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Perspective

Open RAN could deliver up to 30% TCO savings for operators with the right platform strategy and skill set

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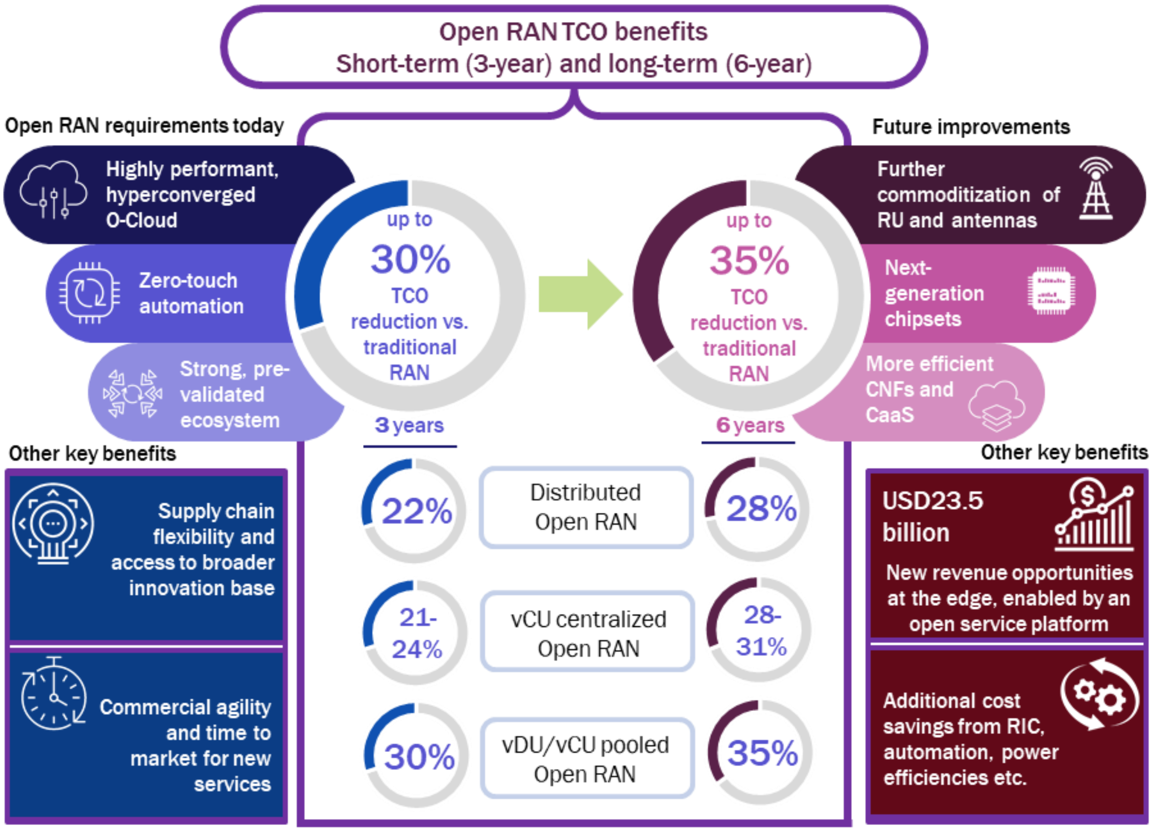
1. Executive summary

Open RAN has gained significant momentum over the last few years because operators want their 5G networks to be more flexible, cost-effective and automated than the traditional physical RAN. Operators aim to achieve a wide range of commercial and operational goals by using disaggregated, cloud-native Open RAN technology for 5G. Total cost of ownership (TCO) reduction is often the most desired objective for implementing Open RAN architecture, but at the same time the most debated one. This highly disruptive technology is at an early stage and operators lack a clear idea and consensus on the impact that Open RAN will have on the TCO of the network. To bring more clarity to the TCO debate and to provide guidance to the industry, Analysys Mason, in conjunction with Wind River, developed a realistic TCO model that analyses the short-term (3 years) and mid-term (6 years) capex and opex implications of deploying Open RAN technology compared to that of traditional RAN deployments.

In our TCO model, we analysed the brownfield deployment scenarios of traditional and Open RAN architecture options (distributed, vCU centralized and vDU/vCU pooling).[1] These scenarios were modelled for three different operator profiles including a Tier-1 operator in Western Europe, a medium-sized incumbent operator in a developed market and a Tier-1 operator in an emerging market. This report discusses the key findings of this TCO analysis (Figure 1).

Figure 1: Overview of Open RAN TCO model results and other key benefits of Open RAN



Source: Analysys Mason

1 vCU = virtual central unit; vDU = virtual distributed unit.

1.1 Distributed Open RAN architecture can deliver up to 22% TCO savings over 3 years and centralising vCU can boost savings to 24%

Our 3-year TCO model shows that in comparison to traditional physical RAN, the distributed Open RAN architecture can reduce TCO by 22% for the Western European Tier-1 operator and by 20% for the medium-size developed market operator. TCO reduction for the emerging market Tier-1 operator is slightly smaller (13%) because traditional physical RAN equipment prices are cheaper the labour cost base is lower in these regions, which reduces the impact of savings from automation. Overall, achieving these costs savings for all operators depends on the adoption of a fit-for-purpose Open RAN platform that consists of the following components.

- Open, commodity radio units and antennas that have lower profit margins than the existing proprietary radio solutions.
- A highly performant, hyperconverged cloud platform that optimizes the number and costs of the Open RAN cloud nodes.
- A strong, pre-validated ecosystem of suppliers that minimises the cost and complexity of disaggregation and openness.
- Zero-touch automation capabilities, such as remote configuration and provisioning of vDU and vCU nodes, which play an important role in keeping indirect capex costs of roll-outs low.

In the vCU centralized Open RAN scenario, TCO reduction figures are similar to those for the distributed architecture and consistent across the operator profiles (for example, 21% for the Western European Tier-1 operator). The major difference in this scenario is that vCU pooling provides better software capex and opex than the distributed architecture but it also leads to additional costs for hardware servers and power in the data center. We found that overall this offsets the gains in software costs. However, if operators are able to reutilize idle data center capacity to host the vCU functions without incurring these additional data center costs they can boost the TCO savings (for example, to 24% for the Western European Tier-1 operator), which can make this scenario more attractive than the distributed architecture.

1.2 vDU/vCU pooling can provide 30% TCO reduction over 3 years but it is not a realistic architecture for many operators today

The pooling of vDU and vCU resources away from the cell site in suitable network locations (for example, far edge data centers for vDU) potentially offers the greatest efficiency benefits of all the modelled scenarios. However, this scenario is also very difficult to realize for many operators today because it requires expensive and available fiber in the fronthaul to meet the latency requirements. In addition, the limited availability of far edge data centers to host vDU functions is another barrier. Overall, the costs associated with these challenges can be highly detrimental to the business case. As such, this scenario is not the main focus for the next 3 years but it will become increasingly viable as the investments in edge computing technology and locations increase. In the hypothetical scenario that we built for completeness, in which the Tier-1 Western European operator already has fronthaul fibre infrastructure in place and access to edge data center locations, vDU/vCU pooling can deliver up to 30% TCO savings over 3 years.

1.3 A highly optimised CaaS layer plays a crucial role in realizing the cost benefits of Open RAN deployments

A key assumption of our TCO model is the use of a highly performant and optimized CaaS platform that underpins the cloud-native Open RAN functions. To assess the impact of the underlying CaaS platform on the TCO, we tested our model for sensitivity with two different CaaS environments. The key capabilities that we analyzed include a hyperconverged control plane architecture that consumes a minimum number of physical cores (for reducing the number of server nodes and opex/power costs), zero-touch automation and low processing latency. Our analysis shows that using a CaaS platform without these features and capabilities in the distributed architecture generates only negligible TCO savings (approximately 4%) for the Tier-1 Western European operator and defeats the Open RAN business case for the emerging market Tier-1 operator because the TCO is 4% higher than for traditional physical RAN.

