option 2 have been chosen and a cost per site has been provided by MNOs to count for the cost of the transport network.

Core network dimensioning

Similar to the backhaul network, for allocating the cost of the core network to TO use cases, multiple options exist:

1. Define cost allocation model to distribute the cost of the core network between the running services/use cases, for example based on the TO traffic from the overall processed traffic by the core network.
2. Assume that the cost needed to upgrade the transport network together with the core network cost is a percentage on top of the cost of the RAN deployed to support TO use cases like 10 % used in [12].
3. Not include it in the cost model.

After discussing the different options with MNOs involved in the project, option 3 have been chosen because the cost of core is considered as part of network evaluation and should not be related to specific 5G use cases.

3.3.1.2 5G network cost model

CAPEX and OPEX

After running the 5G network dimensioning sub-model, it is possible to determine the number of additional 5G cells that need to be installed in order to provide the 5G-Blueprint use cases and enabling functions in a specific deployment scenario. The CAPEX of the RAN can then be calculated by summing the costs of all new RAN sites or macro sites, as well as any RAN sites that require upgrades. The CAPEX of the 5G network infrastructure can be expressed using the following formula:

Equation 10 $$\mathrm{Capex}_{\mathrm{5G\_RAN}} = \mathrm{Capex}_{\mathrm{RAN}} + \mathrm{Capex}_{\mathrm{RAN}_{\mathrm{upgrade}}}$$

Equation 11 $$\mathrm{Capex}_{\mathrm{RAN}} = \mathrm{N}_{\mathrm{MC}} \times \left(\mathrm{Cost}_{\mathrm{MC}} + \mathrm{dist}_{\mathrm{MC\_Agg}} \times \mathrm{cost}_{Fiber}\right) + \mathrm{N}_{\mathrm{SC}} \times \mathrm{Cost}_{\mathrm{SC}}$$

Equation 12 $$\mathrm{Capex}_{\mathrm{RAN}_{\mathrm{upgrade}}} = \mathrm{N}_{\mathrm{RAN\_sites\_upgrade}} \times \mathrm{Cost}_{\mathrm{Site}_{\mathrm{upgrade}}}$$

On the other hand, the operational expenditure (OPEX) of the 5G network infrastructure deployed is depicted in *Equation 13*. Each OPEX component includes the power consumption of the hardware and its maintenance.

Equation 13 $\text{Opex}_{\text{MN\_inf}} = \text{N}_{\text{RAN\_sites}} \times \text{Opex}_{\text{RAN}} + \text{N}_{\text{RAN\_sites\_upgrade}} \times \text{Opex}_{\text{RAN\_upgrade}}$

Additional costs

We have built the cost model using the following assumptions for the additional costs:

- If not known, hardware installation cost can be estimated as 15% of the hardware costs [13]. The cost of the hardware installation is part of the CAPEX costs, and it is expressed by the following formula:

Equation 14 $\text{Cost}_{\text{Inst}} = 15\% \times \text{C}_{\text{Hw}}$

- Maintenance cost is 10 % of the CAPEX costs [13]. Maintenance costs are counted in the OPEX costs.

Equation 15 $\text{M} = 10\% \times \text{CAPEX}$

- In most cases, the overhead cost is defined as the cost of marketing, helpdesk, human resources, finance etc. According to MNOs, it is around 7% on top of the sum of the CAPEX and OPEX costs.

Equation 16 $\text{Ovhd}_{\text{C}}(\text{t}) = 7\% \times (\text{CAPEX}(\text{t}) + \text{OPEX}(\text{t}))$

Total Cost of Ownership (TCO)

The Total Cost of Ownership (TCO) of the proposed solution is counted as the sum of the CAPEX, the OPEX of T years and the overhead costs of T years (T is the project horizon).

Equation 17 $\text{TCO} = \text{CAPEX} + \sum_{t=1}^{T}(\text{OPEX}(\text{t}) + \text{Ovhd}_{\text{c}}(\text{t}))$

Additional assumptions

To consider the cost evolution over time, two assumptions have been considered with regards to CAPEX and OPEX:

- Due to the maturity of the technology and the market competence with regards to a specific new technology, a -3% yearly CAPEX evolution is assumed according to [8]. This assumption is used when we have investment to do over the years (such as the case of TO center and TO-capable vehicles).
- The time value of money is estimated to be 5% [14] and is included in the OPEX. This value does not reflect the exceptional inflation rate we have currently in Europe (as of 2022).

With:

N_{MC}: number of macro cells	$Dist_{MC\_Agg}$: average distance between a macro cell and the nearest aggregation site
N_{SC}: number of small cells	$Cost_{Fiber}$: cost of fiber cable per km
$Cost_{MC}$: cost of macro cell (including tower, antennas...)	$Cost_{Site\_upgrade}$: Cost of upgrading one site to 5G site
$Cost_{SC}$: cost of small cell	$Cost_{Inst}$: cost of HW installation

3.3.2 Cost Model of the Teleoperation center

To deploy a teleoperation center TOC to serve the different TO UCs, two options have been studied in alignment with the identified business models in [2] namely, the TO service provider deploys its own TOC by renting office space in an industrial zone or in the port whereas he is to buy and install the required infrastructure e.g., TO control setups OR the TO service provider will rent a TO equipped room. The cost model of the two options is described below:

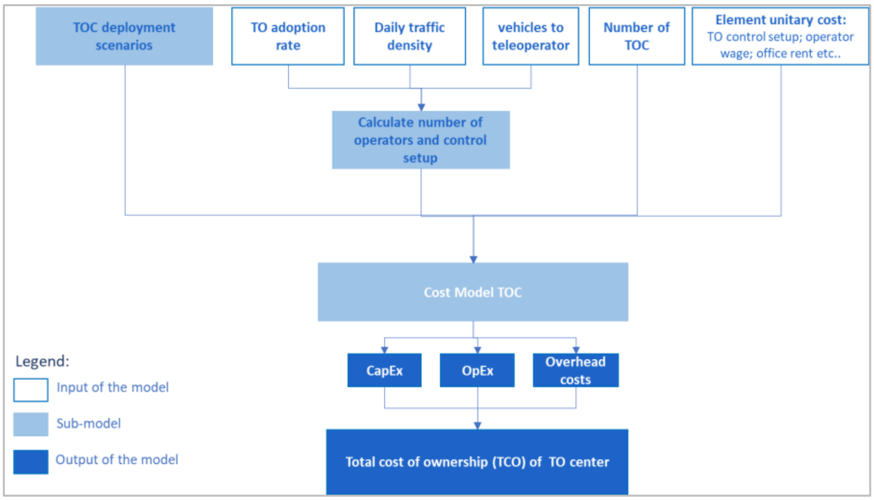


Figure 6 TCO model of the TO center deployment

3.3.2.1 Own TOC

In order to derive the cost of the TOC, we need to know the number of control set-ups to buy and install, as well as the number of operators that will work in the center. This depends heavily on the TO adoption over time assumed for the different vehicles categories (which depends on the TO UC to be provided). To give as much as possible insight into the cost of TOC deployment options, two cases have been studied: 1) dimensioning the TOC based on the maximum number of operators using the TOC on a daily basis, which is derived from TO adoption rates for the different use cases after 10 years-when we expect to have good TO adoption rates, whereas by buying all the control setups already in the first year, the TO service provider might benefit from a significant cost reduction, which we assume to be 8 to 10%. All this is calculated using *Equation 18*2) buying the TO control set-ups and renting the office space required by following the evolution of TO service adoption , in other words: the TOC is scaling up following effective TO adoption rates. In the latter option, the CAPEX yearly evolution is applicable (saving 3% on the yearly cost as explained in the aforementioned “Additional assumptions” section). This is calculated via *Equation 19*. The comparison between the two options gives insights into the cost-efficient option for TO service providers.

CAPEX and OPEX

Equation 18 $\mathrm{CAPEX}_{\mathrm{Own\_TOC}} = (\sum_{\mathrm{i}}^{\mathrm{T}} \mathrm{N}_{\mathrm{CS\_i)}} \times \mathrm{Cost}_{\mathrm{CS\_(i)}}) \times \mathrm{cost}_{\mathrm{reduction}} + \mathrm{IT}_{\mathrm{system}} + \mathrm{TOC}_{\mathrm{furniture}}$

Equation 19 $$\mathrm{CAPEX}_{\mathrm{Own\_TOC}} = \sum_{\mathrm{j=1}}^{10} \sum_{\mathrm{i}}^{\mathrm{T}} \mathrm{Incr\_N}_{\mathrm{CS(i)(j)}} \times (\mathrm{Cost}_{CS(i)} \times CAPEX_{evolution(j)}) + \mathrm{IT}_{\mathrm{system}} + \mathrm{TOC}_{\mathrm{furniture}}$$

To derive the required number of control setups for each type of TO-capable vehicle (T) following the two deployment options described above, option 1) is calculated using *Equation 20* considering the maximum of number of operators that are working daily in the TOC, based on the number of daily expected TO-capable vehicle for year 10 (when we have an important TO adoption rate) whereas 2) is calculated using *Equation 21* considering the incremental number of TO operators for each year following the TO adoption curve(s):

Equation 20 $$\mathrm{N}_{\mathrm{CS\_T}} = \mathrm{N}_{\mathrm{op\_(year10)}\_T}$$

Equation 21 $$\mathrm{N}_{\mathrm{CS\_T}_{\mathrm{year(j)}}} = \mathrm{Incr\_N}_{\mathrm{op\_T}_{\mathrm{year(j)}}}$$

The number of operators for each type of TO-capable vehicles T is calculated using the following

$$\text{Equation 22 } N_{op\_T} = N_{daily\_T} / (TO/VH_{ratio} \times N_{WH})$$

For the OPEX of the TOC, two options have been studied, 1) considering the operators wages depicted in *Equation 23* and 2) without the operators wages calculated using *Equation 24*:

$$\text{Equation 23 } Opex_{Own\_TOC} = Office_{rent} + TOC_{energy} + TOC_{internet} + M + Operator_{wages}$$

$$\text{Equation 24 } Opex_{Own\_TOC} = Office_{rent} + TOC_{energy} + TOC_{internet} + M$$

Whereas the cost for renting office space is derived from:

$$\text{Equation 25 } Office_{rent} = N_{CS} \times Office_{rent\_sqm} \times sqm_{operator}$$

Overhead cost and TCO

To calculate the overhead cost and the TCO, the same formulas as described above are used.

3.3.2.2 Renting TO rooms

The main difference compared to the cost model for deploying an "own TOC" described in the previous section, is that in this scenario, the TO service provider rents a 'TO ready' office equipped with everything e.g., the control setups. So, there is no upfront cost to be paid (no CAPEX), but the monthly renting of TO rooms will be included the OPEX. Similar to deploying the 'Own TOC' case, we calculated the OPEX for both options (including operators wages, which is depicted in *Equation 26* and excluding operators wages, presented by *Equation 27*).

$$\text{Equation 26 } Opex_{TO\_rooms} = N_{CS} \times TO\_room_{rent} + TOC_{energy} + TOC_{internet} + M + Operator_{wages}$$

$$\text{Equation 27 } Opex_{TO\_rooms} = N_{CS} \times TO\_room_{rent} + TOC_{energy} + TOC_{internet} + M$$

For the rest of the cost components, namely the overhead cost and TCO, they follow the same calculation as previously described.

With:

$N_{CS\_(i)}$: number of control setups of type i	$TOC_{furniture}$: cost of non TO furniture needed for the TOC
T: type of TO vehicle :{truck, barge, crane}	$Incr\_N_{CS\_(i)(j)}$: incremental number of control setups of type I at year j
$Cost_{CS\_(i)}$: cost control setup for type i	$CAPEX_{evolution(j)}$: CAPEX reduction percentage at year j
IT_{system} : cost of IT system	$N_{op\_(year10)\_T}$: number of operators at year 10 for the type of TO vehicle T
$Incr\_N_{op\_T_{year(j)}}$: incremental number of operators of type i at year j	N_{daily_T}: number of daily TO of type T to serve
TO/VH_{ratio}: Teleoperator to Vehicle ratio	N_{WH}: number of working hours
$Office_{rent}$: cost of office space rent	TOC_{energy}: cost energy consumption
$TOC_{internet}$: cost of internet subscription	M: hardware maintenance cost
$Office_{rent\_sqm}$: cost of one square meter of office space rent	$sqm_{operator}$: number of square meters per teleoperator
TO_room_{rent}: cost of renting one TO room	

Several deployment options have been studied and here below their summary and presented in Table 1:

- Option 1: Own TOC for pessimistic TO adoption with operator wage and gradual addition of new TO control setups following the yearly TO adoption and considering a yearly CAPEX evolution of -3% as described in the first section.
- Option 2: Own TOC for pessimistic TO adoption without operator wage and gradual addition of new TO control setups following the yearly TO adoption and considering a yearly CAPEX evolution of -3% as described in the first section.
- Option 3: Own TOC for pessimistic TO adoption with operator wage and deployment of control setups from day 1 considering a cost reduction as described in the first section.
- Option 4: Own TOC for pessimistic TO adoption without operator wage and deployment of control setups from day 1 considering a cost reduction as described in the first section.
- Option 5: Own TOC for optimistic TO adoption with operator wage and gradual addition of new TO control setups following the yearly TO adoption and considering a yearly CAPEX evolution of -3% as described in the first section.
- Option 6: Own TOC for optimistic TO adoption without operator wage and gradual addition of new TO control setups following the yearly TO adoption and considering a yearly CAPEX evolution of -3% as described in the first section.
- Option 7: Own TOC for optimistic TO adoption with operator wage and deployment of control setups from day 1 considering a cost reduction as described in the first section.
- Option 8: Own TOC for optimistic TO adoption without operator wage and deployment of control setups from day 1 considering a cost reduction as described in the first section.
- Option 9: TO room rent for pessimistic TO adoption with operator wage.
- Option 10: TO room rent for pessimistic TO adoption without operator wage.
- Option 11: TO room rent for optimistic TO adoption with operator wage.
- Option 12: TO room rent for optimistic TO adoption without operator wage.

Table 1 Summary of the different TOC deployment options

	Pessimistic TO adoption	Optimistic TO adoption	Own TOC	Rent TO room	Deployment control setups day 1	Gradual deployment of control setups	With operator wages	Without operator wages
Option 1	x		x			x	x	
Option 2	x		x			x		x
Option 3	x		x		x		x	
Option 4	x		x		x			x
Option 5		x	x			x	x	
Option 6		x	x			x		x
Option 7		x	x		x		x	
Option 8		x	x		x			x
Option 9	x			x	/	/	x	
Option 10	x			x	/	/		x
Option 11		x		x	/	/	x	

Option 12		x		x	/	/		x

3.3.3 Cost Model of the TO-capable vehicle

For the different type of vehicles being trucks, barges and cranes, we calculate the cost of making them TO-capable by installing the TO system from the manufacturing phase in new vehicles or by retrofitting which translates in CAPEX (*Equation 28*) and the cost of maintaining the installed HW over the project lifetime which translates into OPEX (*Equation 29*).

Equation 28 $\mathrm{CAPEX_{TO\_V}} = N_{TO\_V} \times \mathrm{cost_{TO\_HW}}$

Equation 29 $\mathrm{OPEX_{TO\_V}} = \mathrm{M} \times \mathrm{CAPEX_{TO\_V}}$

For the rest of the cost components, namely the overhead cost and TCO, they follow the same calculation as previously described.

3.4 Forecasting the TO adoption

From the different cost model formulation, it is clear that the number of TO-capable vehicles using the different TO UCs is crucial for the dimension of the 5G network as well as the TO center. To estimate the number of expected connected TO-capable vehicles (barges/trucks etc..); the Bass diffusion model has been adopted. The Bass Diffusion Model is used to forecast the adoption of new products or technologies in a given population *m* [4]. It follows a binary diffusion pattern that has been classified into two types of adopters:

- Innovators *p* – those with earliest adopter tendencies; and
- Imitators *q* – those with tendencies to observe a new product before adopting.

The Bass model equation can be expressed as:

$$T_{TO}(t) = {m * (1 - e^{-(p+q)t})}\Big/{\left(1 + \left(\frac{q}{p}\right) e^{-(p+q)t}\right)}$$

With:

- $T_{TO}(t)$: number of users that adopted the new technology, in our case TO at time t
- *m*: cumulative market potential on the whole product’s lifecycle,
- *p*: coefficient of innovation, and
- *q*: coefficient of imitation.

3.5 Revenue model

This section describes the developed revenue model to be used in the revenue modelling for the different scenarios. Two options can be used to identify the expected direct revenue streams resulting from adopting 5G-based TO transport. The first option is a cost-based pricing where the average cost per user (ACPU) to which a profit margin is added results in an average revenue per user (ARPU). The latter in combination with the expected total number of users over the project lifetime defines the total revenues. The second option rather relies on the estimation of the TO service pricing per connected vehicle, in our case: barge, crane, skid steer or truck, as identified on several discussions with TO service providers. Both revenue identification options are applied and compared among each other to judge whether the estimation of the TO service price makes the business case viable within a considered project lifetime.

3.6 Business case evaluation

In this step of the techno-economic analysis, we evaluate the viability of the business case using the Total Cost of Ownership (TCO) model results described in section 3.3 and the revenue estimation that has been derived based on an Average Cost Per User (ACPU) with an average profit margin added on top, described in section 3.5. the cumulative TCO is compared to the cumulative revenues to determine the Break-even Point (BEP). The break-even point (BEP) in economics is the point at which total cost and total revenue are equal, i.e., "even". There is no net loss or gain, and one has "broken even", though opportunity costs have been paid and capital has received the risk-adjusted, expected return. In short, all costs that must be paid are paid, and there is neither profit nor loss.

3.7 Sensitivity analysis

One of the famous definitions of sensitivity analysis is: “*The study of how uncertainty in the output of a model (numerical or otherwise) can be apportioned to different sources of uncertainty in the model input*” [15]. Therefore, any model is built on a number of assumptions, which implies uncertainty on input parameters. Hence, the goal of the sensitivity analysis is to determine the impact of varying parameters on the outputs of the model. After identifying these parameters, most often the parameters with a marginal impact are discarded while extra attention is given to the important ones.

However, we should make a clear distinction between uncertainty and sensitivity analysis. Uncertainty analysis quantifies the uncertainty of a random variable. This can be an input to a scientific model, an intermediary variable or even the model’s output. Sensitivity analysis on the other hand studies the impact of the uncertainty of the different inputs on the uncertainty of one of the model’s intermediary or output variables. It shows how the uncertainty in the output of a model can be apportioned (numerical or otherwise) to different sources of uncertainty in the model input. Both disciplines are closely related but should not be confused.

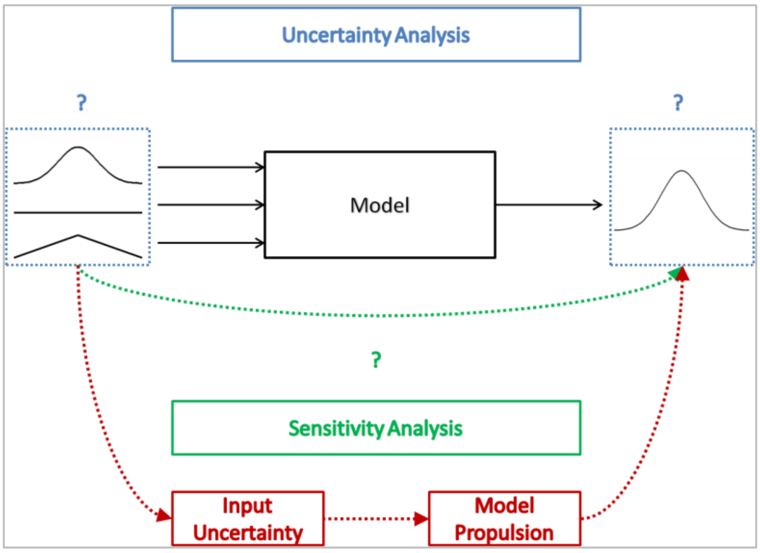


Figure 7 Uncertainty and Sensitivity Analysis

Figure 7 captures this difference. Note that the impact of the input uncertainty on the output uncertainty has two components. The height of the input uncertainty itself as well as how this uncertainty is propelled through the model. Sensitivity analysis addresses the joint effect of these two components, not the impact of one or the other.

4 5G-BLUEPRINT SETTINGS

4.1 Reference scenarios

In order to limit the scope of the teleoperated transport scenarios from a business and governance models perspective, a set of reference scenarios has been defined. Making assumptions in terms of deployment scenarios will allow us to analyze progressively the cost-benefit of providing teleoperation transportation from small to a wider scale deployment.

The three assumed scenarios are based on the specific geographical coverage of the teleoperated transport operation. These scenarios are classified as follows:

- **Scenario 1: geographically limited area with numerous (short distance) transports**: for example, a port area or industrial zone with interconnected supply/manufacturing chains. Examples would be major European ports and manufacturing or chemical plants, where TO would cover short transports within the site and to and from distribution centers in the area. In this scenario, the TO center would be constructed to serve all interested users in the studied area. The 5G connectivity can be made available through private or public networks.
- **Scenario 2: major (national) transport axis with significant transport flows**. TO operation can be offered by an independent Service Provider and/or may concur with 'in house' TO (i.e., if larger players have their own TO center). These scenarios include either roads or waterways where a significant volume of transport flows is present, for example a canal between two ports in the same country. Since public roads often cover a significant part of such transport axis, 5G connectivity providers must cover these segments as well.
- **Scenario 3: public roads and waterways across national borders**. In this scenario, which includes and extends the coverage of the previous ones, the TO operation across borders poses additional challenges. Crucially, in order to avoid any loss of control, TO and 5G connectivity providers need to ensure a seamless handover of connectivity sessions, teleoperated vehicles, and service monitoring. Therefore, this scenario entails the highest complexity for the challenge of guaranteeing continuity of service, but it also offers the largest geographical reach.

4.2 5G connectivity scenarios

Three 5G connectivity options have been identified within the project, being the 5G private network, 5G coverage on-demand and 5G network slicing, and they are defined as follows.

Private networks: as most of the expected incremental benefits from 5G will come from 'vertical' applications. A common feature across industrial use cases is the aspect of private networks for local deployments. Private networks rely on the deployment of dedicated 5G network infrastructure at a customer's site to meet their use cases requirements in term of QoS i.e., latency, throughput, coverage, etc.

However, some MNOs, such as the ones in 5G-Blueprint, may prefer to upgrade their nationwide public networks to provide the additional QoS via so-called coverage on-demand in dedicated locations.

Coverage on-demand can resemble a private network in practice, as it can mean adapting the radio access network to the customer's needs, but with the core network remaining the MNO's public one. In practice, it can result in deploying base stations in the premises of a factory or in a port area, in order to guarantee latency and reliability according to the site owner's needs. Such coverage on-demand can yield the same user experience as a private network, or even higher, since a customized network can be inferior to one that relies on a public core, depending on its characteristics, and hence, cost [2]. In other words, the coverage on demand is an on-demand extension of the public network, customized for teleoperation (TO) use cases. However, this special configuration requires additional maintenance and configuration costs, which were not taken into account in our analysis due to the complexity of estimating them.

Network slicing: a 5G end to end network slicing is a concept for running multiple logical networks (which could be customized with a guaranteed SLA) as virtually independent business operations on a common physical network infrastructure. The technology enabling network slicing is transparent to business customers for whom 5G networks, in combination with network slicing, allow connectivity and data processing tailored to the specific business requirements [16]. In our case, MNOs can also offer some of the benefits of a private network by customizing network slices on top of their public 5G networks to meet teleoperation transportation requirements.

4.3 TO center deployment options

The TO center deployment options have been discussed and described in detail in [2] and described in section 3.3.2. The main two deployment options are: 1) deploying a TO center in the harbor or the industrial zone by leasing the office space there and installing the required TO hardware such as control set-ups, connectivity installations etc. and 2) renting a ready TO room equipped with everything except the tele-operator themselves. In some cases, the logistic companies could engage the TO service provider for a tele-operator in combination with the TO service provision whereas they also may opt for bringing in their own tele-operator to teleoperate their trucks/barges. These two options were also studied in the analysis reported in this deliverable.

4.4 5G-blueprint use cases and Enabling Functions

During the initial phase of the 5G-Blueprint project, 4 use cases have been identified in WP4 [17] to assess the value brought by 5G-based teleoperation, namely:

- UC 4.1: Automated barge control: The channel navigation of the barges will be teleoperated along with part automation within this UC 4.1. Along with channel navigation, port entry and exit cost efficiency in particular will be increased by reducing crew requirements for barge navigation. Vessel navigation during barging will be performed completely by the vessel captain in collaboration with a teleoperating captain in the Shore Control Centre, eliminating further crew interventions. More specifically, UC1a.1 Automated Barge Control: Navigating a river and a canal in a national waterway, UC1a.2 Automated Barge Control: Navigating a river and a canal in a cross-border waterway, and UC1b Automated Barge Control: Navigating, Docking and Unloading in a (busy) port.
- UC 4.2: Automated driver in the loop docking: This use case has been divided into two subcases namely, 4.2a: Automated docking and 4.2b: Teleoperated crane. The subcase automated docking propounds on the idea of driver assistant system for docking articulated vehicles within warehouses and distribution centers by integrating 5G technology. Within the subcase of teleoperated crane, a mobile harbor crane will be retrofitted with teleoperation functionality, so it can be operated from a remote-control center by a teleoperator. The cranes will be first teleoperated for loading and unloading only.
- UC 4.3: CACC based platooning: A platoon of trucks is one where two or more trucks follow one another in close proximity to each other on dedicated stretches of the highway. This is achieved by using a combination of adaptive cruise control, lane-keeping system and V2V communication. Within the 5G BP project, we aim to upscale this existing technology with the use of 5G along with providing an interesting business case. The use case revolves around the use 5G, the driver can be removed from the cabin of the truck and can be placed in a remote location from where he can control the vehicle. The system is aimed at being partly automated wherein the lead vehicle can be driven by a driver in the cabin or a teleoperator and the following vehicle(s) can be automated. The teleoperator of the system can take control of the following vehicle when it is deemed necessary by the system.

- UC 4.4: Remote takeover: Remote takeover defines the process by which a remote operator takes control of a distant vehicle. To enable remote takeover, it is necessary to adjust the vehicles to steer and drive remotely from the control center. Subsequently, the vehicle must be equipped with an onboard unit and cameras providing teleoperation functionality. Another essential component is the teleoperation center, which must provide the technical means to manage vehicles, remote operators, ensure connectivity, and control vehicles' access.

The four use cases are depicted in the figure below:

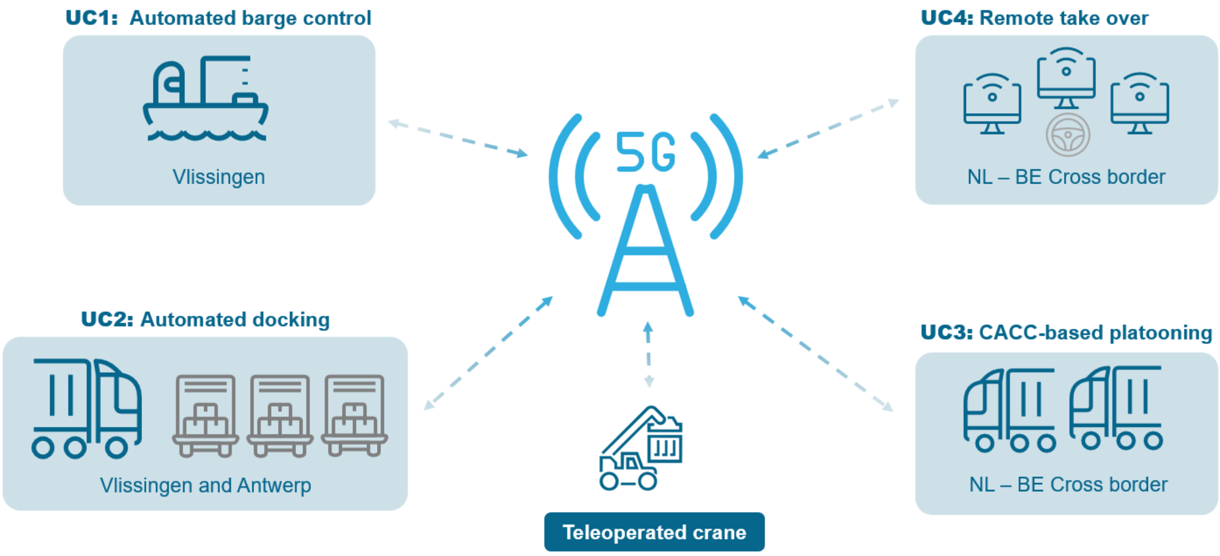


Figure 8 TO use cases

The purpose of the enabling functions is to support the aforementioned use cases and facilitate teleoperated transport by communication of on-site data to the remote operator by use of a dashboard (EF1). As all enabling functions are expected to provide input through the dashboard and they are all very much intertwined and complementary to one another, their description is done via the data they provide to the dashboard and their summary is presented in the Table 2.
Functionalities of the dashboard as described in [18]:

1) Speed advice based on traffic data & route and considering booked intersection timeslots (EF 3).
2) Dynamic map of surroundings that is created based on data collected by one or more operated vehicles by sensors, radar, lidar, camera's (EF 4)
3) Warnings of technical errors, collision avoidance (EF 5), approaching vulnerable road user (EF 2) and other anomalies detected in the transmitted data (EF8)
4) Navigation and routing including ETA (EF7)
5) Container information (EF 6)
6) Place reservation at parking

Table 2 Summary of the enabling functions (EFs)

Enabling functions	Functionality
EF1	Enhanced Awareness dashboard (HMI)
EF2	Vulnerable road user interaction
EF3	Timeslot reservations at intersections
EF4	Distributed perception
EF5	Active collision avoidance
EF6	Container ID recognition
EF7	ETA sharing
EF8	Logistics Chain Optimization

These eight enabling functions are described in more detail in [19]. To study the impact of adopting the developed enabling functions on the business case, several parameters should be analyzed. From a 5G network perspective these enabling functions have different requirements. These requirements are studied in [20] and are taken into account in the network dimension in the different deployment scenarios.

The network requirements in term of uplink (UP) capacity of the selected use cases and enabling functions are studied in [20] and are summarized in the table below. These requirements reflect the case where all the optional features to provide high-quality teleoperation services are included e.g., high quality of the video streams etc. In other words, these figures reflect the maximum UL capacity for teleoperation, however if good compression algorithms are used together with an intelligent combination of camera streams to be send via the network it is assumed these numbers can be significantly reduced. In this study, we build on the maximum numbers to assess a worst-case scenario for the 5G network deployment. However, minimized numbers are considered in the sensitivity analysis to study a kind of best-case scenario where the UL capacity required from the network is minimal -what enables an assessment of such variations on the deployment cost.

Table 3 Summary of the network requirements of the selected UCs and EFs (max scenario considered)

UC/EF	**Required UP capacity**
UC4.1	80 Mbps
UC4.2a	78 Mbps
UC4.2b	80 Mbps
UC4.3	78 Mbps
UC4.4	78 Mbps
eMBB slice	5 Mbps
mIoT slice	1 Mbps
EF4	1 Mbps
EF5	1 Mbps

4.5 Summary of identified business models

Deliverable D3.2 [2] described 6 business models, two for each deployment scenario.

For scenario 1, where TO services would be offered within a port or industrial area with a high frequency of transport flows and from the site to local distribution centers, the following two models were discussed:

- BM1 relies on a more locally orchestrated deployment, with a private 5G network financed by a port authority. In addition, the port would also help finance the deployment of a TO center, in collaboration with local logistics companies. These logistics companies would form a joint venture to offer the TO service within the area.
- BM2 relies on attracting deployment of 5G and TO services by providers with a broader (inter)national focus. With coverage on-demand, an MNO upgrades the capacity of its public network in the port or industrial site. The TO service is done by an independent service provider. Compared to the previous model, here the port/industrial site owner plays more the role of orchestrating rather than financing.

The two business models for scenario 2, which covers a major road/water transport axis within a country, focused on the use case of teleoperation of semi-autonomous barges.

- In BM3, port authorities and TO service providers lease customized network slices as-a-service (NSaaS) from MNOs, who in turn acquire virtual network resources via a slice broker. TO service provision is provided by a specialized service provider that offers an integrated service and deploys its own TO center.

- In BM4, 5G network deployment is based on network sharing; MNOs densify their networks along waterways by relying on active network sharing to substantially reduce costs by jointly investing in masts, antennas and other RAN elements. Regarding the TO service, the provider would be a large transport company with a wide geographical presence and substantial volume of transports. This company would retrain their current captains (or, by extension, drivers) to be licensed to remotely operate vehicles.

For scenario 3, consisting of goods transport across national borders, we assumed a deployment of TO as a support to highly autonomous trucks in complex local roads and adverse climatic conditions.

- In BM5, a vehicle manufacturer integrates the role of TO service provider, offering it as an added value service. In this model, the TO center would be co-located within the premises of a traffic manager, who would lease space for the TO stations. The OEM may even own its own fleet of trucks, implying that the business model of logistics service providers would change to resemble that of a broker.
- In BM6, the TO service provider is a large international match-making platform that owns TO centers across the EU. It would not, however, own the vehicles. The customers of the platform (e.g., transportation companies) would pay a subscription to access the service, complemented with additional optional fees for a priority allocation of a teleoperator in periods of high demand (i.e., premium fees to reduce waiting times).

4.6 Identification of deployment scenarios

As can be seen in the previous sections, we have different reference scenarios where 5G-based teleoperation can be provided and different 5G connectivity and TO center deployment options exist to serve multiple use cases and enabling functions. Mapping these different options all together results in several deployment scenarios. The following sections describe the chosen mapping of the different options and the selection process of the deployment scenarios that consequently have been investigated.

4.6.1 Mapping of different options to use cases and EFs

In this section we map the different reference scenarios, the 5G connectivity options and TCO deployment options to the UCs and EFs as presented in the table below:

Reference scenario	Connectivity Scenario	TO center deployment scenario	Concerned Ucs and EFs
Scenario 1a: geographically limited area for example, a port area/ industrial zone.	(1) 5G coverage on-demand (2) Network slice and (3) 5G private network	(1):TO center in the port/industrial zone (as a start) (2): rented TO room	UC4.1b; UC4.2b; UC4.3 and UC4; EF4 and EF5
Scenario 1b: geographically limited area with numerous (short distance) transports: for example, a port area/ industrial zone.	(1) 5G coverage on-demand (2) Network slice and (3) 5G private network	(1):TO center in the port/industrial zone (as a start) (2): rented TO room	UC4.1a.1; UC4.1b; UC4.2b; UC4.3 and UC5; EF4 and EF5
Scenario 2: major transport axis – significant transport flows via road or water.	(1) 5G coverage on-demand and (2) Network slice	(1): Own TO (2): rented TO room	UC4.1a.1; UC4.3 and UC4; EF4 and EF5
Scenario 3: public road, across national borders.	(1) 5G coverage on-demand and (2) Network slice	(1): Own TO (2): rented TO room	UC4.1a.2; UC4.3 and UC4; EF4 and EF5

4.6.2 Selection of deployment scenarios to analyze

Given the different possible combination presented in the table above and based on a scoring system where consortium partners gave their preferences in term of the different potential deployment scenarios, five deployment scenarios have been selected to be analyzed in detail being:

6. **Deployment scenario 1**: in limited port area, terminals only supporting UC4.1, UC4.2 and UC4.4
7. **Deployment scenario 2**: in port area, terminals and short public roads supporting UC4.1a, UC4.1, UC4.2, UC4.3 and UC4.4
8. **Deployment scenario 3**: major national transport axis – significant transport flows via water supporting UC4.1
9. **Deployment scenarios 4**: major national transport axis – significant transport flows via road supporting UC4.2, UC4.3 and UC4.4
10. **Deployment scenarios 5**: major international transport axis – significant transport flows via road and water: cross-border area supporting UC4.1, UC4.3 and UC4.4

4.7 Description of pilot sites and how they feed the techno-economic analysis

As all the use cases and enabling functions in the 5G-Blueprint project are being extensively tested in the T&L real-life environment with 5G SA/NSA coverage, here we briefly reflect on the three pilot sites where the trialling activities are performed. The input from the testing/trialling activities (e.g., network and use case/enabling functions results and analysis), will be fed from the WP7 to the techno-economic analysis in WP3.

- **Vlissingen pilot site** located in the Netherlands is covered by both 5G NSA and SA (Test network) from KPN. The NSA network is deployed on 700MHz, while SA is provided on a temporary license at 3.5GHz. This pilot site is used for trialing activities of use cases UC4.2 (Automated driver-in-loop docking), UC4.3 (CACC-based platooning), and UC4.4 (Remote take-over). It stretches over the three locations: i) MSP Onions terminal (docking area with the parking lot), ii) Verbrugge Scaldia Terminal (harbor terminal and public road) for real teleoperation on the close roads, and iii) the stretch of road from MSP Onions terminal to the Kloosterboer terminal for shadow-mode testing (control commands sent from the teleoperator to the teleoperated vehicle/barge via 5G, but they are not applied locally).
- **Antwerp pilot site** located in Belgium is covered by both 5G NSA and SA from Telenet. The NSA network is deployed on 2.1GHz and 3.5GHz, with SA coverage on 3.5GHz. This pilot site is mainly leveraged for trialing activities of UC4.1 (Automated barge control), UC4.3, and UC4. As it includes both waterway and roadway testing activities, this site consists of two main locations: i) Right bank of the Port of Antwerp Bruges where the shadow-mode teleoperation of a barge is being performed (UC4.1), and ii) the Transport Roosens Kallo site (container hub) used for both shadow-mode and real teleoperation testing on the closed roads.
- **Zelzate pilot site** located on the border between the Netherlands and Belgium, is the most challenging pilot site in terms of network connectivity as it requires seamless roaming mechanisms that result in further extensions of the 5G Core network functionalities of both mobile network operators. Same as in the case of Antwerp pilot site, use cases UC4.1, UC4.3, and UC4.4, including their supporting enabling functions, will be tested. This pilot site is designed in such a way that it stretches over the canal Gent-Terneuzen (where the barge from UC4.1 will be sailing), through a detailed cross-border trajectory with various environmental conditions, such as urban and rural area, industrial area, highway with civilian cars/trucks, pedestrians and bikers.

The trialing activities in all three pilot sites involve testing of network performance, and shadow-mode and real teleoperation performance, as per KPIs defined in D7.2. The performance of use cases and enabling functions indirectly reflects the behavior of network, and as such, it needs to be thoroughly studied to understand e.g., if uplink throughput for multiple HD video streams, or downlink latency for control commands, are sufficient for performing safe and efficient tele-operation in all three pilot sites. Thus, the results collected in WP7 are being thoroughly studied and compared against the network requirements of use cases/enabling functions defined in D5.1. Such an input will be brought from WP7 to WP3, as it extremely important for the techno-economic analysis, thereby fine-tuning the network dimensioning and making it more realistic.

5 RESULTS ANALYSIS

In this chapter, we detail the cost results of applying the TEA methodology described in chapter 3 to the five selected deployment scenarios. For each deployment scenario, the following structure is used:

1. Definition of the deployment scenario: we start by defining the area where 5G-based teleoperation will be provided, the supported use cases and enabling.
2. Forecast of TO adoption: in this section we use the Bass diffusion model described in chapter 3 to forecast the TO adoption for the different type of vehicles that are covered by the studied use cases.
3. Dimension of the 5G network: this section describes first the area to cover with 5G networks and calculates the UL capacity requirements for each connectivity option and the resulting 5G network infrastructure to support the calculated capacity.
4. Cost model results of 5g network deployment: in this section the cost modelling results of the different 5G connectivity options are presented and compared to each other.
5. TO center deployment cost results: this section summarizes the cost results of deploying TO center considering all the deployment flavors described in section 3.3.2.
6. Cost results of making the different type of vehicles TO-capable
7. Business case evaluation: in this section the ACPU and ARPU are derived, and the total expected revenues are compared to the TCO to identify the BEP.
8. Sensitivity analysis: this section presents the results of varying some key parameters and their impact on the TCO.
9. Main takeaways: in this section we summarize the key findings from the TEA of the studied deployment scenario.

5.1 Deployment scenario 1: in limited port area, terminals only supporting UC4.1, UC4.2 and UC4.4

5.1.1 Definition of the deployment scenario

This deployment scenario is based on the combination of multiple technological options related to where and how to provide TO services. Starting with the “where” question, in this deployment scenario, TO services are provided only in the terminals area of the port of Antwerp (PoA), using two different connectivity options being 1) 5G coverage on demand and 2) 5G network slicing. The use cases supported are: UC4.1b: Automated Barge Control: Navigating, Docking and Unloading in a (bussy) port; UC4.2b: Teleoperated Mobile Harbour Crane/skid steers and UC4: Remote Take Over Operation, together with EF5: Active collision avoidance.

We study the port area as terminals that are operating by different companies. Those terminals are future adopters of TO capabilities to support UC4.1b, UC4.2b, and UC4. Hence, we need to forecast:

- The adoption of 5G networks by those terminals to support TO
- The adoption of TO capabilities for barges
- The adoption of TO capabilities for the cranes

5.1.2 Forecasting of TO adoption in the port

To estimate the number of expected terminals that will adopt TO technology and the expected connected TO-capable vehicles namely barges, trucks, and cranes, the bass diffusion model has been used. This model is described in section 3.4.

5.1.2.1 5G networks adoption rate in the port terminals to support TO use cases

To estimate the number of TO-capable terminals based on 5G networks using the Bass diffusion model, we adopt p and q values from the study carried on wireless network technologies adoption [4]. With p =0.00072 and q = 0.64 and m=26 being the total number of terminals operating in the PoA, we forecasted the number of terminals that will adopt 5G networks to offer TO use cases (presented in Figure 9).

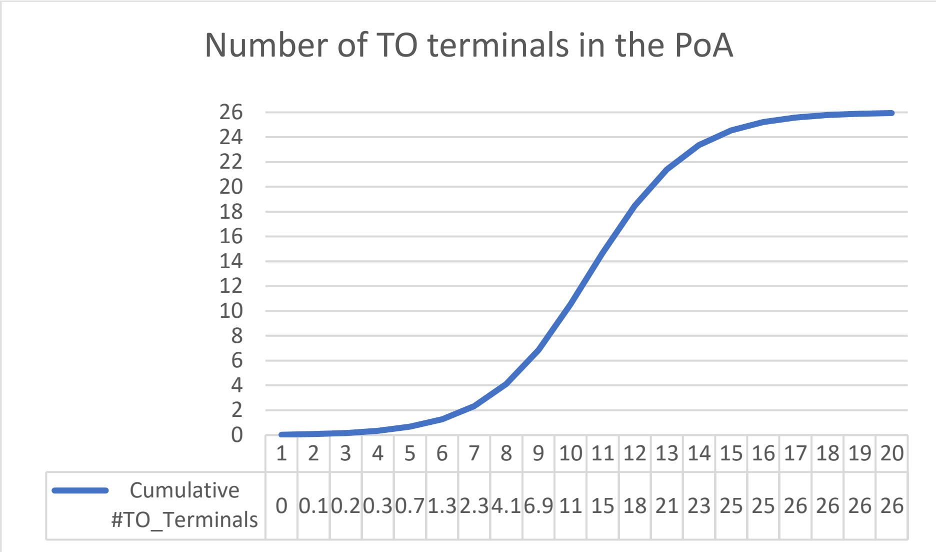


Figure 9 Forecast of the number of terminals that adopt 5G networks to offer TO use cases in the port of Antwerp

According to the TO adoption forecast, only one terminal will adopt 5G-based teleoperation during the first 5 years. Therefore, in this analysis, we consider “Antwerp Gateway” terminal know as DP World: Antwerp gateway Quai 1700 as the pilot terminal that will be the first adopter of 5G-based teleoperation and then expand the deployment and cover the other terminals following the adoption curve presented above.