1.4 Further innovation, cost savings and new revenue opportunities will make the Open RAN business case even more attractive in the near-term

The TCO and business case for Open RAN is likely to improve further over the next few years. In terms of additional future cost savings, we expect that further standardization and commoditization of the physical units, such as RU and antennas, as well as the introduction of chipsets and cloud hardware that are higher-performance and more energy-efficient will boost TCO savings. In anticipation of these benefits, we developed a scenario for Open RAN TCO over 6 years. This scenario shows that TCO savings in each Open RAN scenario increases considerably; for instance, distributed Open RAN TCO benefits grow from 22% to 28% and the savings from the vCU centralized option could potentially rise to 31%.

It is important to note that the business case for Open RAN will not only be driven by capex and opex savings but also by new service opportunities. Open RAN removes the technology barrier for delivering new revenue-generating services at the edge thanks to its provision of a generic compute platform in the RAN. These services include a wide range of industry 4.0 and 5.0 applications such as manufacturing automation, robotics and autonomous vehicles. Analysys Mason estimates that there is a USD24 billion new revenue opportunity in the far edge by 2030 and having an open, flexible cloud-native RAN platform will be a key enabler for operators to seize this opportunity.

2. Operators expect to adopt cloud-native, disaggregated Open RAN to maximise their 5G ROI

Operators have been on a journey to make their networks more software-driven and cloud-based over the past decade. They have started to migrate from vertically integrated, single-purpose appliances to virtual network functions (VNFs) and cloud-native network functions (CNFs) running on cloud infrastructure. Until recently, RAN resisted the process of cloudification that were happening in other network domains because of its stringent performance requirements and complexity. However, technological advancements in hardware (for example, chipsets and commercial-off-the-shelf (COTS) servers) and cloud-native network functions and automation software have made the separation of RAN software from fixed-function hardware technically and economically feasible. Analysys Mason forecasts that vRAN will be the fastest-growing domain in terms of operators' network cloud investment: it will grow from USD293 million in 2021 to USD12.1 billion by 2026.[2]

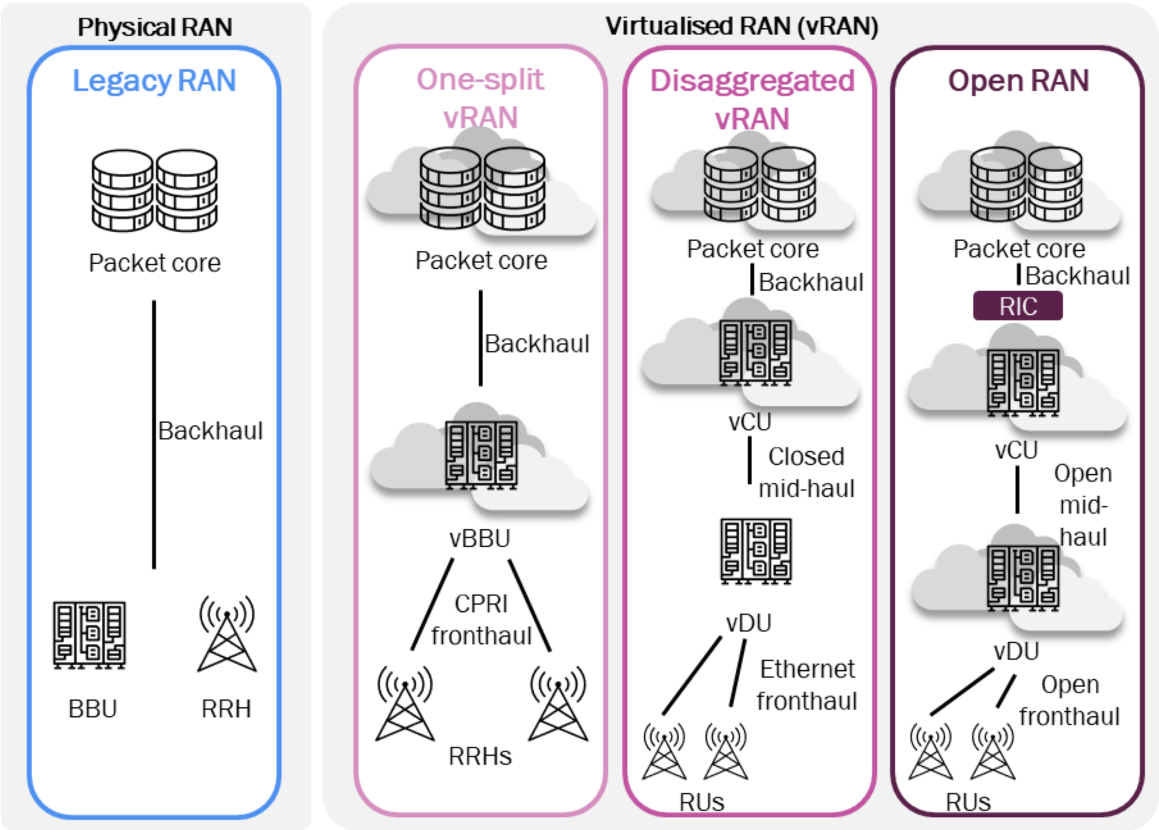
Several components, such as antennas, will remain physical, but many other RAN functions can be virtualised and deployed in a cloud-native infrastructure that consists of Kubernetes-managed, resource-efficient containers and general-purpose hardware and accelerators. In addition, industry initiatives and standards such O-RAN and Open RAN made significant progress in specifying and standardising the functional disaggregation of the RAN (centralized unit (CU), distributed unit (DU) and radio unit (RU)). The functional disaggregation has also made

2 For more information, see Analysys Mason's *Network cloud infrastructure: worldwide forecast 2021–2026*.

it more possible to implement the RAN in a cloud-based way. This in turn could result in a more diverse vendor and technology ecosystem, which is attractive to operators at a time when they are reassessing their supply chains. Such ecosystems will be mainly centred around decomposed cloud-native functions, commodity general-purpose hardware and open, flexible cloud platforms that stitch together these disaggregated components. This is a radical departure from the existing single-vendor/application-based, pre-integrated RAN appliances.

The industry often confuses the terms vRAN and Open RAN and may sometimes use them interchangeably. In this report, we define all types of cloud-based RAN architecture as vRAN, including those from traditional vendors with closed or proprietary interfaces between RAN components. Open RAN, on the other hand, is considered to be a subset of vRAN and refers to the disaggregated vRAN architecture with open, standard internal interfaces that support multi-vendor implementations (Figure 2).

Figure 2: Overview of physical and virtualized RAN architecture

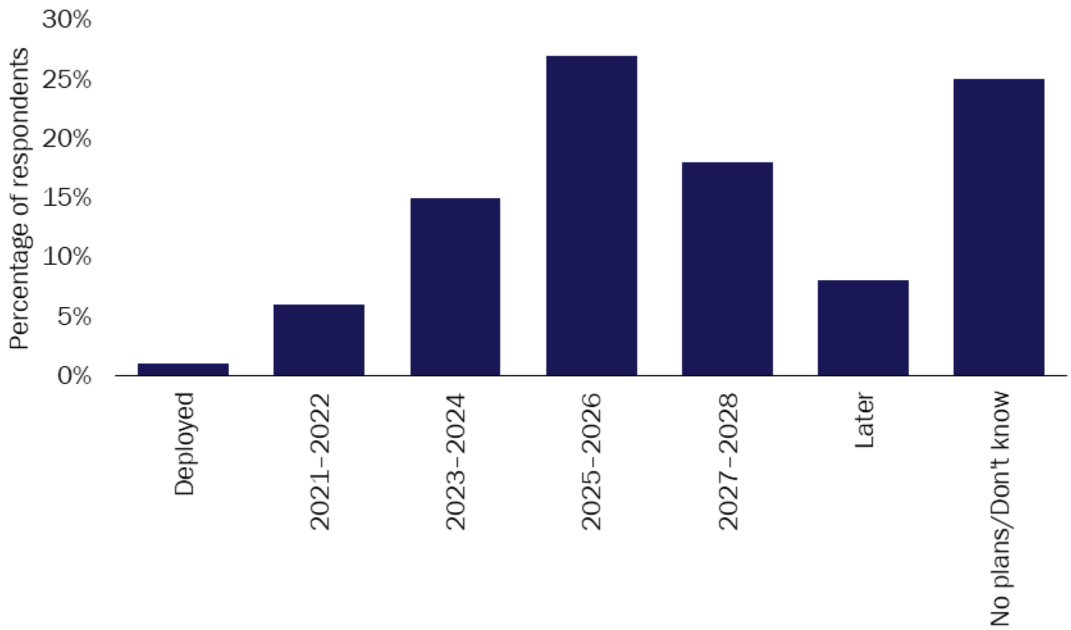


Source: Analysys Mason

A growing number of operators are considering adopting Open RAN as they seek to maximize the benefits of rolling out 5G networks. There is an increasing level of activity and investments, particularly from early-mover operators such as Dish, Rakuten, Verizon and Vodafone for 5G Open RAN, and other operators have also started to devise their plans for the future. Analysys Mason's survey of 82 mobile operators worldwide in 2021 shows that 22% of participant operators expect to have started deploying Open RAN in some part of a commercial macro network by the end of 2024, and this figure rises to 49% by the end of 2026 (

Figure 3). Operators are facing several hurdles with Open RAN, as explained in section 3.1 of this report. However, operators and Open RAN ecosystem stakeholders are working together to overcome these hurdles (section 3.2), which will give more impetus to Open RAN implementations in the near term.

Figure 3: Operators' expected timeframe for starting commercial Open RAN deployments in a macro network[3]



Source: Analysys Mason

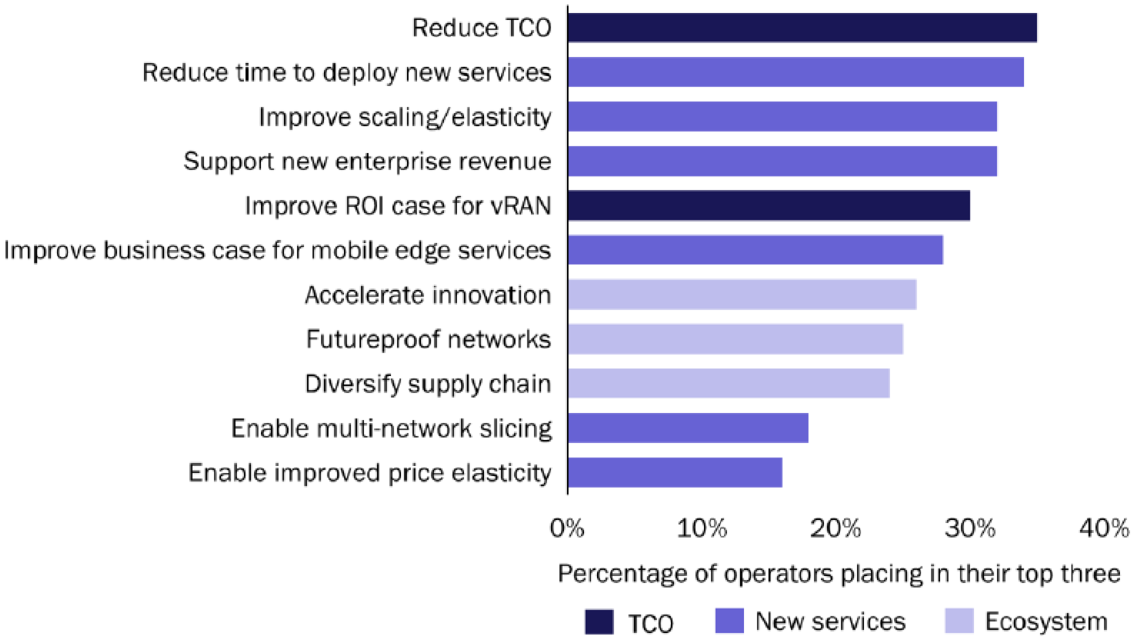
2.1 Cost efficiencies, service agility and supply chain flexibility are the key drivers of Open RAN

Many operators want to pursue the opportunity to offer new services with 5G in a variety of consumer and industry verticals using advanced RAN capabilities such as ultra-low latency and network slicing as well as complementary technologies such as edge computing. 5G is also expected to play a pivotal role in increasing the availability and access to broadband connectivity and to support the digital transformation of enterprises and government services. However, operators are faced with the challenge of large 5G capex and opex bills associated with densifying their networks by adding more sites using traditional network technologies without a proven 'killer application' or use case. This is pushing operators to rethink the way they are designing, procuring and building their networks.

Building the 5G networks with cloud-native, open RAN and zero-touch automation technologies, supported by a fast-innovating, open vendor ecosystem is quickly emerging as a potential solution to tackle these challenges and maximise the return on 5G investments. The growing momentum of open and disaggregated RAN has a wide range of drivers (Figure 4).

3 Question: "What is your expected timeframe for starting commercial Open RAN deployments in a macro network?"; *n* = 82.

Figure 4: Top drivers for adopting Open RAN[4]



Source: Analysys Mason

TCO reduction is a top driver for operators to adopt Open RAN and this mainly rests on the following principles.

- Operators aim to use lower-cost, standardized open RAN hardware (commoditized radio units, general-purpose CPUs, COTS servers) and software components to reduce capex compared to that for traditional physical RAN components, which are expensive and available only from a small number of vendors. Moving to disaggregated RAN architecture with open interfaces can increase supply chain flexibility for operators and reduce single-vendor reliance. In the context of TCO, this is expected to bring a greater level of price competition as well as faster declining technology costs thanks to rapid innovation cycles compared to the existing closed RAN ecosystem.

- Cloud-native RAN infrastructure and tools can reduce operational complexity and lead to opex savings by building zero-touch automation that supports autonomous healing, changes and performance optimizations of Open RAN functions at scale.

It should be noted that the TCO reduction goal with Open RAN is not straightforward to attain. Operators are cautious about the operational and technology hurdles, which are discussed in section 3, and need guidance on how they can achieve the promised cost-savings.

Increased innovation and service agility is a key strategic driver for adopting Open RAN as operators look to boost the ROI on Open RAN beyond cost savings. Open RAN could shake up the supply chain by facilitating the market entry of new specialized players and allow operators to access a broader innovation base, underpinned by industry groups and open-source communities. This means that operators can more quickly take

4 Question: "What are the key commercial drivers to adopt Open RAN architecture? (please select and rank your top 3, with 1 being most significant)"; *n* = 82.

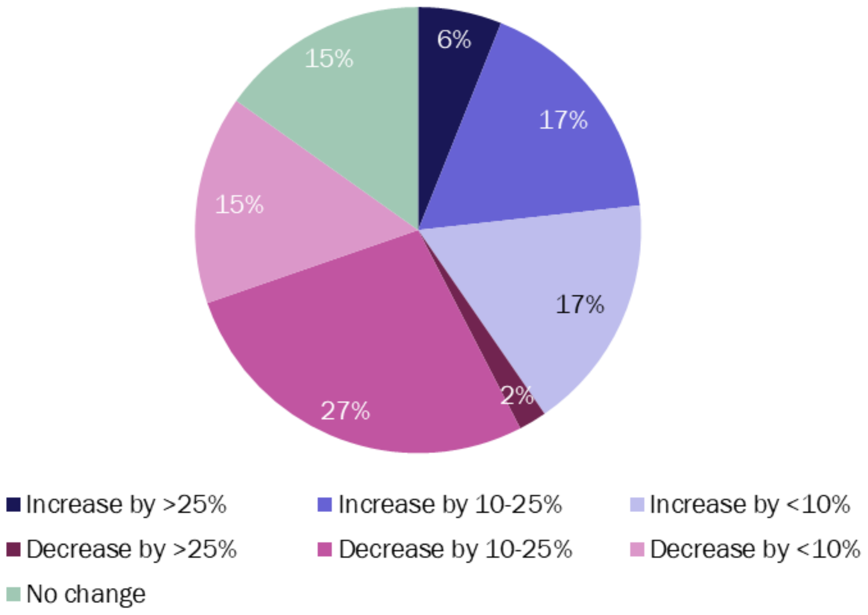
advantage of new innovations to evolve their infrastructure, which in turn enables them to achieve greater cost savings and add new services without relying on a single vendor because the open interfaces offer the possibility to swap one vendor's hardware or software for that of another. Coupling these benefits of open RAN environments with the adoption of cloud-native software and automation as well as new technologies such as RAN Intelligent Controller (RIC), Open RAN could provide more scalability/elasticity in the network and enable faster time to market for new revenue-generating 5G services.