5.1.2.2 TO adoption rate in the barges/ships fleet for UC4.1b:

1. ***Pessimistic/realistic TO adoption scenario***

On the other hand, we need to estimate the daily TO barges in the port, using the same Bass Diffusion model parameters of the wireless technologies to forecast the daily number of TO capable barges that come to the PoA. with a starting daily number of 191 barges and an annual market growth of 3%, we derived the daily TO barges in PoA over 20 years as presented in the figure below:

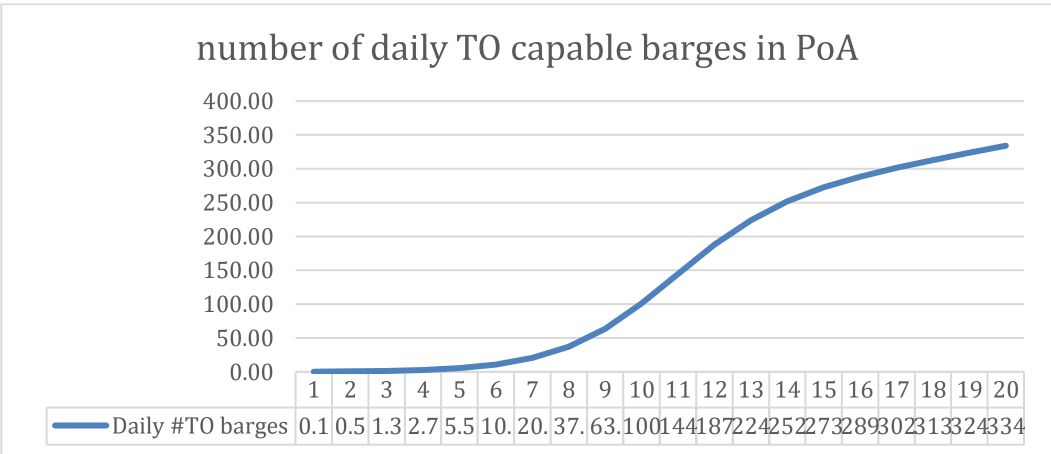


Figure 10 Evolution of expected number of TO-capable barges over the years in PoA in the pessimistic scenario

Similar to previous graph, we see very low adoption in the first five years with only one TO capable barge during the first two years. This is in alignment with number of terminals in the port that provide TO.

Given the total number of terminals in the PoA being 26 and the daily number of barges served we calculated the average served barges/ships per terminal. Using this latter with the daily TO barges/ships that needs to be served, we calculated the required number of terminals that can assist TO barges for the pessimistic scenario and is summarized in the following table:

Table 4 Calculation of the new TO terminals based on the number of TO-barges for the pessimistic scenario

t: year	1	2	3	4	5	6	7	8	9	10
m: # of daily barges in the PoA	191	197	203	209	215	221	228	235	242	249
#TO-adopted barges	0.19	0.57	1.32	2.77	5.56	10.82	20.46	37.17	63.76	100.88
average # of ships per terminal	7.35	7.57	7.79	8.03	8.27	8.52	8.77	9.03	9.31	9.59
# of required TO terminals	0.03	0.1	0.2	0.3	0.7	1.3	2.3	4.1	6.9	10.5
#of required TO terminals if only half serving capacity is for TO barges	1	1	1	1	2	3	5	9	14	21
#of new TO terminals	1	0	0	0	1	1	2	4	5	7

Based on the TO adoption graphs we observed that the yearly number of TO terminals is going hand in hand with the number of TO barges to serve for the pessimistic TO adoption scenario.

2. *Optimistic TO adoption scenario*

In the previous prediction of the TO scenario, the number of early adopters of TO capabilities in barges is very low, hence its name, pessimistic adoption scenario. Therefore, we used other parameters for forecasting a more optimistic adoption of the TO capabilities for barges. Based on a study investigating Bass model parameters for adoption of new technologies in the UK maritime sector [21], we run the Bass model with the parameters found in that study:

- p: innovation coefficient: 0.003
- q: imitation coefficient: 0.5

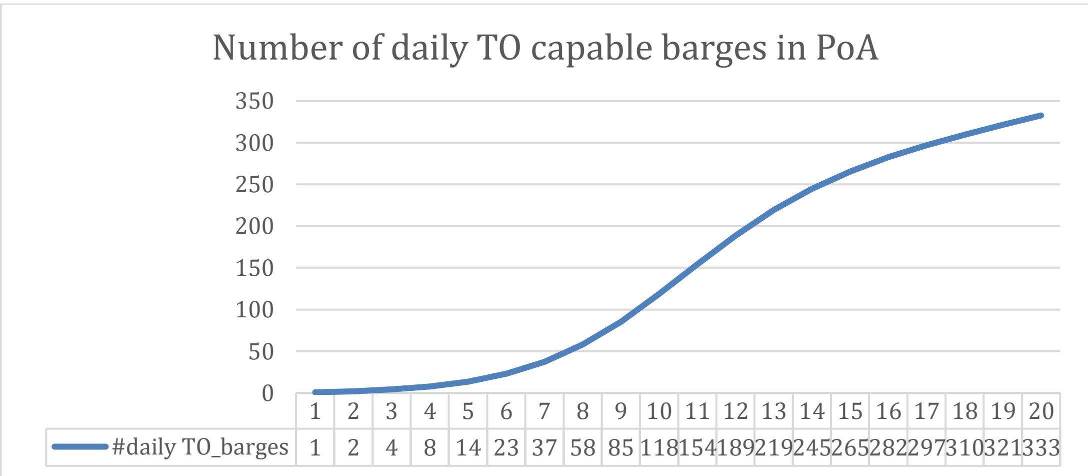


Figure 11 Evolution of expected number of TO-capable barges over the years in PoA in the optimistic scenario

Unlike the previous adoption scenario, we see in this optimistic TO adoption an important number of early adopters of the TO technology, up to 14 barges in the first. And after that we have a very good uptake of the technology. It is worth noting that this is the daily number of barges that will visit the PoA and are supporting the TO technology, not the uptake of TO in an entire barges fleet.

Given the total number of terminals in the PoA being 26 and the daily number of barges served we calculated the average served barges/ships per terminal. Using this latter with the daily TO barges/ships that needs to be served, we calculated the required number of terminals that can assist TO barges for the optimistic scenario and is summarized in the following table:

Table 5 Calculation of the new TO terminals based on the number of TO-barges for the optimistic scenario

t: year	1	2	3	4	5	6	7	8	9	10
m: # of daily barges in the PoA	191	197	203	209	215	221	228	235	242	249
#TO-adopted barges	0.74	2.01	4.17	7.76	13.65	23.02	37.33	57.96	85.41	118.47
average # of ships per terminal	7.35	7.57	7.79	8.03	8.27	8.52	8.77	9.03	9.31	9.59
# of required TO terminals	0.1	0.3	0.5	1.0	1.7	2.7	4.3	6.4	9.2	12.4
#of required TO terminals if only half serving capacity is for TO barges	1	1	2	2	4	6	9	13	20	23
#of new TO terminals	1	0	1	0	2	2	3	4	7	3

Based on the TO adoption graphs and the calculation done in the table above, we observed that the yearly number of required TO terminals is higher than the one found in the TO adoption of terminals and this is due to the higher number of TO barges to serve. Therefore, the required number of TO terminals following an optimistic adoption of the TO technology is presented in the figure below:

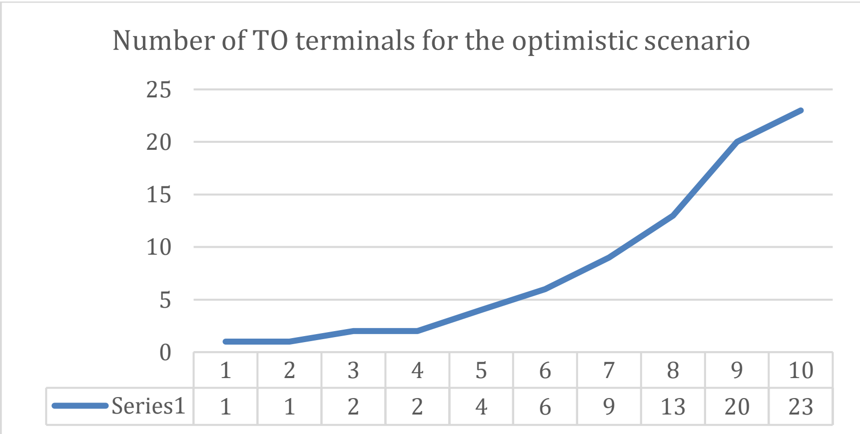


Figure 12 Forecast of the number of terminals that adopt 5G networks to offer TO use cases in the port of Antwerp for the optimistic scenario

5.1.2.3 TO adoption in cranes in PoA for UC4.2b:

For Use case 4.2b, we don't focus only on the mobile harbour crane but also on the other type of cranes where we think teleoperation could have additional benefits for the business case. In fact, even for the Automated stacking cranes (ASC), remote operation is used to ensure the safety of the automated process [22]. Therefore, in our analysis, we need to derive the number of TO capable cranes in the PoA. Using the TO adoption in terminals for both adoption scenarios being the pessimistic and the optimistic ones and assuming an average of 20 cranes per terminal, 4 cranes per group assuming that one group of 4 cranes serves one barge at a time and only half of the groups support TO.

1. *Pessimistic/realistic TO adoption scenario*

The adoption of TO in crane over 20 years is presented in the figure below:

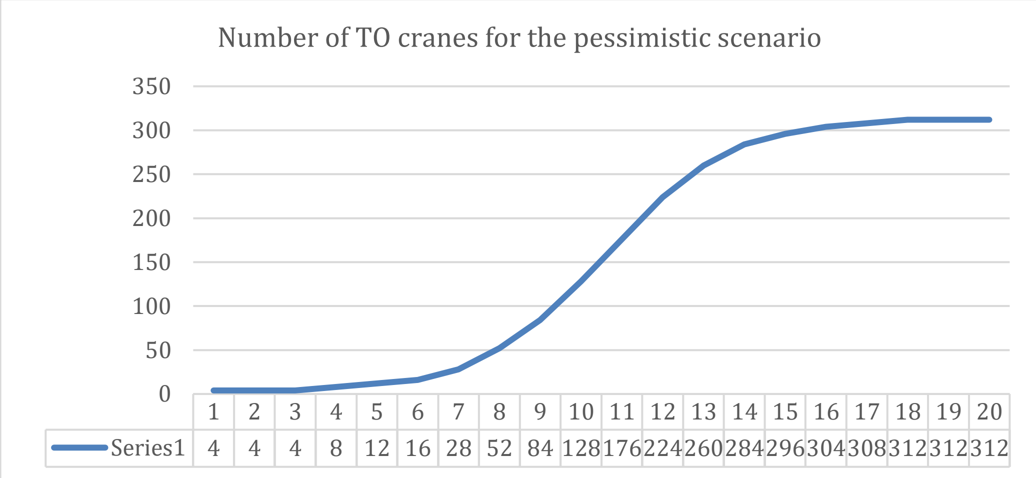


Figure 13 Evolution of expected number of TO-capable cranes for the pessimistic scenario over the years in PoA

2. *Optimistic TO adoption scenario*

The adoption of TO in crane groups over 20 years is presented in the figure below:

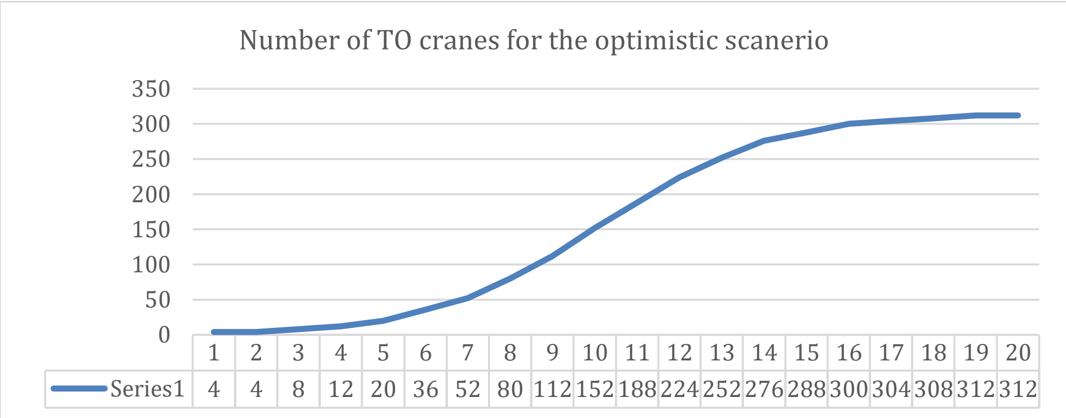


Figure 14 Evolution of expected number of TO-capable cranes for the optimistic scenario over the years in PoA

5.1.2.4 TO adoption in the internal trucks operating in the port terminals

To make the most out of the teleoperation technology, the entire freight loading and unloading process has to be implemented using this technology. Therefore, in this deployment scenario we consider also that the terminal internal trucks (Its) that are responsible for the loading and unloading task from the barge by the means of the Quai Cranes (QC) are also tele-operatable. We adopt the operational model proposed in [23], where we allocate only one IT to each QC, presented in figure (b) of the figure below.

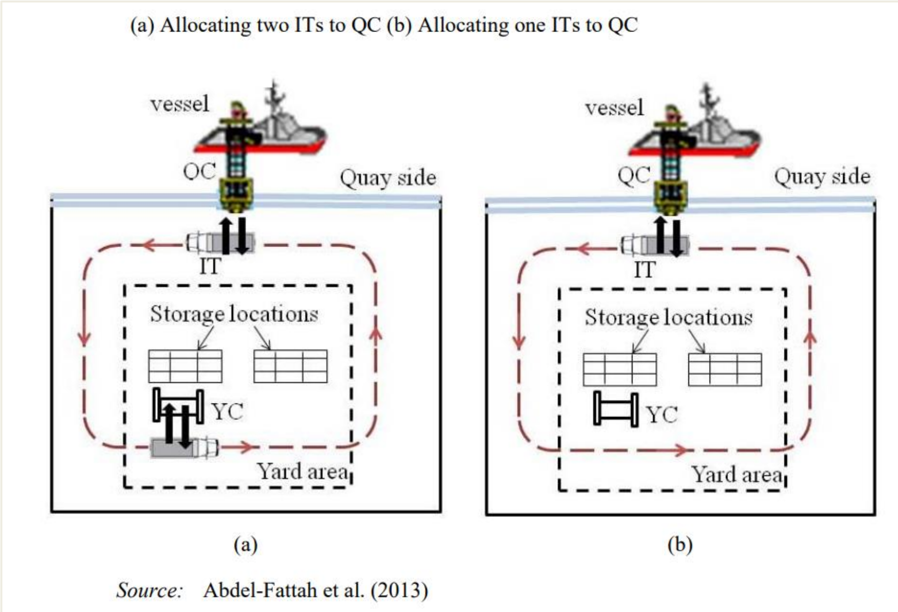


Figure 15 Different options of allocating ITs to QCs

Given that for one barge we assume 4 cranes that are serving it, then per crane to minimize the (un) loading time we assume in this scenario 1 internal truck (IT) serving that crane, thus in total we have 4 internal trucks that are TO/automated per terminal.

If the barge to be served has a bulk load, then we use TO-capable skid steers to unload the bulk cargo. Hence, we assume 4 skid steers per barge.

5.1.3 Dimension of the 5G network in the PoA in Antwerp Gateway and MPET terminals

5.1.3.1 Area to cover

Starting with deploying 5G Networks in the DP world terminal (Antwerp Gateway) and then deploying in more terminals following the adoption curve of "5G networks-based TO adoption rate in the port terminals". The choice of this terminal is in alignment with pilot sites in the PoA and to allow for direct feedback from the trials regarding 5G networks requirements and deployment.

With an inter-site distance of around 2 km and considering the existing network infrastructure presented in Figure 88, we need the following deployment to have the full coverage of the DPW terminal:

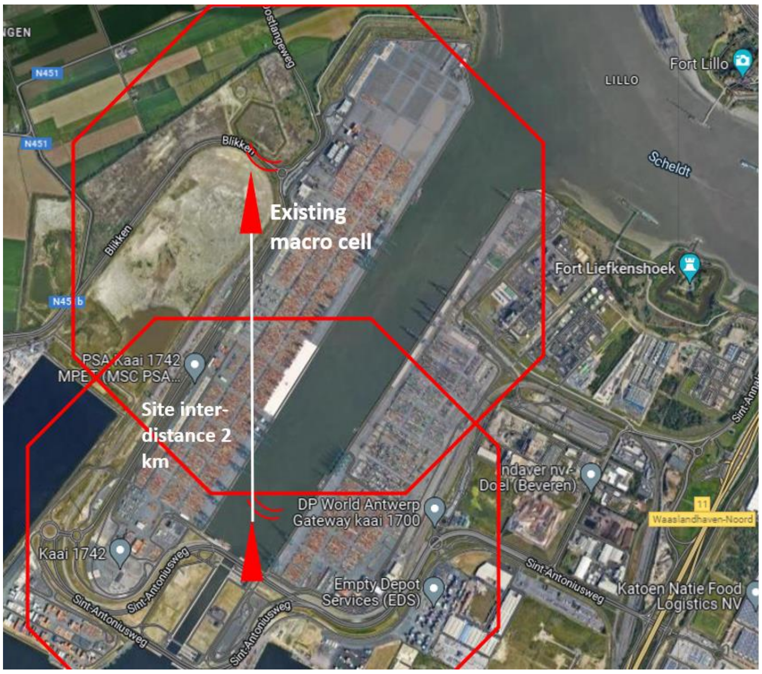


Figure 16 5G network deployment to cover DPW terminal

From the 5G network deployment we can see that to have full coverage of one terminal we can also cover the one in front of it. The distance between the two edges of the two terminal is 1.3 km which is less than the site inter-distance of Macro cells, hence an optimized network planning helps to cover the two terminals with the same macro cells. Therefore, in the following analysis we consider the deployment in these two terminals and afterwards scales up the deployment to follow the TO adoption.

5.1.3.2 Network Capacity requirement

Based on the required UL capacity for the different use cases and different slice types presented in Table 3, for the two terminals DPW and MPET, the total required capacity on the UL for the two types of 5G connectivity options (i.e., 5G coverage on demand and 5G network slicing) has been calculated considering the following assumptions:

- The lifetime of network equipment is 10 years. 10 years is the average since equipment vendors consider from 7-12 years as the lifetime of their equipment. Based on a study on the expected life of telecommunications and cable assets [24], the average lifetime of most of the network hardware is around 10 years.
- 1 TO barge to be served at the same time; since we consider that the maximum served TO barges is the half of the average served barges by the terminal and if we distribute this uniformly over the working hours we will have only one each two hours.
- 8 cranes can be operated simultaneously,4 for each terminal;
- 8 remote driving can be supported at the same time to support the internal trucks/skid steers if we have a bulk cargo; 4 for each terminal;
- 1 existing macro-cell (as showed in Figure 16) and 50% of its UL capacity is used by other applications, so 50% is free and to be used for TO use cases;
- Each macrocell is a tri-sector and each cell has 16 beams following the RAN hardware installed by Telenet in the port, but in reality, on the UL only 8 streams simultaneously can be offered, this is to be validated during the final measurement campaigns;
- The area of the two terminals is 3.211 square kilometre (km^2)

- The macro cell inter-site distance is 2 km.

For **5G coverage on demand** and using the network dimensioning process (explained in section 3.3.1.1) results in a total capacity of 1346 Mbps on the UL . Given the network deployment strategy adopted earlier and explained in section 3.3.1.1, where macro cells are deployed to provide coverage while small cells are to be added to enhance capacity, the network infrastructure needed in the two terminals is one new macro cell and 5 small cells.

For the deploying **5G network slicing** connectivity option in the two terminals DPW and MPET, we need to know the required capacity for the other slices to be offered in these two port terminals. To this end, the non-TO UL capacity needs to be estimated to deploy the network to support both type of services, the TO and the non-TO ones. Based on the two methods of the non-TO capacity calculation explained in 3.3.1.1, the total required capacity has been calculated:

1. Assuming that all the non-TO services are also supported by network slices, the total required capacity is calculated using the following assumptions:
    - Two other types of slices are to be provided in the two terminals, being the eMBB slice serving the normal customers as truck drivers and employees in the two terminals and IoT slice for sensors for example used in the automation of certain processes in the terminal, like the container ID identification etc…
    - 2 IoT slices, one per terminal
    - To calculate the required total capacity, additional input data are needed:
        - Daily served trucks: 5600 (based on the two terminals websites);
        - Number of working hours: 12 hours;
        - Total number of employees of the two terminals ~=350;
        - Active users for eMBB slice percentage =10%.

Therefore, the total Capacity required on the UL is the sum of the total Capacity UL of the TO slice and the total Capacity UL of the eMBB slice and the total capacity UL of the two IoT slices. This results in a total UL capacity of 1757 Mbps. Hence, an additional macrocell is required for ensuring the coverage of the two terminals and 10 small cells are to be deployed to meet the required UL capacity.

2. Assuming that the non-TO services are supported as a regular traffic without dedicated slices for each type of service, the total non-TO capacity is calculated using the data below:
    - Data traffic has been retrieved from the field in GB (GigaByte);
    - Assuming 8 hours as time window in which users are active, the downlink speed has been calculated;
    - Assuming that the UL speed is 5% of the DL speed, the UL capacity is derived,
    - Assuming a 30% regular traffic growth, the requested UL capacity of the regular traffic for the next 2-4 years has been calculated.

Therefore, the total Capacity required on the UL is the sum of the total Capacity UL of the TO slice and the total Capacity UL of the regular traffic. This results in a total UL capacity of 1438 Mbps. Hence, an additional macrocell is required for ensuring the coverage of the two terminals and 6 small cells are to be deployed to meet the required UL capacity.

5.1.4 Cost model results of 5G network deployment

The cost data related to network equipment is not included in this document for the sake of confidentiality .Using the cost data validated by all partners in a data validation round, the cost model has been run for the two types of connectivity options being 5G coverage on demand and 5G network slicing with its two methods of estimating the non-TO capacity and are presented in the following sections. It is important to mention that the cost of the spectrum acquisition is not considered in the cost modelling, since it is very hard to allocate the spectrum cost to a specific use case.

5.1.4.1 Deployment scenario 1.1: 5G Coverage on demand to provide UC4.1b, UC4.2b, UC4.4, EF4 and EF5:

To cover the two terminals under study namely the DPW and the MPET with 5G network to support the TO use cases previously described, the cumulative TCO over 10 years period is € 1,690,360 which results in a cumulative TCO per square kilometre of € 526,428. The average TCO over 10 years timespan per terminal is € 845,180.The different cost components of the 5G network deployment are depicted in the figure below.

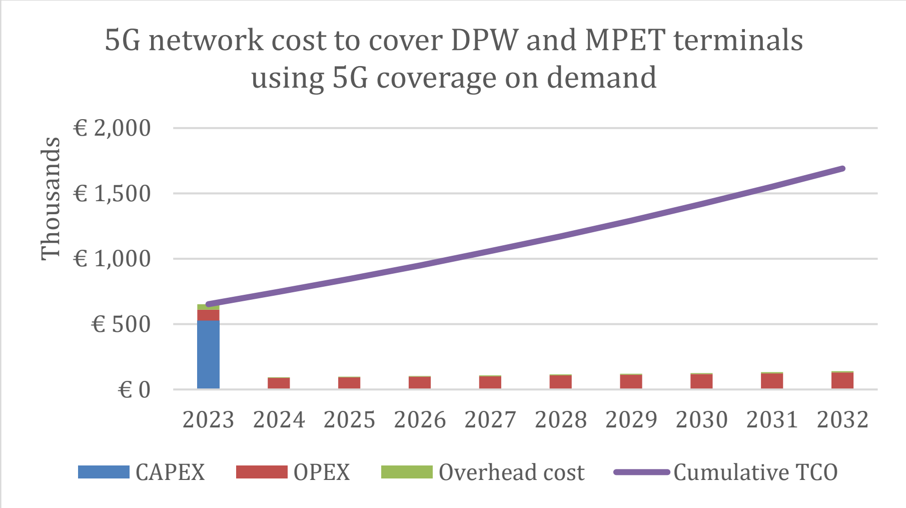


Figure 17 Different cost components and Cumulative TCO over 10 years of the 5G network for 5G coverage on demand option to cover the DPW and the MPET terminals.

To understand what the dominant cost of the TCO is, we visualize a cost breakdown of the TCO in Figure 18. It is clear that the OPEX is the dominant cost element which represents 63% of the TCO. The main cost components of the OPEX are the site rental (32 €k per year) to host the macro cells and small cells, the energy cost (14 €k per year) and the hardware maintenance.

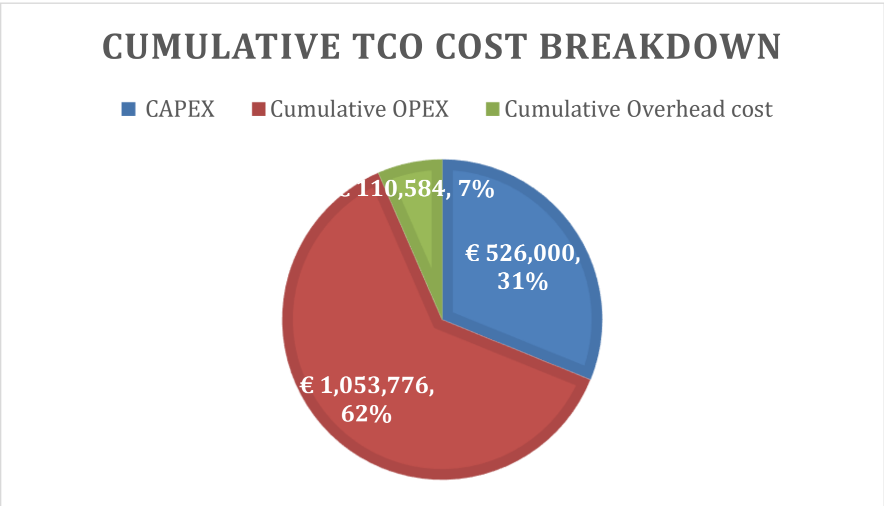


Figure 18 Cost breakdown of the cumulative TCO over 10 years for the coverage on demand option

Following the TO adoption scenarios being the pessimistic and the optimistic uptakes in the port of Antwerp (presented in Figure 9 and Figure 12); the TCO has been calculated for each of the two scenarios.

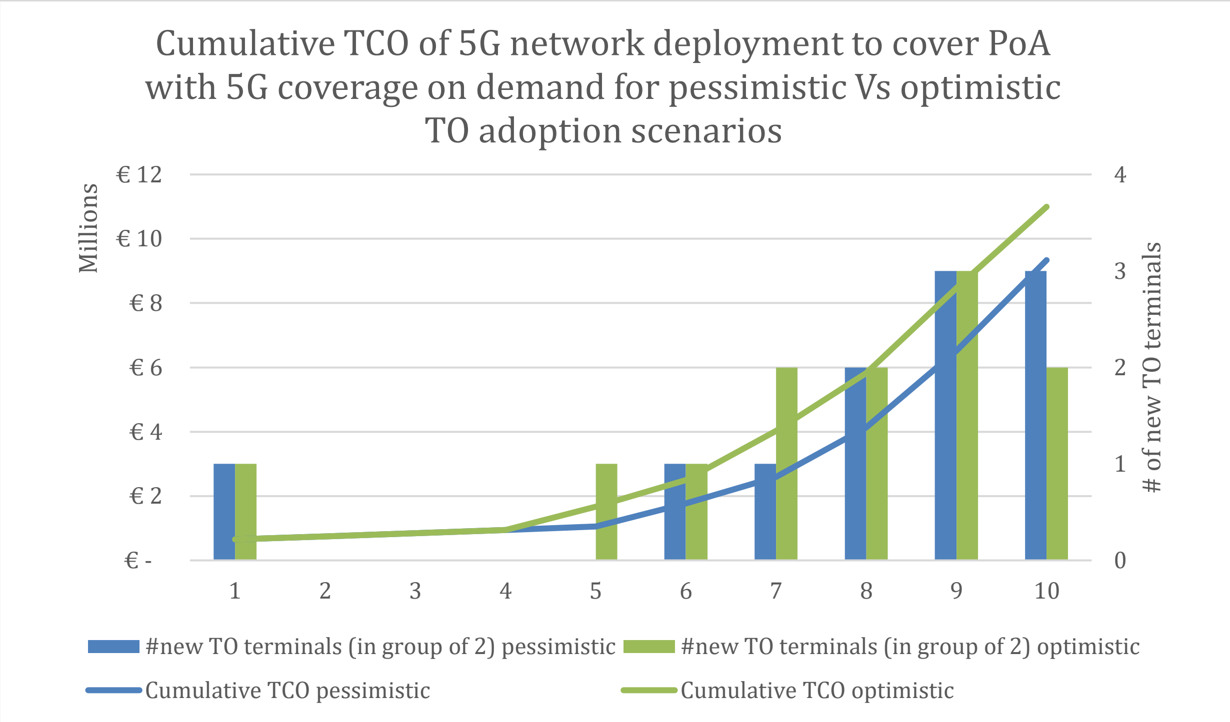


Figure 19 5G coverage on demand TCO comparison between pessimistic and optimistic TO adoption

Figure 19 presents the cumulative TCO of deploying 5G coverage on demand in the PoA for the pessimistic and the optimistic TO adoption. Results show that the TCO for the optimistic scenario is higher than the pessimistic scenario since in the former a higher number of terminals have adopted 5G technology to provide TO use cases. In total, 23 terminals out of 26 have adopted 5G-based TO over 10 years (2023-2032) in the optimistic scenario compared to only 21 terminals in the pessimistic scenario. An interesting insight from this cost analysis is that the average TCO over 10 years timespan per terminal is € 444,569 in the pessimistic TO adoption scenario which is less costly than the average TCO per terminal for the optimistic adoption which is € 478,045. The cost difference is €k 34 per terminal, being 7% cost reduction per terminal. This can be justified by the early adoption of the technology in the optimistic adoption scenario where the cost of the deployment still expensive, while in the pessimistic scenario there was a weak adoption in the first 5 years of the deployment and then there was a mass adoption by the end of the 10 years timespan, which makes the deployment takes benefit from the cost reduction over the years due to the market competition and the maturity of the technology. If we compare the average TCO per terminal over 10 years deployment to the cost of the early deployment in the two terminals DPW and MPET, we see a cost reduction in the TCO of 47.5% for the pessimistic TO adoption and 43.5% for the optimistic scenario. This gives recommendation for both connectivity providers and TO service providers in the port terminals about the good moment of adopting the 5G-based TO technology.

5.1.4.2 Deployment scenario 1.2.1: 5G network slicing to provide UC4.1b, UC4.2b, UC4.4, EF4 and EF5 using one slice for each type of service:

As presented above in section 5.1.3.2, the UL capacity requirement in this connectivity option is 1757 Mbps in which 410 Mbps is required by the non-TO slices.

To cover the two terminals under study namely the DPW and the MPET with 5G network to support the TO use cases previously described using 5G network slicing and assuming that the non-TO services are also to be provided by the mean of slices, the cumulative TCO over 10 years period is € 2,475,472 which results in a cumulative TCO per square kilometre of € 770,935. The average TCO over 10 years timespan per terminal is € 1,237,735.The different cost components of the 5G network deployment are depicted in the figure below.

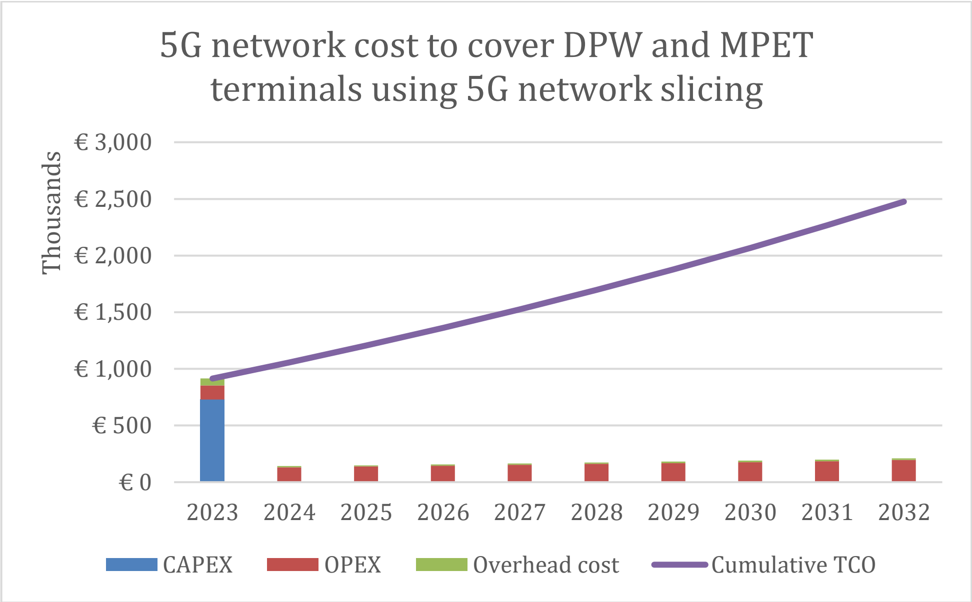


Figure 20 Different cost components and Cumulative TCO over 10 years of the 5G network for 5G Network slicing option

Similar to the previous deployment option, the cost breakdown of the cumulative TCO showed that OPEX is the dominant cost element.

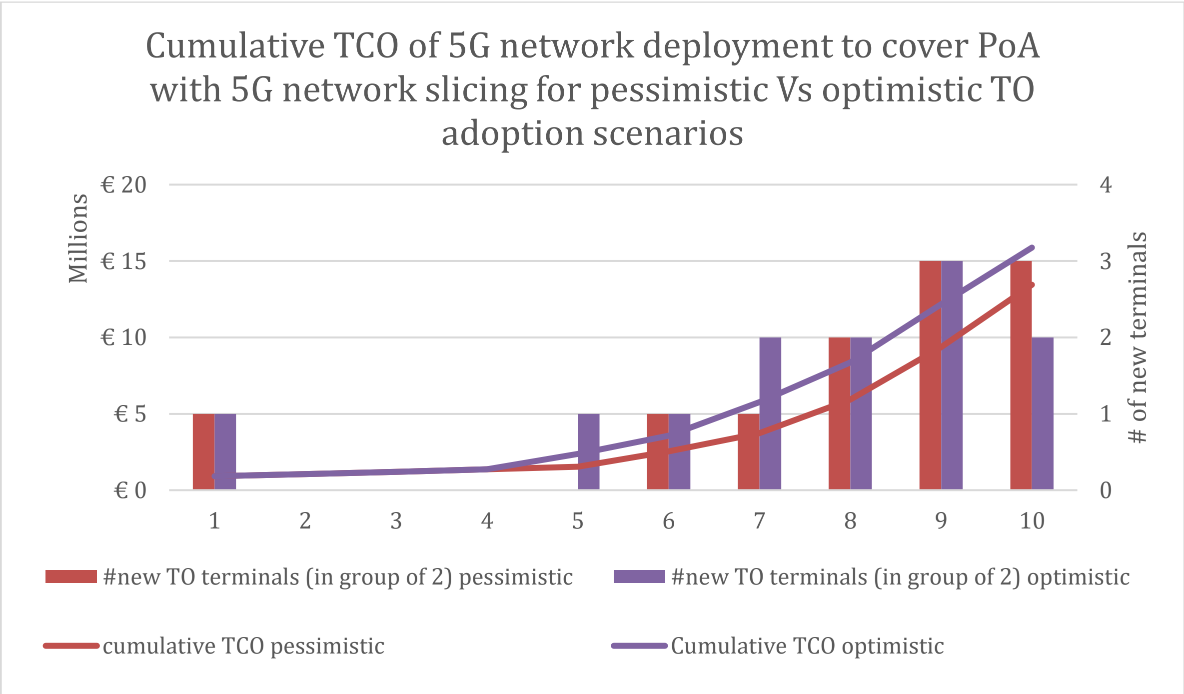


Figure 21 5G network slicing TCO comparison between pessimistic and optimistic TO adoption

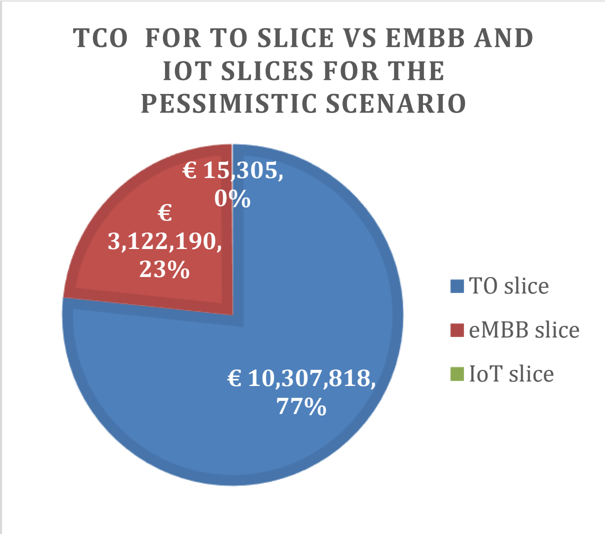
Like the previous deployment scenario (Deployment scenario 1.1: 5G coverage on demand), results in Figure 21 show that the TCO for the optimistic scenario is higher than the pessimistic scenario since in the former a higher number of terminals have adopted 5G technology to provide TO use cases.

We used the allocation model described in section 3.3.1 to allocate the 5G network cost to the three slices using only **throughput metric**: as the network was dimensioned using the UL capacity requirement. The cost sharing coefficient are as follow:

Cost sharing coefficient TO Slice	76.7%

Cost sharing coefficient non-TO Slices	23.3%
Cost sharing coefficient mIoT Slice	1%
Cost Sharing coefficient eMBB Slice	99%

Using these sharing coefficients, the TCO has been divided among the supported slices and is presented in Figure 22.



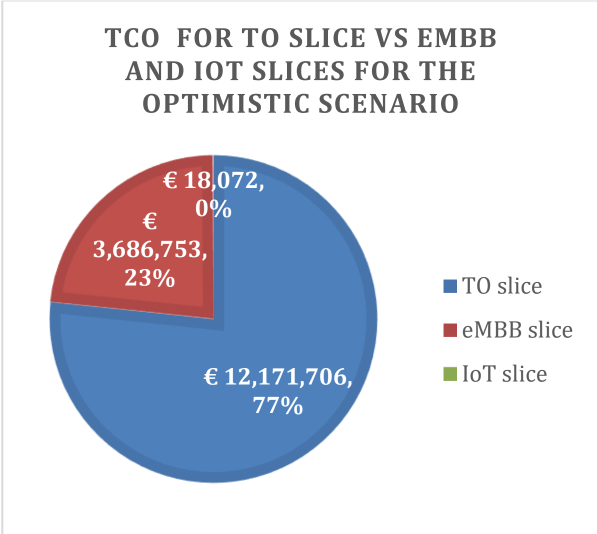


Figure 22 TCO of the TO slice vs eMBB and IoT slices for the pessimistic (on the left-hand side) and the optimistic (on the right-hand side) scenarios to cover the entire PoA

Figure 22 shows that the TO slice bears the bigger part of the TCO this is because the TO slice designed to support he selected UCs and EFs requires 1347 Mbps comparing to only 410 Mbps for the non-TO slices. Another important observation here is that TO is a service very demanding in term of UL capacity however the traditional services are DL-demanding services, which make TO bears the significant deployment cost if the network is designed only based on UL requirement. Yet, if with the same deployment and same services the cost allocation would be made based on the DL requirement, TO slice would bear a significantly low percentage of the deployment cost.

Similar to the previous assessment, also with network slicing, the average TCO over 10 years timespan per terminal deployment for the TO slice only is € 490,848 in the pessimistic TO adoption scenario which is less costly than the average TCO per terminal for the optimistic adoption which is € 529,204.

Compared to the early deployment of 5G network slicing which cost € 948,907 per terminal, deploying at a letter stage could save up to 48% on the cost of the deployment.

5.1.4.3 Deployment scenario 1.2.2: 5G network slicing to provide UC4.1b, UC4.2b, UC4.4, EF4 and EF5 assuming other type of services are provided under the regular traffic:

As presented above in section 5.1.3.2, the UL capacity requirement in this connectivity option is 1438Mbps in which 91 Mbps is required by the non-TO slices as a regular traffic.

To cover the two terminals under study namely the DPW and the MPET with 5G network to support the TO use cases previously described using 5G network slicing and assuming that the non-TO services are covered by the so-called regular traffic, the cumulative TCO over 10 years period is € 1,852,072 which results in a cumulative TCO per square kilometre of € 576,790. The average TCO over 10 years timespan per terminal is € 926,035.The different cost components of the 5G network deployment are depicted in the figure below.

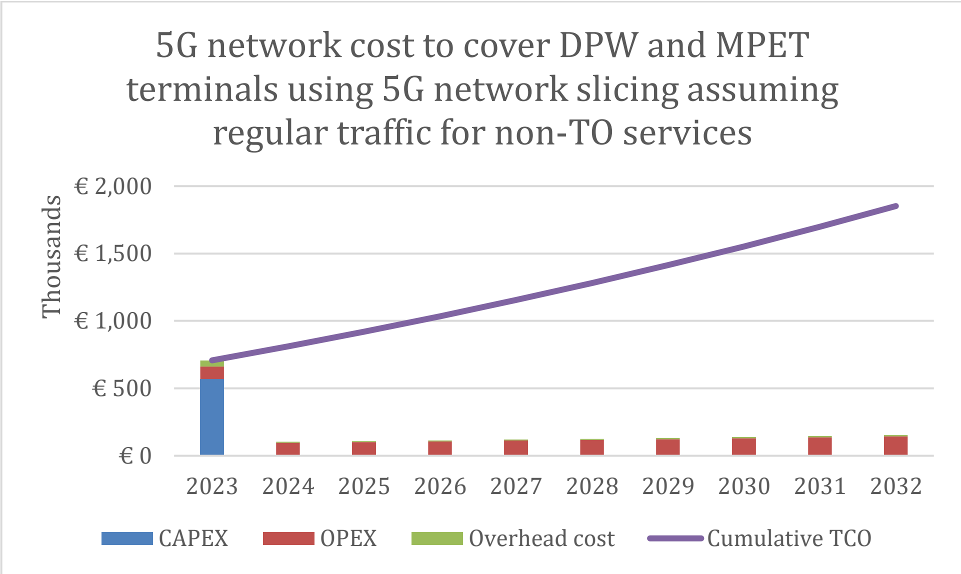


Figure 23 5G network cost to cover DPW and MPET terminals using 5G network slicing assuming regular traffic for non-TO services.

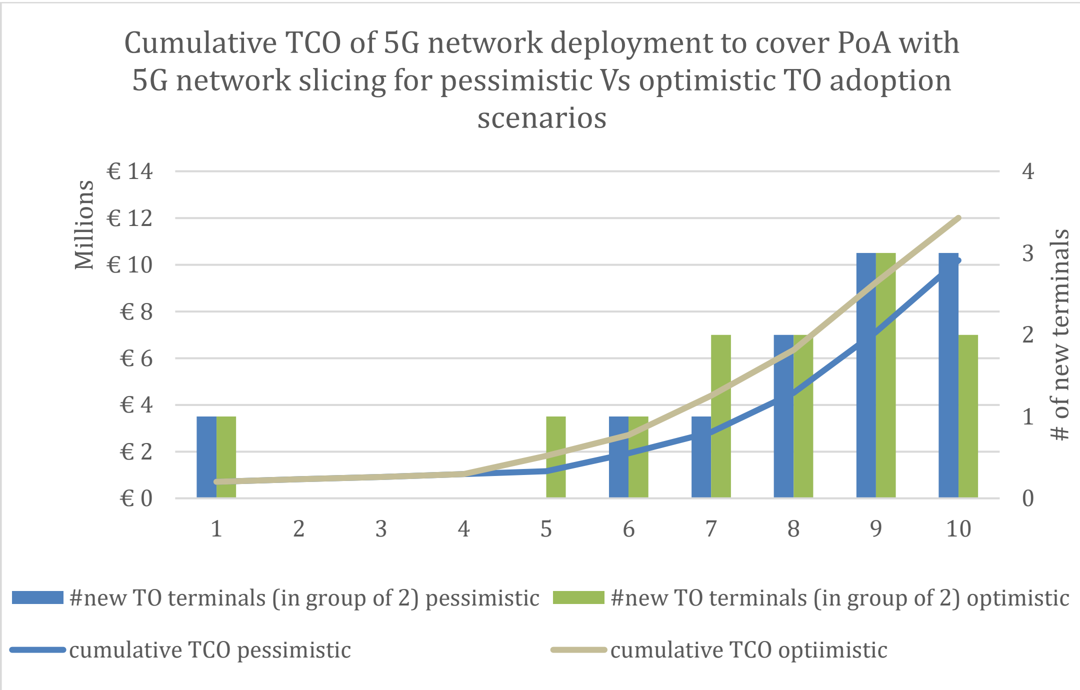


Figure 24 5G network slicing TCO comparison between pessimistic and optimistic TO adoption assuming regular traffic for the non-TO services.