3. TCO concerns about Open RAN could be addressed by a fit-for-purpose cloud-native platform

3.1 Operators are increasingly uncertain about Open RAN TCO savings due to several key challenges and risks

TCO reduction is one of the key reasons for operators to move to an Open RAN architecture and ecosystem. However, operators are not yet convinced, and the industry is increasingly sceptical about the cost saving benefits of Open RAN. In fact, Analysys Mason's survey results show that the operators are divided in their opinion about the cost impact of Open RAN implementation (Figure 5). Adoption will depend on overcoming scepticism about Open RAN's ability to reduce TCO. This scepticism exists because of several uncertainties and risks around deployment costs, technology and ecosystem maturity, and operational impact, especially at the early stage. As such, operators' TCO evaluations of Open RAN should be limited to the short term (for example, 3 years) initially because most of these early stage challenges and additional costs will probably be alleviated over time as the technology and its ecosystem matures.

Figure 5: Operators' expectations for Open RAN's impact on TCO compared with that for traditional physical RAN[5]



Source: Analysys Mason

5 Question: "Do you expect your network costs for the RAN to change as a result of implementing Open RAN?"; *n* = 82.

Open RAN represents a major departure from the traditional way in which operators design, procure, deploy and manage their large and complex RAN and it also redefines operators' relationships with their suppliers. Operators lack a clear idea and consensus on the TCO of adopting Open RAN technology, mainly because of the following potential challenges and risks.

- **Performance trade-offs and deployment footprint.** RAN is still a greenfield area for network cloud and operators need the general purpose hardware and cloud-native software of Open RAN to handle the intensive compute requirements of RAN on par with traditional physical RAN in a cost-effective manner. The capex (servers, software licences, implementation and integration services) and opex (labor and power costs) involved in rolling out distributed cloud nodes across hundreds or thousands of sites can be prohibitively expensive if the underlying cloud infrastructure is not fit for purpose. Also, 5G is a moving target: each release brings additional performance requirements on the processors and as 5G moves to millimetre wave spectrum for some applications, the processing burden of the beamforming will be high and could outrun improvements in COTS hardware performance.

- **Integration costs and complexity.** Virtualization and disaggregation of RAN leads to a more complex architecture than the traditional physical RAN and incurs additional costs of re-aggregation and integration of the system components, which are provided by a diverse set of suppliers, to ensure carrier-grade performance and resilience. Therefore, having a mix and match approach to Open RAN with many different suppliers that lack pre-validation and testing could require large amount of engineering resources, support by external system integrators and time.

- **Lack of experience/skills for the management of distributed network edge.** RAN has a highly distributed architecture and the disaggregated, virtualized components of Open RAN need to be deployed and operated across a large number of network edge locations such as cell sites and metro DCs. Operators typically do not yet possess the right skills and toolsets to automate and orchestrate this highly critical, distributed infrastructure and resources at a large scale. Without acquiring these capabilities, the current mode of slow, labour-intensive operations in such environment would negate the cost, agility and scalability benefits of Open RAN.

3.2 Operators need to adopt an Open RAN platform strategy and technology that maximises the return from their investments

Operators and Open RAN ecosystem are working together to address the challenges and risks discussed in the previous section. This primarily involves creating a highly optimized, flexible Open RAN platform (O-Cloud software and hardware) that is increasingly becoming possible today with a strong pre-validated ecosystem of RAN functions vendors, chip vendors and cloud technology providers. Figure 6 illustrates the key pillars of such platform and Figure 7 provides detailed features and capabilities operators should look for when building it.

Our research and interviews with operators indicate that building an Open RAN platform as described in Figure 7 will be essential to overcome the barriers and realize the commercial goals of the Open RAN, especially the TCO savings. To test this hypothesis and provide the much-needed industry guidance on a realistic TCO, Analysys Mason built a complete, holistic TCO model based on such Open RAN platform and ecosystem, which is presented in the next section.

Figure 6: Key pillars of a successful Open RAN platform

Source: Analysys Mason

Figure 7: Key features and capabilities of the Open RAN platform

Requirement	Rationale
Highly performant and secure O-Cloud infrastructure	A Kubernetes-based O-Cloud infrastructure that supports: • the highly demanding processing requirements of the 5G RAN's real-time functions as well as advanced technologies such as MIMO • optimization of the number of server and power requirements in order to reduce costs to deploy and scale the distributed hardware footprint • both centralized and distributed RAN architecture • the execution of decomposed, cloud-native microservices on bare metal infrastructure • time-synchronization and heterogeneous architecture with multiple accelerators while retaining openness and programmability • cloud-native network functions (Open RAN and others) from multiple vendors as well as other enterprise and consumer service applications • a high-level of security and reliability to host all network functions and applications with strict isolation between them.
Distributed orchestration and zero-touch automation	Open RAN needs zero-touch automation and orchestration that spans the entire lifecycle, including Day 0 deployment (remote, automated software installation), Day 1 (preparation for operation, tests and validations) and Day 2+ ongoing live operations (self-healing, self-optimisation, updates and upgrades with CI/CD)
A complete, pre- validated ecosystem	A pre-validated ecosystem of Open RAN vendors that can provide an open, standards-based full-featured stack to reduce integration costs and time to test/deploy.

Source: Analysys Mason

4. Open RAN based on hyperconverged cloud with zero-touch automation can deliver 30% 3-year TCO savings

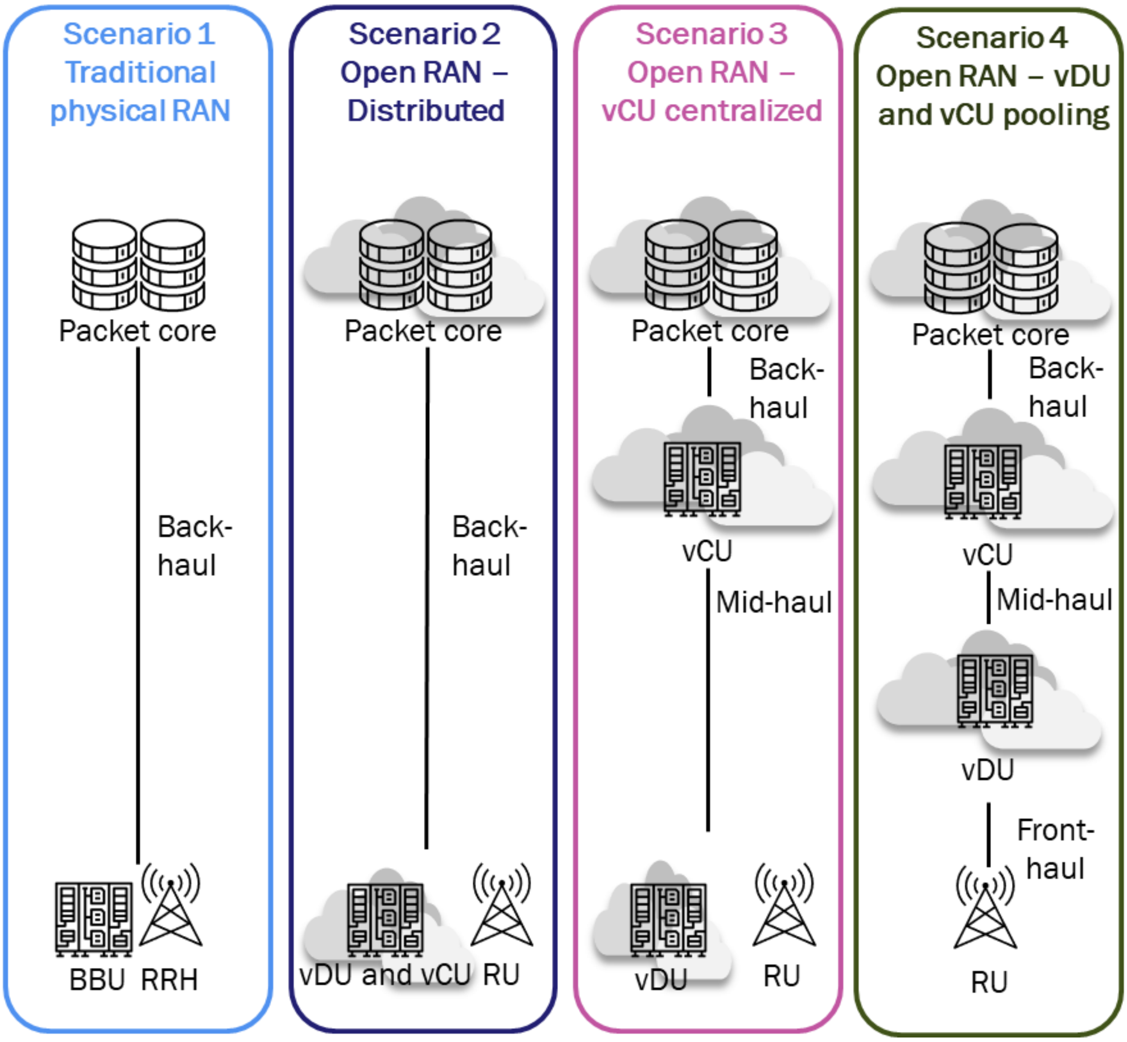
Analysys Mason has developed a comparative TCO analysis of disaggregated, Open RAN and traditional physical RAN for 5G, in collaboration with Wind River. Using inputs and validation from Tier-1 operators from developed and emerging markets, we constructed a set of models based on various RAN deployment scenarios and regional characteristics of operators to demonstrate and pinpoint the comparative capex and opex for end-to-end 5G RAN implementations.