We used the allocation model described in section 3.3.1 to allocate the 5G network cost to the TO slice and the regular traffic using only **throughput metric**: as the network was dimensioned using the UL capacity requirement. The cost sharing coefficient are as follow:

Cost sharing coefficient TO Slice	93.7%
Cost sharing coefficient regular traffic	6.3%

Using these sharing coefficients, the TCO has been divided among the TO slice and the regular traffic and is presented in the figure below.

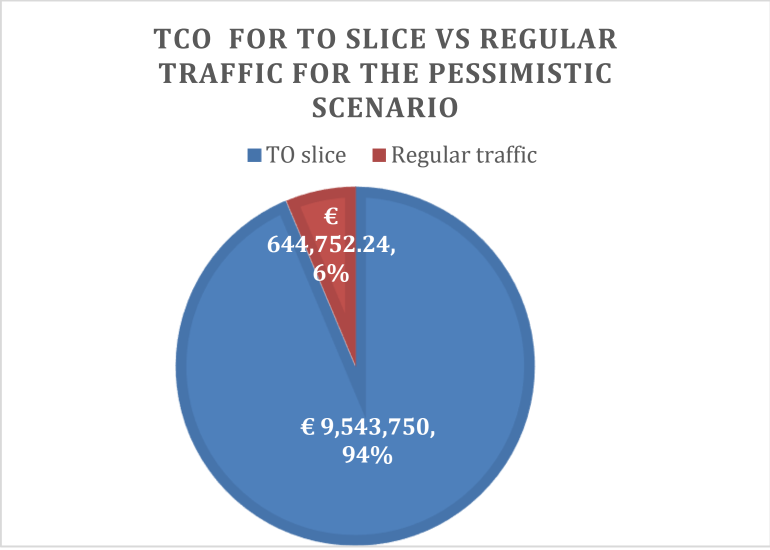


Figure 25 TCO of the TO slice vs regular traffic for the pessimistic scenario

Figure 25 clearly shows that the TO slice has the bigger part of the cost deployment since the regular traffic has a very low requirements in term of UL capacity.

5.1.4.4 Cost comparison between the three 5G connectivity deployment options

Bringing the cost results of the three 5G connectivity deployment options together to assess which option is the most cost effective one. In the comparison we only compare the cost share for the TO slice/service from the three cases.

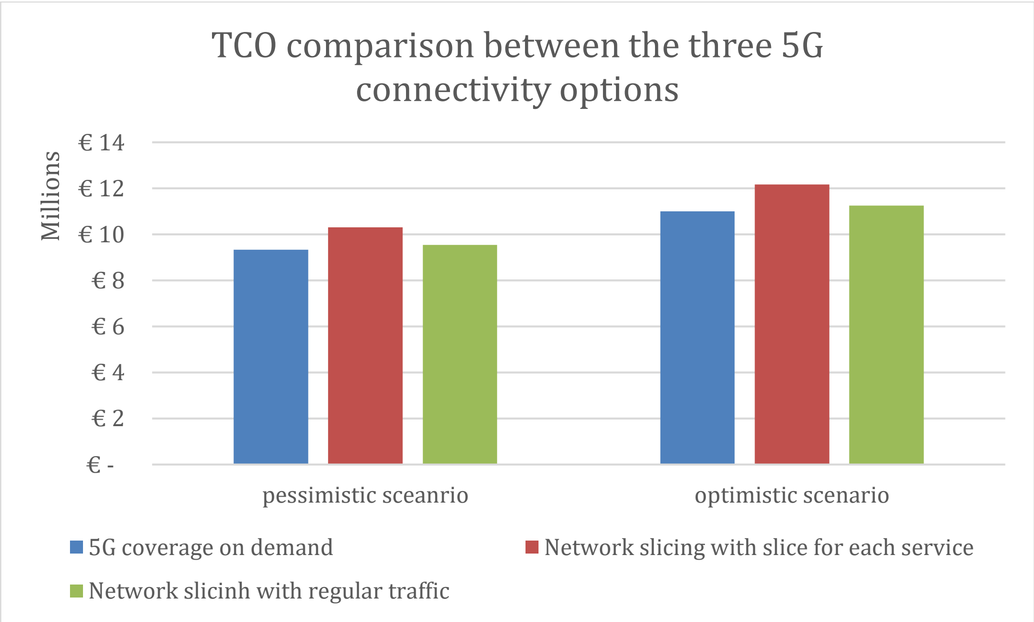


Figure 26 TCO comparison between the three 5G connectivity options

From the cost comparison illustrated in Figure 26 we can deduct that the network slicing with providing a separate slice for each service is the costliest option, this is due to mainly three reasons, first, the network slicing option in its two flavors being one slice for each service or regular traffic for all the services counts in the cost calculation for the cost of a new billing system to provide the dynamic billing of network slices compared to the legacy system. This system is very expensive (between € 1 to 3 million) and its cost should be distributed among all MNO's sites providing network slicing. Second, the low demand of the non-TO slices on the UL capacity makes the TO slice bear the significant part of the deployment cots. And three, the deployment strategy used in the 5G network dimensioning make the use of macro cells only for coverage and any addition requirement in term of capacity is served by deploying additional small cells. While macro cells have the capability of supporting many data streams thanks to the MIMO technology (in our case 16 beams), small cells can only provide single streams. This makes any additional need of the UL capacity translates into the installation of many small cells whereas it can be more cost effective to deploy one single macro cells providing up to 16 times the small cells capacities.

In section 5.1.8 we will study how cost effective is adapting the network deployment strategy in term of replacing small cells by macro cell.

As a conclusion of the cost comparison, the 5G coverage on demand is the cost-effective deployment option under the mentioned assumptions and circumstances.

5.1.5 TO center deployment cost results:

In this section the cost results for the deployment options of TOC in the port of Antwerp to provide the selected use cases and EFs for the two TO adoptions scenarios namely the optimistic and the pessimistic are discussed. Several deployment options have been identified and summarized in section 3.3.2.. Cost data used to run the model are summarized in Table 25. The cumulative TCO for the different options has been calculated over the project lifetime (i.e., 10 years) and presented in Figure 27.

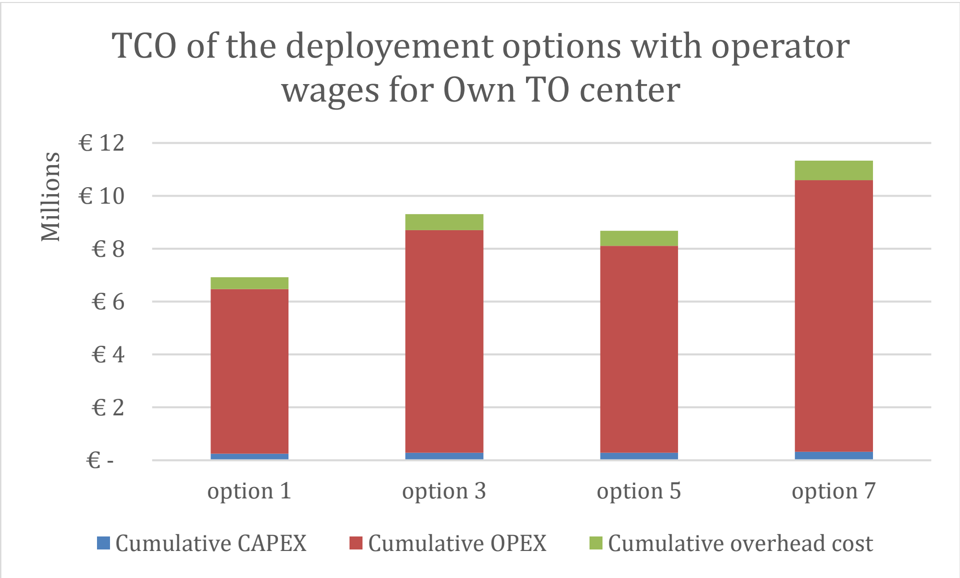


Figure 27 Comparison between the different deployment options for having a teleoperation center based on the cumulative TCO over 10 years for own TO center with operator wages

Figure 27 shows the cost comparison between 4 deployment options of the TO center, being:

- Option 1: Own TOC for pessimistic TO adoption with operator wage and gradual addition of new TO control setups following the yearly TO adoption and considering a yearly CAPEX evolution of -3%.
- Option 3: Own TOC for pessimistic TO adoption with operator wage and deployment of control setups from day 1 considering a cost reduction.
- Option 5: Own TOC for optimistic TO adoption with operator wage and gradual addition of new TO control setups following the yearly TO adoption and considering a yearly CAPEX evolution of -3%.
- Option 7: Own TOC for optimistic TO adoption with operator wage and deployment of control setups from day 1 considering a cost reduction.

With comparing options 1 vs 3 and options 5 vs 7, we can deduct that deploying the TOC with a gradual addition of the control setups following the TO uptake is more cost-effective than buying all the control setups at the start of the deployment with a 10% cost reduction. The cost saving is around 25%.

If we compare the same settings between pessimistic and optimistic TO adoption (i.e., 1 vs 5 and 3 vs 7), it is clear that the cost of deploying TO center assuming an optimistic adoption is more expensive than the deployment in a pessimistic uptake scenario. This is due to the higher number of TO-capable vehicles that need to be served in the optimistic scenario vs the pessimistic one and their resulting cost in term of operator wages and required hardware. The cumulative operator wages in the optimistic scenario are around € 7.4 million comparing to only € 5.7 million for the pessimistic scenario which is 21% more expensive.

As shown in Figure 27, the main cost component of the TCO is OPEX, which represents 89% of the total cost. A cost breakdown of OPEX shows that operator wage is the dominant cost element of OPEX, as depicted in the figure below. It represents 93% of the total OPEX and the rest 7% are distributed among office space renting, Internet subscription and energy cost.

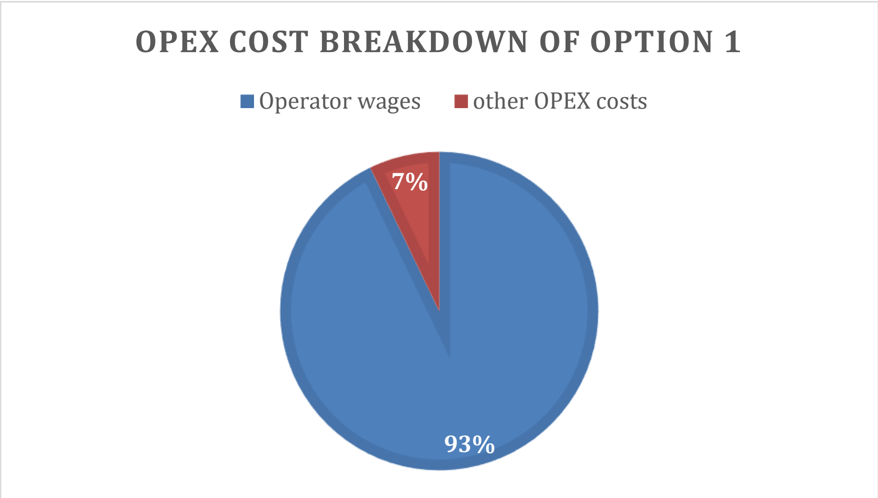


Figure 28 OPEX cost breakdown of TO center deployment option 1

If logistic companies want to bring their own operators, then the TCO of deploying the TO center is much cheaper (cost reduction by 89%) and is illustrated in the figure below.

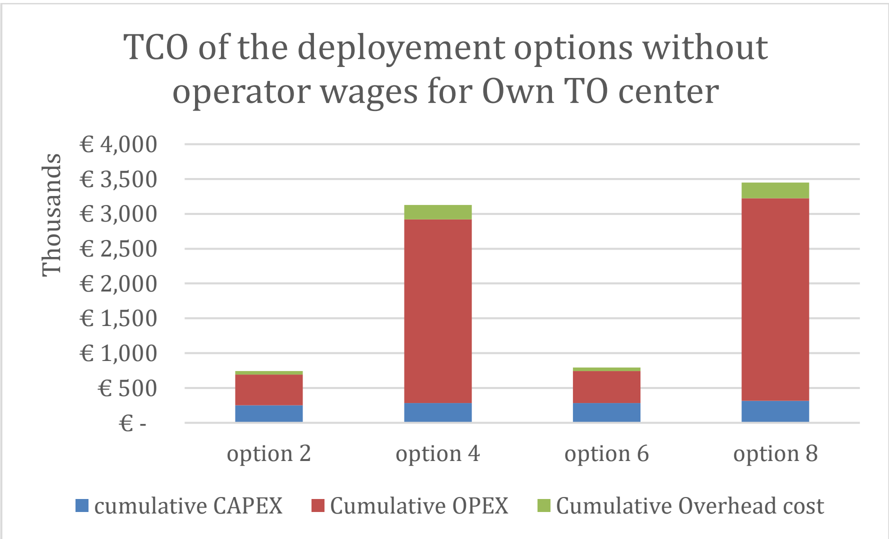


Figure 29 Comparison between the different deployment options for having a teleoperation center based

on the cumulative TCO over 10 years for own TO center without operator wages

Figure 29 shows the cost comparison between 4 deployment options of the TO center without considering operator wages, being:

- Option 2: Own TOC for pessimistic TO adoption without operator wage and gradual addition of new TO control setups following the yearly TO adoption and considering a yearly CAPEX evolution of -3%.
- Option 4: Own TOC for pessimistic TO adoption without operator wage and deployment of control setups from day 1 considering a cost reduction.
- Option 6: Own TOC for optimistic TO adoption without operator wage and gradual addition of new TO control setups following the yearly TO adoption and considering a yearly CAPEX evolution of -3%.
- Option 8: Own TOC for optimistic TO adoption without operator wage and deployment of control setups from day 1 considering a cost reduction.

Similar to the previous comparison, comparing options 2 vs 4 and options 6 vs 8, we can deduct that deploying the TOC with a gradual addition of the control setups following the TO uptake is more cost-effective than buying all the control setups at the start of the deployment with a 10% cost reduction. The cost saving is around 70%. Unlike the first comparison, the significant cost of deploying control setup at day one is due to the need to rent office space for these control setups. An important cost savings could be by renting out the spare control setups as an equipped TO room to other TO service providers until the point where we have a good uptake of the TO services and therefore using the installed control setups.

What if the TO service provider decide from the start to rent an equipped TO room and only bring their operators or give the possibility to their clients, namely the logistic companies to bring their own operators, these different deployment scenarios are analyzed under the following option:

- Option 9: TO room rent for pessimistic TO adoption with operator wage.
- Option 10: TO room rent for pessimistic TO adoption without operator wage.
- Option 11: TO room rent for optimistic TO adoption with operator wage.
- Option 12: TO room rent for optimistic TO adoption without operator wage.

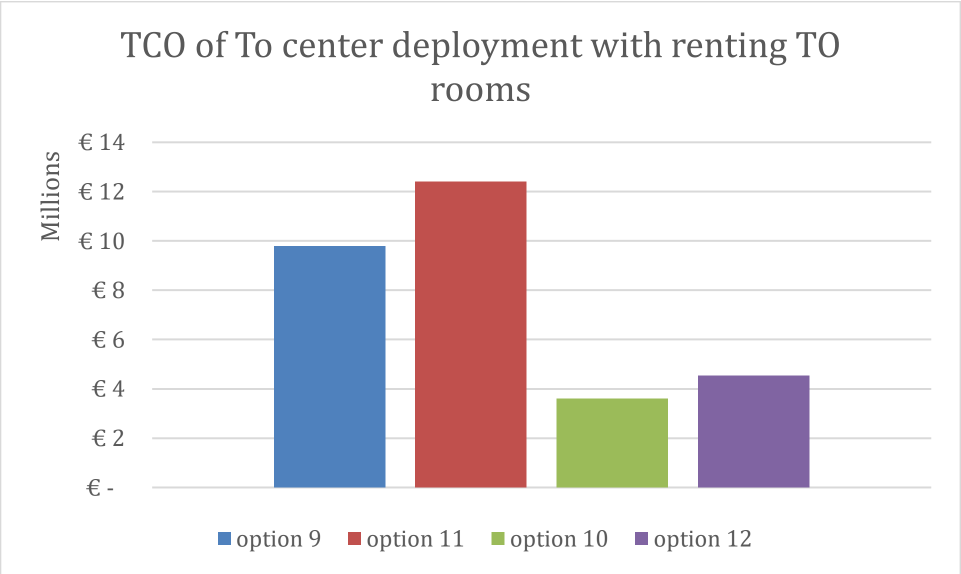


Figure 30 TCO of deploying TO center with renting TO rooms

Figure 30 presents the results of TCO calculation of the 4 deployment options described above. Cost results shows the cost difference between the pessimistic and optimistic scenarios, option 9 vs option 11 and option 10 vs option 12. It is reasonable to see that the optimistic scenario is more costly than the pessimistic scenario since we have more TO vehicles to serve and hence need more operator to pay and more TO room to rent. Like the previous deployment scenario, the operator wages make a great difference in the total deployment cost up to 63% of the total TCO. Yet, unlike the previous options, another important element of the OPEX is the cost of renting the TO equipped rooms which represents 32% of the OPEX, as can be seen in the following figure.

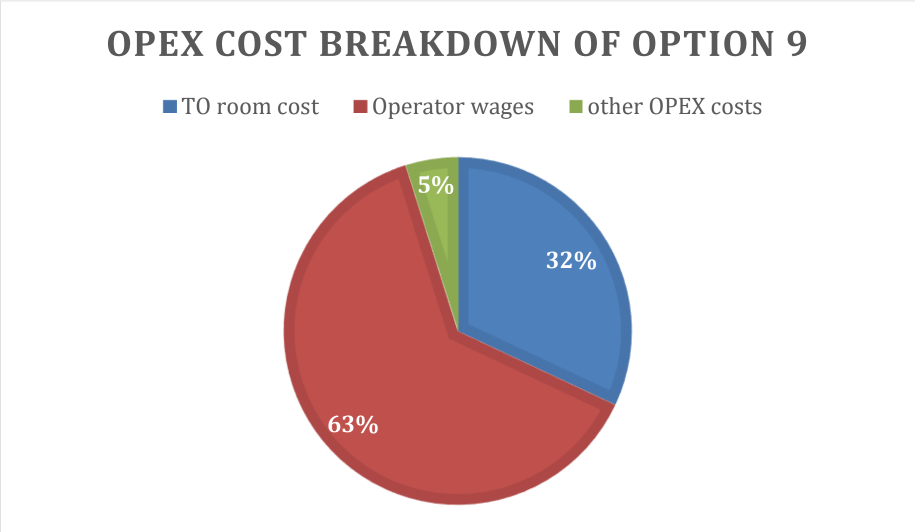


Figure 31 OPEX cost breakdown of option 9

Another important finding is that deploying own TO center is less expensive than renting a pre-equipped TO rooms from other TO service providers; €9 million vs €12 million.

5.1.6 TO-capable barges, cranes, skid steers and trucks cost results:

In this deployment scenario we need TO barge for UC4.1 and TO cranes for UC4.2 and we assume also the use of internal trucks for the loading and unloading of barges which are supported by UC4.4 (the remote takeover). If we have a bulk cargo, then we need skid steers that are also supported by UC4.4. The number of TO barges and cranes served/used daily in the port of Antwerp is presented in section 5.1.2. The number forecasted for barges are based on the yearly individual visits of barges in the port of Antwerp. And for trucks and skid steers we assume that we have 4 per terminal and they follow the uptake of TO in the port terminals discussed also in section 5.1.2. The TCO of the different type of vehicles to make them TO-capable for the two TO adoption scenarios is presented in the table below.

Table 6 TCO of different vehicle types

Adoption scenario	Barges	Cranes	Trucks	Skid steers
pessimistic	€ 252,000,000	€ 9,534,394	€ 1,217,091	€ 1,281,148
optimistic	€ 315,000,000	€ 11,444,344	€ 1,335,411	€ 1,405,696

The TCO of barges to make them TO-capable is the significant cost among the 4 types of vehicles this is due first to the number of barges studied in this scenario, which is higher than the other vehicle types, 1848 barges over 10 years vs 252 cranes, trucks and skid steers all together and 2171 barges vs 276 for the pessimistic and optimistic scenario respectively. And second because the cost of making one barge tele-operatable is way expensive than the other type of vehicles, at least the double for cranes and around 10 times for trucks and skid steers.

5.1.7 Business case evaluation

Using a cost-based pricing as discussed in section 3.5 which is based on the ACPU and adding on top of it a profit margin to arrive to an ARPU, the cumulative revenue was calculated for this deployment scenario with two profit margins namely 15% and 30%. The ACPU was calculated considering the Total number of connected items that used the 5G network and the TO center over 10 years for a monthly and a daily use. In other words, The ACPU per month and per day have been calculated.

5.1.7.1 Pessimistic TO adoption

Considering a pessimistic TO uptake, the total number of connected vehicles (i.e., barges, cranes, trucks and skid steers) over 10 years is 13,584. This number is calculated considering that the target is to arrive to a monthly ARPU.

Th ACPU per connected vehicle per month has been calculated for the different deployment of the 5G networks and the TO center, which is assumed also to have a monthly subscription.

Table 7 Summary of the ACPU for 5G connectivity and the TO service

	TCO	ACPU/month	ACPU per day/connected TO session
5G Network			
5G COD	€ 9,335,959	€ 687	€ 26
5G NS	€ 10,307,818	€ 759	€ 29
5G NS regular traffic	€ 9,543,750	€ 703	€ 27
TO Center			
Own TOC with operator wages gradual deployment	€ 6,927,821	€ 510	€ 20
Own TOC with operator wages deployment day 1	€ 9,310,767	€ 685	€ 26
Rent TOC with Operator wages	€ 9,792,194	€ 721	€ 28
Own TOC without operator wages gradual deployment	€ 742,837	€ 55	€ 2
Own TOC without operator wages deployment day 1	€ 3,125,783	€ 230	€ 9
Rent TOC without Operator wages	€ 3,607,209	€ 266	€ 10

Based on the cost-effective deployment options colored with green in the table above and assuming 15% and 30% profit margin, the ARPU per month per connected vehicle has been derived for the two services together namely the 5G connectivity and TO service. Results are summarized in the table below.

Table 8 ARPU for the different options

ACPU monthly with operator	ARPU 15% with operator wages	ARPU 30% with operator wages	ACPU monthly cost **without** operator	ARPU **without** wages 15%	ARPU **without** wages 30%

wages			wages		
€ 1,197	€ 1,377	€1,556	€ 742	€ 853	€ 965

By bringing the cumulative revenue and TCO together, the BEP can be assessed as described in section 3.6. and is presented in the figure below while considering operators as part of the TO service. The BEP assessment for excluding operator from the TO service is presented in the Appendix A in Figure 89.

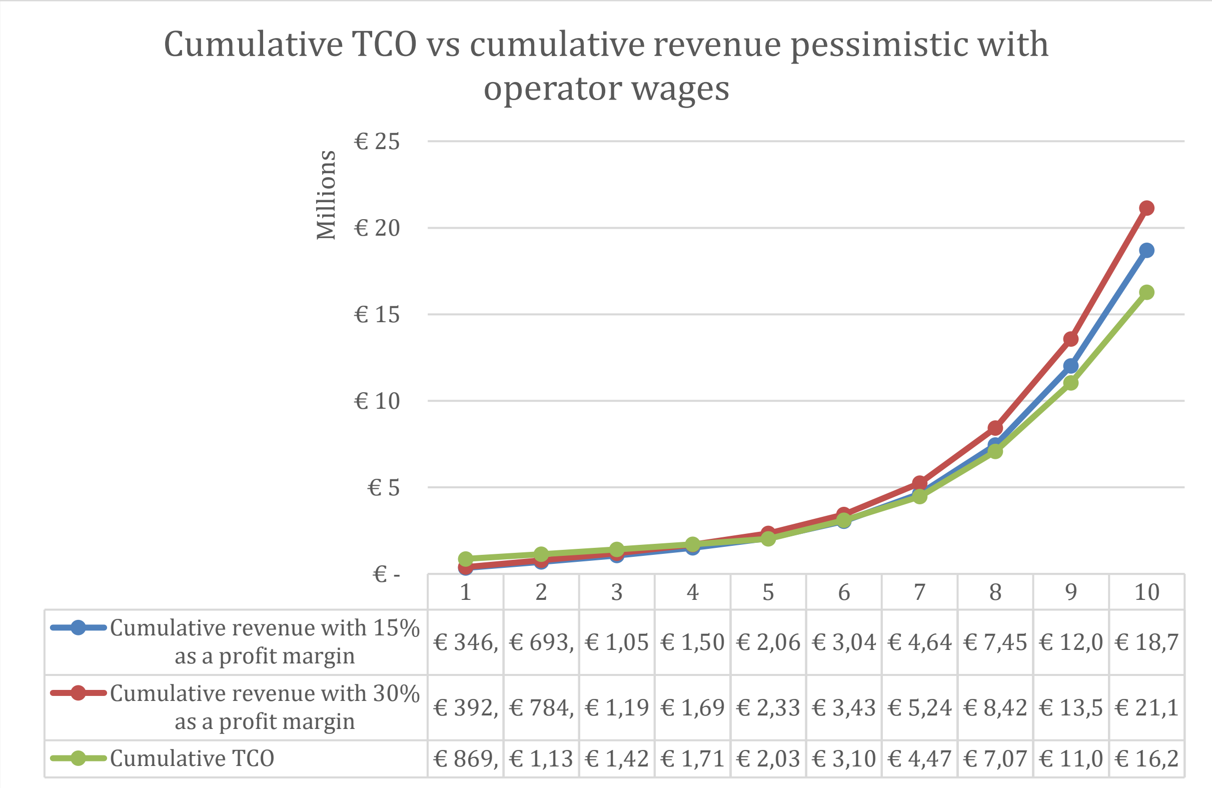


Figure 32 BEP assessment for the pessimistic TO adoption considering operators as part of the TO service

As explained previously the break-even point (BEP) in economics is the point at which total cost and total revenue are equal, i.e., "even". There is no net loss or gain. In short, all costs that must be paid are paid, and there is neither profit nor loss. Starting from that point onwards revenues are higher than costs which mean that the studied business case is profitable. As shown in Figure 32, the BEP is reached around year 5 and from year 5 the revenues are exceeding the cost with means that 5G-based TO service is profitable with adopting the cost-based pricing explained previously.

It is noteworthy to mention that in this calculation only the 5G connectivity and TO services in the port of Antwerp are considered which means analysing the business case from TO service providers using 5G connectivity. The costs/revenues from the different TO-capable vehicles are not included here because they serve in multiple ports/areas and cannot be exclusively allocated to the port under study. In addition, the direct benefit from using TO services for cranes, internal trucks and skid steers such as time saving will be assessed while validating the identified business models in D3.4. However, the cost of making vehicles TO-capable per type of vehicle per trip is provided in this analysis and serves as input to the business model validation exercise and is presented in the table below.

Table 9 The average cost per type of vehicle per trip to make it TO-capable for the pessimisic scenario

Pessimistic scenario	TCO	average cost per vehicle	average cost per trip/served barge	Average cost per ton
Barges	€ 252,000,000	€ 136,323	€ 22	0.67 euro cent
Cranes	€ 9,534,394	€ 74,487	€ 12	0.36 euro cent
Trucks	€ 1,217,091	€ 14,489	€ 2	0.08 euro cent
Skid steers	€ 1,281,148	€ 15,252	€ 3	0.09 euro cent

For barges, we assume lifespan of 40 years and 153 trips a year per barge with 3300 tons as maximum load as assumed in [25]. For cranes, internal terminal trucks, and skid steers, we assume that they serve on average 2 barges a day for 300 days a year and for 10 years lifespan.

5.1.7.2 Optimistic TO adoption

Considering an optimistic TO adoption, the total number of connected vehicles (i.e., barges, cranes, trucks and skid steers) over 10 years is 18216. This number is calculated considering that the target is to arrive to a monthly ARPU.

Th ACPU per connected vehicle per month has been calculated for the different deployment of the 5G networks and the TO center, which is assumed also to have a monthly subscription.

Table 10 Summary of the ACPU for 5G connectivity and the TO service

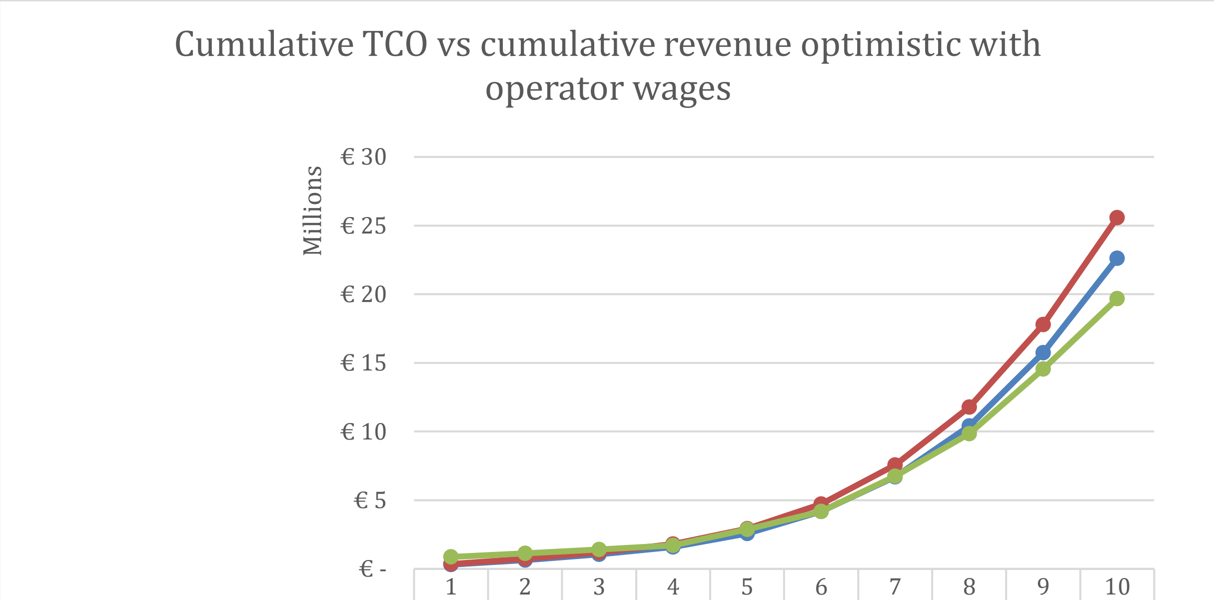
	TCO	ACPU/month	ACPU per day/connected TO session
5G Network			
5G COD	€ 10,995,037	€ 604	€ 23
5G NS	€ 12,171,706	€ 668	€ 26
5G NS regular traffic	€ 11,246,774	€ 617	€ 24
TO Center			
Own TOC with operator wages gradual deployment	€ 8,677,056	€ 476	€ 18
Own TOC with operator wages deployment day 1	€ 11,300,000	€ 620	€ 24
Rent TOC with Operator wages	€ 12,400,000	€ 681	€ 26
Own TOC without operator wages gradual deployment	€ 792,898	€ 44	€ 2
Own TOC without operator wages deployment day 1	€ 3,447,710	€ 189	€ 7
Rent TOC without Operator wages	€ 4,536,675	€ 249	€ 10

Based on the cost-effective deployment options colored with green in the table above and assuming 15% and 30% profit margin, the ARPU per month per connected vehicle has been derived for the two services together namely the 5G connectivity and TO service. Results are summarized in the table below.

Table 11 ARPU for the different options

ACPU monthly with operator wages	ARPU 15% with operator wages	ARPU 30% with operator wages	ACPU monthly cost **without** operator wages	ARPU **without** wages 15%	ARPU **without** wages 30%
€ 1,080	€ 1,242	€ 1,404	€ 647	€ 744	€ 841

By bringing the cumulative revenue and TCO together, the BEP can be assessed as described in section 3.6. and is presented in the figure below while considering operators as part of the TO service. The BEP assessment for excluding operator from the TO service is presented in the Appendix A in Figure 90.



	1	2	3	4	5	6	7	8	9	10
Cumulative revenue with 15% as a profit margin	€ 312,9	€ 640,8	€ 1,058	€ 1,594	€ 2,578	€ 4,172	€ 6,691	€ 10,41	€ 15,73	€ 22,62
Cumulative revenue with 30% as a profit margin	€ 353,7	€ 724,4	€ 1,196	€ 1,802	€ 2,914	€ 4,717	€ 7,564	€ 11,77	€ 17,79	€ 25,57
Cumulative TCO	€ 869,2	€ 1,138	€ 1,421	€ 1,718	€ 2,878	€ 4,188	€ 6,743	€ 9,838	€ 14,55	€ 19,67

Figure 33 BEP assessment for the optimistic TO adoption considering operators as part of the TO service

As shown in Figure 33, the BEP is reached around year 5 for the revenues considering 30% as profit margin and around year 8 for the 15% profit margin. From year 5 and year 8 for 30% and 15% respectively, the revenues are exceeding the cost with means that 5G-based TO service is profitable with adopting the cost-based pricing explained previously.

As explained before, this calculation considers only the 5G connectivity and TO services in the port of Antwerp which means analysing the business case from TO service providers using 5G connectivity. The costs/revenues from the different TO-capable vehicles are not included here because they serve in multiple ports/areas and cannot be exclusively allocated to the port under study. In addition, the direct benefit from using TO services for cranes, internal trucks and skid steers such as time saving will be assessed while validating the identified business models in D3.4. However, the cost of making vehicles TO-capable per type of vehicle per trip is provided in this analysis and serves as input to the business model validation exercise and is presented in the table below.

Table 12 The average cost per type of vehicle per trip to make it TO-capable for the optimistic scenario

Pessimistic scenario	TCO	average cost per vehicle	average cost per trip/served barge	Average cost per ton
Barges	€ 315,000,000	€ 145,098	€ 24	0.72 euro cent

Cranes	€ 11,444,344	€ 75,292	€ 13	0.39 euro cent
Trucks	€ 1,335,411	€ 14,515	€ 2	0.08 euro cent
Skid steers	€ 1,405,696	€ 15,279	€ 3	0.09 euro cent

As explained in the previous adoption scenario, for barges, we assume lifespan of 40 years and 153 trips a year per barge with 3300 tons as maximum of load as assumed in [25]. For cranes, internal terminal trucks, and skid steers, we assume that they serve on average 2 barges a day for 300 days a year and for 10 years lifespan.

5.1.7.3 Pessimistic Vs Optimistic TO adoption: cost comparison

If we compare the two TO adoption scenarios, we observe that the ACPU in the optimistic scenario is less than the pessimistic scenario, this is due to the higher number of connected items that are sharing the total cost of the deployment. Which makes the cost-based pricing with a low profit margin like 15% have a late break-even in the optimistic scenario (around year 8) compared to the pessimistic one (around year 5). However, for equipping the different vehicle type with TO capabilities, the average cost per type of vehicle in the pessimistic scenario is less than the one in the optimistic scenario for all type of vehicle except cranes. This can be explained by the low adoption in the first five years and the late mass purchase of TO hardware in the pessimistic scenario when we have a good cost reduction on the hardware due to the market competition and technology maturity.

5.1.8 Sensitivity analysis

5.1.8.1 Varying the number of beams

The RAN hardware used in the deployment supports MIMO with 16 beams on the UL. This hardware is 60% more expensive than the one supporting 8 beams and the later in its turn 60% more expensive than the one providing 4 beams. Thus, in this sensitivity analysis, we assessed the impact of using the different type of RAN hardware on the TCO of the 5G connectivity using 5G coverage on demand option to cover the two terminals namely the DPW and MPET. Based on the total required capacity by the studied use cases and EFs in this deployment scenario namely UC4.1, UC4.2, UC4.4, EF4 and EF5, the network dimension is done assuming the three different types of RAN hardware in their capability in term of number of beams provided on the UL. The cost comparison between the three RAN hardware option is depicted in the figure below.

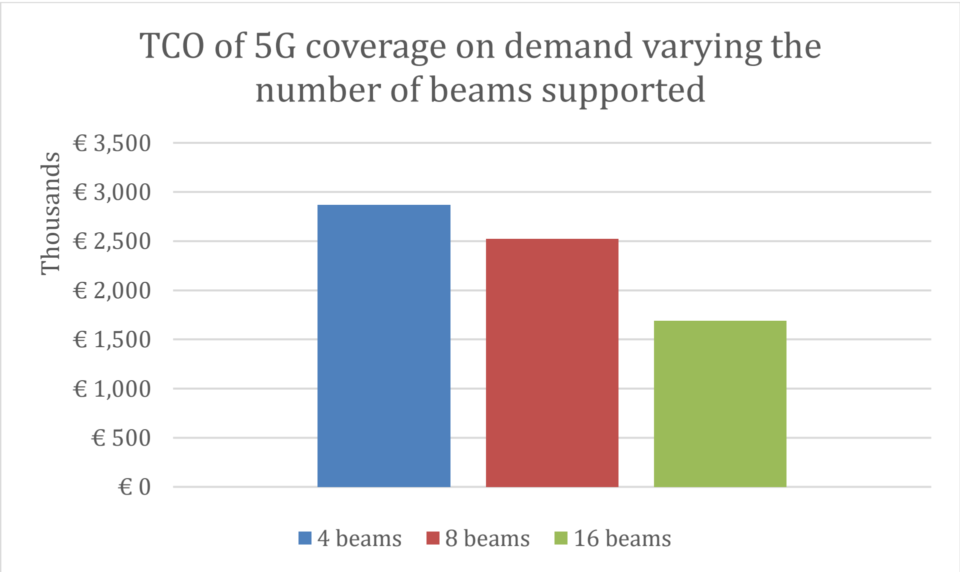


Figure 34 TCO of 5G coverage on demand varying the number of beams supported

Figure 34 shows that even using the most expensive type of RAN hardware being the one supporting 16 beams is more cost-effective than the cheap ones due to the efficient use of its capabilities to meet the required UL capacity to support the selected UCs and EFs.

5.1.8.2 Impact of changing the network deployment strategy

In the 5G network dimension section, section 3.3.1.1, the strategy adopted to dimension the 5G network was explained in detail. In brief, the strategy is based on the use of macro cells only to provide the coverage to the studied area and to meet the UL capacity requested by the selected UCs and EFs, additional small cells are installed. We refer to this strategy in this section as “network deployment strategy 1”. However, based on the network dimensioning done for the first deployment scenarios we observed, especially for the 5G network slicing option, that when we need a significant UL capacity the number of the required small cells is very high, moving from 5 small cells for the 5G coverage on demand option to 10 small cells for the 5G network slicing option. This is due to that small cell can provide only 3 beam/data stream on the UL compared to 16 beams for macro cells thanks to MIMO. Therefore, in this section we studied the impact of changing the network deployment strategy by adding one additional macro cell first to decrease the need to install a lot of small cells, we refer to this strategy here as “network deployment strategy 2”.

To cover the two studied terminals with 5G networks for the two different strategies we require the following deployment:

Table 13 Required infrastructure in term of macro and small cells for the two network deployment strategies

	Network deployment strategy 1	Network deployment strategy 2
5G coverage on demand	1 Macro Cell + 5 Small Cells	2 Macro Cells
5G network slicing	1 Macro Cell + 10 Small Cells	2 Macro Cell + 2 Small Cells

Using the cost model we compared the two 5G connectivity options namely the 5G coverage on demand and 5G network slicing using the two different network deployment strategies for the two TO adoption scenarios being the pessimistic scenario (depicted in Figure 35) and the optimistic one (depicted in Figure 36). The TCO presented in the two figures is of covering the entire PoA following the terminals adoption the 5G-based TO.

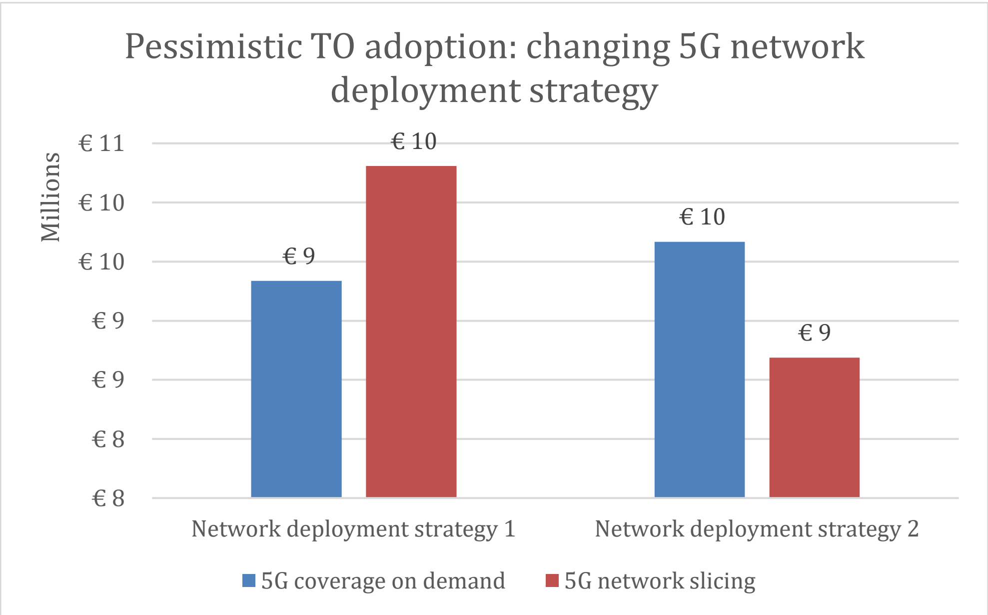


Figure 35 Pessimistic TO adoption: changing 5G network deployment strategy

Figure 35 shows that changing the network strategy by adding one additional macro cell to substitute 5 small cells for the 5G coverage on demand option will introduce more deployment cost. Yet, seems more cost efficient to substitute 8 small cells by one macro cell for the 5G network slicing connectivity option which results in 16% cost reduction of the total deployment cost (from 10.4 to 8.7 million euro). This cost reduction due to network strategy changing makes the 5G network slicing option more cost effective than the 5G coverage on demand option in the two network deployment strategies. This cost reduction results in a **7% cost reduction** in the final **ACPU for the connectivity service**.

Similar to the pessimistic scenario, results of the cost comparison of the two network strategies for an optimistic TO adoption presented in the following figure shows that changing the network deployment strategies towards installing more macro cells instead of small cells makes sense only when we have a significant number of small cells, higher than 8. The cost reduction for 5G network slicing option is around 17% which also results in an **8% cost reduction** in the final **ACPU for the connectivity service**.