Our comprehensive TCO model analyses the brownfield deployment scenarios of traditional and main Open RAN architecture options (Figure 8) for three hypothetical operator profiles:

- a large Tier-1 operator in Western Europe
- a medium-sized incumbent in a developed market
- a large Tier-1 operator in a developing market.

Each option reflects the real-life spectrum allocations, subscriber numbers, network traffic, design and cost parameters of operators for their respective sizes and geographies.

Figure 8: TCO model scenarios[6]



Source: Analysys Mason

6 Packet core is excluded from the TCO model.

Key modelling assumptions

The key modelling assumptions for the TCO model operator profiles are provided in Figure 9. RAN technology and architecture choices and modelled technology components (Figure 10) are assumed to be the same in all these profiles. All hardware, software and labor costs in the model reflect the regional variances for both traditional physical RAN and Open RAN scenarios.

The O-Cloud platform (CaaS) modelled in this TCO exercise is aligned with the key features and capabilities outlined in Figure 7 in the previous section. We assume that the O-Cloud platform has been pre-validated with Intel's FlexRAN reference architecture and that it runs on general-purpose COTS servers based on 3rd Generation Intel Xeon Scalable processors.

Figure 9: Key assumptions for modelled operator profiles

Attribute	Tier-1 in Western Europe	Medium-sized incumbent in a developed market	Tier-1 in a developing market
Country population	60 000 000	40 000 000	50 000 000
Market share of subscribers	33%	33%	33%
5G coverage of territory (end of year 3)	35%	35%	35%
Total number of RAN sites (end of year 3)	2000	1700	900

Source: Analysys Mason

Figure 10: Assumptions used in the TCO model by architecture type

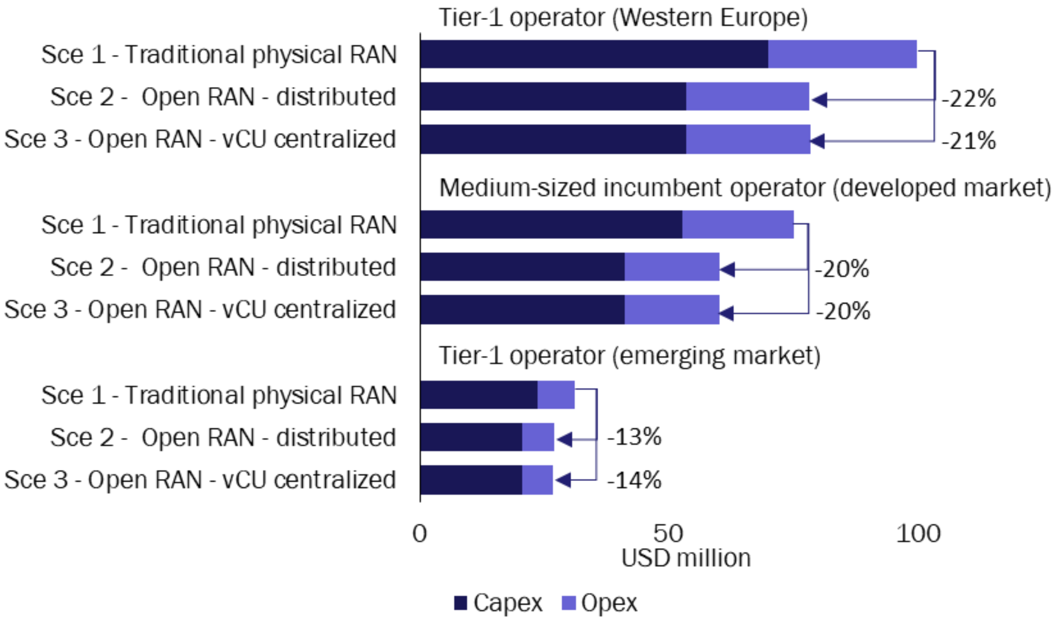
Architecture	Assumption
Radio spectrum	Mid-band 5G spectrum: 3.5GHz (100MHz) and 700MHz (2×10 MHz)
Geo-types	Coverage areas are split into five geo-types based on population density: dense urban, urban, suburban, rural, very rural
xHaul	• 5G demand is calculated as an incremental cost to existing transport capacity • Technology mix includes leased lines, xDSL, Microwave and own fibre
Capex parameters	Hardware, software and professional services for: • physical RAN: BBU, RRH, backhaul • Open RAN 7.2: RU, vDU, vCU, CaaS, orchestration, xHaul (RIC is excluded) Cell site passive infrastructure (towers, poles and roofs) are excluded
Opex parameters	Headcount, power and space and support and maintenance
Length of analysis	3 years and 6 years

Source: Analysys Mason

4.1 TCO reduction is significant enough to justify the move to Open RAN today but operators need to have the right technology stack and skillsets

Figure 11 illustrates the cumulative, 3-year TCO for the three RAN deployment scenarios for each of the three operator profiles.

Figure 11: Cumulative 3-year TCO for the RAN deployment scenarios



Source: Analysys Mason

Our model shows that the overall TCO savings from distributed Open RAN (scenario 2) and the vCU centralized option (scenario 3) are very similar across the operator profiles. Although vCU pooling in a remote data center provides better software capex and opex in the latter scenario, it also leads to additional hardware server and power costs in the data center. This offsets the gains in software costs. However, if operators are able to reutilize spare data center capacity to host the vCU functions without incurring these additional data centre costs, scenario 3 provides a better TCO than scenario 2. For instance, in the case of the Tier-1 operator in Western Europe, total savings increase from 21% to 24%.

The Open RAN cost savings are the most pronounced (up to 22%) in the Tier-1 Western European operator's Open RAN implementation thanks to its larger scale; greater unit price difference between Open RAN and traditional physical RAN components; and higher opex savings with zero-touch automation. Figure 12 provides the detailed breakdown of the key capex and opex items and cost differences between RAN scenarios for the Tier-1 Western European operator. The medium-sized incumbent operators' Open RAN TCO savings (up to 20%) are comparable to those of the Tier-1 Western European operator, albeit slightly lower due to less economies of scale. The key cost items and differences between the scenarios are consistent between these two profiles (see the annex (section 7) of this report for the breakdown of the TCO results for the medium-sized incumbent operator.)