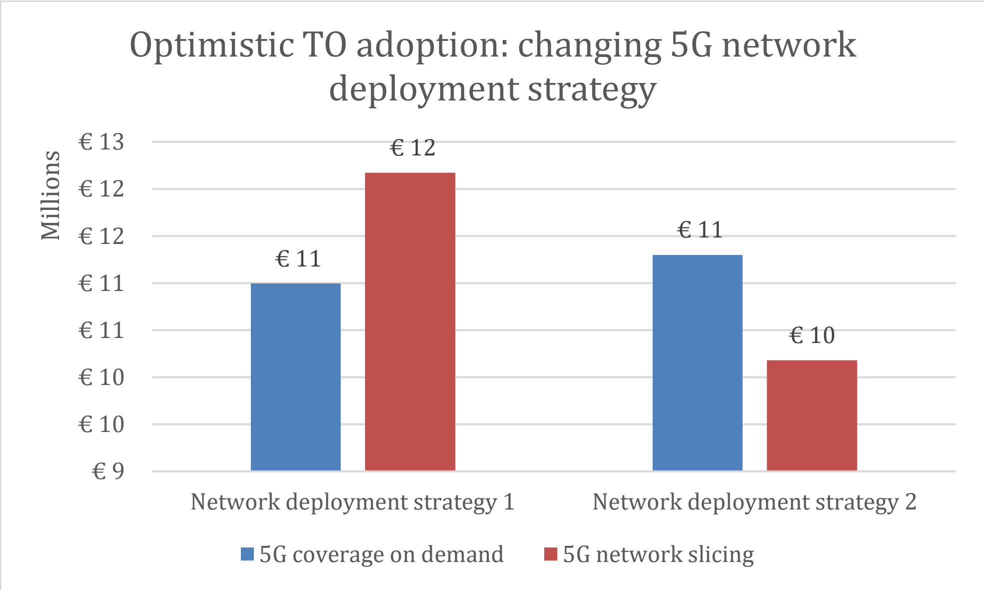


Figure 36 Optimistic TO adoption: changing 5G network deployment strategy

5.1.8.3 Use of only skid steers in the terminals

The ACPU and the resulting ARPU calculated for this deployment scenario is considerably high to be charged monthly per vehicle served in the port even with changing the network deployment strategy still around 560 euro for connectivity only and for the cost effective TO center deployment option is also around 500 euro. Therefore, one might consider starting only by supporting TO in skid steers with bulk cargo where the environment is sometimes dangerous for skid steers derivers. Hence, we studied in this section the impact on deployment cost for both 5G network and TO center, of supporting only skid steers in the terminals besides barges, which means no TO cranes nor TO terminal internal trucks. Cost results have been compared to the initial case where internal trucks and cranes are also supported. Table 14 summarizes the key findings.

Table 14 cost comparison between the initial case and providing only skid steers in the terminals

Optimistic scenario	Skid steers only: ACPU/month	Cranes, internal trucks and skid steers: ACPU/month	Cost increase by going to skid steers only
5G coverage on demand	€ 739.38	€ 604	18%

Own TOC with operator wages gradual deployment	€ 670	€ 476	29%
Own TOC without operator wages gradual deployment	€ 73	€ 44	40%

Results shown in the table above prove that providing TO service to fewer vehicles in the terminals results in a higher ACPU at the end. As we can see from the table, serving skid steers only is 18% more expensive on the 5G connectivity level and 29-40% more expensive on the TO service level. Therefore, it is better to support as much use cases as possible, thus higher number of connected vehicles will share the deployment costs which results in a lower ACPU.

5.1.1 Main takeaways

Techno-economic analysis of the deployment scenario 1, which focuses on providing the 5G-based TO services in a limited area within the port namely terminals only, showed that:

- For 5G network deployment:
  - The 5G coverage on demand is the cost-effective deployment option under the mentioned assumptions and circumstances.
  - The network slicing with providing a separate slice for each service is the costliest option, this is due to several reasons among which we list the low demand of the non-TO slices on the UL capacity makes the TO slice bear the significant part of the deployment cots.
  - If we compare the average TCO per terminal over 10 years deployment to the cost of the early deployment in the two terminals DPW and MPET, we see a cost reduction in the TCO of 47.5% for the pessimistic TO adoption and 43.5% for the optimistic scenario. This gives recommendation for both connectivity providers and TO service providers in the port terminals about the good moment of adopting the 5G-based TO technology.
  - OPEX is the dominant cost element which represents 63% of the TCO.
  - Sensitivity analysis with varying the type of RAN hardware used to support MIMO shows that even using the most expensive type of RAN hardware being the one supporting 16 beams is more cost-effective than the cheap ones due to the efficient use of its capabilities to meet the required UL capacity to support the selected UCs and EFs.
  - Changing the network strategy by adding one additional macro cell to substitute few small cells (up to 5) will introduce more deployment cost. Yet, seems more cost efficient to substitute 8 small cells by one macro cell for the 5G network slicing connectivity option which results in 16-18% cost reduction of the TCO. This cost reduction makes the 5G network slicing option more cost effective than the 5G coverage on demand option in the two network deployment strategies. This cost reduction results in a 7-8% cost reduction in the final ACPU for the connectivity service.
- For TO center deployment:
  - deploying the TOC with a gradual addition of the control setups following the TO uptake is more cost-effective than buying all the control setups at the start of the deployment with a 10% cost reduction. The cost saving is around 25%.
  - The cost of deploying TO center assuming an optimistic adoption is more expensive than the deployment in a pessimistic uptake scenario.
  - The main cost component of the TCO is OPEX, which represents 89% of the total cost.
  - A cost breakdown of OPEX shows that operator wage is the dominant cost element which represents 93% of the total OPEX and the rest 7% are distributed among office space renting, Internet subscription and energy cost.
  - Deploying own TO center is less expensive than renting a pre-equipped TO rooms from other TO service providers; cost reduction of up to 25%.
- From the business case evaluation:
  - The ACPU in the optimistic scenario is less than the one in the pessimistic scenario,

due to the higher number of the different types of connected vehicles.
  - For the pessimistic TO adoption, the BEP is reached around year 5 for the two profit margin assumptions being 15% and 30%. Yet, the BEP is around 5 and 8 years for the optimistic scenario for the 30% and 15% respectively.
  - Focusing on only few use cases, for example only skid steers in the terminals to serve TO barges above results in a higher ACPU at the end. Serving skid steers only is 18% more expensive on the 5G connectivity level and 29-40% more expensive on the TO service level. Therefore, it is better to support as much use cases as possible, thus higher number of connected vehicles will share the deployment costs which results in a lower ACPU

5.2 Deployment scenario 2: in port area, terminals and short public roads supporting UC4.1a, UC4.1, UC4.2, UC4.3 and UC4.4

5.2.1Definition of the deployment scenario

This deployment scenario is based on the combination of multiple technological options related to where and how to provide TO services. Starting with the “where” question, in this deployment scenario, TO services are provided in the terminals area of the port of Antwerp (PoA) with short public roads inside the port, using two different connectivity options being 1) 5G coverage on demand and 2) 5G network slicing. The use cases supported are: UC4.1a.1: Automated Barge Control: Navigating a river and a canal in a national waterway, UC4.1b: Automated Barge Control: Navigating, Docking and Unloading in a (bussy) port; UC4.2a: automated docking, UC4.2b: Teleoperated Mobile Harbour Crane/skid steers, UC4.3: Cooperative Adaptive Cruise Control (CACC) based platooning and UC4: Remote Take Over Operation, together with EF4: Distributed perception and EF5: Active collision avoidance.

We study the port area as terminals that are operating by different companies. Those terminals are future adopters of TO capabilities to support UC4.1b, UC4.2b, and UC4. Hence, we need to forecast:

- The adoption of 5G networks by those terminals to support TO
- The adoption of TO capabilities for barges
- The adoption of TO capabilities for the cranes
- The adoption of TO capabilities for the trucks

The TO adoption for port terminals, barges and cranes are detailed previously in section 0. In this deployment scenario is the TO adoption for trucks that are served by the different port terminals.

5.2.2Forecasting of TO adoption in the port for trucks

For Use case 4.2a and UC4.3 and UC4.4, we need to derive the number of TO capable trucks in the PoA. Starting with the two terminals; DPW and MPET and then scale up for the other terminals following the TO adoption in terminals. Like previously presented TO adoption, here also we follow the two adoption scenarios namely the pessimistic and the optimistic scenarios. We assumed an annual growth of 3% in the truck fleet served by the two terminals and starting with 5600 served trucks a day and using the bass diffusion model, the TO adoption in the daily trucks served by the two terminals under study is presented in the following figures:

1. Pessimistic/realistic TO adoption scenario

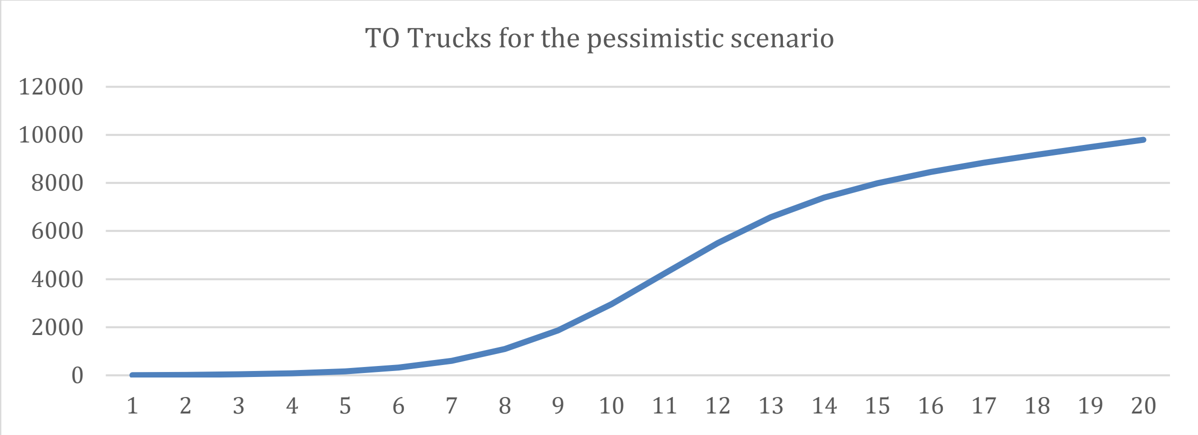


Figure 37 Evolution of expected number of TO-capable trucks for the pessimistic scenario in DPW + MPET terminals over the years

2. Optimistic TO adoption scenario

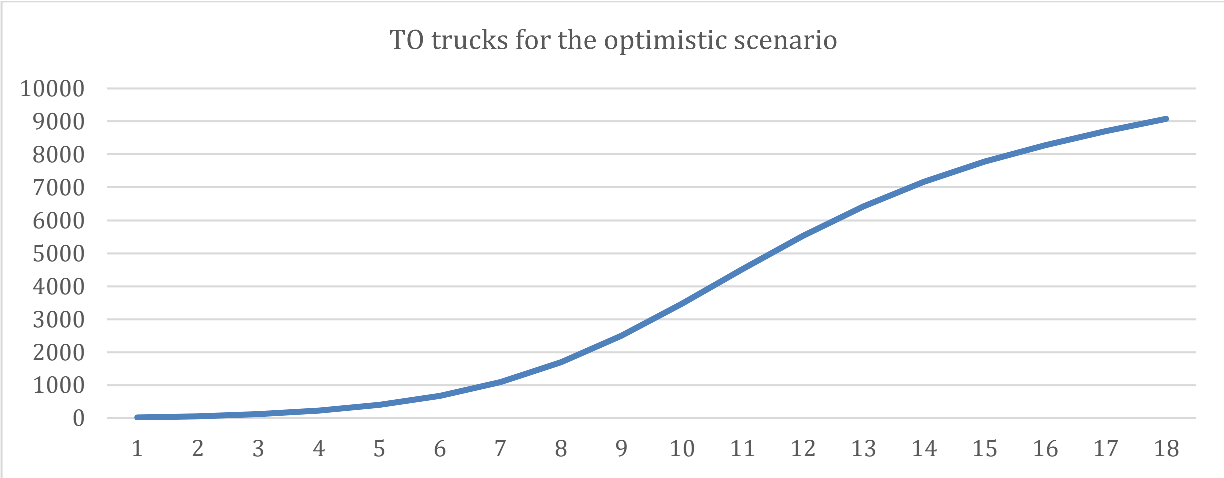


Figure 38 Evolution of expected number of TO-capable trucks for the optimistic scenario in DPW + MPET terminals over the years

Based on discussions with partners from the port and logistic companies, the daily served trucks can be divided into 35% doing short-haul journeys, which means going to warehouses inside the port area and 65% of them are doing long-haul journeys and exit the port region. For the long-haul trucks, we assume that 25% of them will be served by remote driving (UC4.4) and 75% by TO platooning (UC4.3) with 4 trucks per platoon.

5.2.3 Dimension of the 5G network in the PoA in Antwerp Gateway and MPET terminals and in the river entrance of the port

5.2.3.1 Area to cover

Similar to the previous deployment scenario, we need to deploy 5G Networks in the DP world terminal (Antwerp Gateway) to support the selected UCs and then deploying in more terminals following the adoption curve of “5G networks-based TO adoption rate in the port terminals”. With an inter-site distance of around 2 km and considering the existing network infrastructure presented in Figure 16. The main difference with the deployment scenario is in the number of small cells needed, since the number of macro cells if derived in function of the area to cover and since it is the same area, no difference in term of number of macro cells with the deployment scenario 1. In addition, for UC1a we consider the navigation of the TO barges in the entrance of the port of Antwerp with a length of 4 km (the Schelde river on the Belgian side). The required network infrastructure to cover the port entrance is presented in Figure 39. Based on the existing network (presented in Figure 88) two additional macro cells are needed to provide the full coverage of the river segment under study.

Figure 39 5G network deployment to cover PoA waterway entrance

5.2.3.2 Network Capacity requirement

Based on the required UL capacity for the different use cases and different slice types presented in Table 3, for the two terminals DPW and MPET, the total required capacity on the UL for the two types of 5G connectivity options (i.e., 5G coverage on demand and 5G network slicing) has been calculated considering the following assumptions:

- 1 TO barge to be served at the same time;
- 8 cranes can be operated simultaneously,4 for each terminal;
- For the pessimistic TO adoption: 8 remote driving can be supported at the same time to support the internal trucks/skid steers if we have a bulk cargo; 4 for each terminal;
- For the optimistic TO adoption: 16 remote driving can be supported at the same time to support the internal trucks/skid steers if we have a bulk cargo; 8 for each terminal;
- 1 existing macro-cell (as showed in Figure 16) and 50% of its UL capacity is used by other applications, so 50% is free and to be used for TO use cases; same holds for the existing macro cell on the river entrance of the port ;
- Each macrocell is a tri-sector and each cell has 16 beams following the RAN hardware installed by Telenet in the port, but in reality, on the UL only 8 streams simultaneously can be offered, this is to be validated during the final measurement campaigns;
- The area of the two terminals is 3.211 square kilometre (km^2)

- The length of port entrance is 4 km.
- The width of port entrance is 1.3 km.
- The macro cell inter-site distance is 2 km.
- Daily served trucks: 5600 (based on the two terminals websites)
- Number of working hours=12 like an average, it is mentioned on the two terminals websites that they are working 24 h, but if we want to extrapolate the results of these two terminals to other port terminals, we need to work with average working hours.
- We assume that the average length of the road from the terminal to the warehouse (where the docking will take place) is 1 km, it can be more but we assume we need an operator to drive the truck for an average length of 1 km
- Truck speed in docking :10 km/hour
- We assume the length in which platooning is taking place is 2 km (first mile after leaving the terminal).

For **5G coverage on demand** and using the network dimensioning process (explained in section 3.3.1.1) results in a total capacity of 2811 Mbps on the UL . Given the network deployment strategy adopted earlier and explained in section 3.3.1.1, where macro cells are deployed to provide coverage while small cells are to be added to enhance capacity, the network infrastructure needed in the two terminals is one new macro cell and 24 small cells for the pessimistic scenario. While for the optimistic scenario, the total capacity on the UL is of 3623 Mbps which requires the installation of 1 macro cell and 34 small cells. For the river entrance of the port, the required capacity on the UL needed is 240 Mbps which means we only need to install 2 macro cells.

For the deploying **5G network slicing** connectivity option in the two terminals DPW and MPET, we need to know the required capacity for the other slices to be offered in these two port terminals. To this end, the non-TO UL capacity needs to be estimated to deploy the network to support both type of services, the TO and the non-TO ones. Based on the two methods of the non-TO capacity calculation explained in 3.3.1.1, the total required capacity has been calculated:

3. <u>Assuming that all the non-TO services are also supported by network slices</u>, the total required capacity is calculated using the following assumptions:
   - Two other types of slices are to be provided in the two terminals, being the eMBB slice serving the normal customers as truck drivers and employees in the two terminals and IoT slice for sensors for example used in the automation of certain processes in the terminal, like the container ID identification etc…
   - 2 IoT slices, one per terminal
   - To calculate the required total capacity, additional input data are needed:
     - Total number of employees of the two terminals ~=350;
     - Active users for eMBB slice percentage =10%.

Therefore, the total Capacity required on the UL is the sum of the total Capacity UL of the TO slice and the total Capacity UL of the eMBB slice and the total capacity UL of the two IoT slices. This results in a total UL capacity of 3221 Mbps and 4033 Mbps for the pessimistic and optimistic scenario respectively. Hence, an additional macrocell is required for ensuring the coverage of the two terminals and 29 and 39 small cells Mbps for the pessimistic and optimistic scenario respectively are to be deployed to meet the required UL capacity. For the river entrance of the port, the required capacity on the UL needed is 240 Mbps which is the same as the 5G coverage on demand case, thus, we only need to install 2 macro cells.

4. Assuming that the non-TO services are supported as a regular traffic without dedicated slices for each type of service, the total non-TO capacity is calculated using the data below:
    - Data traffic has been retrieved from the field in GB (Gigabyte);
    - Assuming 8 hours as time window in which users are active, the downlink speed has been calculated;
    - Assuming that the UL speed is 5% of the DL speed, the UL capacity is derived,
    - Assuming a 30% regular traffic growth, the requested UL capacity of the regular traffic for the next 2-4 years has been calculated.

Therefore, the total Capacity required on the UL is the sum of the total Capacity UL of the TO slice and the total Capacity UL of the regular traffic. This results in a total UL capacity of 2902 Mbps and 4033 Mbps for the pessimistic and optimistic scenario respectively. Hence, an additional macrocell is required for ensuring the coverage of the two terminals and 25 and 35 small cells are to be deployed to meet the required UL capacity for the pessimistic and optimistic scenario respectively.

5.2.4 Cost model results of 5G network deployment

Using the cost data validated by all partners in a data validation round, the cost model has been run for the two types of connectivity options being 5G coverage on demand and 5G network slicing with its two methods of estimating the non-TO capacity and are presented in the following sections.

5.2.4.1 Deployment scenario 2.1: 5G Coverage on demand to provide UC4.1a, UC4.1, UC4.2, UC4.3, UC4.4, EF4 and EF5:

To cover the two terminals under study namely the DPW and the MPET with 5G network to support the TO use cases previously described, the cumulative TCO over 10 years period is € 4,651,512 which results in a cumulative TCO per square kilometre of € 1,448,618. The average TCO over 10 years timespan per terminal is € 2,325,756.The different cost components of the 5G network deployment are depicted in the figure below.

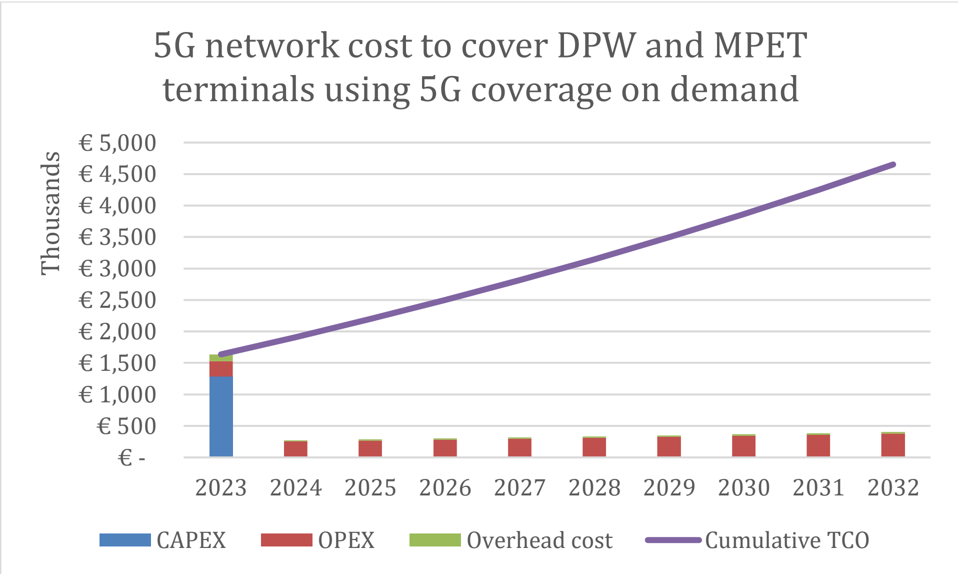


Figure 40 Different cost components and Cumulative TCO over 10 years of the 5G network for 5G coverage on demand option to cover the DPW and the MPET terminals.

To understand what the dominant cost of the TCO is, we visualize a cost breakdown of the TCO in Figure 89. It is clear that the OPEX is the dominant cost element which represents 66% of the TCO. The main cost components of the OPEX are the site rental (32 €k per year) to host the macro cells and small cells, the energy cost (14 €k per year) and the hardware maintenance.

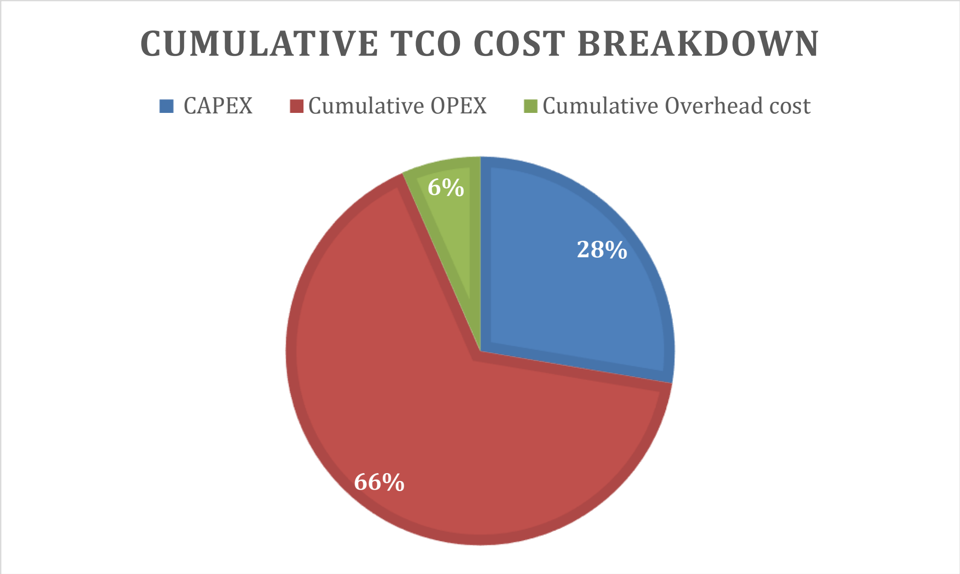


Figure 41 Cost breakdown of the cumulative TCO over 10 years for the coverage on demand option

The TCO of the 5G cost deployment to cover the entrance of the PoA to support UC4.1.1a is presented in the figure below.

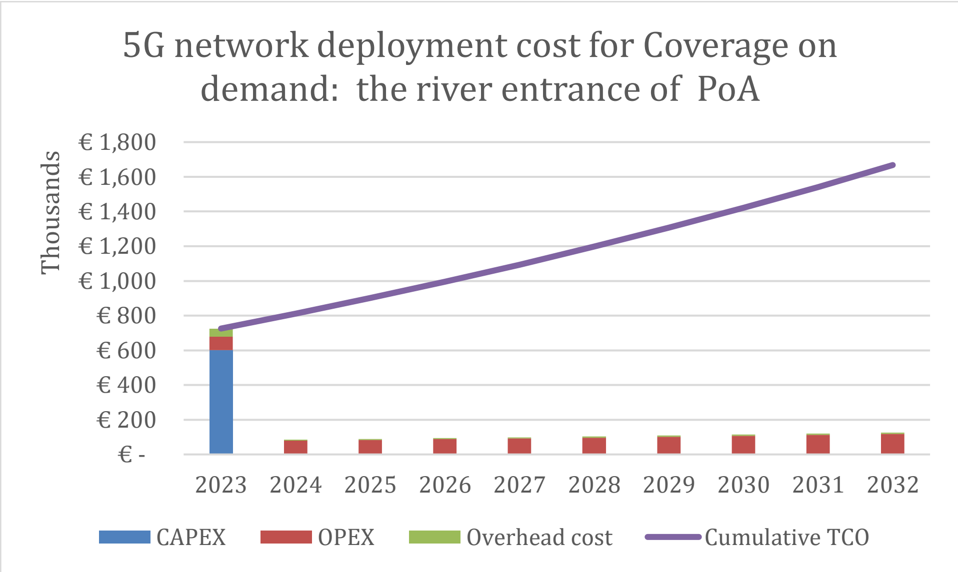


Figure 42 5G network deployment cost for Coverage on demand: the river entrance of PoA

Following the TO adoption scenarios being the pessimistic and the optimistic uptakes in the port of Antwerp (presented in Figure 9 and Figure 12); the TCO has been calculated for each of the two scenarios to cover the port and to provide the selected use cases in terminals together with the entrance of the port for navigating the TO barges in the canal.

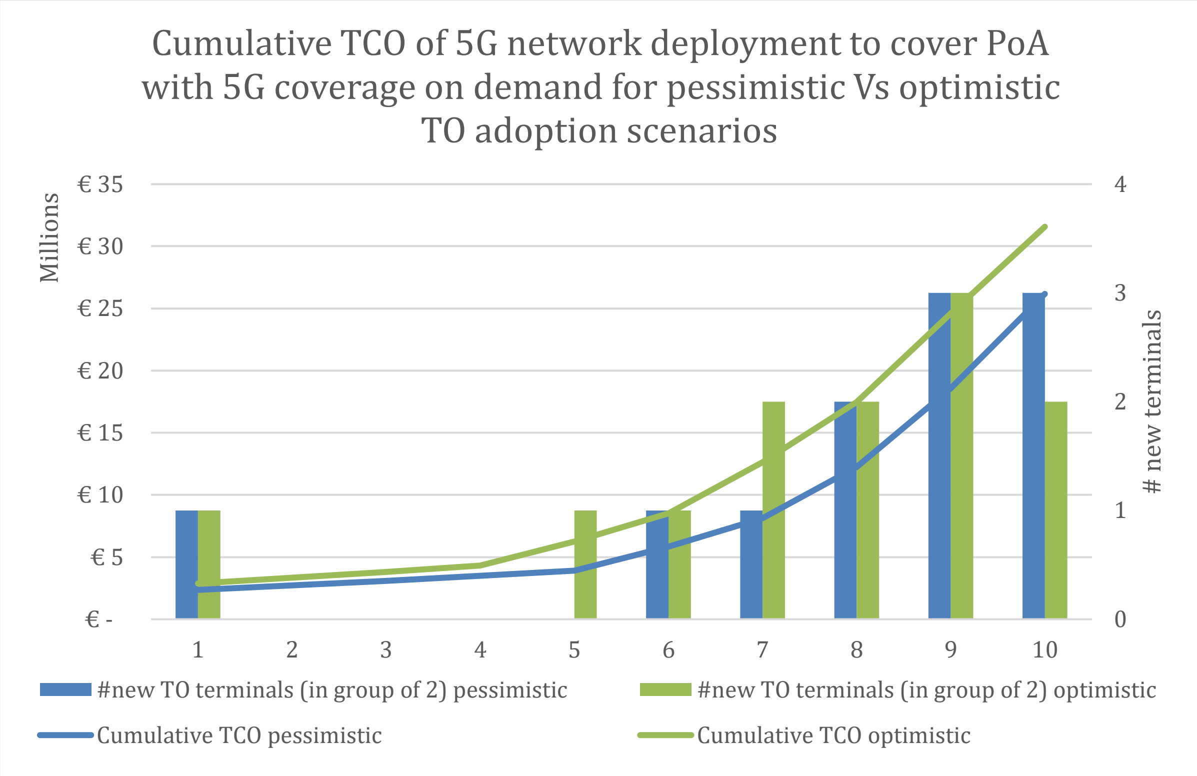


Figure 43 5G coverage on demand TCO comparison between pessimistic and optimistic TO adoption

Figure 43 presents the cumulative TCO of deploying 5G coverage on demand in the PoA for the pessimistic and the optimistic TO adoption. Results show that the TCO for the optimistic scenario is higher than the pessimistic scenario since in the former a higher number of terminals have adopted 5G technology to provide TO use cases. In total, 23 terminals out of 26 have adopted 5G-based TO over 10 years (2023-2032) in the optimistic scenario compared to only 21 terminals in the pessimistic scenario. An interesting insight from this cost analysis is that the average TCO over 10 years timespan per terminal is € 1,166,840 in the pessimistic TO adoption scenario which is less costly than the average TCO per terminal for the optimistic adoption which is € 1,372,817. The cost difference is €k 205 per terminal, being 15% cost reduction per terminal. This can be justified by the early adoption of the technology in the optimistic adoption scenario where the cost of the deployment still expensive, while in the pessimistic scenario there was a weak adoption in the first 5 years of the deployment and then there was a mass adoption by the end of the 10 years timespan, which makes the deployment takes benefit from the cost reduction over the years due to the market competition and the maturity of the technology. If we compare the average TCO per terminal over 10 years deployment to the cost of the early deployment in the two terminals DPW and MPET, we see a cost reduction in the TCO of 50% for the pessimistic TO adoption and 41% for the optimistic scenario. This gives recommendation for both connectivity providers and TO service providers in the port terminals about the good moment of adopting the 5G-based TO technology.

5.2.4.2 Deployment scenario 2.2.1: 5G network slicing to provide UC4.1a, UC4.1, UC4.2, UC4.3, UC4.4, EF4 and EF5 using one slice for each type of service:

As presented above in section 5.2.3.2, the UL capacity requirement in this connectivity option is 3221 Mbps and 4033 Mbps for the pessimistic and optimistic scenario respectively in which 410 Mbps is required by the non-TO slices.

To cover the two terminals under study namely the DPW and the MPET with 5G network to support the TO use cases previously described using 5G network slicing and assuming that the non-TO services are also to be provided by the mean of slices, the cumulative TCO over 10 years period is € 5,436,624 which results in a cumulative TCO per square kilometre of € 1,693,125.

The average TCO over 10 years timespan per terminal is € 2,718,312.The different cost components of the 5G network deployment are depicted in the figure below.

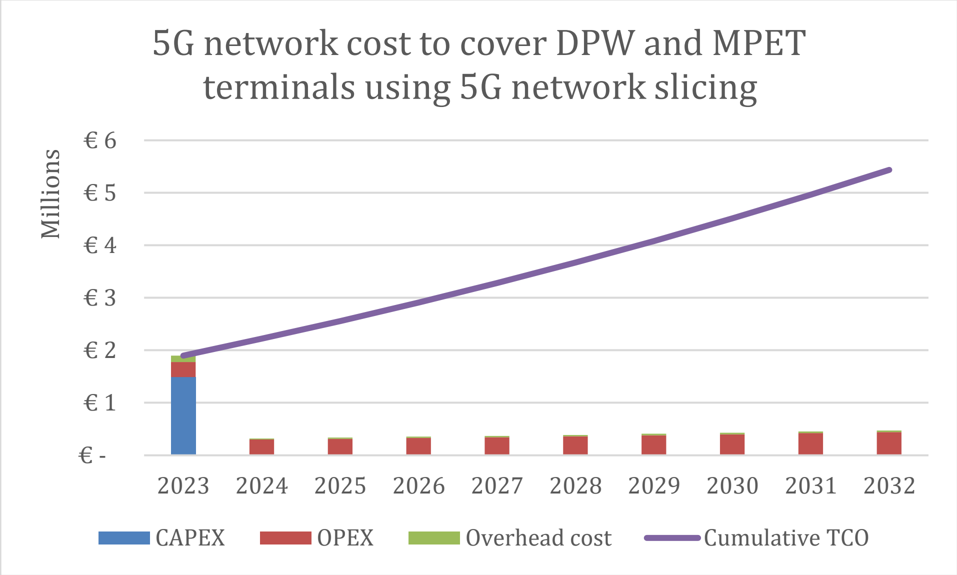


Figure 44 Different cost components and Cumulative TCO over 10 years of the 5G network for 5G Network slicing option

Similar to the previous deployment option, the cost breakdown of the cumulative TCO showed that OPEX is the dominant cost element.

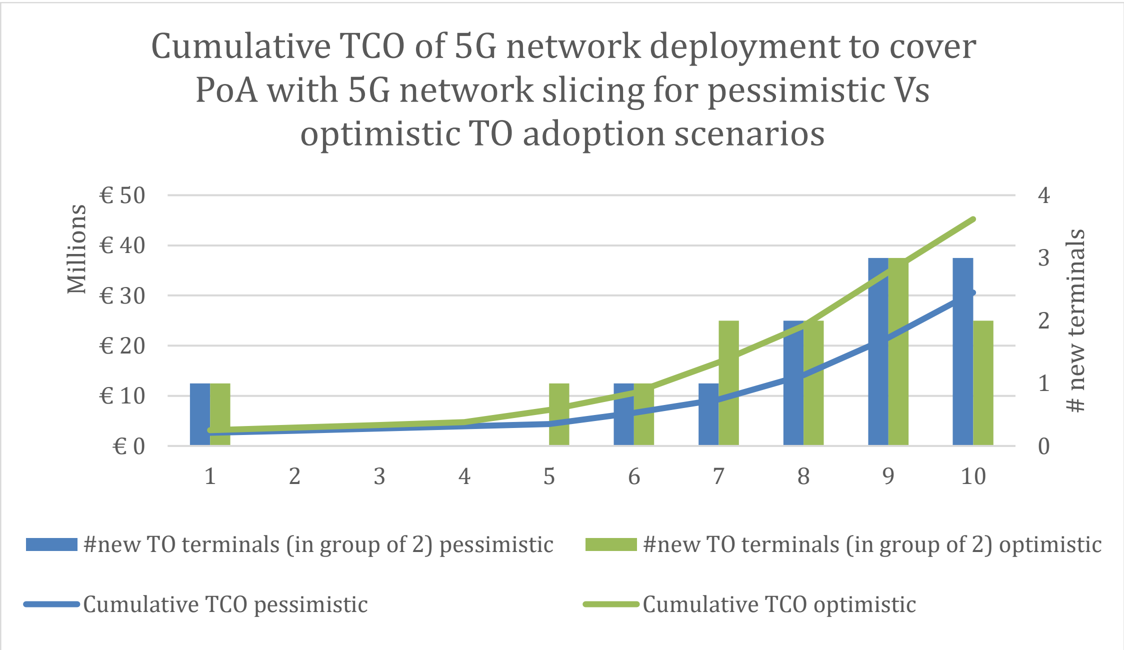


Figure 45 5G network slicing TCO comparison between pessimistic and optimistic TO adoption

Like the previous deployment scenario (Deployment scenario 2.1: 5G coverage on demand), results in Figure 45 show that the TCO for the optimistic scenario is higher than the pessimistic scenario since in the former a higher number of terminals have adopted 5G technology to provide TO use cases.

We used the allocation model described in section 3.3.1 to allocate the 5G network cost to the three slices using only **throughput metric**: as the network was dimensioned using the UL capacity requirement. The cost sharing coefficient are as follow:

	Pessimistic	Optimistic
Cost sharing coefficient TO Slice	87.3%	89.8%
Cost sharing coefficient non-TO Slices	12.7%	10.2%
Cost sharing coefficient mIoT Slice	1%	1%
Cost Sharing coefficient eMBB Slice	99%	99%

Using these sharing coefficients, the TCO has been divided among the supported slices and is presented in Figure 46.

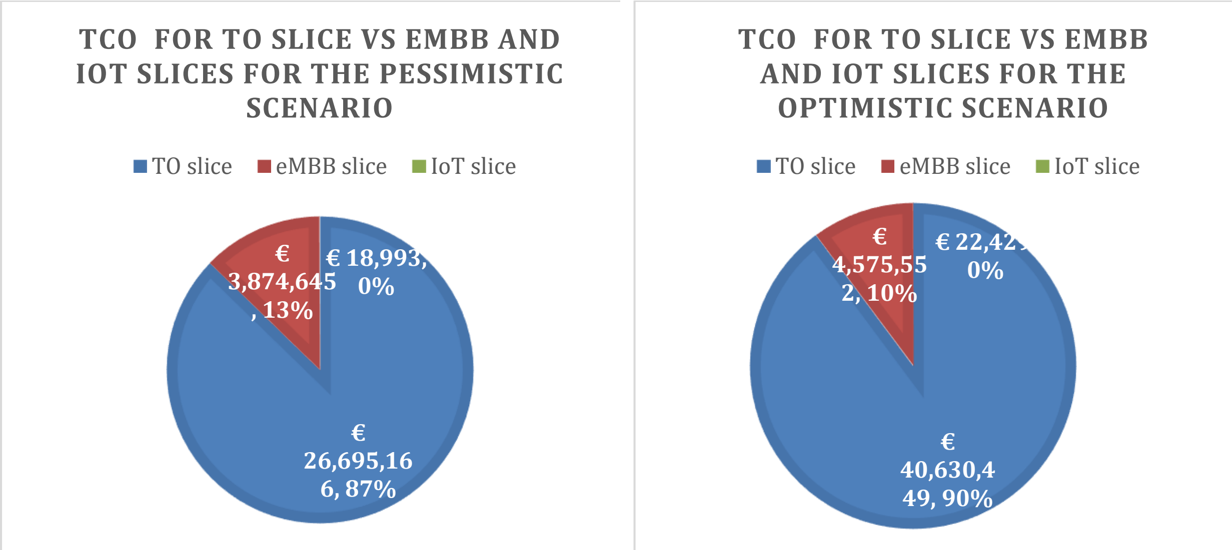


Figure 46 TCO of the TO slice vs eMBB and IoT slices for the pessimistic (on the left-hand side) and the optimistic (on the right-hand side) scenarios to cover the entire PoA

Figure 46 shows that the TO slice bears the bigger part of the TCO this is because the TO slice designed to support he selected UCs and EFs requires 3221 Mbps and 4033 Mbps for the pessimistic and optimistic scenario respectively comparing to only 410 Mbps for the non-TO slices. Another important observation here is that TO is a service very demanding in term of UL capacity however the traditional services are DL-demanding services, which make TO bears the significant deployment cost if the network is designed only based on UL requirement. Yet, if with the same deployment and same services the cost allocation would be made based on the DL requirement, TO slice would bear a significantly low percentage of the deployment cost.

Similar to the previous assessment, also with network slicing, the average TCO over 10 years timespan per terminal deployment for the TO slice only is € 1,271,198in the pessimistic TO adoption scenario which is less costly than the average TCO per terminal for the optimistic adoption which is€ 1,766,541.

Compared to the early deployment of 5G network slicing which cost € 2,718,312 per terminal, deploying at a letter stage could save up to 53% on the cost of the deployment.

5.2.4.3 Deployment scenario 2.2.2: 5G network slicing to provide UC4.1a, UC4.1, UC4.2, UC4.3, UC4.4, EF4 and EF5 assuming other type of services are provided under the regular traffic:

As presented above in section 5.1.3.2, the UL capacity requirement in this connectivity option is 1438Mbps in which 91 Mbps is required by the non-TO slices as a regular traffic.

To cover the two terminals under study namely the DPW and the MPET with 5G network to support the TO use cases previously described using 5G network slicing and assuming that the non-TO services are covered by the so-called regular traffic, the cumulative TCO over 10 years period is € 1,852,072 which results in a cumulative TCO per square kilometre of € 576,790. The average TCO over 10 years timespan per terminal is € 926,035.The different cost components of the 5G network deployment are depicted in the figure below.

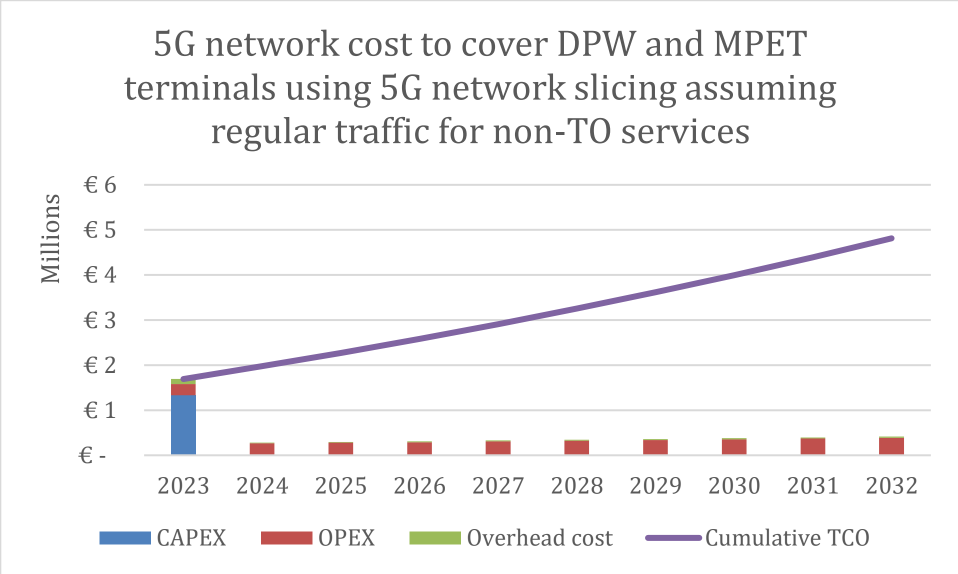


Figure 47 5G network cost to cover DPW and MPET terminals using 5G network slicing assuming regular traffic for non-TO services.

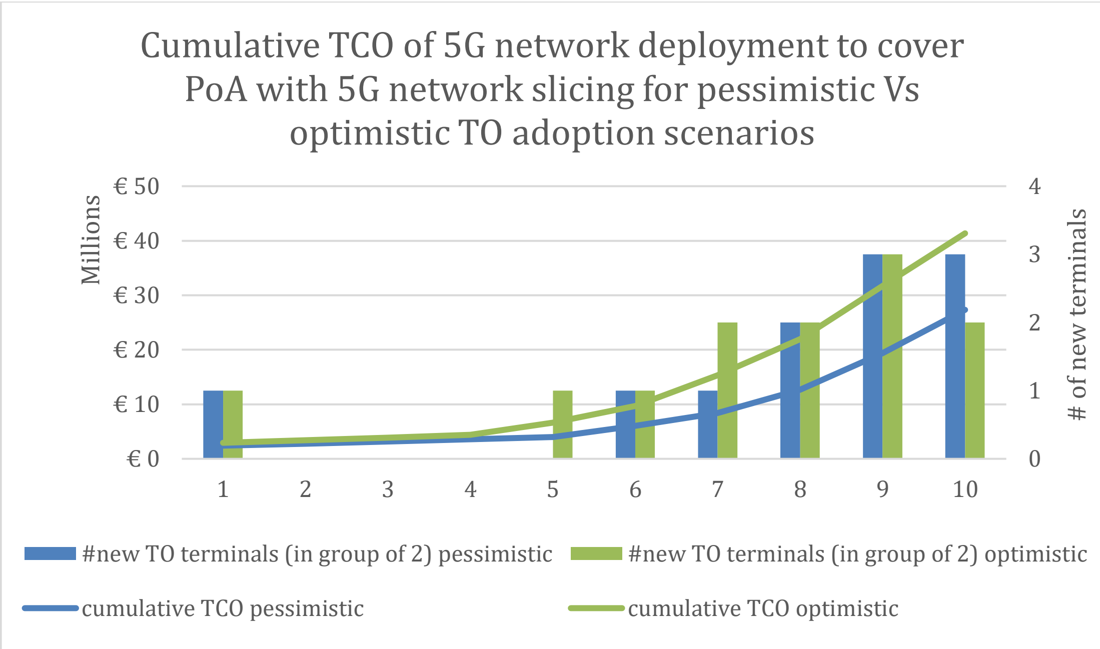


Figure 48 5G network slicing TCO comparison between pessimistic and optimistic TO adoption assuming regular traffic for the non-TO services.

We used the allocation model described in section 3.3.1 to allocate the 5G network cost to the TO slice and the regular traffic using only **throughput metric**: as the network was dimensioned using the UL capacity requirement. The cost sharing coefficient are as follow:

	Pessimistic	Optimistic
Cost sharing coefficient TO Slice	96.8%	97.5%
Cost sharing coefficient regular traffic	3.2%	2.5%

Using these sharing coefficients, the TCO has been divided among the TO slice and the regular traffic and is presented in the figure below.