Figure 12: TCO breakdown for Tier-1 operator in Western Europe

TCO component	Scenario 1 Traditional physical RAN	Scenario 2 Open RAN – distributed	Scenario 2 compared with Scenario 1	Scenario 3 Open RAN – vCU centralized	Scenario 3 compared with Scenario 1
Capex					
RAN hardware and software	USD68 640 828	USD52 272 689	–24%	USD52 171 359	–24%
Backhaul and other	USD1 281 434	USD1 281 434	0	USD1 281 434	0
Total capex	**USD69 922 062**	**USD53 553 923**	**–23%**	**USD53 452 593**	**–24%**
Opex					
Supplier support and maintenance	USD18 376 258	USD9 624 860	–48%	USD9 085 670	–51%
Additional FTE costs	N/a	USD 2 058 884	N/a	USD2 058 884	N/a
Power costs	USD11 409 490	USD13 013 723	+14%	USD13 501 599	+18%
Rack space costs	N/a	USD3297	N/a	USD236 264	N/a
Total opex	**USD29 785 748**	**USD24 700 764**	**–17%**	**USD24 882 417**	**–16%**
TCO (3-year)	**USD99 707 810**	**USD78 254 686**	**–22%**	**USD78 335 010**	**–21%**

Source: Analysys Mason

Open RAN TCO reduction in the Tier-1 emerging market operators’ deployment is slightly smaller (up to 14%) than both of the developed market operator profiles (Figure 13). This is mainly due to cheaper traditional physical RAN equipment prices in these regions as well as lower labor cost base, which reduces the impact of automation savings.

Figure 13: TCO breakdown for emerging market Tier-1 operator

TCO component	Scenario 1 Traditional physical RAN	Scenario 2 Open RAN – distributed	Scenario 2 compared to Scenario 1	Scenario 3 Open RAN – vCU centralized	Scenario 3 compared to Scenario 1
Capex					
RAN hardware and software	USD17 682 156	USD14 537 543	–18%	14 467 723	–18%
Backhaul and other	USD5 972 110	USD5 972 110	0	USD5 972 110	0
Total capex	23 654 267	USD20 509 654	–13%	20 439 834	–14%
Opex					
Supplier support and maintenance	USD5 495 735	USD3 329 438	–39%	USD2 869 779	–48%
Additional FTE costs	N/a	USD1 029 442	N/a	USD1 029 442	N/a
Power costs	USD1 866 532	USD2 125 557	+14%	USD2 204 232	+18%

TCO component	Scenario 1 Traditional physical RAN	Scenario 2 Open RAN – distributed	Scenario 2 compared to Scenario 1	Scenario 3 Open RAN – vCU centralized	Scenario 3 compared to Scenario 1
Rack space costs	N/a	USD1648	N/a	USD39 217	N/a
Total opex	USD7 362 267	USD6 486 085	–12%	USD6 142 670	–17%
TCO (3–year)	USD31 016 534	USD26 995 739	–13%	USD26 582 503	–14%

Source: Analysys Mason

The use of open, commodity radio units (RU) and antennas instead of existing proprietary radio solutions is one of the major drivers of the Open RAN capex savings and arguably the most attainable one. Also, the lower cost Open RAN hardware and software comes with the benefit of reduced vendor support and maintenance expenses compared to those of traditional RAN, which helps to reduce opex.

The disaggregation and virtualization of BBU into vDU and vCU makes a critical contribution to the overall Open RAN capex savings, largely due to the demands of the real-time 5G RAN processes in layers 1 and 2 in vDUs. Physical limitations in cell sites and large costs associated with cloud hardware servers deployed across thousands of locations can be detrimental to the Open RAN business case. Our TCO model shows that a highly performant, hyperconverged O-Cloud platform is essential to optimize the number and costs of the Open RAN cloud nodes in order to achieve the capex reductions shown in Figure 12 and Figure 13. In addition, based on our operator interviews, we estimated that zero-touch automation capabilities in cell site deployments (for example, configuration, provisioning of vDU and vCU cloud nodes) can provide cost savings in the range of USD1500–2000 per site depending on the region. Zero touch automation plays an important role in keeping indirect capex costs low.

System integration costs are a major concern related to the Open RAN TCO as discussed in section 3. This typically stems from the increased costs and efforts of testing, validation and integration of the functional components and cloud infrastructure that come from many different vendors in a mix-and-match style of deployment. Our TCO model and deployment scenarios assume that all the cloud-native network functions (vCU and vDU) are provided by a single Open RAN vendor and these are pre-validated with the underlying CaaS platform and cloud hardware in order to minimize the cost and complexity of disaggregation and openness.

Despite Open RAN offering savings in many key TCO items, several opex areas generate higher costs than the traditional physical RAN environment. Our interviews with operators that are in the process of implementing Open RAN, showed that they need to make upfront investments for skill acquisition, which will be an ongoing opex to maintain the skill set level. These investments are needed to build the required level of operational automation in Open RAN, cloud-native infrastructure, which is largely unfamiliar to many operators today. These costs are reflected in the 'additional FTE costs' line item in Figure 12 and Figure 13. In addition, the power costs of Open RAN are currently higher than the appliance-based RAN solutions. This is mainly driven by the fact that the power efficiency of general-purpose COTS servers are not yet on par with the proprietary BBUs that benefit from the optimized power consumption of specialized chipsets (for example, ASICs).

Overall, these TCO results show that the cost savings from Open RAN are significant enough for operators to start their journey to Open RAN today if they base their deployments on the right technology stack and ecosystem, particularly the right O-Cloud platform as discussed in section 4.3. They will also need to make upfront investments to acquire the necessary cloud and automation skills and realise potential operational efficiencies. We also expect that the TCO savings of Open RAN will probably improve considerably over the next few years, which could further increase the attractiveness of the business case. This is discussed in section 5.

4.2 vDU and vCU pooling in Open RAN can reduce 3-year TCO by 30% if operators already have access to fibre fronthaul and edge data centres

vDU and vCU pooling (scenario 4) is the most advanced deployment scenario and potentially offers the following benefits that come from the aggregation/pooling both vDU and vCU resources in centralized data centre locations compared to the distributed architecture:

- more-efficient utilization of Open RAN hardware and software as well as spectrum resources, which reduces the overall RAN component capex and opex
- mitigation of physical space limitations in cell sites and optimization of the Open RAN server footprint to reduce power costs
- ability to leverage existing experience and skills in network cloud operations in centralized data centers; operators typically have less experience of a highly distributed cloud infrastructure.

Despite the greater efficiency benefits of this scenario, several key challenges may limit the adoption of this architecture.

- This scenario poses more stringent latency requirements as time-sensitive functions are moved further away from the radio units at cell sites. This requires expensive and available fiber infrastructure in the fronthaul to meet the front-haul latency demands.

- The availability of edge data centers to host vDU functions is another challenge because operators may not possess the data center environments in locations within the required distances. This may result in additional investments for building them or partnering with colocation providers.

Overall, this implementation scenario may not be realistic for all operators today because the costs associated with these challenges can be highly detrimental to the business case. As such, this scenario is not the main focus for the next 3 years but it will be increasingly viable as the edge investments grow. In the hypothetical scenario that we built for completeness, in which the Tier-1 WE operator already has fronthaul fibre infrastructure in place and access to edge data center locations, operators could achieve up to 30% savings as shown in Figure 14.

Figure 14: TCO results for fully centralized Open RAN for Tier-1 operator in Western Europe

TCO	Scenario 1 Traditional physical RAN	Scenario 4 Open RAN – fully distributed
Capex	69 922 062	46 716 161
Opex	29 785 748	22 722 292
Total	99 707 810	69 438 453
Delta from Scenario 1: traditional physical RAN	N/a	–30%

Source: Analysys Mason

4.3 The strong business case for Open RAN requires highly optimized cloud platforms with zero-touch automation capabilities

As discussed in section 3, the underlying O-Cloud platform plays a critical role in enabling successful Open RAN deployments. To assess the impact of the underlying cloud platform on the TCO, we tested our model for sensitivity with two different CaaS environments for O-Cloud with varying capabilities (Figure 15).

Figure 15: Key assumptions for the O-Cloud platform comparison

Assumptions	O-Cloud CaaS platform 1 (TCO model baseline)	O-Cloud CaaS platform 2
Architecture	Hyperconverged – single server per cell site	Requires two servers per cell site due to the need for an additional separate management server
Number of physical cores required by the platform	2	6
Zero-touch automation	Yes	No
Latency (processing)	9 µ	26 µ

Source: Analysys Mason

One of the key areas of comparison between the CaaS platforms is their impact on the server hardware footprint which is mainly driven by the control plane **architecture** and **the number of physical cores required by the platform:**

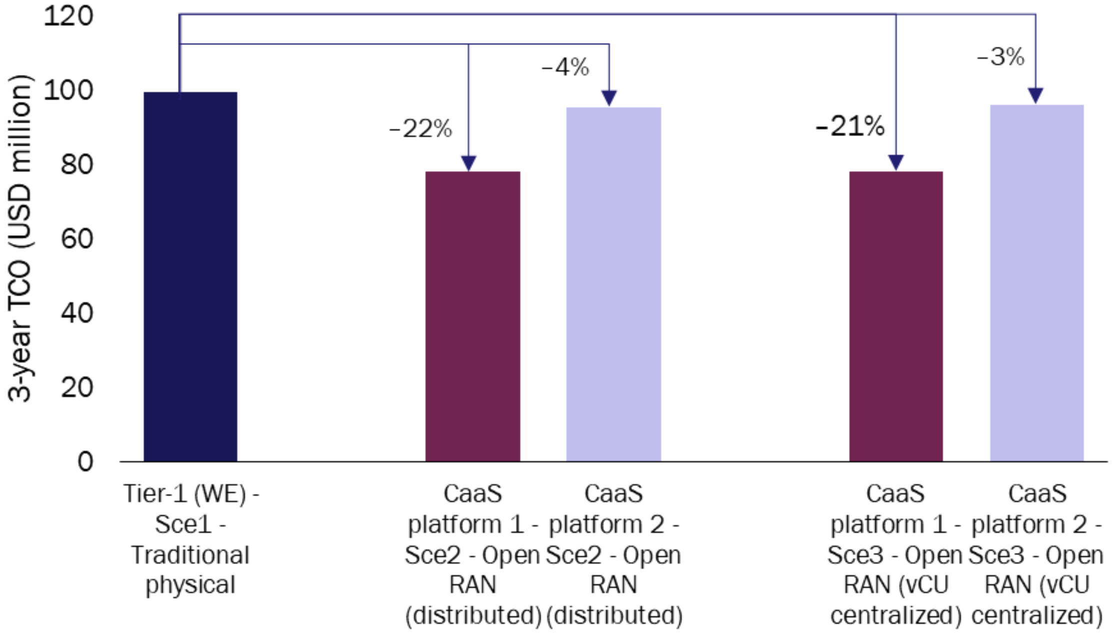
- Our TCO model is based on a hyperconverged platform that enables the deployment of cloud-native functions (vCU, vDU) and Kubernetes-based container orchestration (control plane) together in a single COTS server with compute, storage and networking resources. The alternative platform assumed for this sensitivity analysis requires an additional server for the control plane/management at each cell site location, which doubles the footprint of distributed cloud nodes.

- The number of physical cores that CaaS platform consumes is also important because the RAN network functions, which are still being developed and optimized for cloud-native infrastructure, take up most of the physical cores available in a COTS server. As the network demands grow and operators look to add new applications in their RAN clouds, having a resource-efficient CaaS platform such as two cores rather than 6 or more cores per node can help operators to control their hardware investments and power costs.

Other key factors we tested for sensitivity are **zero-touch automation capabilities** in Open RAN roll-outs and processing **latency**. As highlighted in the previous section, automated configuration and provisioning can deliver considerable cost savings. Lower processing latency within a CaaS platform, on the other hand, gives more room for transport latency which enables further centralization and pooling of Open RAN functions (such as the fully centralized scenario discussed in section 4.2) as these can be deployed further away from the cell sites.

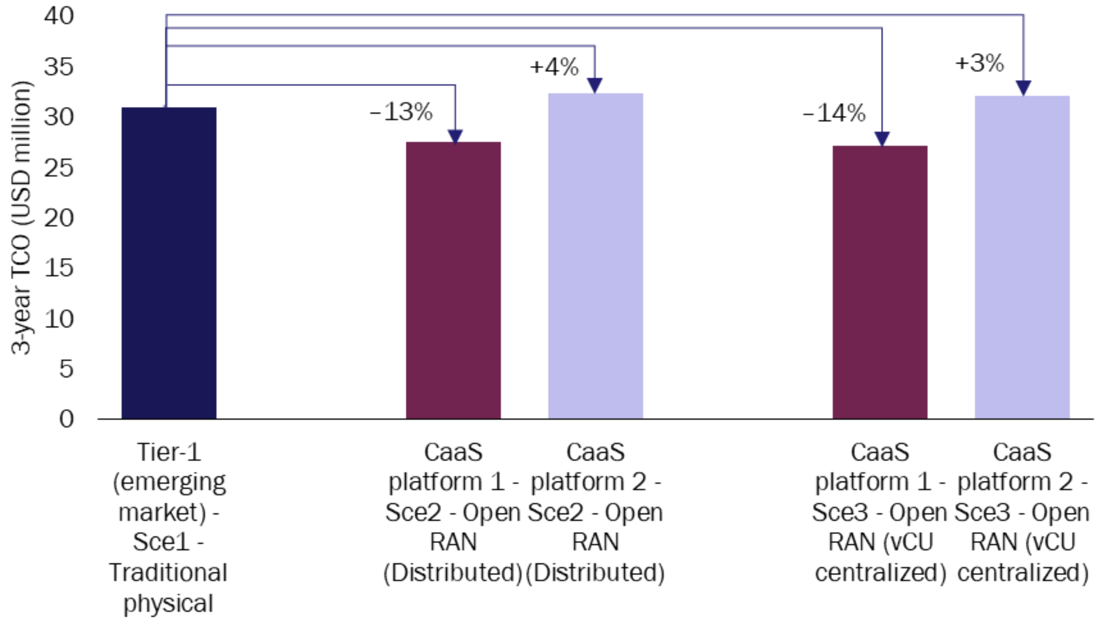
Our comparative analysis of the two cloud platforms show that a hyperconverged cloud platform with zero-touch automation and lower processing latency is crucial to make Open RAN economically viable: the alternative platform without these features and capabilities would only deliver a negligible amount of TCO savings for the Tier-1 Western European operator profile (Figure 16) and it actually makes the Open RAN more expensive than the traditional physical RAN for the emerging market Tier-1 operator (Figure 17).

Figure 16: TCO model results with CaaS platforms 1 and 2, Tier-1 Western European operator



Source: Analysys Mason

Figure 17: TCO model results with CaaS platforms 1 and 2, Tier-1 emerging market operator



Source: Analysys Mason

5. Open RAN business case will improve with further cost reductions and new service opportunities

5.1 Faster innovation in Open RAN ecosystem is likely to boost TCO savings in the near term

As discussed in section 2.1, one of the key benefits of Open RAN is that it lowers the market entry barriers for new, disruptive vendors and helps operators to shake up their supply chain. This cultivates a more diverse and richer RAN and network cloud ecosystem consisting of specialist technology suppliers, which could together innovate across all the layers of RAN hardware and software components faster than a closed RAN supply chain that is dominated by a few vendors.