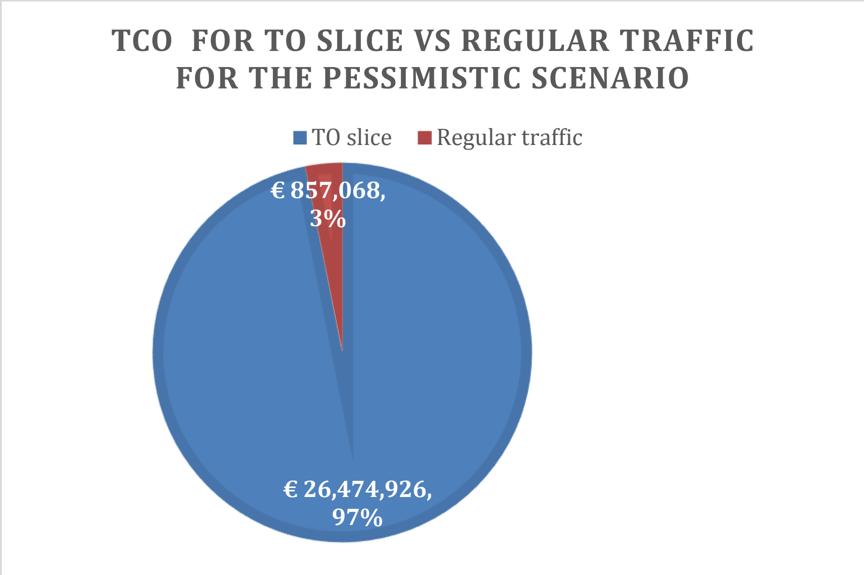


Figure 49 TCO of the TO slice vs regular traffic for the pessimistic scenario

Figure 49 clearly shows that the TO slice has the bigger part of the cost deployment since the regular traffic has a very low requirements in term of UL capacity.

5.2.4.4 Cost comparison between the three 5G connectivity deployment options

Bringing the cost results of the three 5G connectivity deployment options together to assess which option is the most cost effective one. In the comparison we only compare the cost share for the TO slice/service from the three cases.

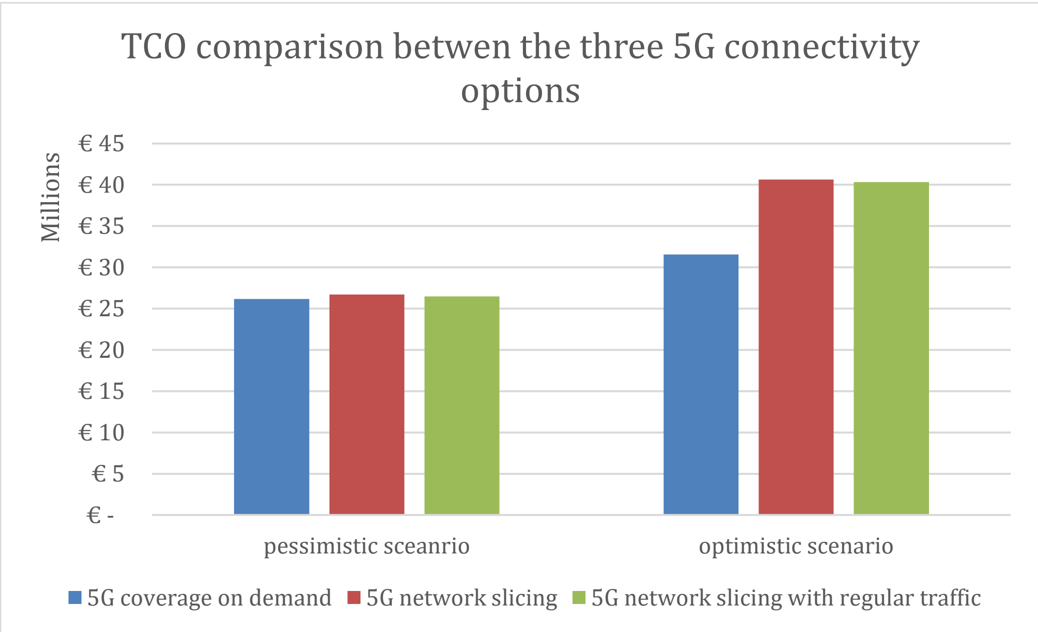


Figure 50 TCO comparison between the three 5G connectivity options

From the cost comparison illustrated in Figure 50, we can deduct that the network slicing with providing a separate slice for each service is the costliest option, this is due to many reasons as explained in section 5.1.4.4. The cost difference in the pessimistic scenario is marginal between the three connectivity options. Yet it becomes very pronounced in the optimistic scenario, this is due to the higher number of connected vehicles which makes the total required capacity higher and hence more small cells to be installed to meet this capacity requirement.

In section 5.1.8 we studied how cost effective is adapting the network deployment strategy in term of replacing small cells by macro cell. And results showed that changing the network strategy by adding one additional macro cell to substitute few small cells (up to 5) will introduce more deployment cost. Yet, seems more cost efficient to substitute 8 small cells by one macro cell for the 5G network slicing connectivity option which results in 16-18% cost reduction of the TCO. This cost reduction makes the 5G network slicing option more cost effective than the 5G coverage on demand option in the two network deployment strategies. This cost saving is expected to be more significant in this deployment scenario since we have higher number of small cells to deploy.

As a conclusion of the cost comparison, the 5G coverage on demand is the cost-effective deployment option under the mentioned assumptions and circumstances.

5.2.5 TO center deployment cost results:

In this section the cost results for the deployment options of TOC in the port of Antwerp to provide the selected use cases and EFs for the two TO adoptions scenarios namely the optimistic and the pessimistic are discussed. Several deployment options have been identified and summarized in section 3.3.2.. Cost data used to run the model are summarized in Table 25. The cumulative TCO for the different options has been calculated over the project lifetime (i.e., 10 years) and presented in Figure 51.

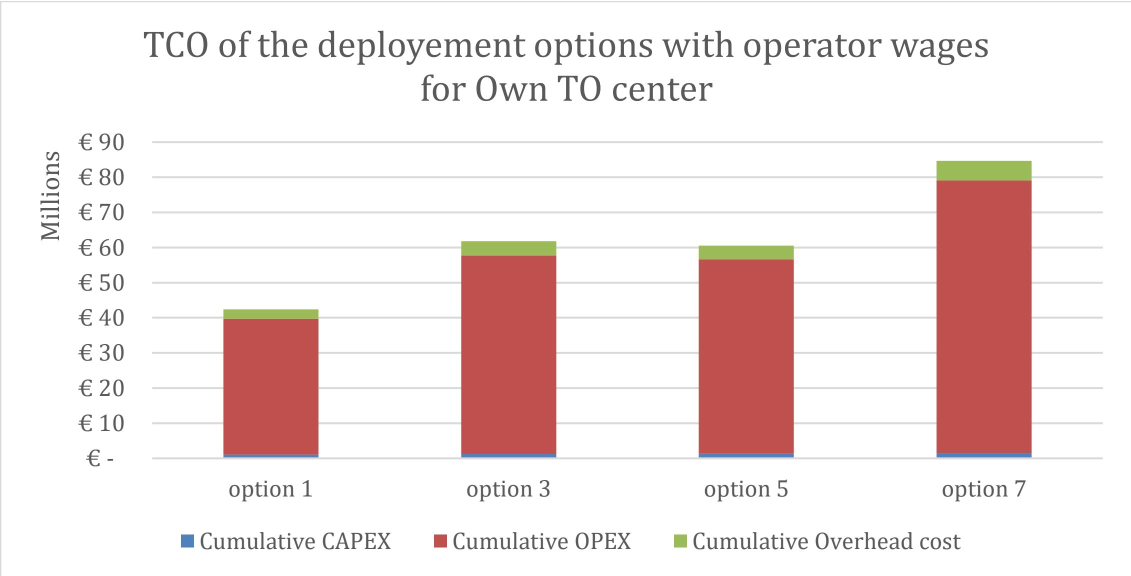


Figure 51 Comparison between the different deployment options for having a teleoperation center based on the cumulative TCO over 10 years for own TO center with operator wages

Figure 27 shows the cost comparison between 4 deployment options of the TO center, being:

- Option 1: Own TOC for pessimistic TO adoption with operator wage and gradual addition of new TO control setups following the yearly TO adoption and considering a yearly CAPEX evolution of -3%.
- Option 3: Own TOC for pessimistic TO adoption with operator wage and deployment of control setups from day 1 considering a cost reduction.
- Option 5: Own TOC for optimistic TO adoption with operator wage and gradual addition of new TO control setups following the yearly TO adoption and considering a yearly CAPEX evolution of -3%.
- Option 7: Own TOC for optimistic TO adoption with operator wage and deployment of control setups from day 1 considering a cost reduction.

With comparing options 1 vs 3 and options 5 vs 7, we can deduct that deploying the TOC with a gradual addition of the control setups following the TO uptake is more cost-effective than buying all the control setups at the start of the deployment with a 10% cost reduction. The cost saving is around 31%.

If we compare the same settings between pessimistic and optimistic TO adoption (i.e., 1 vs 5 and 3 vs 7), it is clear that the cost of deploying TO center assuming an optimistic adoption is more expensive than the deployment in a pessimistic uptake scenario. This is due to the higher number of TO-capable vehicles that need to be served in the optimistic scenario vs the pessimistic one and their resulting cost in term of operator wages and required hardware. The cumulative operator wages in the optimistic scenario are around € 52 million comparing to only € 37 million for the pessimistic scenario which is 28% more expensive.

As shown in Figure 51, the main cost component of the TCO is OPEX, which represents 91% of the total cost. A cost breakdown of OPEX shows that operator wage is the dominant cost element of OPEX, as depicted in the figure below. It represents 98% of the total OPEX and the rest 2% are distributed among office space renting, Internet subscription and energy cost.

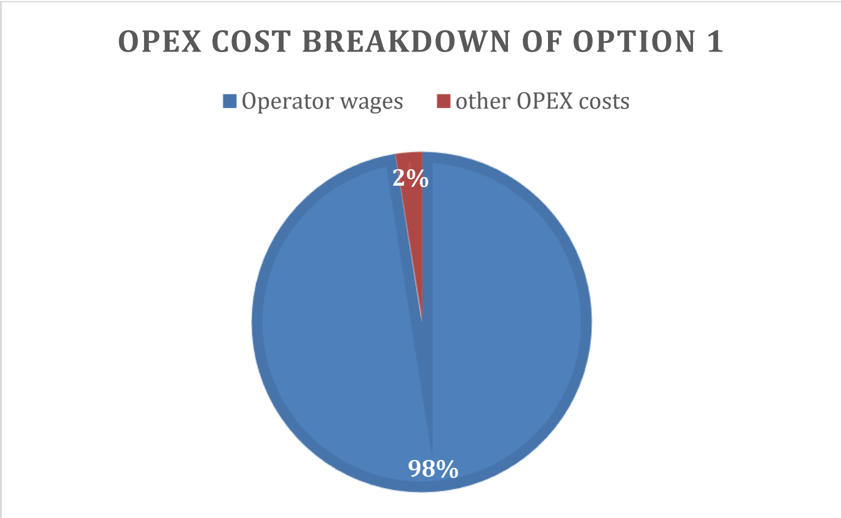


Figure 52 OPEX cost breakdown of TO center deployment option 1

If logistic companies want to bring their own operators, then the TCO of deploying the TO center is much cheaper (cost reduction by 96%) and is illustrated in the figure below.

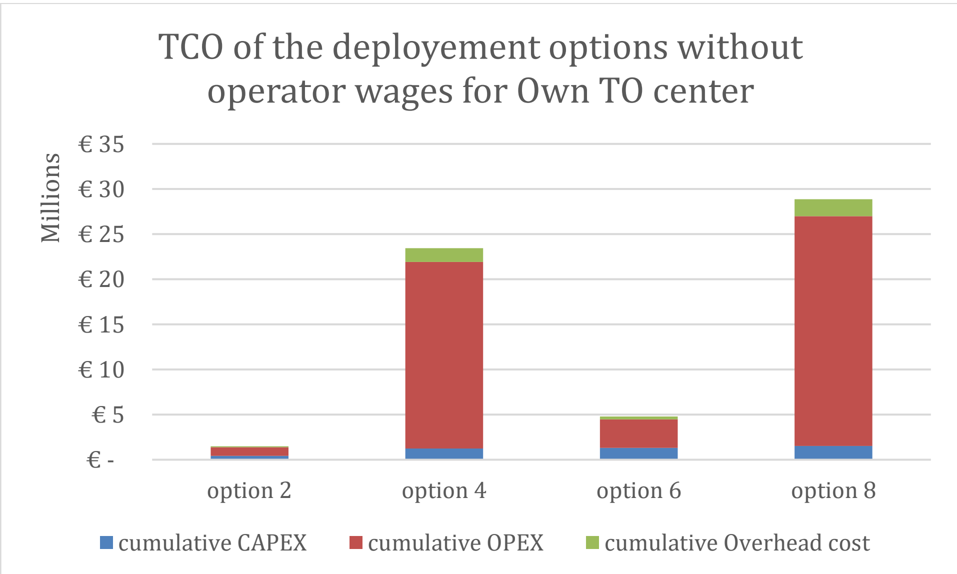


Figure 53 Comparison between the different deployment options for having a teleoperation center based on the cumulative TCO over 10 years for own TO center without operator wages

Figure 29 shows the cost comparison between 4 deployment options of the TO center without considering operator wages, being:

- Option 2: Own TOC for pessimistic TO adoption without operator wage and gradual addition of new TO control setups following the yearly TO adoption and considering a yearly CAPEX evolution of -3%.
- Option 4: Own TOC for pessimistic TO adoption without operator wage and deployment of control setups from day 1 considering a cost reduction.
- Option 6: Own TOC for optimistic TO adoption without operator wage and gradual addition of new TO control setups following the yearly TO adoption and considering a yearly CAPEX evolution of -3%.
- Option 8: Own TOC for optimistic TO adoption without operator wage and deployment of control setups from day 1 considering a cost reduction.

Similar to the previous comparison, comparing options 2 vs 4 and options 6 vs 8, we can deduct that deploying the TOC with a gradual addition of the control setups following the TO uptake is more cost-effective than buying all the control setups at the start of the deployment with a 10% cost reduction. The cost saving is around 90%. Unlike the first comparison, the significant cost of deploying control setup at day one is due to the need to rent office space for these control setups. An important cost savings could be by renting out the spare control setups as an equipped TO room to other TO service providers until the point where we have a good uptake of the TO services and therefore using the installed control setups.

What if the TO service provider decide from the start to rent an equipped TO room and only bring their operators or give the possibility to their clients, namely the logistic companies to bring their own operators, these different deployment scenarios are analyzed under the following option:

- Option 9: TO room rent for pessimistic TO adoption with operator wage.
- Option 10: TO room rent for pessimistic TO adoption without operator wage.
- Option 11: TO room rent for optimistic TO adoption with operator wage.
- Option 12: TO room rent for optimistic TO adoption without operator wage.

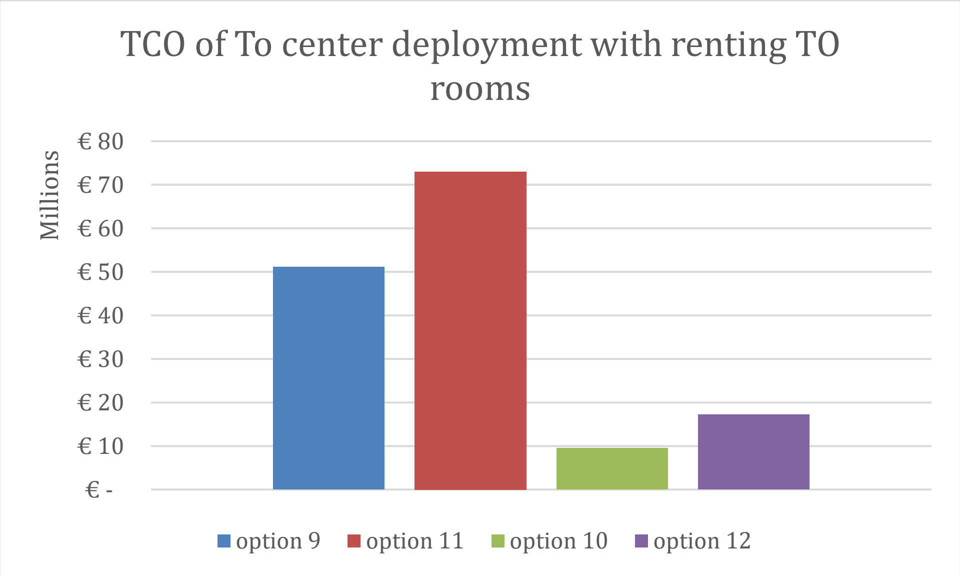


Figure 54 TCO of deploying TO center with renting TO rooms

Figure 54 presents the results of TCO calculation of the 4 deployment options described above. Cost results shows the cost difference between the pessimistic and optimistic scenarios, option 9 vs option 11 and option 10 vs option 12. It is reasonable to see that the optimistic scenario is more costly than the pessimistic scenario since we have more TO vehicles to serve and hence need more operator to pay and more TO room to rent. Like the previous deployment scenario, the operator wages make a great difference in the total deployment cost up to 81% of the total TCO. Yet, unlike the previous options, another important element of the OPEX is the cost of renting the TO equipped rooms which represents 17% of the OPEX, as can be seen in the following figure.

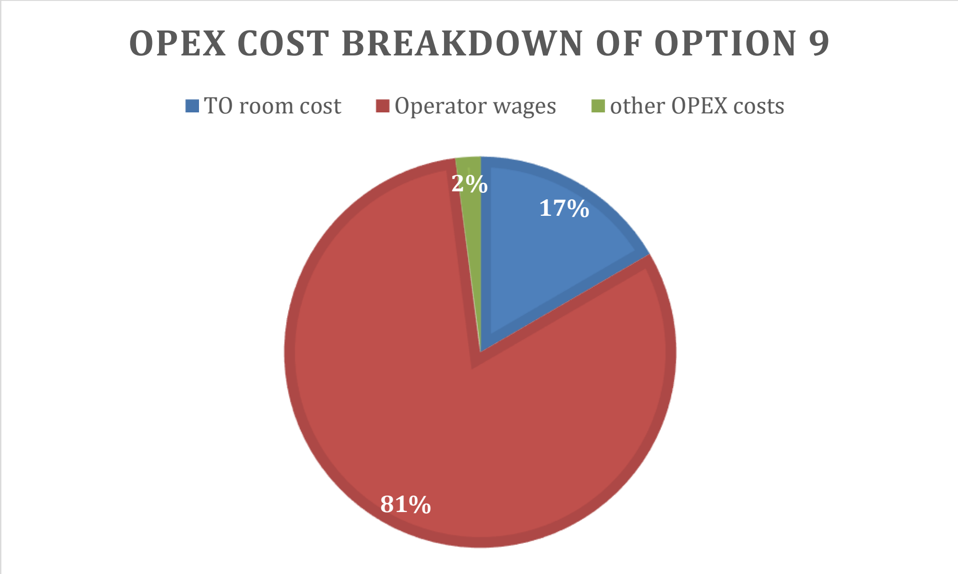


Figure 55 OPEX cost breakdown of option 9

Another important finding is that deploying own TO center is less expensive than renting a pre-equipped TO rooms from other TO service providers; €42 million vs €51 million.

5.2.6 TO-capable barges, cranes, skid steers and trucks cost results:

Similar figures have been found in this analysis to the ones presented in section 5.1.6, except for the average cost per trucks. This latter has decreased significantly due to the higher number of trucks retrofitted to support the TO capabilities and most of them were at the last 5 years of the time life of the analysis which took benefit from the hardware cost decrease due to market competition and maturity of the technology. The TCO of the different type of vehicles to make them TO-capable for the two TO adoption scenarios is presented in the table below.

Table 15 TCO of different vehicle types

Adoption scenario	Barges	Cranes	Trucks	Skid steers
pessimistic	€ 252,000,000	€ 9,534,394	€ 32,400,000	€ 1,281,148
optimistic	€ 315,000,000	€ 11,444,344	€ 32,500,000	€ 1,405,696

5.2.7 Business case evaluation

Using a cost-based pricing as discussed in section 3.5 which is based on the ACPU and adding on top of it a profit margin to arrive to an ARPU, the cumulative revenue was calculated for this deployment scenario with two profit margins namely 15% and 30%. The ACPU was calculated considering the Total number of connected items that used the 5G network and the TO center over 10 years for a monthly and a daily use. In other words, The ACPU per month and per day have been calculated.

5.2.7.1 Pessimistic TO adoption

Considering a pessimistic TO uptake, the total number of connected vehicles (i.e., barges, cranes, trucks and skid steers) over 10 years is 678,480. This number is calculated considering that the target is to arrive to a monthly ARPU.

Th ACPU per connected vehicle per month has been calculated for the different deployment of the 5G networks and the TO center, which is assumed also to have a monthly subscription.

Table 16 Summary of the ACPU for 5G connectivity and the TO service

	TCO	ACPU/month	ACPU per day/connected TO session
5G Network			
5G COD	€ 26,171,422	€ 38.57	€ 1.48
5G NS	€ 26,695,166	€ 39.35	€ 1.51
5G NS regular traffic	€ 26,474,926	€ 39.02	€ 1.50
TO Center			
Own TOC with operator wages gradual deployment	€ 42,400,000	€ 62.49	€ 2.40
Own TOC with operator wages deployment day 1	€ 61,800,000	€ 91.09	€ 3.50
Rent TOC with Operator wages	€ 51,100,000	€ 75.32	€ 2.90
Own TOC without operator wages gradual deployment	€ 1,489,130	€ 2.19	€ 0.08
Own TOC without operator wages deployment day 1	€ 23,400,000	€ 34.49	€ 1.33
Rent TOC without Operator wages	€ 9,506,012	€ 14.01	€ 0.54

Based on the cost-effective deployment options colored with green in the table above and assuming 15% and 30% profit margin, the ARPU per month per connected vehicle has been derived for the two services together namely the 5G connectivity and TO service. Results are summarized in the table below.

Table 17 ARPU for the different options

ACPU monthly with operator wages	ARPU 15% with operator wages	ARPU 30% with operator wages	ACPU monthly cost **without** operator wages	ARPU **without** wages 15%	ARPU **without** wages 30%
€ 101.07	€ 116.23	€ 131.39	€ 40.77	€ 46.88	€ 53.00

By bringing the cumulative revenue and TCO together, the BEP can be assessed as described in section 3.6. and is presented in the figure below while considering operators as part of the TO service. The BEP assessment for excluding operator from the TO service is presented in the Appendix A in Figure 91.

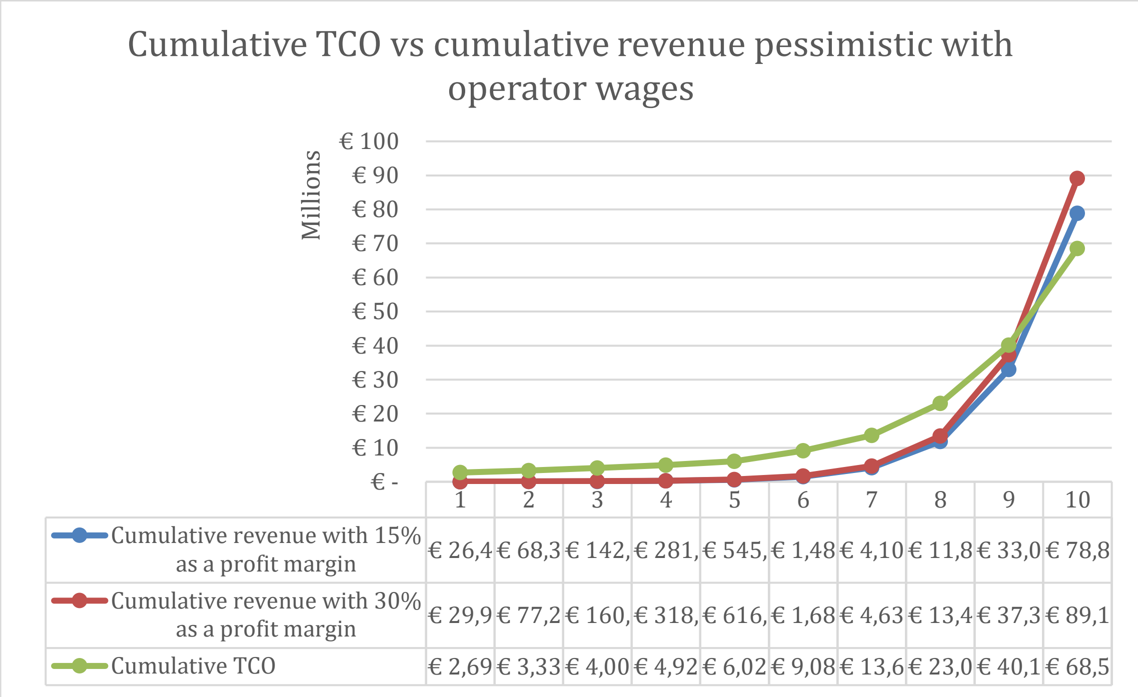


Figure 56 BEP assessment for the pessimistic TO adoption considering operators as part of the TO service

As explained previously the break-even point (BEP) in economics is the point at which total cost and total revenue are equal, i.e., "even". There is no net loss or gain. In short, all costs that must be paid are paid, and there is neither profit nor loss. Starting from that point onwards revenues are higher than costs which mean that the studied business case is profitable. As shown in Figure 56, the BEP is reached around year 9 and from year 9 the revenues are exceeding the cost with means that 5G-based TO service is profitable with adopting the cost-based pricing explained previously.

It is noteworthy to mention that in this calculation only the 5G connectivity and TO services in the port of Antwerp are considered which means analysing the business case from TO service providers using 5G connectivity. The costs/revenues from the different TO-capable vehicles are not included here because they serve in multiple ports/areas and cannot be exclusively allocated to the port under study. In addition, the direct benefit from using TO services for cranes, internal trucks and skid steers such as time saving will be assessed while validating the identified business models in D3.4. However, the cost of making vehicles TO-capable per type of vehicle per trip is provided in this analysis and serves as input to the business model validation exercise and is presented in the table below.

Table 18 The average cost per type of vehicle per trip to make it TO-capable for the pessimisic scenario

Pessimistic scenario	TCO	average cost per vehicle	average cost per trip/served barge	Average cost per ton
Barges	€ 252,000,000	€ 136,323	€ 22	0.67 euro cent
Cranes	€ 9,534,394	€ 74,487	€ 12	0.36 euro cent
Trucks	€ 32,400,000	€ 11,192	€ 2	0.08 euro cent
Skid steers	€ 1,281,148	€ 15,252	€ 3	0.09 euro cent

For barges, we assume lifespan of 40 years and 153 trips a year per barge with 3300 tons as maximum load as assumed in [25]. For cranes, internal terminal trucks, the trucks for long-haul journeys, and skid steers, we assume that they serve on average 2 barges/make 2 trips a day for 300 days a year and for 10 years lifespan.

5.2.7.2 Optimistic TO adoption

Considering an optimistic TO adoption, the total number of connected vehicles (i.e., barges, cranes, trucks and skid steers) over 10 years is 1,066,440. This number is calculated considering that the target is to arrive to a monthly ARPU.

Th ACPU per connected vehicle per month has been calculated for the different deployment of the 5G networks and the TO center, which is assumed also to have a monthly subscription.

Table 19 Summary of the ACPU for 5G connectivity and the TO service

	TCO	ACPU/month	ACPU per day/connected TO session
5G Network			
5G COD	€ 31,574,789	€ 29.61	€ 1.14
5G NS	€ 40,630,449	€ 38.10	€ 1.47
5G NS regular traffic	€ 40,345,116	€ 37.83	€ 1.46
TO Center			
Own TOC with operator wages gradual deployment	€ 60,600,000	€ 56.82	€ 2.19
Own TOC with operator wages deployment day 1	€ 84,700,000	€ 79.42	€ 3.05
Rent TOC with Operator wages	€ 73,000,000	€ 68.45	€ 2.63
Own TOC without operator wages gradual deployment	€ 4,783,596	€ 4.49	€ 0.17
Own TOC without operator wages deployment day 1	€ 28,900,000	€ 27.10	€ 1.04
Rent TOC without Operator wages	€ 17,200,000	€ 16.13	€ 0.62

Based on the cost-effective deployment options colored with green in the table above and assuming 15% and 30% profit margin, the ARPU per month per connected vehicle has been derived for the two services together namely the 5G connectivity and TO service. Results are summarized in the table below.

Table 20 ARPU for the different options

ACPU monthly with operator wages	ARPU 15% with operator wages	ARPU 30% with operator wages	ACPU monthly cost **without** operator wages	ARPU **without** wages 15%	ARPU **without** wages 30%
€ 86.43	€ 99.40	€ 112.36	€ 34.09	€ 39.21	€ 44.32

By bringing the cumulative revenue and TCO together, the BEP can be assessed as described in section 3.6. and is presented in the figure below while considering operators as part of the TO service. The BEP assessment for excluding operator from the TO service is presented in the Appendix A in Figure 92.

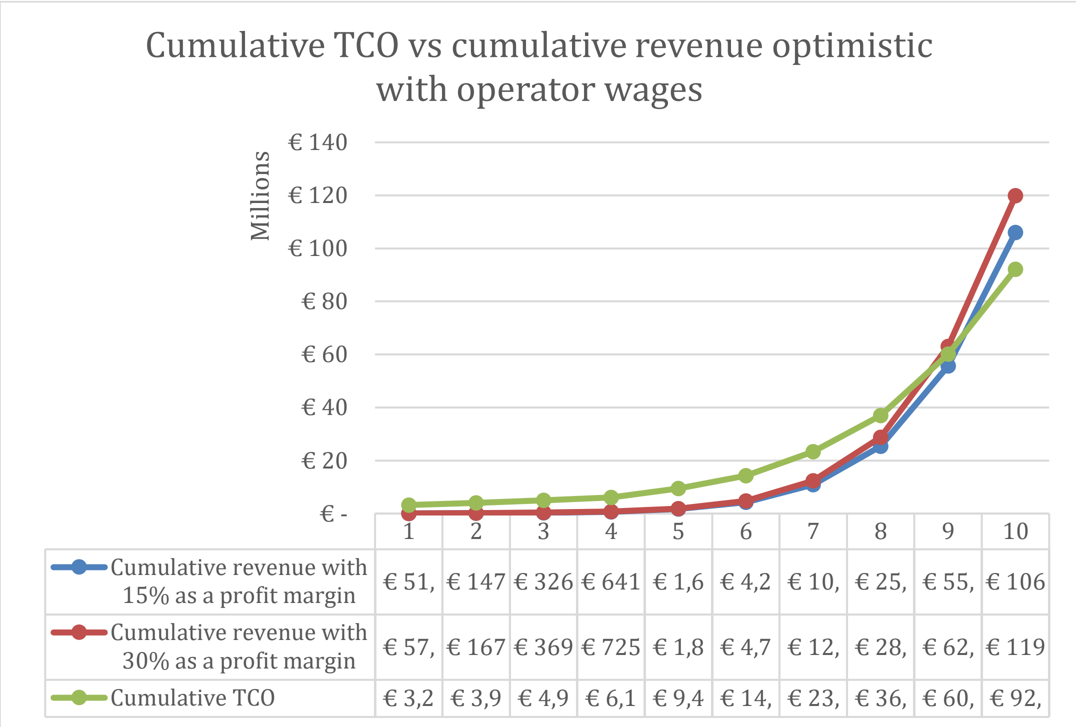


Figure 57 BEP assessment for the optimistic TO adoption considering operators as part of the TO service

As shown in Figure 57, the BEP is reached around year 9 for the revenues considering 30% as profit margin and around year 10 for the 15% profit margin. From year 9 and year 10 for 30% and 15% respectively, the revenues are exceeding the cost with means that 5G-based TO service is profitable with adopting the cost-based pricing explained previously.

As explained before, this calculation considers only the 5G connectivity and TO services in the port of Antwerp which means analysing the business case from TO service providers using 5G connectivity. The costs/revenues from the different TO-capable vehicles are not included here because they serve in multiple ports/areas and cannot be exclusively allocated to the port under study. In addition, the direct benefit from using TO services for cranes, internal trucks and skid steers such as time saving will be assessed while validating the identified business models in D3.4. However, the cost of making vehicles TO-capable per type of vehicle per trip is provided in this analysis and serves as input to the business model validation exercise and is presented in the table below.

Table 21 The average cost per type of vehicle per trip to make it TO-capable for the optimistic scenario

Pessimistic scenario	TCO	average cost per vehicle	average cost per trip/served barge	Average cost per ton
Barges	€ 315,000,000	€ 145,098	€ 24	0.72 euro cent
Cranes	€ 11,444,344	€ 75,292	€ 13	0.39 euro cent
Trucks	€ 32,500,000	€ 10,065	€ 2	0.08 euro cent
Skid steers	€ 1,405,696	€ 15,279	€ 3	0.09 euro cent

As explained in the previous adoption scenario, for barges, we assume lifespan of 40 years and 153 trips a year per barge with a maximum load of 3300 tons as assumed in [25]. For cranes, internal terminal trucks, and skid steers, we assume that they serve on average 2 barges a day for 300 days a year and for 10 years lifespan.

5.2.7.3 Pessimistic Vs Optimistic TO adoption: cost comparison

If we compare the two TO adoption scenarios, we observe that the ACPU in the optimistic scenario is less than the pessimistic scenario up to 15% less, this is due to the higher number of connected items that are sharing the total cost of the deployment. Which makes the cost-based pricing with a low profit margin like 15% have a late break-even in the optimistic scenario (around year 10) compared to the pessimistic one (around year 10). However, for equipping the different vehicle type with TO capabilities, the average cost per type of vehicle in the pessimistic scenario is less than the one in the optimistic scenario for all type of vehicle except cranes. This can be explained by the low adoption in the first five years and the late mass purchase of TO hardware in the pessimistic scenario when we have a good cost reduction on the hardware due to the market competition and technology maturity.

5.2.8 Sensitivity analysis

In the previous sensitivity analysis of the deployment scenario 1, the impact of adopting different RAN hardware type supporting different number of beams on the TCO of the 5G network was investigated. In addition, the impact of changing the network deployment strategy together with supporting only skid steers in the terminals were analyzed. In this deployment scenario, UC4.3 Cooperative Adaptive Cruise Control (CACC) based platooning is analyzed together with the other use cases that were analyzed in the previous deployment scenario 1. Therefore, and since we assumed 4 trucks per platoon in the analysis presented so far in this section, in the sensitivity analysis we will study the impact of varying the number of trucks per platoon on the TCO of the 5G networks and on the TCO of the own TO center deployment.

Starting with the impact on the 5G network deployment cost. We run the cost model for 5G coverage on demand option for the optimistic scenario to cover the two terminals while varying the number of trucks per platoon from 2 to 10. Result of the TCO is presented in the figure below.

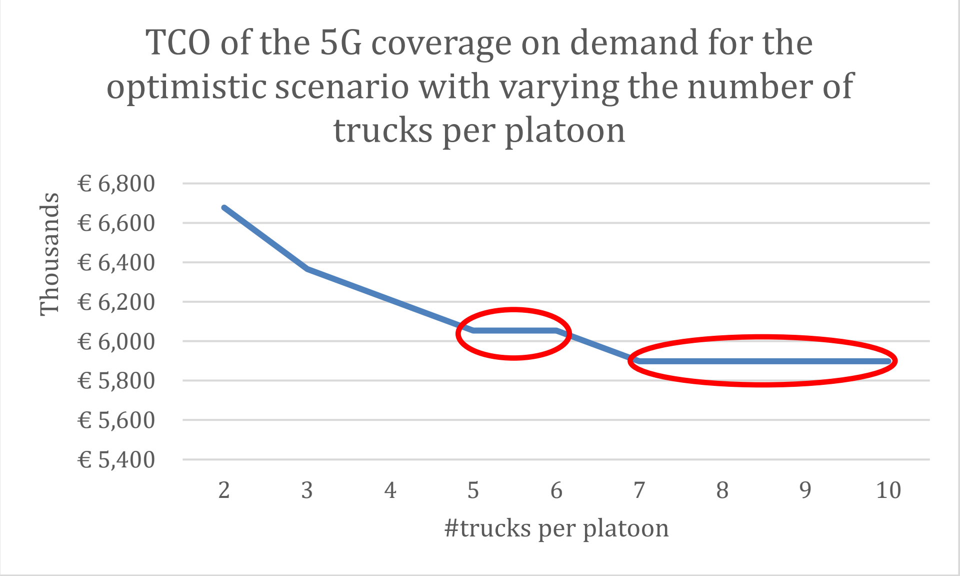


Figure 58 TCO of the 5G coverage on demand for the optimistic scenario with varying the number of trucks per platoon

Figure 58 shows the decrease of the TCO with the increase of number of trucks per platoon which is explained by the fact that if we have more trucks per platoon, we will have a smaller number of platoons in total which means less TO sessions to support by the network. Yet, we see that for 5 and 6 trucks per platoon we ended up with the same TCO which means that the required 5G network infrastructure needed to support 6 trucks per platoon is the same as 5 per platoon, same observation is seen for 7 to 10 trucks per platoon. This means that the 5G network infrastructure installed to fulfill the capacity requirement of 10 trucks per platoon can serves up to 7 trucks per platoon but going from 7 to 6 needs installing more small cells to support the increase in the total number of platoons. It is worthy to note that the number of trucks per platoon is also limited by the maximum allowed time to be reserved by the intelligent traffic light controller for the platoon and by the maximum speed of the trucks.

Same variation of the number of trucks per platoon was made in order to study the impact on the TCO of deploying the TO center. Unlike the 5G network cost, increasing the number of trucks per platoon results always in decreasing the TCO of the TO center due to the decrease of number of operators needed to serve the total number of platoons. This observation is depicted

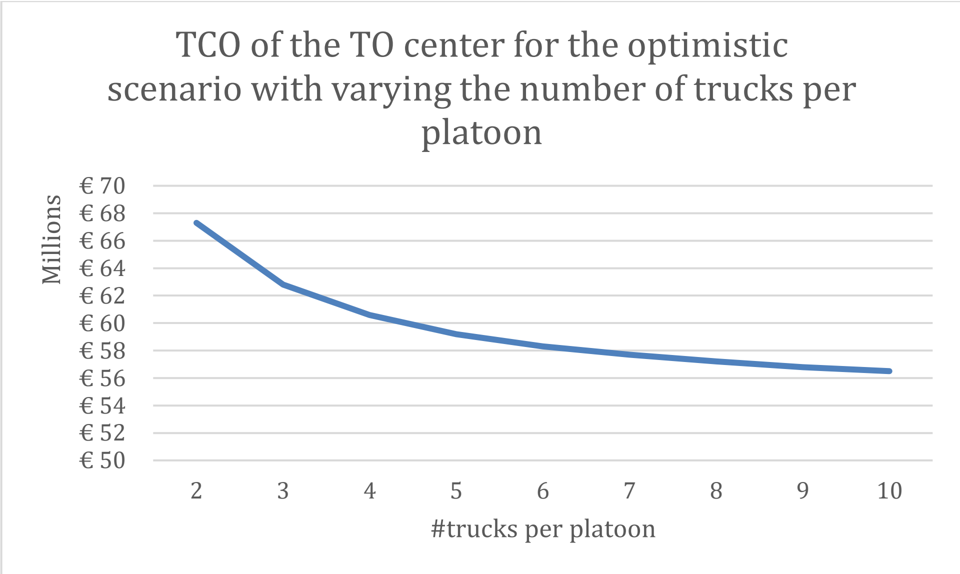


Figure 59 TCO of the TO center for the optimistic scenario with varying the number of trucks per platoon

5.2.9 Main takeaways

Techno-economic analysis of the deployment scenario 2, which focuses on providing the 5G-based TO services in port area, terminals, and short public roads, showed that:

- For 5G network deployment:
  - The 5G coverage on demand is the cost-effective deployment option under the mentioned assumptions and circumstances.
  - The network slicing with providing a separate slice for each service is the costliest option, this is due to several reasons among which we list the low demand of the non-TO slices on the UL capacity makes the TO slice bear the significant part of the deployment cots.
  - If we compare the average TCO per terminal over 10 years deployment to the cost of the early deployment in the two terminals DPW and MPET, we see a cost reduction in the TCO of up to 50% depending on the TO adoption scenario. This gives recommendation for both connectivity providers and TO service providers in the port terminals about the good moment of adopting the 5G-based TO technology.
  - OPEX is the dominant cost element which represents 63% of the TCO.
  - Sensitivity analysis show the decrease of the TCO with the increase of number of trucks per platoon which is explained by the fact that if we have more trucks per platoon so a smaller number of TO session for the total number of platoons.
- For TO center deployment:
  - deploying the TOC with a gradual addition of the control setups following the TO uptake is more cost-effective than buying all the control setups at the start of the deployment with a 10% cost reduction. The cost saving is around 31%.
  - The cost of deploying TO center assuming an optimistic adoption is more expensive than the deployment in a pessimistic uptake scenario.
  - The main cost component of the TCO is OPEX, which represents 91% of the total cost.
  - A cost breakdown of OPEX shows that operator wage is the dominant cost element which represents 98% of the total OPEX and the rest 2% are distributed among office

space renting, Internet subscription and energy cost.
  - Deploying own TO center is less expensive than renting a pre-equipped TO rooms from other TO service providers; cost reduction of up to 25%.
- From the business case evaluation:
  - The ACPU in the optimistic scenario is less than the one in the pessimistic scenario, due to the higher number of the different types of connected vehicles, being € 86 vs € 101.
  - For the pessimistic TO adoption, the BEP is reached around year 9 for the two profit margin assumptions being 15% and 30%. Yet, the CEP is around 9 and 10 years for the optimistic scenario for the 30% and 15% respectively.

5.3 Deployment scenario 3: major national transport axis – significant transport flows via water

5.3.1 Definition of the deployment scenario

This deployment scenario is based on the combination of multiple technological options related to where and how to provide TO services. Starting with the "where" question in this deployment scenario TO services are to be provided in the waterway entrance of the port of Antwerp (PoA) for UC4.1a.1: Automated Barge Control: Navigating a river and a canal in a national waterway, using two different connectivity options being 1) 5G coverage on demand and 2) 5G network slicing. For this specific location, two variants of the deployment scenarios exist being SC3.1 only the use case in the waterway entrance of the port is supported which is UC4.1a.1: Automated Barge Control: Navigating a river and a canal in a national waterway and SC3.2 in addition to UC4.1a, we cover the two terminals close to the waterway entrance of the port being Noordzee and Europa terminal. Therefore, the supported use cases would be UC4.1a, UC4.1b: Automated Barge Control: Navigating, Docking and Unloading in a (bussy) port; UC4.2b: Teleoperated Mobile Harbour Crane; and UC4.4: Remote Take Over Operation together with EF4: Distributed perception and EF5: Active collision avoidance. The TO adoption of barges and cranes are detailed previously in section 0.

5.3.2 Dimension of the 5G network

5.3.2.1 Area to cover

For UC1a we consider the navigation of the TO barges in the entrance of the port of Antwerp with a length of 4 km, the Schelde river on the Belgian side. The required network infrastructure to cover the port entrance is presented in Figure 39. Based on the existing network (presented in Figure 88) two additional macro cells are needed to provide the full coverage of the river segment under study.

5.3.2.2 Network Capacity requirement

Based on the required UL capacity for the different use cases and different slice types presented in Table 3, the total required capacity on the UL for the two types of 5G connectivity options (i.e., 5G coverage on demand and 5G network slicing) has been calculated considering the following assumptions besides the ones presented previously in the two other scenarios:

- Daily served trucks around 5600 (based on the two terminals websites) for DPW and MPET, but assuming similar number, 5000 trucks for the two terminals namely the Noordzee and Europa terminals.
- Average barge speed: 13 km/h (taken from the port website)
- Duration of one barge to traverse the waterway entrance = (The length of port entrance/ Average barge speed)

To calculate the maximum number of barges traversing the waterway entrance, we use the following formula:

Equation 30 $$N_{barges\_SUM} = {N_{barges_{daily}}}/{N_{Working\_hours}} \times Duration_{barge\_entrance}$$

SC 3.1: UC4.1a.1: Automated Barge Control: Navigating a river and a canal in a national waterway:

For **5G coverage on demand** and using the network dimensioning process (explained in section 3.3.1.1) results in a total capacity of 240 Mbps on the UL for UC4.1a. Given the network deployment strategy adopted earlier and explained in section 3.3.1.1, where macro cells are deployed to provide coverage while small cells are to be added to enhance capacity, the network infrastructure needed is 2 macro cells.

For the deploying **5G network slicing** connectivity option, we need to know the required capacity for the other slices to be offered in the studied area. To this end, the non-TO UL capacity needs to be estimated to deploy the network to support both type of services, the TO and the non-TO ones. Based on the two methods of the non-TO capacity calculation explained in 3.3.1.1, the total required capacity has been calculated:

5. Assuming that all the non-TO services are also supported by network slices, the total required capacity is calculated using the following assumptions:
   - Two other types of slices are to be provided in the two terminals, being the eMBB slice serving the normal customers as truck drivers and employees in the two terminals and IoT slice for sensors for example used in the automation of certain processes in the terminal, like the container ID identification etc…
   - 4 IoT slices, one per terminal and another 2 slices for the two factories in the vicinity
   - To calculate the required total capacity, additional input data are needed:
     - Total number of employees of the two terminals and the two factories in the vicinity~=500
     - Active users for eMBB slice percentage =10%.

Therefore, the total Capacity required on the UL is the sum of the total Capacity UL of the TO slice and the total Capacity UL of the eMBB slice and the total capacity UL of the 4 IoT slices. This results in a total UL capacity of 497 Mbps. Hence, we only need to install 2 macro cells.

6. Assuming that the non-TO services are supported as a regular traffic without dedicated slices for each type of service, the total non-TO capacity is calculated using the data below:
   - Data traffic has been retrieved from the field in GB (Gigabyte);
   - Assuming 8 hours as time window in which users are active, the downlink speed has been calculated.
   - Assuming that the UL speed is 5% of the DL speed, the UL capacity is derived,
   - Assuming a 30% regular traffic growth, the requested UL capacity of the regular traffic for the next 2-4 years has been calculated.

Therefore, the total Capacity required on the UL is the sum of the total Capacity UL of the TO slice and the total Capacity UL of the regular traffic. This results in a total UL capacity of 332 Mbps. Hence, an additional 2 macro cells are required for ensuring the coverage and also to meet the required UL capacity.

SC 3.2: UC4.1a.1 and UC4.1b, UC4.2b and UC4.4 in the two terminals

For **5G coverage on demand** and using the network dimensioning process (explained in section 3.3.1.1) results in a total capacity of 1586 Mbps. Given the network deployment strategy adopted earlier and explained in section 3.3.1.1, where macro cells are deployed to provide coverage while small cells are to be added to enhance capacity, the network infrastructure needed is 2 macro cells.

For the deploying **5G network slicing** connectivity option, we need to know the required capacity for the other slices to be offered in the studied area. To this end, the non-TO UL capacity needs to be estimated to deploy the network to support both type of services, the TO and the non-TO ones. Based on the two methods of the non-TO capacity calculation explained in 3.3.1.1, the total required capacity has been calculated:

7. Assuming that all the non-TO services are also supported by network slices, the total required capacity is calculated using the following assumptions:
    - Two other types of slices are to be provided in the two terminals, being the eMBB slice serving the normal customers as truck drivers and employees in the two terminals and IoT slice for sensors for example used in the automation of certain processes in the terminal, like the container ID identification etc…
    - 4 IoT slices, one per terminal and another 2 slices for the two factories in the vicinity
    - To calculate the required total capacity, additional input data are needed:
        - Total number of employees of the two terminals and the two factories in the vicinity~=500
        - Active users for eMBB slice percentage =10%.

Therefore, the total Capacity required on the UL is the sum of the total Capacity UL of the TO slice and the total Capacity UL of the eMBB slice and the total capacity UL of the 4 IoT slices. This results in a total UL capacity of 2048 Mbps in which 462 Mbps for the non-TO slices. Hence, we only need to install 2 macro cells and 6 small cells.

8. Assuming that the non-TO services are supported as a regular traffic without dedicated slices for each type of service, the total non-TO capacity is calculated using the data below:
    - Data traffic has been retrieved from the field in GB (Gigabyte);
    - Assuming 8 hours as time window in which users are active, the downlink speed has been calculated.
    - Assuming that the UL speed is 5% of the DL speed, the UL capacity is derived,
    - Assuming a 30% regular traffic growth, the requested UL capacity of the regular traffic for the next 2-4 years has been calculated.

Therefore, the total Capacity required on the UL is the sum of the total Capacity UL of the TO slice and the total Capacity UL of the regular traffic. This results in a total UL capacity of 1677 Mbps in which 91 Mbps for the regular traffic. Hence, an additional 2 macro cells are required for ensuring the coverage and 1 small cell to meet the required UL capacity.

5.3.3 Cost model results of 5G network deployment

Using the cost data validated by all partners in a data validation round, the cost model has been run for the two types of connectivity options being 5G coverage on demand and 5G network slicing with its two methods of estimating the non-TO capacity and are presented in the following sections.

5.3.3.1 Cost comparison between the three 5G connectivity deployment options for SC3.1

Bringing the cost results of the three 5G connectivity deployment options together to assess which option is the most cost effective one. In the comparison we only compare the cost share for the TO slice/service from the three cases.

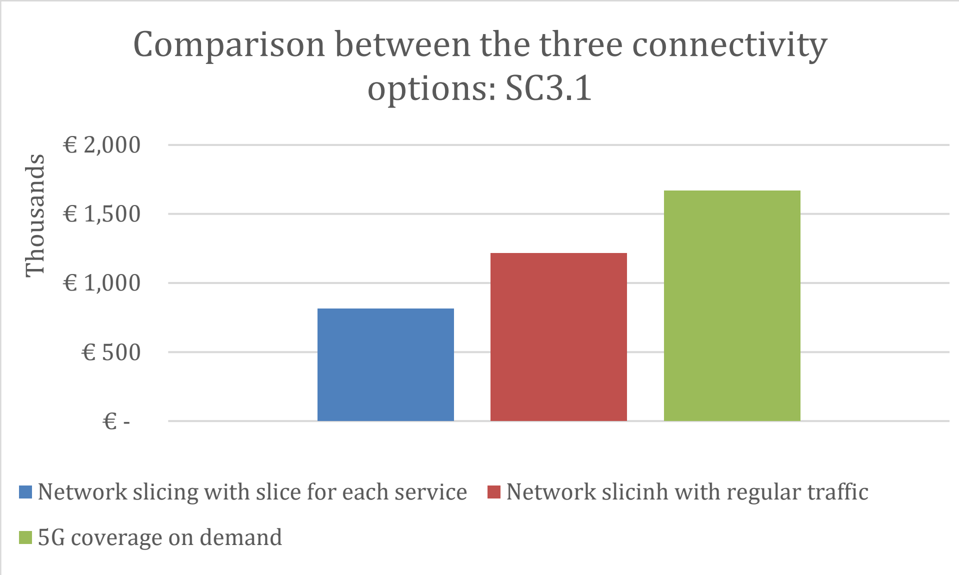


Figure 60 TCO comparison between the three 5G connectivity options

From the cost comparison illustrated in Figure 60, we can deduct that the network slicing with providing a separate slice for each service is the cost-effective option, this is due to low UL capacity needed to support UC4.1a which is navigating a TO barge in the river. The cost of deployment is shared among the different services provided in the vicinity of the river. Yet, the coverage on demand option is the costliest option.

The cost sharing for the 5G network slicing is illustrated in the figure below.

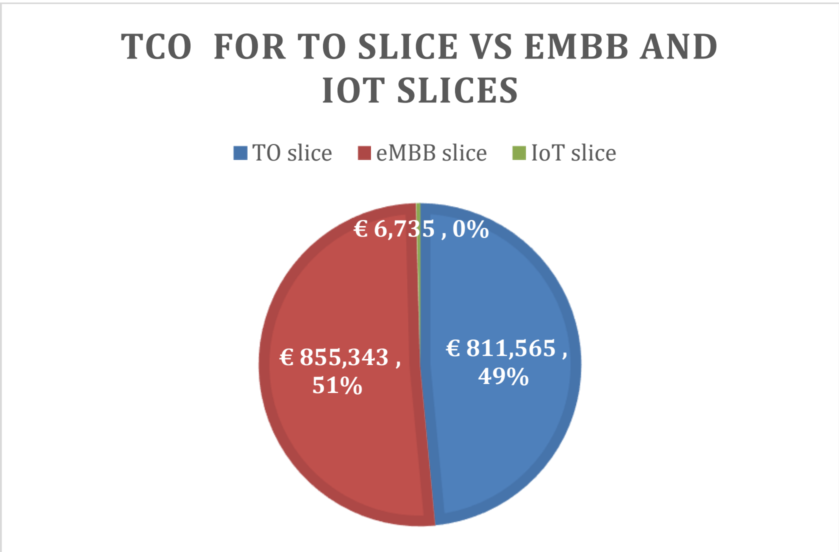


Figure 61 TCO of the TO slice vs eMBB and IoT slices

As we can see in Figure 61, the TO slice bears only 49% of the total deployment cost. The cumulative TCO per square kilometre is € 156,070, € 233,635 and, € 320,727 for the 5G network slicing with providing a separate slice for each service, 5G network slicing with regular traffic, and 5G coverage on demand respectively.

As a conclusion of the cost comparison, the 5G network slicing with slice for each service is the cost-effective deployment option under the mentioned assumptions and circumstances.

5.3.3.2 Cost comparison between the three 5G connectivity deployment options for SC3.2

Bringing the cost results of the three 5G connectivity deployment options together to assess which option is the most cost effective one. In the comparison we only compare the cost share for the

TO slice/service from the three cases.

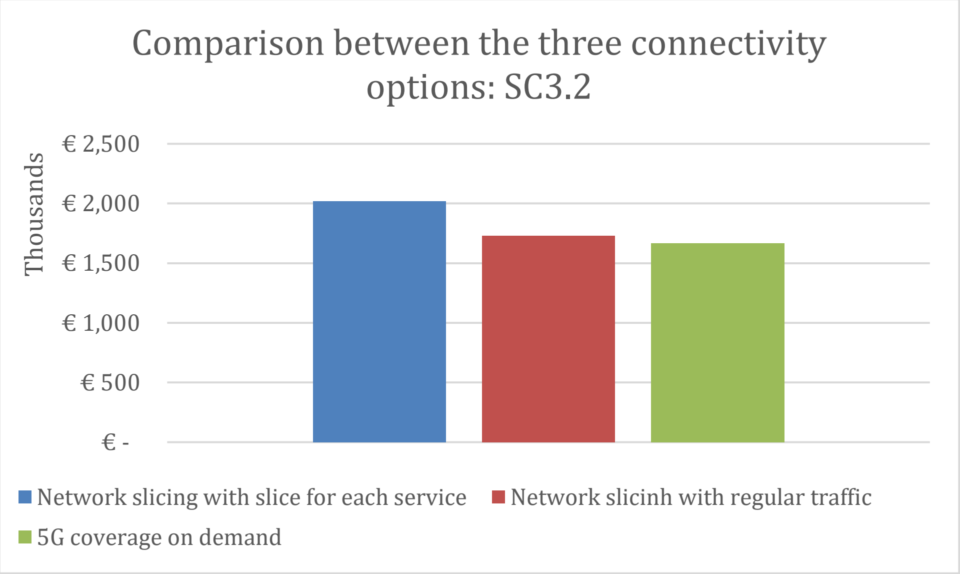


Figure 62 TCO comparison between the three 5G connectivity options

From the cost comparison illustrated in Figure 62, we can deduct that the network slicing with providing a separate slice for each service is the costliest option, this is due to many reasons as explained in section 5.1.4.4. The cost difference in the pessimistic scenario is marginal between the three connectivity options. Yet it becomes very pronounced in the optimistic scenario, this is due to the higher number of connected vehicles which makes the total required capacity higher and hence more small cells to be installed to meet this capacity requirement.

In section 5.1.8 we studied how cost effective is adapting the network deployment strategy in term of replacing small cells by macro cell. And results showed that changing the network strategy by adding one additional macro cell to substitute few small cells (up to 5) will introduce more deployment cost. Yet, seems more cost efficient to substitute 8 small cells by one macro cell for the 5G network slicing connectivity option which results in 16-18% cost reduction of the TCO. This cost reduction makes the 5G network slicing option more

The cost sharing for the 5G network slicing is illustrated in the figure below.

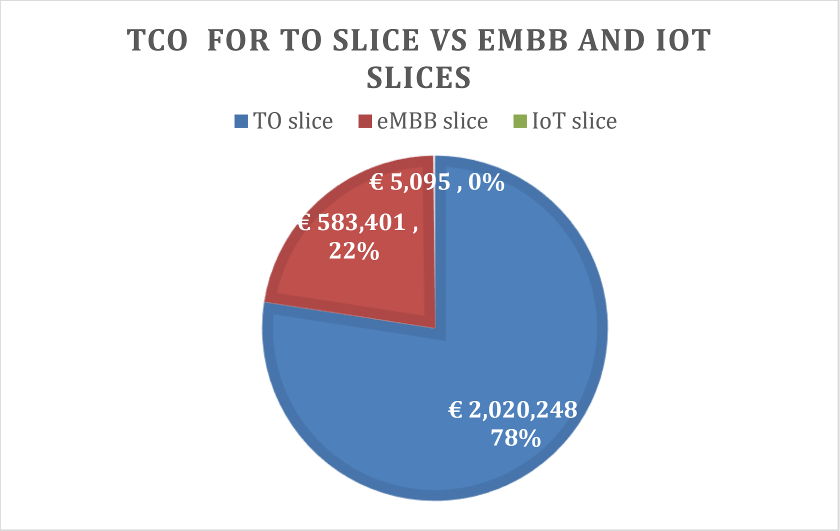


Figure 63 TCO of the TO slice vs eMBB and IoT slices

As we can see in Figure 61, the TO slice bears 78% of the total deployment cost. The cumulative TCO per square kilometre is € 388,509, € 332,734 and , € 320,727 for the 5G network slicing with providing a separate slice for each service, 5G network slicing with regular traffic, and 5G coverage on demand respectively.

As a conclusion of the cost comparison, the 5G coverage on demand is the cost-effective deployment option under the mentioned assumptions and circumstances.

5.3.1 TO center deployment and TO-capable vehicles

In this deployment scenario we studied a segment of the river: the entrance of the PoA, therefore the focus is on the 5G network deployment and the cost of the TO center and cost of making the different vehicles TO-capable are studied under the previous deployment scenario in section 5.2.5, where this specific location within the port was also included in the analysis.

5.3.2 Main takeaways

Techno-economic analysis of the deployment scenario 3, which focuses on providing the 5G-based TO services in major transport axis – significant transport flows via water, showed that:

- For providing only the navigation of TO barges in the river, the 5G network slicing with slice for each service is the cost-effective deployment option.
- Yet for providing more use cases and covering the two terminals next to the entrance, the 5G coverage on demand is the cost cost-effective deployment option.
- When only UC4.1a is supported, the cumulative TCO per square kilometer is € 156,070, € 233,635 and, € 320,727 for the 5G network slicing with providing a separate slice for each service, 5G network slicing with regular traffic, and 5G coverage on demand respectively.
- Whereas, when a set of use cases are provided, namely UC4.1a.1 and UC4.1b, UC4.2b, and UC4.4, The cumulative TCO per square kilometer is € 388,509, € 332,734, and € 320,727 for the 5G network slicing with providing a separate slice for each service, 5G network slicing with regular traffic, and 5G coverage on demand respectively. Which is up to 51% more expensive than providing UC4.1a alone.

5.4 Deployment scenarios 4: major national transport axis – significant transport flows via road

5.4.1Definition of the deployment scenario

In the previous deployment scenarios, the focus was on the PoA for the different set of use cases, yet, in the deployment scenario, the TO services will be provided in a national transport axis which is the road next to the port of Vlissingen. This is in alignment with the trials in the port of Vlissingen. Where TO trucks will go from the Verbrugge terminal to MSP onions warehouses. The supported use cases are use cases UC4.2: Automated driver-in-loop docking, UC4.3: CACC-based platooning, and UC4.4: Remote takeover terminal together with EF4: Distributed perception and EF5: Active collision avoidance. It stretches over the three locations: i) MSP Onions terminal (docking area with the parking lot), ii) Verbrugge Scaldia Terminal (harbor terminal and public road) for real teleoperation on the close roads, and iii) the stretch of road from MSP Onions terminal to the Kloosterboer.

In this deployment scenario we need to estimate the TO adoption for trucks that are served port of Vlissingen that can use the segment road under study.

5.4.2Forecasting of TO adoption in the port for trucks

For Use case 4.2a and UC4.3 and UC4.4, we need to derive the number of TO capable trucks in the studied area. Based on input from North Sea port, the number of trucks inside and close to the port are around 3900 trucks a day. Like previously presented TO adoption, here also we follow the two adoption scenarios namely the pessimistic and the optimistic scenarios. We assumed an annual growth of 3% in the truck fleet served by the port and using the bass diffusion model, the TO adoption in the daily trucks served is presented in the following figures:

1. ***Pessimistic/realistic TO adoption scenario***

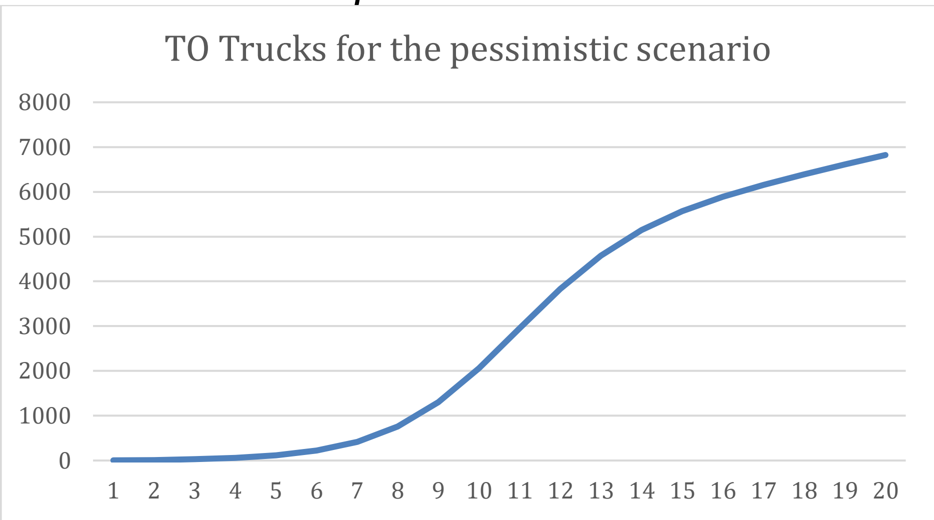


Figure 64 Evolution of expected number of TO-capable trucks for the pessimistic scenario over the years

2. ***Optimistic TO adoption scenario***

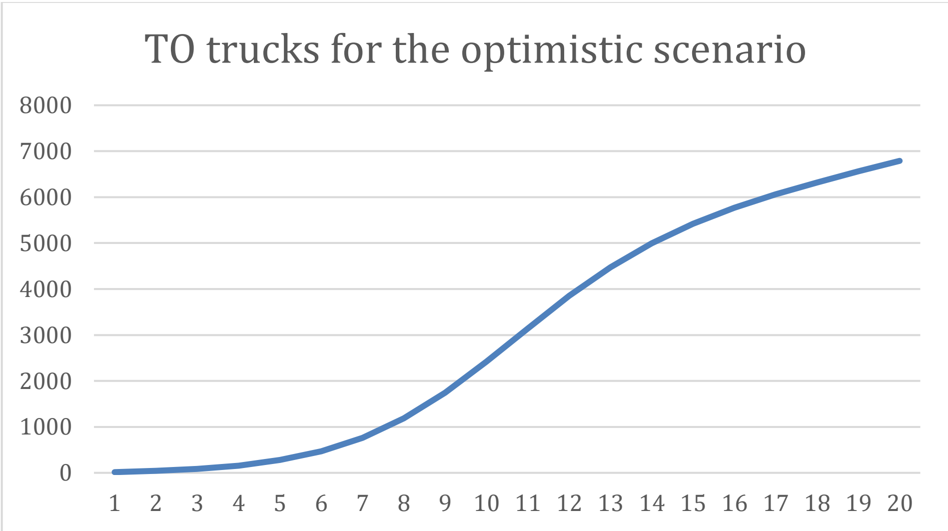


Figure 65 Evolution of expected number of TO-capable trucks for the optimistic over the years

Based on discussions with partners from the port and logistic companies, the daily served trucks can be divided into 35% doing short-haul journeys, which means going to warehouses inside the port area and 65% of them are doing long-haul journeys and exit the port region. For the long-haul trucks, we assume that 25% of them will be served by remote driving (UC4.4) and 75% by TO platooning (UC4.3) with 4 trucks per platoon.

5.4.3 Dimension of the 5G network

5.4.3.1 Area to cover

Similar to the previous deployment scenario, we need to deploy 5G Networks in port of Vlissingen and close to the studied roads to support the selected UCs. With an inter-site distance of around 2 km and considering the existing network infrastructure presented in Figure 93. Since to go from Verbrugge terminal to MSP onions there are two ways, via N254 road or via Europaweg Noord and wince the two roads are close to each other, the same network infrastructure is deployed to cover both roads.

The required network infrastructure to cover the two road segments connecting Verbrugge terminal to MSP onions of a 6.5 km length is presented in Figure 66. Based on the existing network (presented in Figure 93) two additional macro cells are needed to provide the full coverage of the road segments under study.

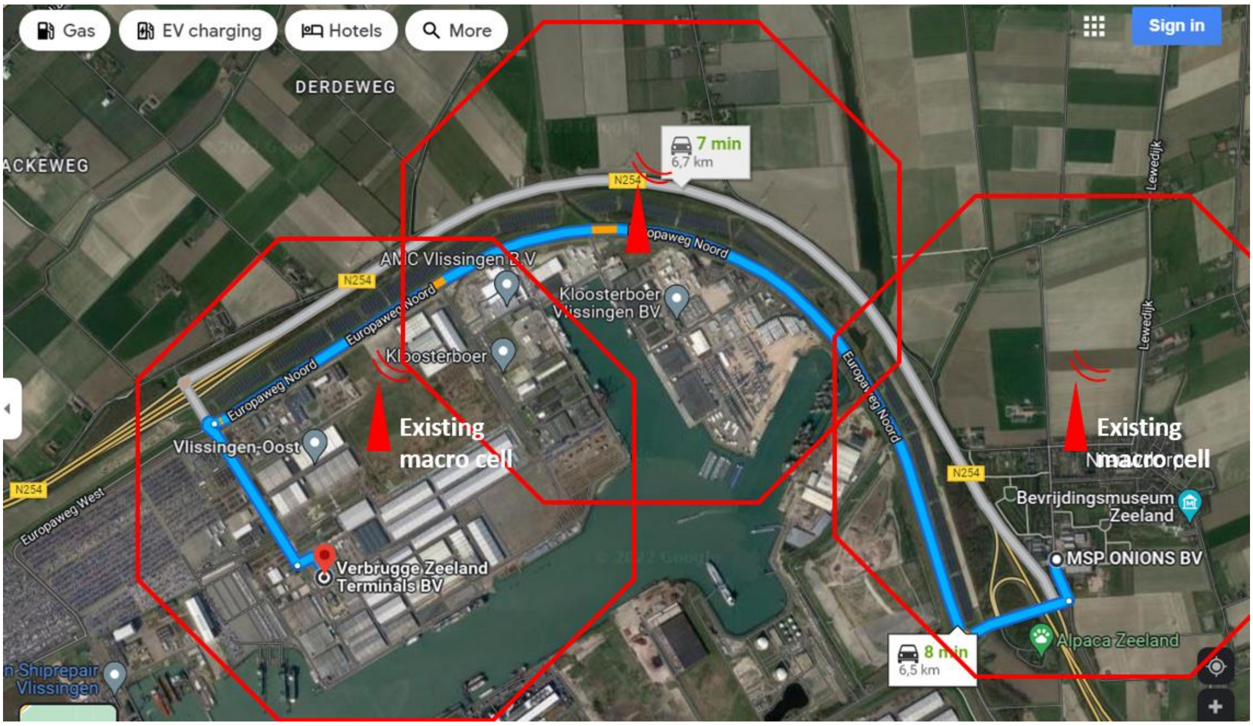


Figure 66 5G network deployment to cover two roads connecting Verbrugge terminal to MSP onions

5.4.3.2 Network Capacity requirement

Based on the required UL capacity for the different use cases and different slice types presented in Table 3, the total required capacity on the UL for the two types of 5G connectivity options (i.e., 5G coverage on demand and 5G network slicing) has been calculated considering the following assumptions and input:

- 2 existing macro-cell (as showed in Figure 16) and 50% of their UL capacities are used by other applications, so 50% is free and to be used for TO use cases;
- Each macrocell is a tri-sector and each cell has 16 beams following the RAN hardware installed in and around the port, but in reality, on the UL only 8 streams simultaneously can be offered, this is to be validated during the final measurement campaigns;
- The length of the two roads is 6.5 km.
- The distance between the two roads is 300m.
- The macro cell inter-site distance is 2 km.
- Truck speed is 70 km/hour[1]
- Analysis has shown that the traffic concentration begins to rise at 11:00 a.m. and declines at 5:30 pm. Consequently, most of the truck traffic enters the port area in that

[1] It is worth noting that the speed of TO trucks in the tests was lower than the average speed of 70 km/h. However, it is reasonable to assume that once the technology matures and appropriate legal frameworks are established, the speed of TO trucks will also be able to reach this average.

span of six and a half hours. Therefore, it will be estimated that 80 percent of the combined traffic enters the port and exits during those 6.5 hours.

- There are 4 exit points from the terminal, two of them lead to the two roads under study.

Considering the maximum number of TO adopted trucks that can use the two road segments and considering a homogenous distribution over time and space of the connected trucks, for the pessimistic TO adoption scenario, we need to serve simultaneously 10 trucks which means 1 truck platoon (U4.3) and 3 remote driving (UC4.2 and UC4.4). Yet, for the optimistic TO adoption scenario, we need to support with the network 13 trucks which means 2 truck platoons are served at the same time and 5 remote driving (UC4.2 and UC4.4).

For validating these calculations regarding the number of trucks to be served in the road by one macro cell: base station, we used the formula from the 5G meta-study [8] as follows:

$$\frac{(Peak\ hourly\ traffic\ \#/h)}{Velocity\ (\frac{km}{h})} * ISD\ (km) = road\ traffic\ per\ base\ station\ (\#\ of\ vehicles)$$

Using the above formula and given, that 80% of the daily served trucks (namely 3120) are served in the peak hours (6.5 hours) which results in 520 trucks/h and given that we have 4 exit points which two of them leads to the roads under study, this results in 260 trucks/h in the two segments in the peak hours. Using the formula with assuming 70 km/h as the truck speed, it results in 7 trucks per macro cell/BS, which in total is 21 trucks for the three macro cells in place. Using the pessimistic and optimistic TO adoption, results in around 10 and 13 connected trucks respectively.

For **5G coverage on demand** and using the network dimensioning process (explained in section 3.3.1.1) results in a total capacity of 314 Mbps on the UL. While for the optimistic scenario, the total capacity on the UL is of 548 Mbps. Given the network deployment strategy adopted earlier and explained in section 3.3.1.1, where macro cells are deployed to provide coverage while small cells are to be added to enhance capacity, the network infrastructure needed is one new macro cell and 0 small cells for both the pessimistic and optimistic scenario.

For the deploying **5G network slicing** connectivity option, we need to know the required capacity for the other slices to be offered in these two port terminals. To this end, the non-TO UL capacity needs to be estimated to deploy the network to support both type of services, the TO and the non-TO ones. Based on the two methods of the non-TO capacity calculation explained in 3.3.1.1, the total required capacity has been calculated:

9. Assuming that all the non-TO services are also supported by network slices, the total required capacity is calculated using the following assumptions:
   - Two other types of slices are to be provided in the terminals in the vicinity, being the eMBB slice serving the normal customers as truck drivers and employees in the terminals and IoT slice for sensors for example used in the automation of certain processes in the terminal, like the container ID identification etc…
   - 2 IoT slices,
   - To calculate the required total capacity, additional input data are needed:
     - Total number of employees of the terminals ~=350;
     - Active users for eMBB slice percentage =10%.

Therefore, the total Capacity required on the UL is the sum of the total Capacity UL of the TO slice and the total Capacity UL of the eMBB slice and the total capacity UL of the two IoT slices. This results in a total UL capacity of 572 Mbps and 806 Mbps for the pessimistic and optimistic scenario respectively. Hence, an additional macrocell is required for ensuring the coverage of the two road segments and 0 and 3 small cells Mbps for the pessimistic and optimistic scenario respectively are to be deployed to meet the required UL capacity.

10. Assuming that the non-TO services are supported as a regular traffic without dedicated slices for each type of service, the total non-TO capacity is calculated using the data below:
    - Data traffic has been retrieved from the field in GB (Gigabyte);
    - Assuming 8 hours as time window in which users are active, the downlink speed has been calculated;
    - Assuming that the UL speed is 5% of the DL speed, the UL capacity is derived,
    - Assuming a 30% regular traffic growth, the requested UL capacity of the regular traffic for the next 2-4 years has been calculated.

Therefore, the total Capacity required on the UL is the sum of the total Capacity UL of the TO slice and the total Capacity UL of the regular traffic. This results in a total UL capacity of 405 Mbps and 639 Mbps for the pessimistic and optimistic scenario respectively. Hence, an additional macrocell is required for ensuring the coverage of the two terminals and 0 small cells for the pessimistic and optimistic scenario.

5.4.4 Cost model results of 5G network deployment

Using the cost data validated by all partners in a data validation round, the cost model has been run for the two types of connectivity options being 5G coverage on demand and 5G network slicing with its two methods of estimating the non-TO capacity and are presented in the following sections.

5.4.4.1 Deployment scenario 4.1: 5G Coverage on demand

To cover the two road segments under study with 5G network to support the TO use cases previously described, the cumulative TCO over 10 years period is € 756,672 which results in a cumulative TCO per kilometre of € 116,411. The different cost components of the 5G network deployment are depicted in the figure below.

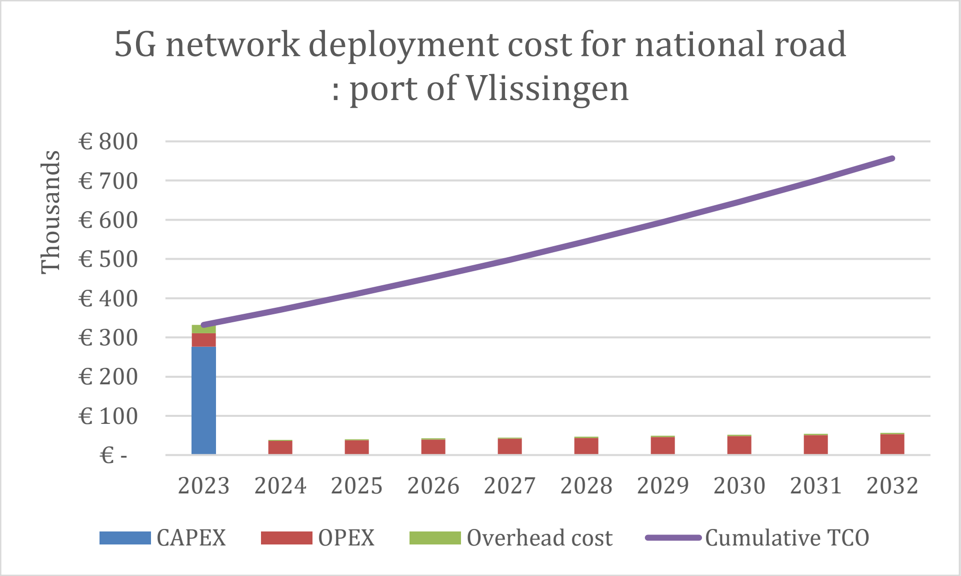


Figure 67 Different cost components and Cumulative TCO over 10 years of the 5G network for 5G coverage on demand.

To understand what the dominant cost of the TCO is, we visualize a cost breakdown of the TCO. Result shows that OPEX is the dominant cost element which represents 57% of the TCO. The main cost components of the OPEX are the site rental (32 €k per year) to host the macro cells and small cells, the energy cost (14 €k per year) and the hardware maintenance.

5.4.4.2 Deployment scenario 4.2.1: 5G network slicing using one slice for each type of service:

As presented above, the UL capacity requirement in this connectivity option is 572 Mbps and 806 Mbps for the pessimistic and optimistic scenario respectively in which 258 Mbps is required by the non-TO slices.

To cover the two road segments under study with 5G network to support the TO use cases previously described using 5G network slicing and assuming that the non-TO services are also to be provided by the mean of slices, the cumulative TCO over 10 years period is € 762,533 and € 1,230,084 which results in a cumulative TCO per kilometre of € 117,313 and € 189,244 for the pessimistic and optimistic scenario respectively. The different cost components of the 5G network deployment for the pessimistic and optimistic scenario are depicted in the figure below.

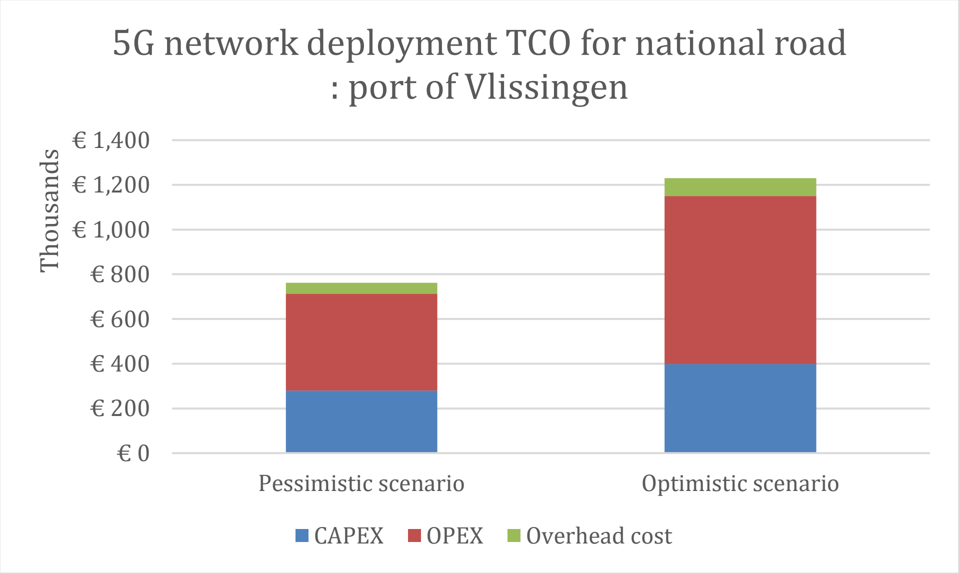


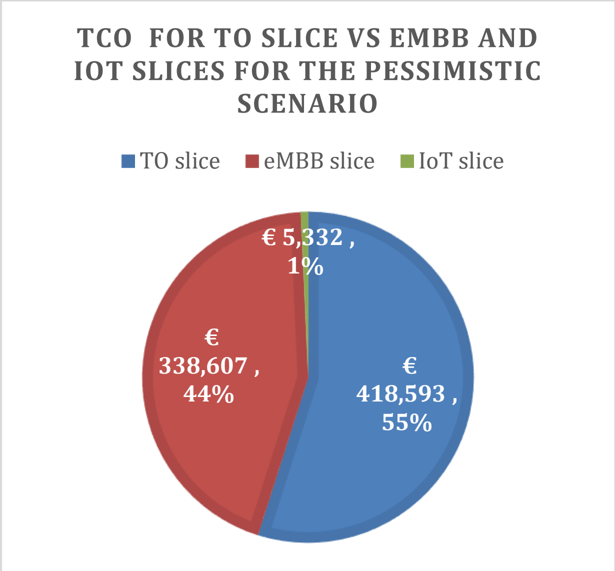
Figure 68 Different cost components and Cumulative TCO over 10 years of the 5G network for 5G Network slicing

As shown in the figure above, OPEX is the dominant cost element of the TCO.

We used the allocation model described in section 3.3.1 to allocate the 5G network cost to the three slices using only **throughput metric**: as the network was dimensioned using the UL capacity requirement. The cost sharing coefficient are as follow:

	Pessimistic	Optimistic
Cost sharing coefficient TO Slice	55%	68%
Cost sharing coefficient non-TO Slices	45%	32%
Cost sharing coefficient mIoT Slice	2%	2%
Cost Sharing coefficient eMBB Slice	98%	98%

Using these sharing coefficients, the TCO has been divided among the supported slices and is presented in Figure 69.



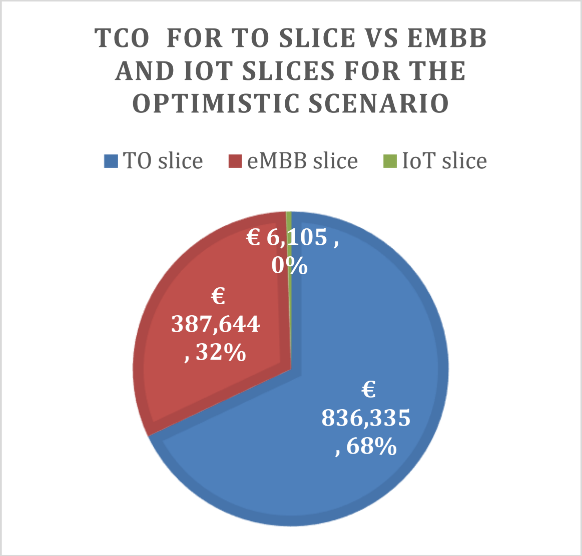


Figure 69 TCO of the TO slice vs eMBB and IoT slices for the pessimistic (on the left-hand side) and the optimistic (on the right-hand side) scenarios

Figure 69Figure 46 shows that the TO slice bears the bigger part of the TCO being 55% and 68% for the pessimistic and optimistic scenario respectively. This is due to the important UL capacity required by the TO slice (i.e., requires 314 Mbps and 548 Mbps for the pessimistic and optimistic scenario respectively) comparing to only 258 Mbps for the non-TO slices.

5.4.4.3 Deployment scenario 4.2.2: 5G network slicing assuming other type of services are provided under the regular traffic:

As presented above, the UL capacity requirement in this connectivity option is 405 Mbps and 639 Mbps for the pessimistic and optimistic scenario respectively in which 91 Mbps is required by the regular traffic.

To cover the two road segments under study with 5G network to support the TO use cases previously described using 5G network slicing and assuming that the non-TO services are provided under the umbrella of the regular traffic, the cumulative TCO over 10 years period is € € 762,533 which results in a cumulative TCO per kilometre of € 117,313 for both the pessimistic and optimistic scenario respectively. The different cost components of the 5G network deployment for the pessimistic and optimistic scenario are depicted in the figure below.

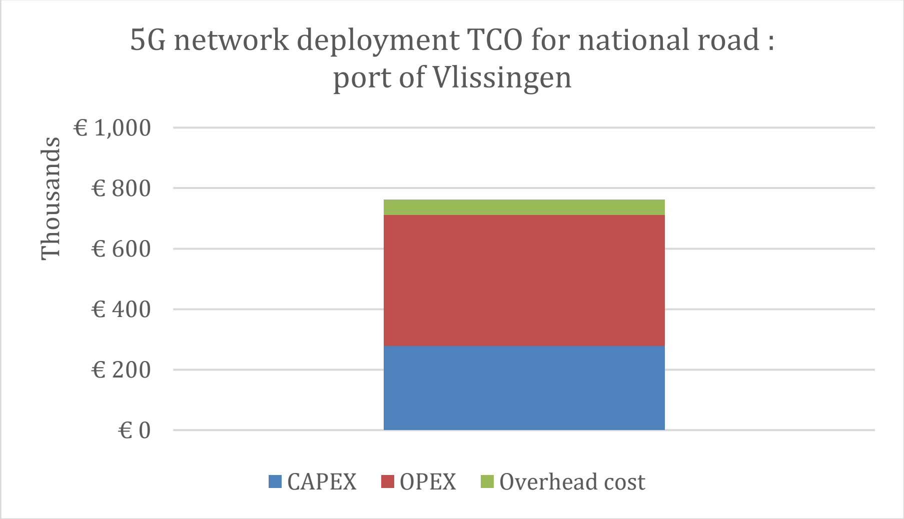


Figure 70 5G network cost using 5G network slicing assuming regular traffic for non-TO services for both pessimistic and optimistic scenario.

We used the allocation model described in section 3.3.1 to allocate the 5G network cost to the TO slice and the regular traffic using only **throughput metric**: as the network was dimensioned using the UL capacity requirement. The cost sharing coefficient are as follow:

	Pessimistic	Optimistic
Cost sharing coefficient TO Slice	77.5%	86%
Cost sharing coefficient regular traffic	22.5%	14%

Using these sharing coefficients, the TCO has been divided among the TO slice and the regular traffic and is presented in the figure below.

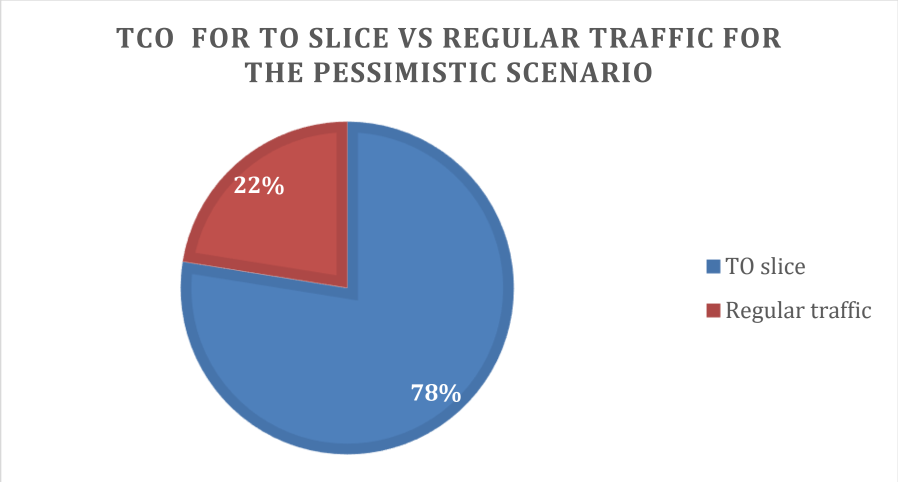


Figure 71 TCO of the TO slice vs regular traffic for the pessimistic scenario

Figure 71 clearly shows that the TO slice has the bigger part of the cost deployment since the regular traffic has a very low requirements in term of UL capacity and the same observation also for the optimistic scenario.

5.4.4.4 Cost comparison between the three 5G connectivity deployment options

Bringing the cost results of the three 5G connectivity deployment options together to assess which option is the most cost effective one. In the comparison we only compare the cost share for the TO slice/service from the three cases.

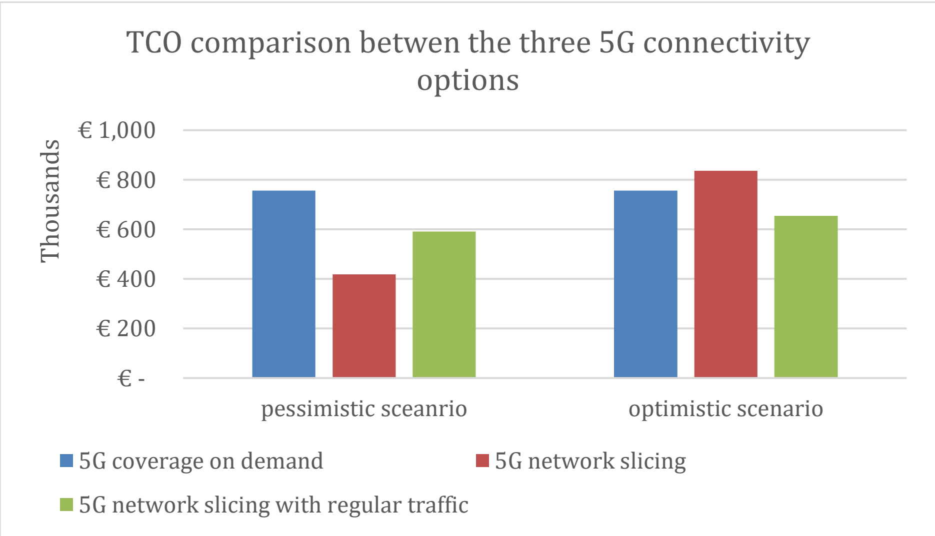


Figure 72 TCO comparison between the three 5G connectivity options

From the cost comparison illustrated in Figure 72, we can deduct that for the pessimistic scenario, the network slicing with providing a separate slice for each service is the most cost-effective option with 45% and 29% as cost reduction comparing to the 5G coverage on demand and 5G network slicing with regular traffic respectively. Yet in the optimistic scenario, this connectivity option namely the 5G network slicing becomes the costliest one dur to the increase in the number of connected vehicles which implies the increase in the UL capacity requested from the network. The cost-effective solution in the optimistic scenario is the 5G network slicing with considering the non-TO services under the regular traffic.

Given the number of connected trucks for the 10 years timespan being 14400 and 18720 trucks for the pessimistic and optimistic scenario respectively, we calculated the monthly ACPU and the ACPU per km in order to be extrapolated to other locations. Results are presented in the table below.

Table 22 Average monthly ACPU per km for the different connectivity options

	Pessimistic	Optimistic
Coverage on demand	€ 8.08	€ 6.22
Network slicing with slice for each service	€ 4.47	€ 6.87
NS with regular traffic	€ 6.32	€ 5.37

5.4.5 TO center deployment and TO-capable vehicles

In this deployment scenario, we studied two road segments within the port of Vlissingen, therefore the focus is on the 5G network deployment, hence, the cost of the TO center and cost of making the different vehicles TO-capable are studied under the previous deployment scenario in section 5.2.5, where different UCs studied in this deployment scenario where also included in the analysis.

5.4.6 Sensitivity analysis

In the previous sensitivity analysis of the deployment scenario 1, the impact of adopting different RAN hardware type supporting different number of beams on the TCO of the 5G network was investigated. In addition, the impact of changing the network deployment strategy together with supporting only skid steers in the terminals were analyzed. In the deployment scenario 2, UC4.3 Cooperative Adaptive Cruise Control (CACC) based platooning is analyzed together with the other use cases that were analyzed in the previous deployment scenario 1. Therefore, and since we assumed 4 trucks per platoon in the analysis, in the sensitivity analysis we studied the impact of varying the number of trucks per platoon on the TCO of the 5G networks and on the TCO of the own TO center deployment.

In this deployment scenario, we saw that with the network infrastructure deployed for each connectivity option, we have an important free UL capacity except for the 5G network slicing connectivity option in the optimistic scenario. Therefore, it resulted in an over-dimensioning of the network by using the RAN hardware supporting 16 beams. In this section, we run the cost model for the different connectivity options using the RAN hardware providing only 8 beams and we compared results with results of the previous deployment costs.

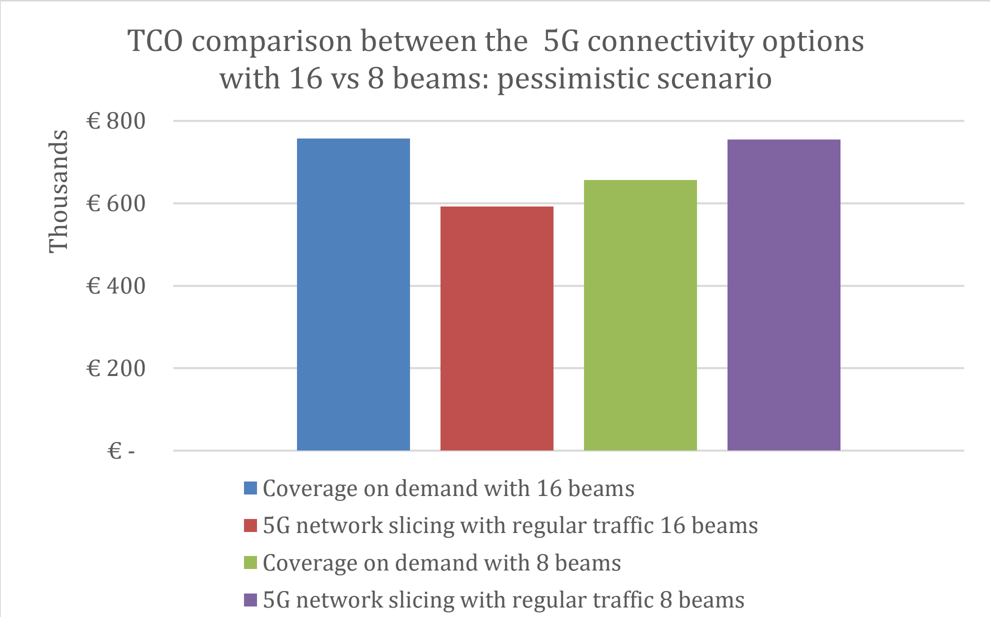


Figure 73 TCO comparison between the 5G connectivity options with 16 vs 8 beams: pessimistic scenario

Changing the type of RAN hardware to provide only 8 beams to solve the over dimensioning of the network leads to a cost saving of 13% for the coverage on demand connectivity option, yet it didn't make it the cost-effective solution, still 5G network slicing with a slice for each service and also with considering regular traffic the most cost-effective options with considering 16 beams RAN hardware.

5.4.7 Main takeaways

Techno-economic analysis of the deployment scenario 4, which focuses on providing the 5G-based TO services in major transport axis – significant transport flows via road, showed that:

- For the pessimistic scenario, the network slicing with providing a separate slice for each service is the most cost-effective option with 45% and 29% as cost reduction comparing to the 5G coverage on demand and 5G network slicing with regular traffic respectively.
- Yet in the optimistic scenario, this connectivity option namely the 5G network slicing becomes the costliest one due to the increase in the number of connected vehicles which implies the increase in the UL capacity requested from the network. The cost-effective solution in the optimistic scenario is the 5G network slicing with considering the non-TO services under the regular traffic.
- Changing the type of RAN hardware to provide only 8 beams to solve the over dimensioning of the network leads to a cost saving of 13% for the coverage on demand connectivity option, yet it didn't make it the cost-effective solution, still 5G network slicing with a slice for each service and also with considering regular traffic the most cost-effective options with considering 16 beams RAN hardware.

5.5 Deployment scenarios 5: major international transport axis – significant transport flows via road and water: cross-border area

5.5.1 Definition of the deployment scenario

In this deployment scenario, the TO services will be provided in the cross-border area between The Netherlands and Belgium including road and waterway international transport axis. This is in alignment with the trials in that site. The supported use cases are UC4.1, UC4.3, and UC4.4, including their supporting enabling functions, will be tested. The pilot site is designed in such a way that it stretches over the canal Gent-Terneuzen (where the barge from UC4.1 will be sailing), through a detailed cross-border trajectory with various environmental conditions, such as urban and rural area, industrial area, highway with civilian cars/trucks and pedestrians. The helicopter view of the studied area is depicted in the figure below.

Figure 74 Helicopter view of Zelzate-SaS van gent cross-border area

In this deployment scenario we need to estimate the TO adoption for trucks that are using the roads in that specific area and also barges that are using the Terneuzen-Gent canal.

5.5.2Forecasting of TO adoption for barges

For Use case UC4.1, we need to derive the number of TO capable barges in the studied area. Based on input from [26] and [27], about 70,000 ships a year pass through the canal, which means 192 ships a day. To know the number of TO barges crossing the canal each day we used the bass diffusion model explained previously, the TO adoption in the daily barges crossing the canal is presented in the following figures:

1. ***Pessimistic/realistic TO adoption scenario***

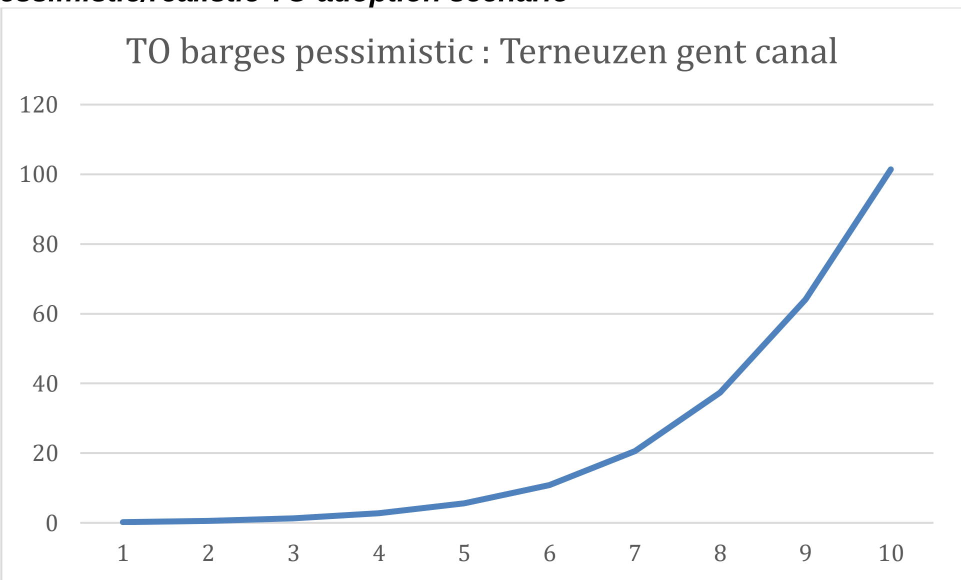


Figure 75 Evolution of expected number of TO-capable barges for the pessimistic scenario over the years

2. Optimistic TO adoption scenario

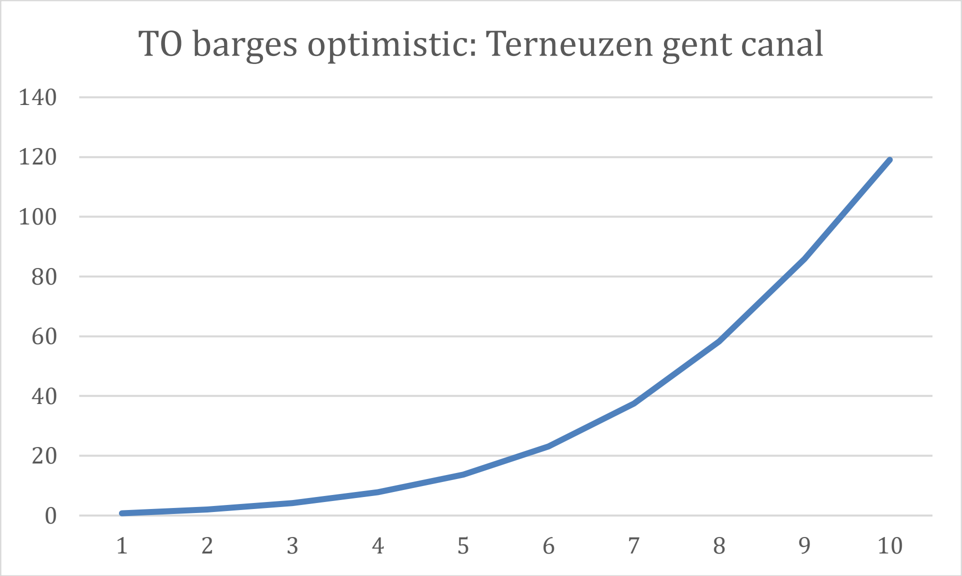


Figure 76 Evolution of expected number of TO-capable barges for the optimistic over the years

As we can see from the two graphs, after 10 years we will have a maximum of 102 and 120 TO barges using the canal daily for the pessimistic and optimistic TO adoption scenarios respectively.

5.5.3Forecasting of TO adoption for trucks

For Use case UC4.1, we need to derive the number of TO capable trucks in the studied area. Based on input from the Flemish traffic indicator [28] and presented in Figure 96, about 4000 a day using the R4 towards the area under study. To know the number of TO trucks each day we used the bass diffusion model explained previously, the TO adoption in the daily trucks is presented in the following figures:

1. Pessimistic/realistic TO adoption scenario

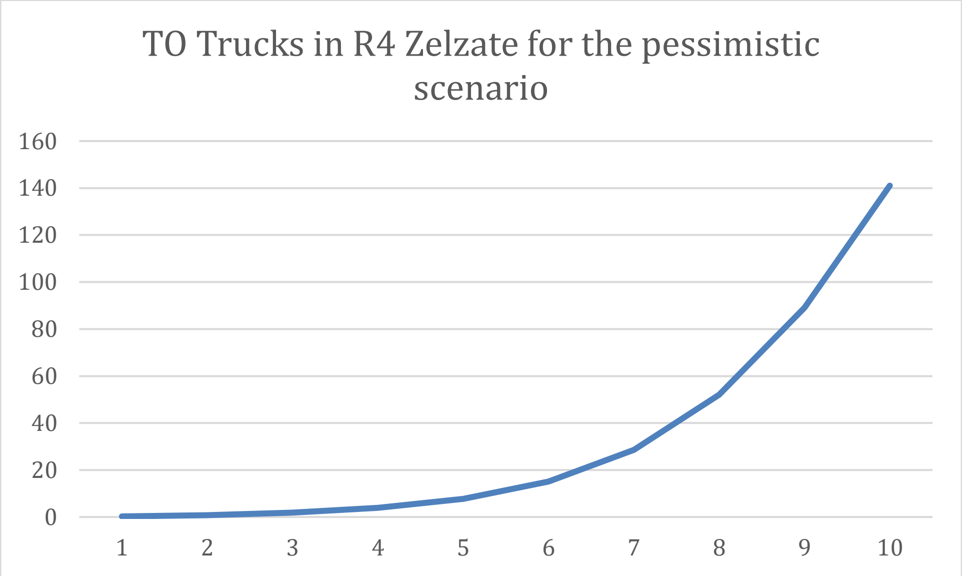


Figure 77 Evolution of expected number of TO-capable trucks for the pessimistic scenario over the years

2. Optimistic TO adoption scenario

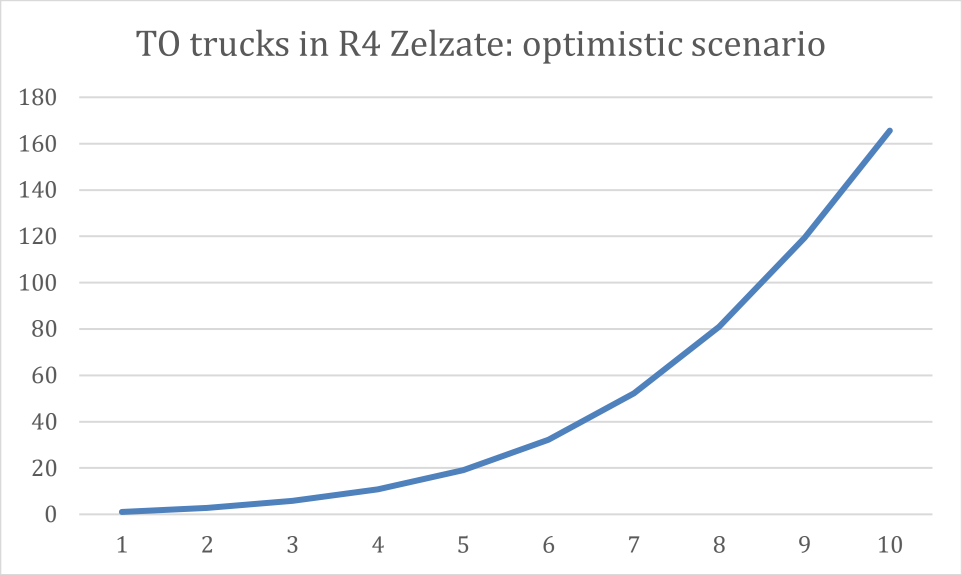


Figure 78 Evolution of expected number of TO-capable trucks for the optimistic over the years

As we can see from the two graphs, after 10 years we will have a maximum of 141 and 160 TO trucks using the R4 towards Zelzate daily for the pessimistic and optimistic TO adoption scenarios respectively.

5.5.4 Dimension of the 5G network in the PoA in Antwerp Gateway and MPET terminals and in the river entrance of the port

5.5.4.1 Area to cover

Similar to the previous deployment scenario, we need to deploy 5G Networks in the cross-border area to support the selected UCs. With an inter-site distance of around 2 km and considering the existing network infrastructure presented in Figure 94 and in Figure 95 with a length of 2.3 km and a width of 2.2 km, the required network infrastructure to cover the studied area is presented in Figure 79. Based on the existing network two additional macro cells are needed to provide the full coverage of the canal and roads segment under study.

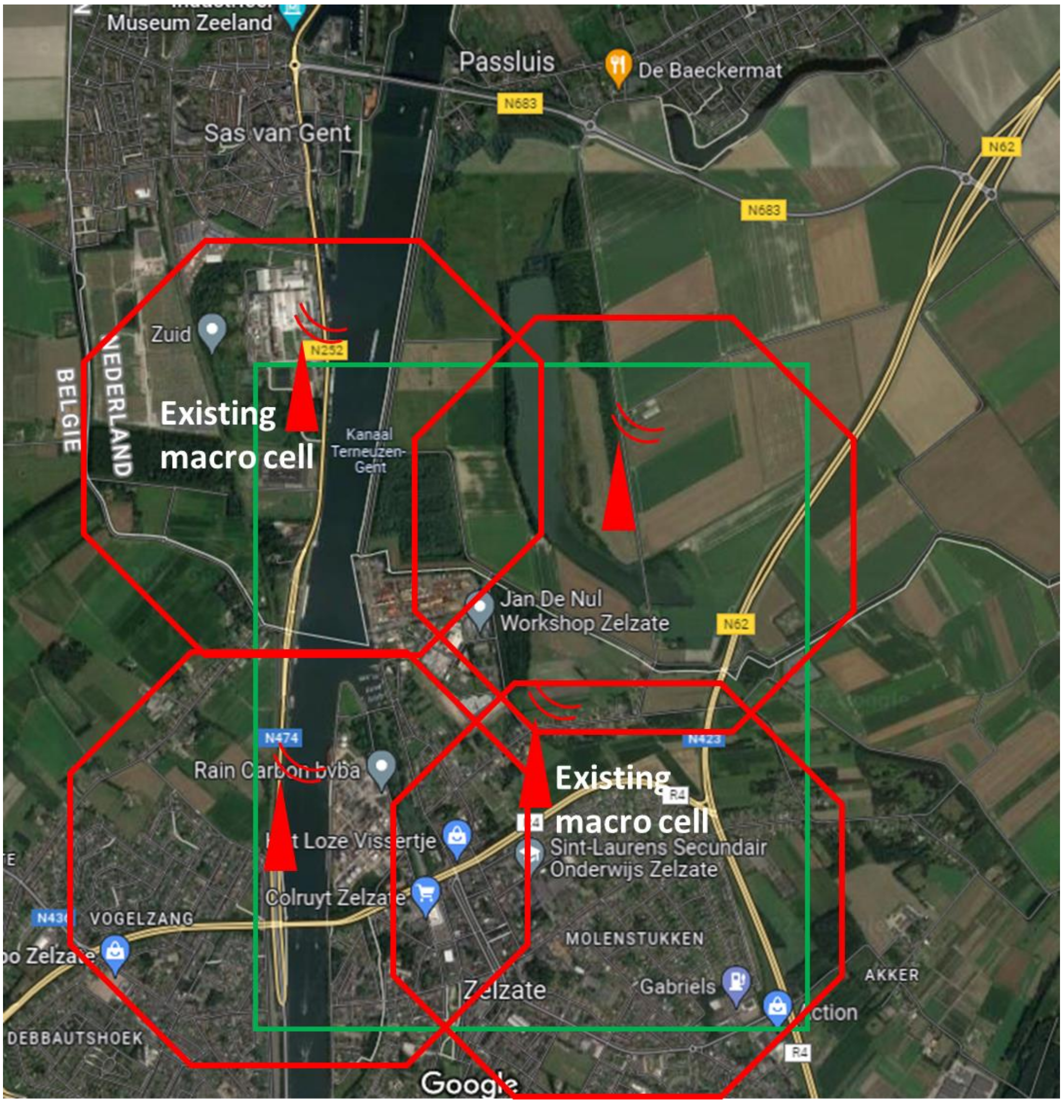


Figure 79 5G network deployment to cover roads and the canal in the cross-border areas

5.5.4.2 Network Capacity requirement

Based on the required UL capacity for the different use cases and different slice types presented in Table 3, the total required capacity on the UL for the two types of 5G connectivity options (i.e., 5G coverage on demand and 5G network slicing) has been calculated considering the following assumptions and input:

- 2 existing macro-cell (as showed in Figure 16) and 50% of their UL capacities are used by other applications, so 50% is free and to be used for TO use cases;
- Each macrocell is a tri-sector and each cell has 16 beams following the RAN hardware installed, but in reality, on the UL only 8 streams simultaneously can be offered, this is to be validated during the final measurement campaigns.
- The studied area has a length of 2.3 km and a width of 2.2 km.
- The macro cell inter-site distance is 2 km.

- Truck speed is 70 km/h[2]
- Barges speed is 13 km/h
- it will be estimated that 80 percent of the traffic cross the area during those 12 hours.

For the barges, and according to Bass diffusion model we have a maximum of 102 a day for pessimistic, with considering 80% of the traffic during daytime (12 h), it results in 6.8 barges per hour almost 7 barges. We have a maximum of 120 a day for optimistic scenario with 80% of the traffic during daytime (12 h), it resulted in 8 barges per hour and given the average speed of barges 13km/h, this results in around 1 per km per hour. The canal length in the studied area is 2.5 km which means 2 or 3 per hour in that region
For trucks; and according to Bass diffusion model, a maximum of 141 per hour for pessimistic and 166 per hour for pessimistic, and using the formula presented in section 5.4.3.2 with speed on the highway is 70/h [29]: 2 trucks per KM for pessimistic and 2.37 trucks per km for optimistic adoption, so for10.5 km= almost 25 trucks in that region per hour for the optimistic and 21 for the pessimistic scenario. Using the same assumptions as previously regarding the number of trucks for platooning and remote driving namely 35% for remote driving versus 65% for platooning, it resulted in 9 trucks remote driving and 4 platoons for the optimistic scenario and 7 remote driving and 4 platoons for the pessimistic scenario.

For **5G coverage on demand** and using the network dimensioning process (explained in section 3.3.1.1) results in a total capacity of 1020 Mbps on the UL for the pessimistic scenario. While for the optimistic scenario, the total capacity on the UL is of 1256 Mbps. Given the network deployment strategy adopted earlier and explained in section 3.3.1.1, where macro cells are deployed to provide coverage while small cells are to be added to enhance capacity, the network infrastructure needed is two macro cells and 0 small cells for both the pessimistic and optimistic scenario.

For the deploying **5G network slicing** connectivity option, we need to know the required capacity for the other slices to be offered in these two port terminals. To this end, the non-TO UL capacity needs to be estimated to deploy the network to support both type of services, the TO and the non-TO ones. Based on the two methods of the non-TO capacity calculation explained in 3.3.1.1, the total required capacity has been calculated:

<u>Assuming that the non-TO services are supported as a regular traffic without dedicated slices for each type of service</u>, the total non-TO capacity is calculated using the data below:

- Data traffic has been retrieved from the field in GB (Gigabyte);
- Assuming 8 hours as time window in which users are active, the downlink speed has been calculated;
- Assuming that the UL speed is 5% of the DL speed, the UL capacity is derived,
- Assuming a 30% regular traffic growth, the requested UL capacity of the regular traffic for the next 2-4 years has been calculated.

Therefore, the total Capacity required on the UL is the sum of the total Capacity UL of the TO slice and the total Capacity UL of the regular traffic. This results in a total UL capacity of 1293 Mbps and 1529 Mbps for the pessimistic and optimistic scenario respectively in which 273 Mbps for regular traffic. Hence, two additional macro cells are required for ensuring the coverage of the two terminals and 1 and 4 small cells for the pessimistic and optimistic scenario respectively.

[2] It is worth noting that the speed of TO trucks in the tests was lower than the average speed of 70 km/h. However, it is reasonable to assume that once the technology matures and appropriate legal frameworks are established, the speed of TO trucks will also be able to reach this average.

5.5.5 Cost model results of 5G network deployment

Using the cost data validated by all partners in a data validation round, the cost model has been run for the two types of connectivity options being 5G coverage on demand and 5G network slicing with its two methods of estimating the non-TO capacity and are presented in the following sections.

5.5.5.1 Deployment scenario 4.1: 5G Coverage on demand

To cover the cross-border area with 5G network to support the TO use cases previously described, the cumulative TCO over 10 years period is € 1,513,344 which results in a cumulative TCO per square kilometre of € 299,080 for both the pessimistic and optimistic scenarios. The different cost components of the 5G network deployment are depicted in the figure below.

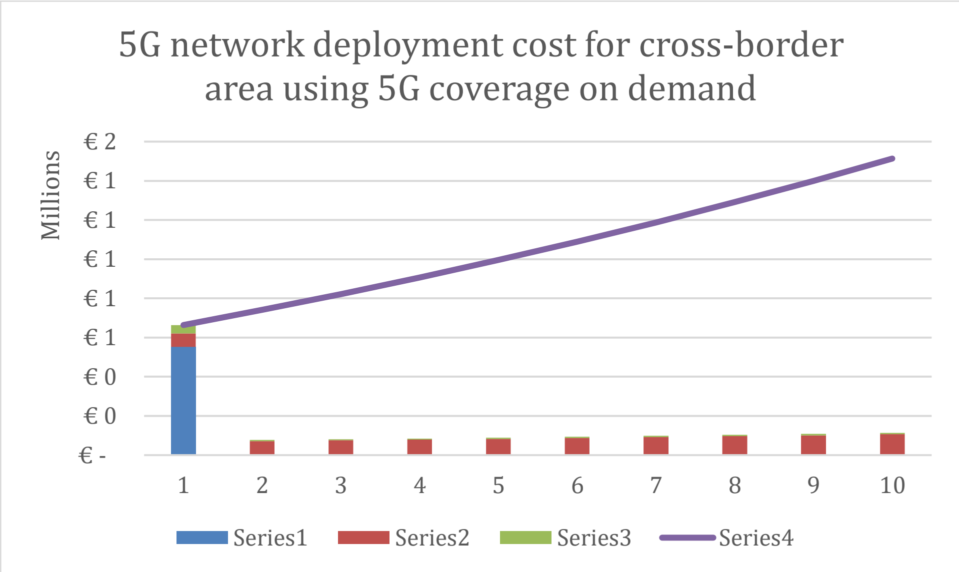


Figure 80 Different cost components and Cumulative TCO over 10 years of the 5G network for 5G coverage on demand.

To understand what the dominant cost of the TCO is, we visualize a cost breakdown of the TCO. Result shows that OPEX is the dominant cost element which represents 57% of the TCO. The main cost components of the OPEX are the site rental (32 €k per year) to host the macro cells and small cells, the energy cost (14 €k per year) and the hardware maintenance.

5.5.5.2 Deployment scenario 4.2.2: 5G network slicing assuming other type of services are provided under the regular traffic:

As presented above, the UL capacity requirement in this connectivity option is 1293 Mbps and 1529 Mbps for the pessimistic and optimistic scenario respectively in which 273 Mbps is required by the regular traffic.

To cover the area under study with 5G network to support the TO use cases previously described using 5G network slicing and assuming that the non-TO services are provided under the umbrella of the regular traffic, the cumulative TCO over 10 years period is € 1,675,056 and € 2,142,606 which results in a cumulative TCO per square kilometre of € 331,039 and € 423,440 for the pessimistic and optimistic scenario respectively. The different cost components of the 5G network deployment for the pessimistic and optimistic scenario are depicted in the figure below.

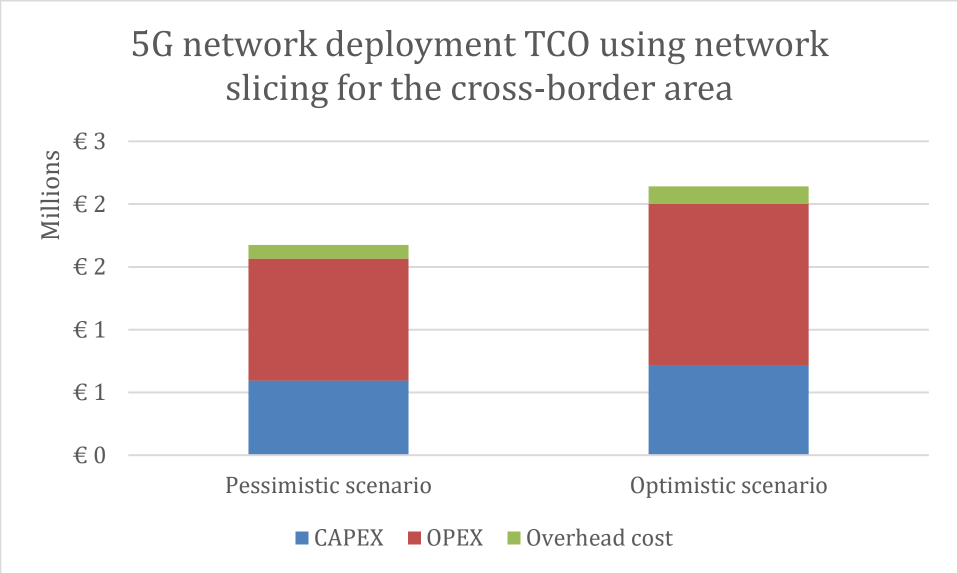


Figure 81 5G network cost using 5G network slicing assuming regular traffic for non-TO services for both pessimistic and optimistic scenario.

We used the allocation model described in section 3.3.1 to allocate the 5G network cost to the TO slice and the regular traffic using only **throughput metric**: as the network was dimensioned using the UL capacity requirement. The cost sharing coefficient are as follow:

	Pessimistic	Optimistic
Cost sharing coefficient TO Slice	79%	82%
Cost sharing coefficient regular traffic	21%	18%

Using these sharing coefficients, the TCO has been divided among the TO slice and the regular traffic and is presented in the figure below.

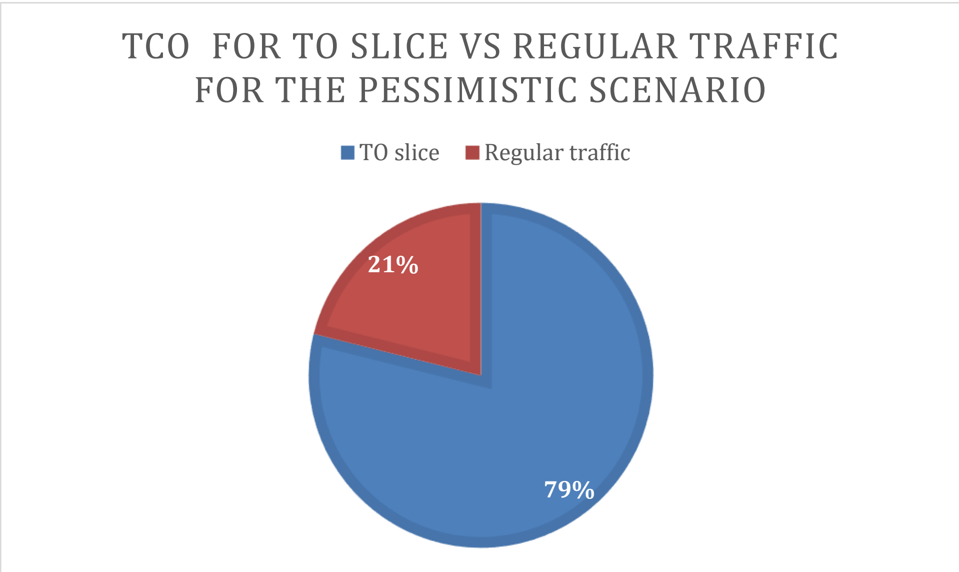


Figure 82 TCO of the TO slice vs regular traffic for the pessimistic scenario

Figure 82 clearly shows that the TO slice has the bigger part of the cost deployment since the regular traffic has a very low requirements in term of UL capacity and the same observation also for the optimistic scenario.

5.5.5.3 Cost comparison between the three 5G connectivity deployment options

Bringing the cost results of the three 5G connectivity deployment options together to assess which option is the most cost effective one. In the comparison we only compare the cost share for the TO slice/service from the three cases.

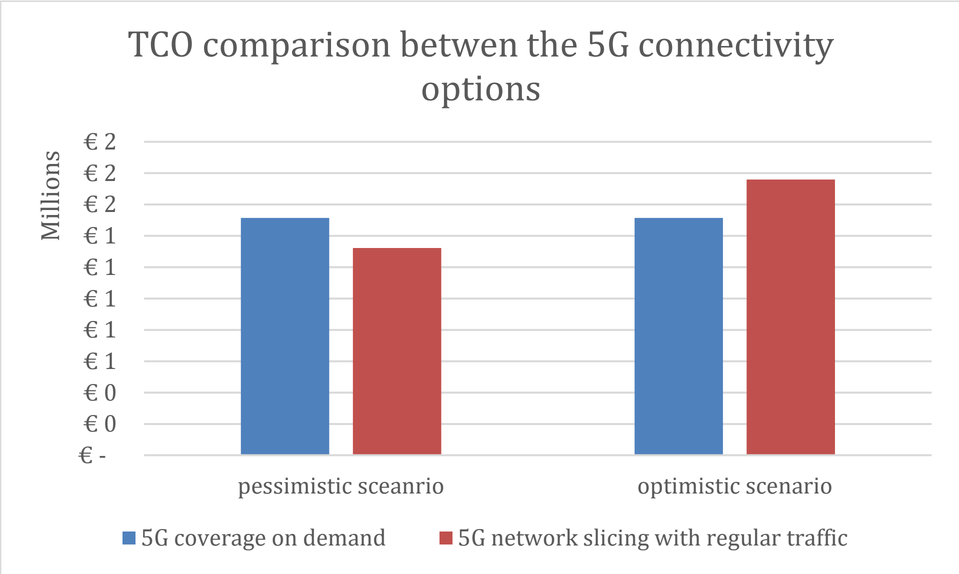


Figure 83 TCO comparison between the 5G connectivity options

From the cost comparison illustrated in Figure 83, we can deduct that for the pessimistic scenario, the network slicing with providing a separate slice for each service is the most cost-effective option. Yet in the optimistic scenario, this connectivity option namely the 5G network slicing becomes the costliest one due to the increase in the number of connected vehicles which implies the increase in the UL capacity requested from the network. This resulted in the deployment of more small cells in the optimistic scenario (4 versus 1 in the pessimistic scenario). As a result, the total cost of ownership (TCO) for the deployment increased, but the cost sharing coefficient for the TO slice also increased (82% in the optimistic scenario versus 79% in the pessimistic scenario). This means that the TO slice bears the incremental cost of the deployment.

On the other hand, the increase in uplink capacity for the coverage on demand in the optimistic scenario did not require any additional infrastructure, because the same deployment (2 macro cells) could support the increased capacity. Therefore, the cost of the deployment remained the same in both scenarios.

Overall, the most cost-effective solution in the optimistic scenario was 5G coverage on demand.

Given the number of connected barges and trucks for the 10 years timespan crossing that area being 7022 and 10109 for the pessimistic and optimistic scenario respectively, we calculated the monthly ACPU and the ACPU per square km in order to be extrapolated to other locations. Results are presented in the table below.

Table 23 Average monthly ACPU per square km for the different connectivity options

	Pessimistic	Optimistic
Coverage on demand	€ 42.59	€ 29.59
NS with regular traffic	€ 37.19	€ 34.41

5.5.6 Sensitivity analysis

In this study, we used the maximum UL capacity required for the different use cases to assess the worst-case scenario of the 5G network deployment. Moreover, in this sensitivity analysis, we run the cost model for both 5G coverage on demand and 5G network slicing for the pessimistic and the optimistic TO adoption scenarios with varying the UCs UL capacity requirement. The goal is to first study the best-case scenario where the UL capacity required from the network is minimal and assess its impact on the deployment cost comparing to the worst-case scenario. And second, to also study the impact of varying the UCs UL capacity if neither the minimum nor the maximum is the exact required value but something in between.

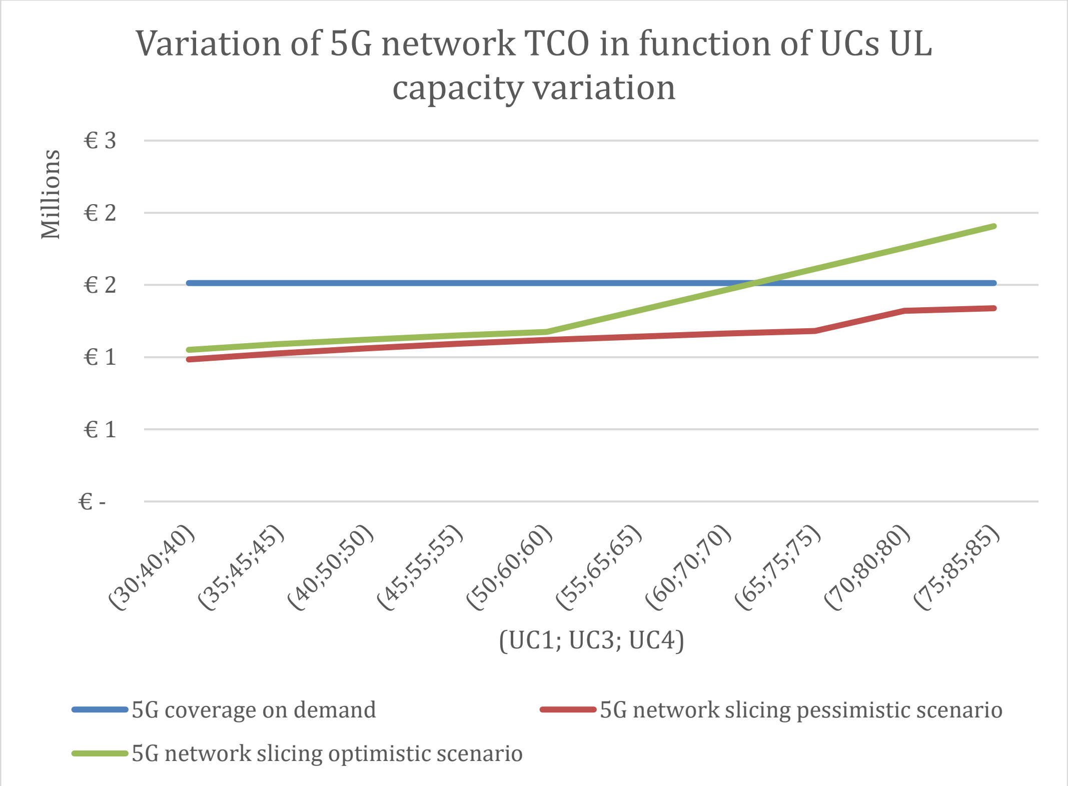


Figure 84 Variation of 5G network TCO in function of UCs UL capacity variation

In Figure 84, results for the coverage on demand showed that for both TO adoption scenarios (being the pessimistic and the optimistic scenarios), the TCO is constant. This means that the driver of the deployment cost is the coverage and by deploying 2 macro cells to fulfill the coverage requirement for the studied area, the UL capacity provided by these two new macro cells is sufficient to support the selected use cases starting from their minimum requirements till their maximum. Yet, for the 5G network slicing connectivity option, results in the figure above show that with increasing the capacity requirement for the studied use cases, namely UC4.1, UC4.3 and, UC4.4, the TCO for both TO adoption scenarios is also increasing. For the pessimistic TO adoption, the 5G network slicing is always more cost-effective than the 5G coverage on demand. However, for the optimistic scenario, 5G network slicing option is cheaper than the 5G coverage on demand until the point (UC4.1=65 Mbps; UC4.3=75 Mbps; UC4.4=75 Mbps). Reaching that point makes the 5G network slicing option more costly, due to the important number of small cells needed to meet the UL capacity required, as explained in the previous section.

The cost deployment reductions resulting from moving from the maximum UCs capacity requirement to the minimum ones are captured in the figure below.

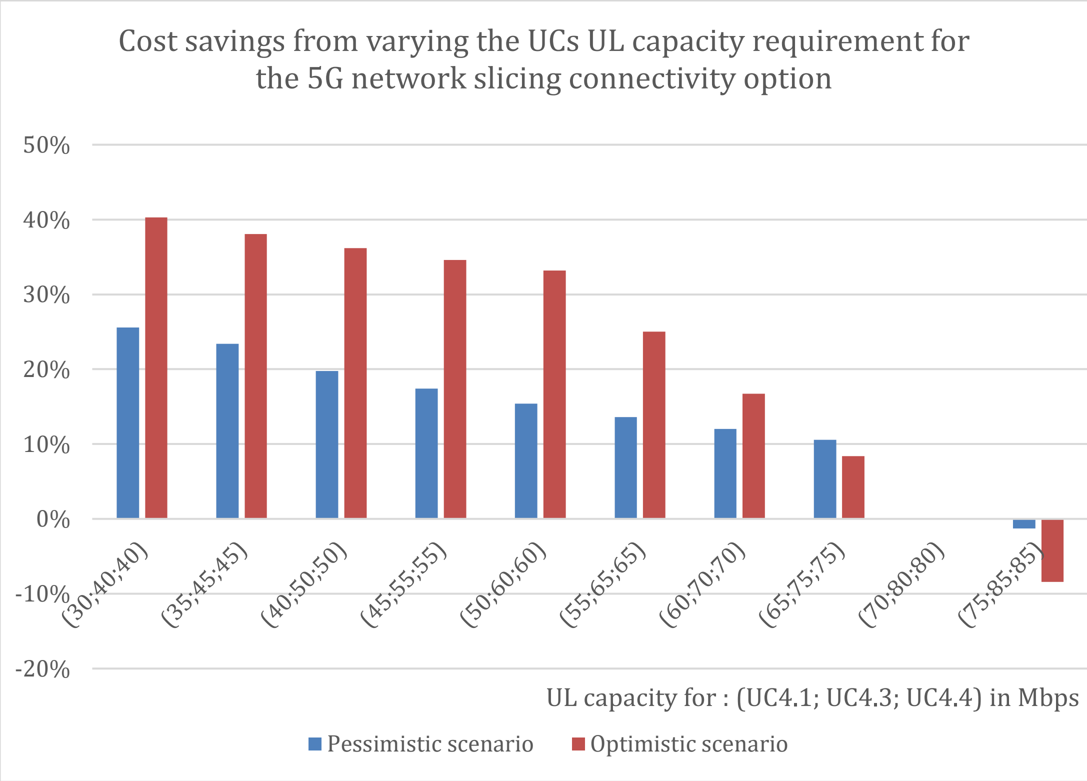


Figure 85 Cost savings from varying the UCs UL capacity requirement for the 5G network slicing connectivity option

Deploying the 5G network while considering only the minimum capacity requirements from the selected use cases results in 26% and 40% cost reductions for the pessimistic and optimistic scenarios respectively comparing to the case where the maximum values are considered, as can be seen in Figure 85. Yet, if we increase the UCs capacity requirement by only 5 Mbps per UC comparing to the maximum values considered in this study, it results in increasing the cost of deployment by up to 8% as can be seen in the point (75;85;85) on the graph above.

5.5.7 Main takeaways

Techno-economic analysis of the deployment scenario 5, which focuses on providing the 5G-based TO services in major transport axis – significant cross-border transport flows via road and water, showed that:

- For the pessimistic scenario, the network slicing with providing a separate slice for each service is the most cost-effective option.
- Yet in the optimistic scenario, this connectivity option namely the 5G network slicing becomes the costliest one due to the increase in the number of connected vehicles which implies the increase in the UL capacity requested from the network. This resulted in the deployment of more small cells in the optimistic scenario (4 versus 1 in the pessimistic scenario). As a result, the total cost of ownership (TCO) for the deployment increased, but the cost sharing coefficient for the TO slice also increased (82% in the optimistic scenario versus 79% in the pessimistic scenario). This means that the TO slice bears the incremental cost of the deployment.
- On the other hand, the increase in uplink capacity for the coverage on demand in the optimistic scenario did not require any additional infrastructure, because the same deployment (2 macro cells) could support the increased capacity. Therefore, the cost of the deployment remained the same in both scenarios.
- Sensitivity analysis showed that deploying 5G network slicing to provide the minimum UCs UL capacity requirements resulted in 26%-40% of TCO cost reduction comparing to the worst-case studied where the maximum requirements were considered.

5.6 Comparison between the studied deployment scenarios

Here we bring all the results from the deployment scenarios together and compare between them from a cost perspective.

Table 24 Cost summary of the different connectivity options for the selected deployment scenarios

	Connectivity option	Pessimistic: TCO	Optimistic: TCO	Pessimistic: TCO per km	Optimistic: TCO per km
DSC1	Coverage on demand	€ 9,335,959	€ 10,995,037	€ 138,452	€ 148,877
	Network slicing	€ 10,307,818	€ 12,171,706	€152,865	€ 164,810
	NS with regular traffic	€ 9,543,750	€ 11,246,774	€ 141,534	€ 152,286
DSC2	Coverage on demand	€ 26,171,422	€ 31,574,789	€ 388,122	€ 427,536
	Network slicing	€ 26,695,166	€ 40,630,449	€ 395,889	€ 550,153
	NS with regular traffic	€ 26,474,926	€ 40,345,116	€ 392,622	€ 546,289
DSC 3	Coverage on demand	€ 1,667,782		€ 320,727	
	Network slicing	€ 811,565		€ 156,070	
	NS with regular traffic	€ 1,214,904		€ 233,635	
DSC 4	Coverage on demand	€ 756,672	€ 756,672	€ 116,411	€ 116,411
	Network slicing	€ 418,593	€ 836,335	€ 64,399	€ 128,667
	NS with regular traffic	€ 591,199	€ 653,941	€ 90,954	€ 100,606
DSC5	Coverage on demand	€ 1,513,344	€ 1,513,344	€ 299,080	€ 299,080
	NS with regular traffic	€ 1,321,390	€ 1,760,048	€ 261,144	€ 347,836

The cost-effective deployment option is colored with green in the table above for each deployment scenario. The TCO per KM for the cost-effective solution for the pessimistic TO adoption is depicted in the figure below.

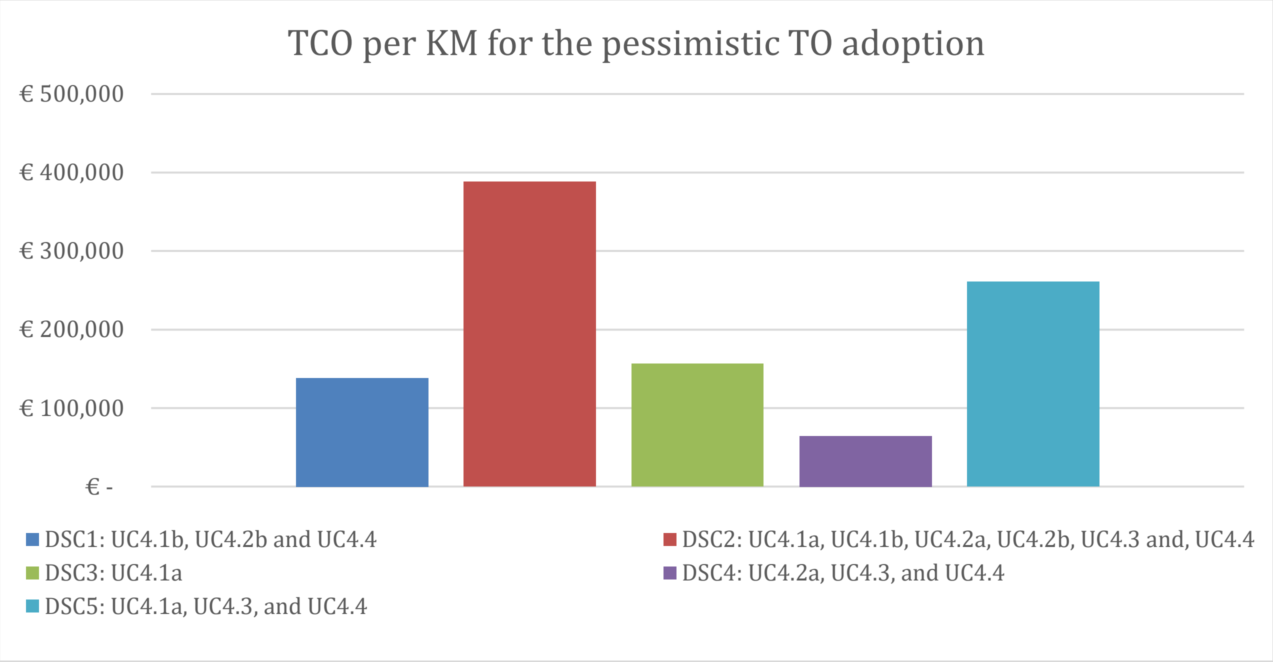


Figure 86 TCO per KM for the pessimistic TO adoption

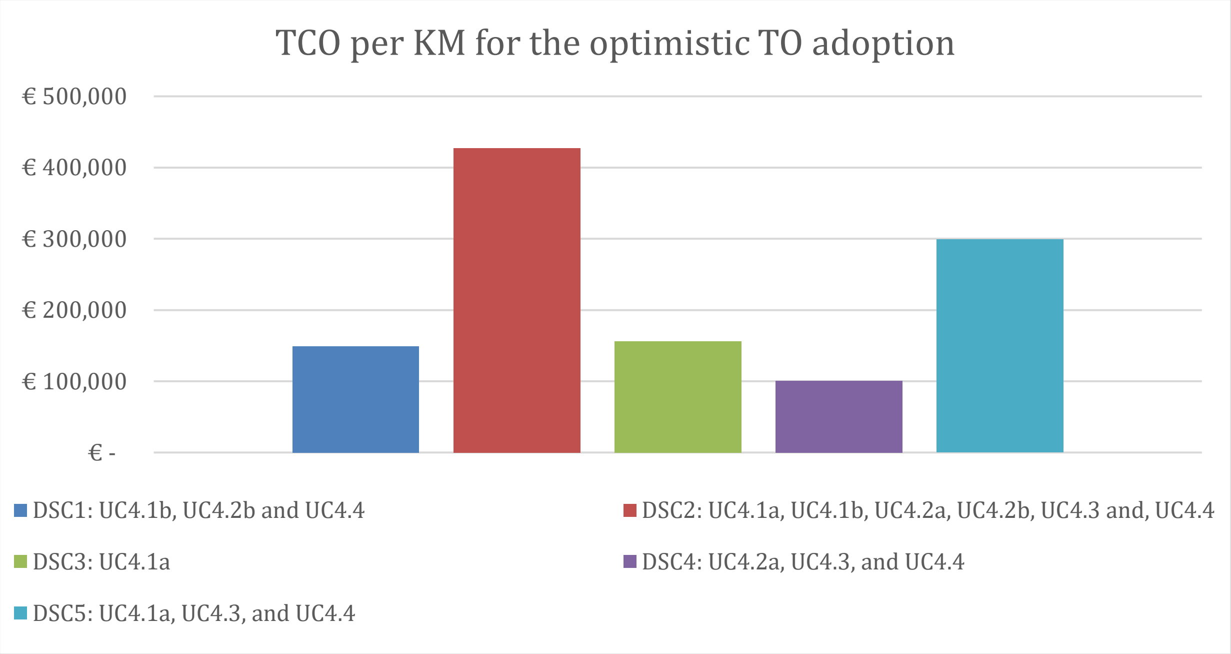


Figure 87 TCO per KM for the optimistic TO adoption

From the two graphs presented in the figures above, we can deduct first that the more TO use cases we provide the more costly is the 5G network deployment. The only exception is DSC3 where we support only UC4.1a and it is more costly than DSC4 where three use cases are supported, this is due to the large area that we need to cover; the river segment.

If we take into account the ACPU for all the deployment scenarios, we see that the more use cases we offer, the more connected vehicles we have and the less is the ACPU. For instance, the ACPU in DSC1 is 18 times more than the one in DSC2, being € 687 vs € 38 for 5G connectivity and 8 times more for the TO center deployment.

5.7 Analysis limitations

One limitation of this analysis is that it does not include the cost of the enabling functions.

Allocating these costs to the TO use cases was difficult due to the nature of the enabling functions. Most of them are software-based and are used in various logistics services, not just for TO services. In addition, it was challenging to monetize the additional effort required for manual configurations at border sites, so this was also not included in the analysis. As a recommendation, MNOs may consider automating these types of configurations to reduce the cost of providing seamless connectivity in a cross-border setting. It is also worth mentioning that there is a lack of cost data available in the literature on the deployment of 5G private networks based on user UL (uplink) capacity requirements. As a result, it was not possible to extend these results to our analysis. To ensure fairness in the comparison between the different 5G connectivity options, we decided to exclude the 5G private network option.

6 CONCLUSION AND RECOMMENDATIONS

In this deliverable a techno-economic analysis has been carried out based on the scenario analysis technique to assess cost-effective deployment options for 5G network and also deploying a TO center. Five deployment scenarios have been studied in detail with different variation in term of 5G connectivity options adopted as well as the TO center deployment. Two TO user adoption scenarios are considered – being a pessimistic and a (more) optimistic scenario.

Techno-economic analysis of the deployment scenario 1, which focuses on providing the 5G-based TO services in a limited area within the port namely terminals only, showed that:

- For 5G network deployment:
  - The 5G coverage on demand is the cost-effective deployment option under the mentioned assumptions and circumstances.
  - The network slicing option, which provides a separate slice for each service, is the most expensive option due to low demand for non-TO slices on the uplink capacity, resulting in the TO slice bearing a significant portion of deployment costs.
  - If we compare the average TCO per terminal over 10 years deployment to the cost of the early deployment in the two terminals DPW and MPET, we see a cost reduction in the TCO of 47.5% for the pessimistic TO adoption and 43.5% for the optimistic scenario. This gives recommendation for both connectivity providers and TO service providers in the port terminals about the good moment of adopting the 5G-based TO technology.
  - OPEX is the dominant cost element which represents 63% of the TCO.
  - Sensitivity analysis with varying the type of RAN hardware used to support MIMO shows that even using the most expensive type of RAN hardware being the one supporting 16 beams is more cost-effective than the cheap ones due to the efficient use of its capabilities to meet the required UL capacity to support the selected UCs and EFs.
  - Changing the network strategy by adding one additional macro cell to substitute few small cells (up to 5) will introduce more deployment cost. Yet, seems more cost efficient to substitute 8 small cells by one macro cell for the 5G network slicing connectivity option which results in 16-18% cost reduction of the TCO. This cost reduction makes the 5G network slicing option more cost effective than the 5G coverage on demand option in the two network deployment strategies. This cost reduction results in a 7-8% cost reduction in the final ACPU for the connectivity service.
- For TO center deployment:
  - deploying the TOC with a gradual addition of the control setups following the TO uptake is more cost-effective than buying all the control setups at the start of the deployment with a 10% cost reduction. The cost saving is around 25%.
  - The cost of deploying TO center assuming an optimistic adoption is more expensive than the deployment in a pessimistic uptake scenario.
  - The main cost component of the TCO is OPEX, which represents 89% of the total cost.
  - A cost breakdown of OPEX shows that operator wage is the dominant cost element which represents 93% of the total OPEX and the rest 7% are distributed among office space renting, Internet subscription and energy cost.
  - Deploying own TO center is less expensive than renting a pre-equipped TO rooms from other TO service providers; cost reduction of up to 25%.
- From the business case evaluation:
  - The ACPU in the optimistic scenario is less than the one in the pessimistic scenario, due to the higher number of the different types of connected vehicles.
  - For the pessimistic TO adoption, the BEP is reached around year 5 for the two profit margin assumptions being 15% and 30%. Yet, the BEP is around 5 and 8 years for the optimistic scenario for the 30% and 15% respectively.
  - Focusing on only few use cases, for example only skid steers in the terminals to serve TO barges results in a higher ACPU at the end.

  - Serving skid steers only is 18% more expensive on the 5G connectivity level and 29-40% more expensive on the TO service level.
  - Therefore, to ensure that the deployment of TO services is as cost-effective as possible, it is important to support as many use cases as possible. By connecting a higher number of vehicles, the costs of deployment can be shared among a larger group, resulting in a lower average cost per unit (ACPU).

Techno-economic analysis of the deployment scenario 2, which focuses on providing the 5G-based TO services in the port area including terminals and short public roads, showed that:

- For 5G network deployment:
  - The 5G coverage on demand is the cost-effective deployment option under the mentioned assumptions and circumstances.
  - The network slicing with providing a separate slice for each service is the costliest option, this is due to low demand for the studied non-TO slices (namely the eMBB and IoT slices) on the uplink capacity, resulting in the TO slice bearing a significant portion of deployment costs.
  - If we compare the average TCO per terminal over 10 years deployment to the cost of the early deployment in the two terminals DPW and MPET, we see a cost reduction in the TCO of up to 50% depending on the TO adoption scenario. This gives recommendation for both connectivity providers and TO service providers in the port terminals about the good moment of adopting the 5G-based TO technology.
  - OPEX is the dominant cost element which represents 63% of the TCO.
  - Sensitivity analysis show the decrease of the TCO with the increase of number of trucks per platoon which is explained by the fact that if we have more trucks per platoon so a smaller number of TO session for the total number of platoons.
- For TO center deployment:
  - Deploying the TOC with a gradual addition of the control setups following the TO uptake is more cost-effective than buying all the control setups at the start of the deployment with a 10% cost reduction. The cost saving is around 31%.
  - The cost of deploying TO center assuming an optimistic adoption is more expensive than the deployment in a pessimistic uptake scenario.
  - The main cost component of the TCO is OPEX, which represents 91% of the total cost.
  - A cost breakdown of OPEX shows that operator wage is the dominant cost element which represents 98% of the total OPEX and the rest 2% are distributed among office space renting, Internet subscription and energy cost.
  - Deploying own TO center is less expensive than renting a pre-equipped TO rooms from other TO service providers; cost reduction of up to 25%.
- From the business case evaluation:
  - The ACPU in the optimistic scenario is less than the one in the pessimistic scenario, due to the higher number of the different types of connected vehicles, being € 86 vs € 101.
  - For the pessimistic TO adoption, the BEP is reached around year 9 for the two profit margin assumptions being 15% and 30%. Yet, the CEP is around 9 and 10 years for the optimistic scenario for the 30% and 15% respectively.

Techno-economic analysis of the deployment scenario 3, which focuses on providing the 5G-based TO services in major transport axis – significant transport flows via water, showed that:

- The cost-effective deployment option for providing only navigation services to TO barges in the river is 5G network slicing with a separate slice for each service. However, for providing a wider range of use cases and covering the two terminals next to the entrance, 5G coverage on demand is the most cost-effective option.
- When only UC4.1a is supported, the cumulative total cost of ownership (TCO) per square kilometer is as follows: €156,070 for 5G network slicing with a separate slice for each service, €233,635 for 5G network slicing with regular traffic, and €320,727 for 5G coverage on demand.

- When a wider range of use cases are provided, including UC4.1a.1, UC4.1b, UC4.2b, and UC4.4, the cumulative TCO per square kilometer is as follows: €388,509 for 5G network slicing with a separate slice for each service, €332,734 for 5G network slicing with regular traffic, and €320,727 for 5G coverage on demand. Providing this wider range of use cases can be up to 51% more expensive than just providing UC4.1a alone.

Techno-economic analysis of the deployment scenario 4, which focuses on providing the 5G-based TO services in major transport axis – significant transport flows via road, showed that:

- For the pessimistic scenario, the network slicing with providing a separate slice for each service is the most cost-effective option with 45% and 29% as cost reduction comparing to the 5G coverage on demand and 5G network slicing with regular traffic respectively.
- Yet in the optimistic scenario, this connectivity option namely the 5G network slicing becomes the costliest one due to the increase in the number of connected vehicles which implies the increase in the UL capacity requested from the network. The cost-effective solution in the optimistic scenario is the 5G network slicing with considering the non-TO services under the regular traffic.
- Changing the type of RAN hardware to provide only 8 beams to solve the over dimensioning of the network leads to a cost saving of 13% for the coverage on demand connectivity option, yet it didn't make it the cost-effective solution, still 5G network slicing with a slice for each service and with considering regular traffic the most cost-effective options with considering 16 beams RAN hardware.

Techno-economic analysis of the deployment scenario 5, which focuses on providing the 5G-based TO services in major transport axis – significant cross-border transport flows via road and water, showed that:

- For the pessimistic scenario, the network slicing with providing a separate slice for each service is the most cost-effective option.
- Yet in the optimistic scenario, this connectivity option namely the 5G network slicing becomes the costliest one due to the increase in the number of connected vehicles which implies the increase in the UL capacity requested from the network. The cost-effective solution in the optimistic scenario is the 5G coverage on demand.
- Sensitivity analysis showed that deploying 5G network slicing to provide the minimum UCs UL capacity requirements resulted in 26%-40% of TCO cost reduction comparing to the worst-case studied where the maximum requirements were considered.

Comparing all deployment scenarios investigated, we found that providing more TO use cases generally leads to a more costly 5G network deployment. The only exception is deployment Scenario 3, supporting just use case UC4.1a (automated barge control) is more expensive than deployment Scenario 4, where three (road based) use cases are supported. This is due to the large area that must be covered in deployment Scenario 3, specifically the river segment. If we consider the Average Cost per User (ACPU) for the deployment scenarios considered, we see that offering more use cases implying a higher number of connected vehicles will lead to a lower ACPU. For example, the ACPU in deployment Scenario 1 is 18 times higher than in deployment Scenario 2, at €687 versus €38 for 5G connectivity and 8 times higher for TO center deployment.

Based on these results, we recommend starting the deployment of TO services in a limited area, including short road distances, and providing as many use cases as possible in order to have a higher number of connected vehicles that will share the cost of deployment and make the services more affordable. When significant TO adoption has been reached, the deployment can be scaled up to cover major national and international transport routes.

The results of the TEA showed that 5G coverage on demand was the most cost-effective deployment option for providing teleoperated services in a limited port area. Yet, 5G network slicing with a separate slice for each service will be more cost-effective as long as a good network deployment strategy is adopted. In a port area with terminals and short public roads, 5G coverage on demand was the most cost-effective option. For major national transport axes with significant transport flows via water or road, 5G network slicing with regular traffic was found to be the most cost-effective deployment option in our analysis. For a major international transport axis with significant transport flows via water and road in a cross-border area, 5G coverage on demand was the most cost-effective option when considering the maximum uplink capacity of use cases. However, if the use case requirements are minimized, 5G network slicing becomes the more cost-effective deployment option.

We recommend reducing use case requirements for uplink capacity in order to save costs. For example, using good video compression and network status prediction algorithms can lead to a 26%-40% reduction in total cost of ownership (TCO) compared to the worst-case scenario, in which the maximum requirements were considered.

In addition, using small cells in addition to macro cells can be an effective strategy for enhancing uplink capacity in a network deployment, but it is not without limitations. Deploying a large number of small cells (more than 8) can be more costly than adding one more macro cell due to the use of MIMO within the macro cell RAN hardware. This is because the cost of deploying many small cells may outweigh the benefits of the additional uplink capacity they provide.

Finally, adopting one or more cost saving strategies for the network deployment as presented in section 2.3 might help significantly reducing the network deployment cost.

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APPENDIX A DEPLOYMENT SCENARIO: RELATED DATA

Deployment scenario1: 5G network dimensioning

The existing 5G network infrastructure in the port of Antwerp is depicted in the heatmap below:

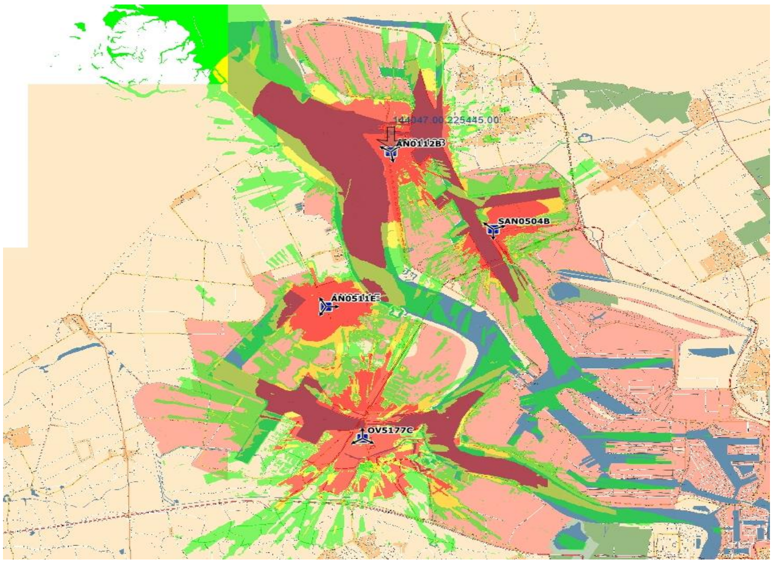


Figure 88 N78 Coverage Port of Antwerp [30]

As shown in figure above, the area colored in red, yellow, and green illustrate the N78 coverage are in Port of Antwerp. The red area indicates an expected signal strength of as least -94dbm. The yellow area indicates the expected signal strength between -98 to -95dbm. The green indicates the expected signal strength of minimum -106dbm. For the 5G BP use cases where most UEs are on mobile, only the red and yellow area can be considered as useable [30].

Deployment scenario1: Cost modelling results

The BEP assessment for deployment scenario 1 without operator wages for the pessimistic scenario is presented in the figure below.

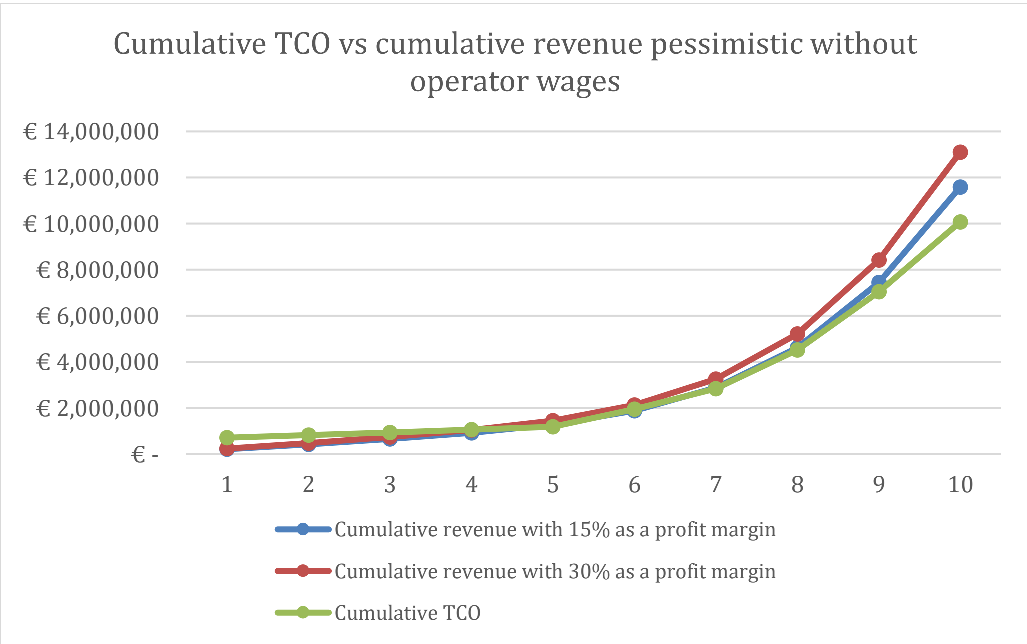


Figure 89 Cumulative TCO vs cumulative revenue pessimistic without operator wages

The BEP assessment for deployment scenario 1 without operator wages for the optimistic scenario is presented in the figure below.

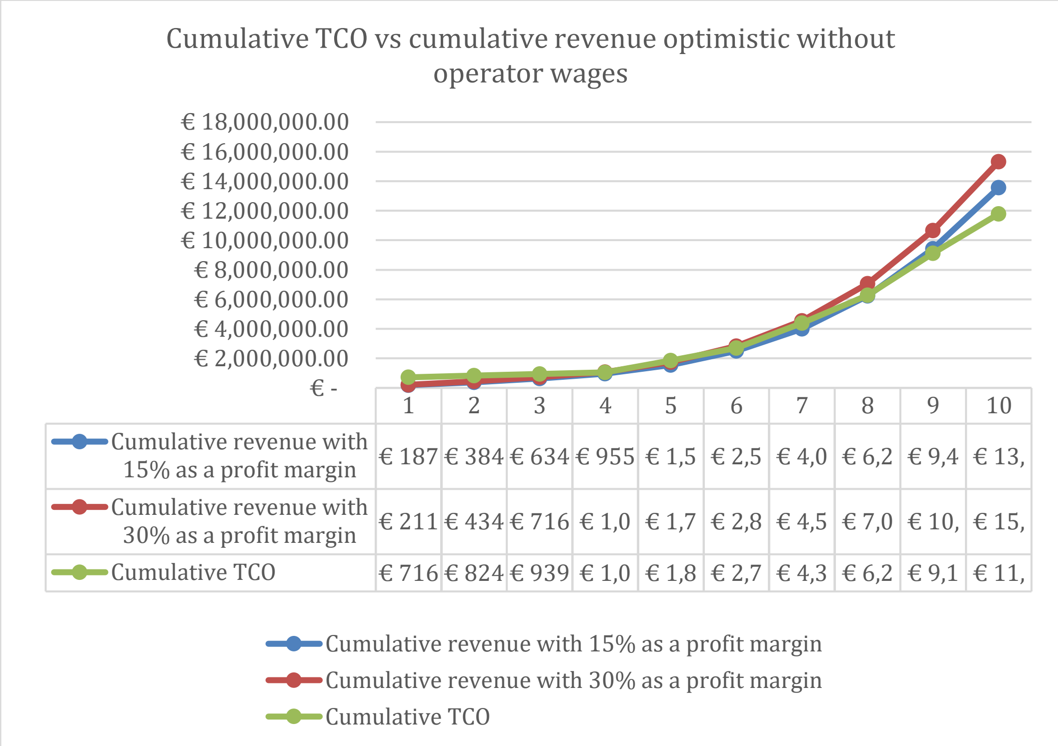


Figure 90 Cumulative TCO vs cumulative revenue optimistic without operator wages

Deployment scenario2: Cost modelling results

The BEP assessment for deployment scenario 2 without operator wages for the pessimistic scenario is presented in the figure below.

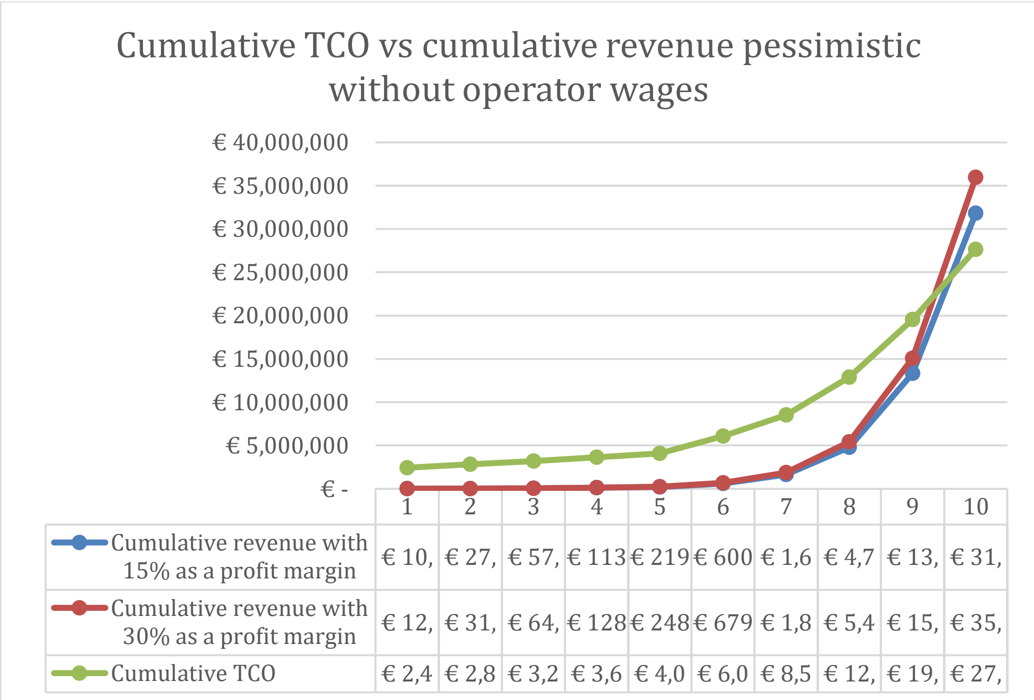


Figure 91 Cumulative TCO vs cumulative revenue pessimistic without operator wages

The BEP assessment for deployment scenario 2 without operator wages for the optimistic scenario is presented in the figure below.

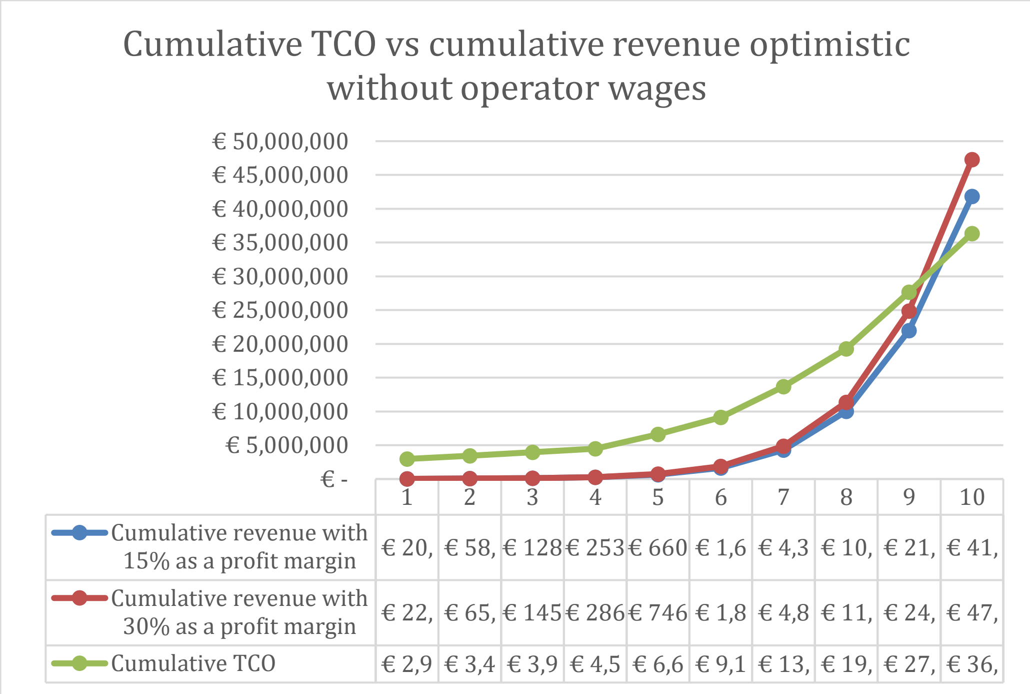


Figure 92 Cumulative TCO vs cumulative revenue optimistic without operator wages

Deployment scenario 4: 5G network dimensioning

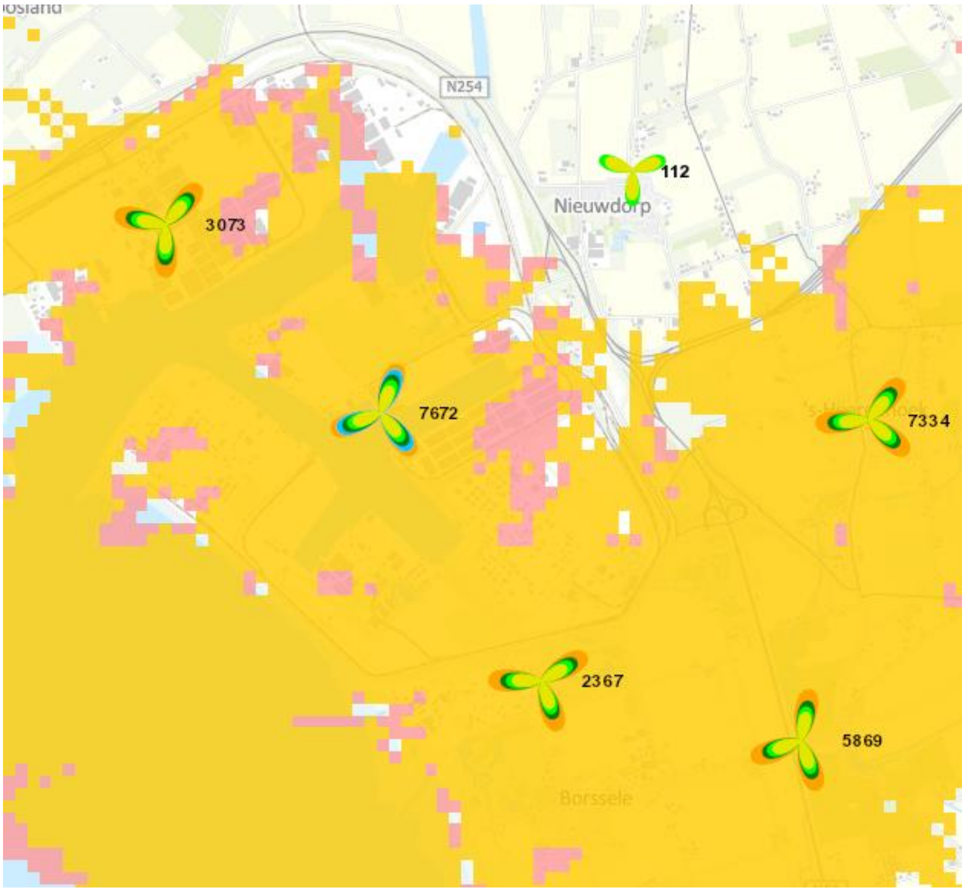


Figure 93 Existing 5G infrastructure in the port of Vlissingen [30]

Deployment scenario 5: 5G network dimensioning

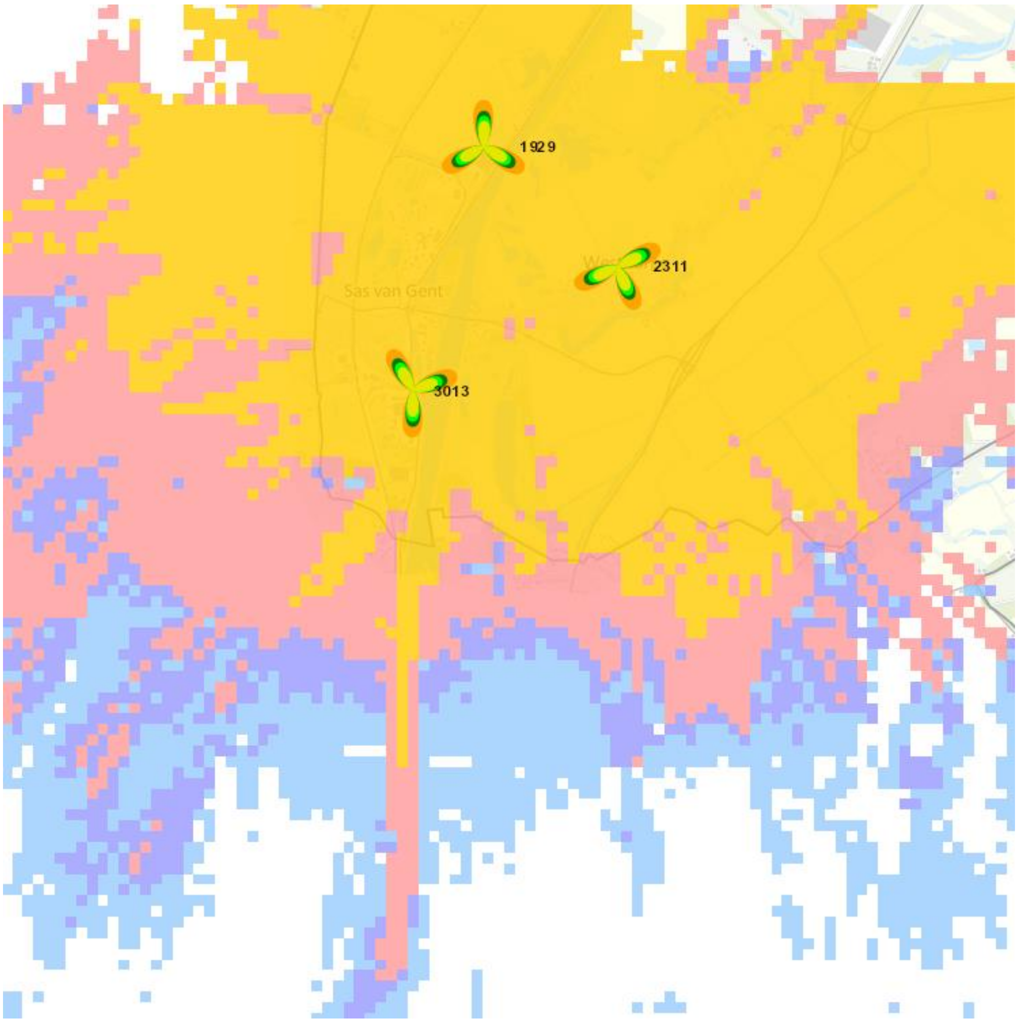


Figure 94 Existing 5G infrastructure in cross-border area: Zelzate-SaaS van gent from the side of SaS van gent [30]

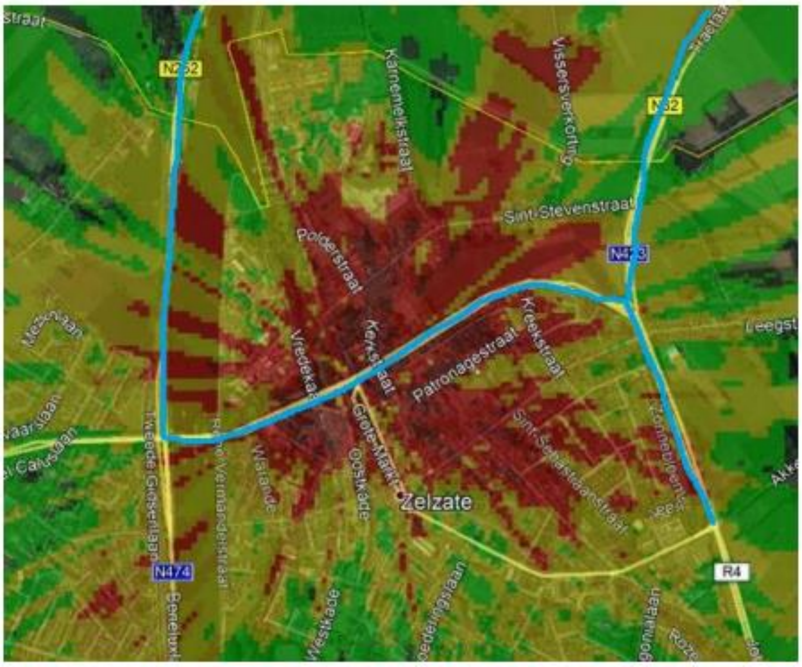
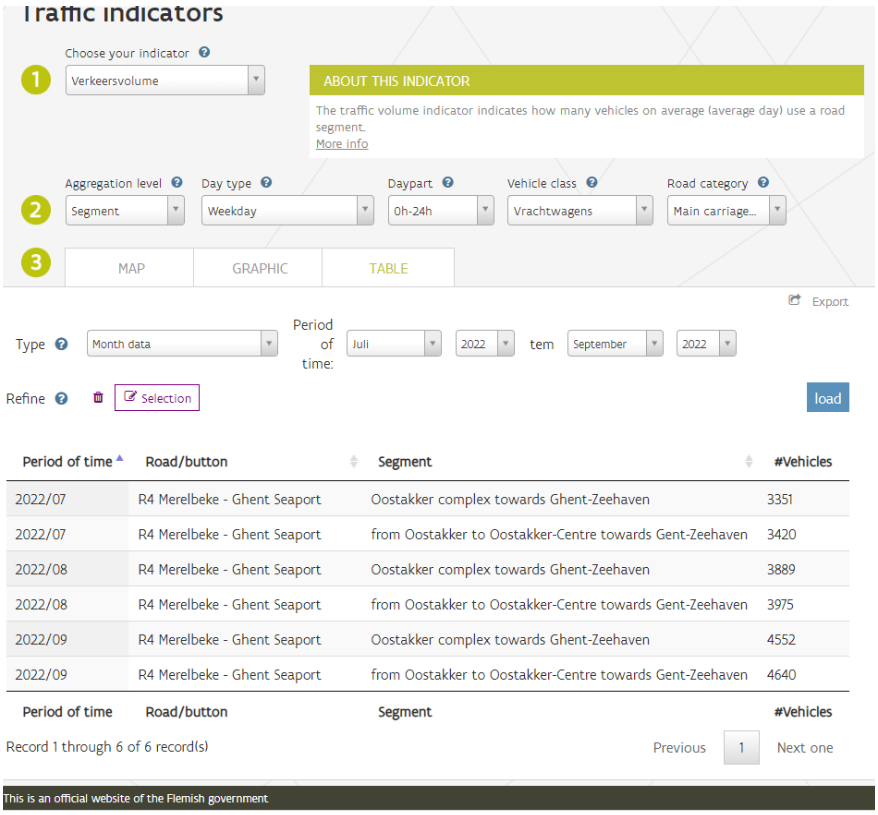


Figure 15: Telenet 3.5GHz coverage in Zalzate

Figure 95 Existing 5G infrastructure in cross-border area: Zelzate-SaaS van gent from the side of zelzate [30]



Traffic indicators

1 Choose your indicator: Verkeersvolume

ABOUT THIS INDICATOR

The traffic volume indicator indicates how many vehicles on average (average day) use a road segment.
More info

2 Aggregation level: Segment | Day type: Weekday | Daypart: 0h-24h | Vehicle class: Vrachtwagens | Road category: Main carriage...

3 MAP | GRAPHIC | TABLE

Export

Type: Month data | Period of time: Juli 2022 tem September 2022

Refine | Selection | load

Period of time	Road/button	Segment	#Vehicles
2022/07	R4 Merelbeke - Ghent Seaport	Oostakker complex towards Ghent-Zeehaven	3351
2022/07	R4 Merelbeke - Ghent Seaport	from Oostakker to Oostakker-Centre towards Gent-Zeehaven	3420
2022/08	R4 Merelbeke - Ghent Seaport	Oostakker complex towards Ghent-Zeehaven	3889
2022/08	R4 Merelbeke - Ghent Seaport	from Oostakker to Oostakker-Centre towards Gent-Zeehaven	3975
2022/09	R4 Merelbeke - Ghent Seaport	Oostakker complex towards Ghent-Zeehaven	4552
2022/09	R4 Merelbeke - Ghent Seaport	from Oostakker to Oostakker-Centre towards Gent-Zeehaven	4640
Period of time	Road/button	Segment	#Vehicles

Record 1 through 6 of 6 record(s) | Previous | 1 | Next one

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Figure 96 traffic indicators about trucks going from gent to Zelzate and Saas van gent

Cost data

Table 25 Cost input data

TO-Service center Costs	Unit	Value	Comment	Source
TO-center office rent	€/m²/year	275		[31]
Office space per operator	m2/operator	16	4*4m	SeaFar
TO-center control setup	€	250000	for ship control/for trucks keep VTRON assumption	SeaFar
TO remote station	€/month	800	renting: including support and maintenance	VTRON
TO remote control room	€/month	1550	renting: including support and maintenance	VTRON
internet connectivity	€/year	2400	100 euro per month for fibre , €2400 (only for the office, not covering ship-shore connectivity via 4G) - 2 fibres for redundancy	[32]
TOC energy Consumption	kwh/year	23260	Large-scale consumer	[33]
TO truck operator	€/year	43868		[34]
TO Crane operator	€/year	43868		[34]
TO Barge/ship operator	€/year	55000		Seafar
TO kit truck	€	14250	for 5G	VTRON
TO barge New	€	125000	Full Seafar Control System new	Seafar
TO barge retrofitting	€	175000	Full Seafar Control System with retrofit	Seafar
TO kit crane	€	85000	50% of the cost of retrofitting one barge	Assumption
TO kit skid steer	€	15000		Roboauto
Cost KWh	euro cents	27		TELENET
maintenance Rate MNO		7%	on top of CAPEX	KPN/TELENET
Overhead Cost Rate MNO		7%	on top of CAPEX + OPEX	KPN/TELENET