As the adoption of Open RAN grows, it will attract more innovation and investments, and commercial hurdles will be alleviated. Today, indications are that the TCO and business case for Open RAN is likely to improve further over the next few years (Figure 18). For example, chipset providers such as Intel are strongly committed to developing high-performance, energy-efficient processors to support demanding vDU functions. These next-generation, general purpose CPUs are expected to help operators further optimize their Open RAN hardware investments. In addition to the evolution of the cloud infrastructure, further standardization and commoditization of the physical units such as radio units and antennas and achieving greater scale in the manufacturing of these components will probably reduce deployment and integration costs and boost the Open RAN TCO benefits.

Figure 18: Near-term innovations expected to improve Open RAN TCO

Potential areas for TCO improvements	Rationale	Assumed impact on TCO at Year 4 (vs. today)
Open RAN RU and antennas	Open RAN RU and antenna reference designs could become highly standardized over the next 3 years, which leads to commoditization and further cost reduction of these components	• 25% lower cost RU and antenna
Next-generation chipsets – lightweight HW	Chipset innovations could result in new server form factors that are smaller scale, lower cost and more power efficient than existing COTS servers today	• 50% lower server capex • 50% less power consumption
Next-generation chipsets – resource optimization	Next-gen CPUs are expected to reduce the number of physical cores required for to run vDU and vCU cloud-native functions and the O-Cloud/CaaS platform, which would lead to fewer servers and/or free resources to support the deployment of more applications	• 60% reduction in the xNF core consumption • 50% reduction in the CaaS software core consumption

Source: Analysys Mason

In anticipation of these future benefits, we extended our initial 3-year TCO model to 6 years[7] and added two scenarios. These estimate the impact of new innovations and declining cost trends in order to provide a more complete view of the capex and opex benefits of Open RAN. It is important to note that operators' ability to

[7] This extended analysis take account of increases in capacity demands of the RAN over time (for example, higher traffic/subscriber loads) but excludes advanced technologies such as massive MIMO or 6G.

maximize these future benefits will largely depend on gaining early experience of key Open RAN technologies and carrying out the operational changes needed to support Open RAN well in advance of the new innovations appearing.

For simplicity, this perspective report only presents the future-looking, evolutionary analysis developed for the Tier-1 Western European operator profile, but the results are consistent and proportional across all three operator profiles. The first analysis applies to scenarios 2 and 3 and assumes that the operator:

- implements lower-cost RU and antennas together with a lightweight HW for vCUs and vDUs in year 4 as part of regular lifecycle replacement of the first-generation solutions
- targets only suburban, rural and very rural areas (~2000 sites) which are more suitable for the lightweight HW due to relatively low performance demands compared to dense, urban areas.

Figure 19 shows that these future innovations and cost improvements could boost TCO savings from the initial 3-year 21% (vCU centralized) to 22% (distributed) (Figure 12 in section 4) to 28% for the both scenarios for the Tier-1 Western European operator over a period of 6 years.

Figure 19: 6-year TCO analysis of Open RAN scenarios 2 and 3 with the future improvements for Tier-1 Western European operator

	Traditional physical RAN	Scenario 2 Open RAN (distributed)	Scenario 3 Open RAN (vCU centralized)
Capex	231 212 239	159 042 927	158 826 360
Opex	111 098 014	87 494 321	86 811 328
Total	342 310 254	246 537 248	245 637 687
Difference compared to traditional physical RAN	N/a	–28%	–28%

Source: Analysys Mason

The second future-looking analysis is based on the same level of cost reduction for the RU and antennas but assumes the use of more powerful, next-generation chipsets that optimize and reduce the core consumption of xNFs by 60% and CaaS software by 50%. These chipsets provide the highest level of benefits in scenario 4 where vDU and vCU resources are pooled in highly compute-intensive servers. Similar to the previous analysis, this is implemented as part of the regular lifecycle replacement of the existing servers in year 4. Figure 20 shows that TCO savings for the scenario 4 increases from 30% (Figure 14) to 35% as a result of these additional benefits.

Figure 20: 6-year TCO analysis of Open RAN scenario 4 with the future improvements for Tier-1 Western European operator

	Traditional physical RAN	Sce4 -Open RAN (fully centralized)
Capex	231 212 239	145 781 272
Opex	111 098 014	75 603 713
Total	342 310 254	221 384 985
Difference compared to traditional physical RAN	N/a	–35%

Source: Analysys Mason

Our interviews revealed that operators and their Open RAN suppliers are exploring other potential areas for cost-efficiencies (Figure 21) in addition to those discussed above. These were not quantified in our TCO model but operators expect that they will have a sizable impact on Open RAN TCO in future, further increasing the attractiveness of the business case.

Figure 21: Other potential areas for Open RAN TCO reduction

Areas	Description
Higher performance, lower-cost radio units	Innovation and expansion in the silicon ecosystem is expected to bring not only reduced cost but also new performance efficiencies in the RU and RF-layers through new generation of chips such as SoCs, FPGAs and ASICs.
RAN energy savings under low traffic load	Operators can potentially reduce the energy consumption in RAN during low traffic load situations thanks to the software automation and RIC capabilities which can trigger sleep mode and deactivation of carriers.
Integration and deployment replicability	As the development of reference designs and blueprints from working groups mature and more operators implement Open RAN at scale, integration complexity and interoperability issues will disappear gradually and it will be much faster and cheaper to expand and replicate Open RAN designs for different geographies and deployment scenarios.
Open RAN skills and expertise	Open RAN specifications and Kubernetes, cloud-native software are highly complex areas that continue to evolve at a rapid rate. There is currently a limited pool of experts which adds to implementation cost. Operators expect that these necessary skills and expertise will become more available and cheaper as Open RAN gains more traction.

Source: Analysys Mason

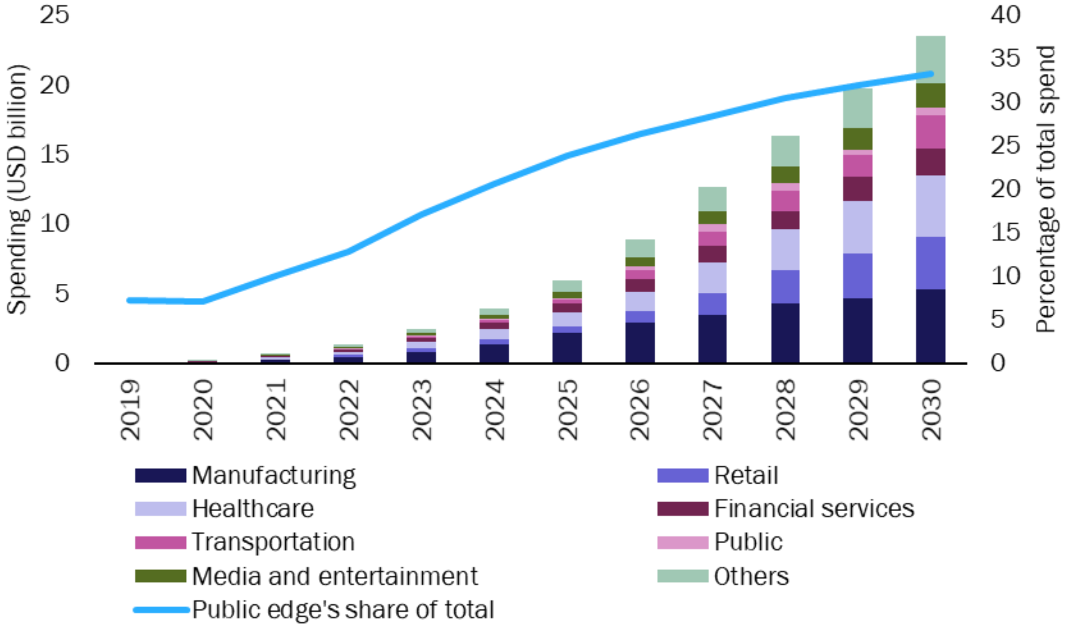
5.2 Beyond TCO savings, new services and revenue streams can be enabled by Open RAN to ensure an attractive ROI

Our TCO model demonstrates significant cost savings for Open RAN today and in future compared to traditional approaches but operators can target new revenue opportunities to improve the Open RAN business case. Open RAN removes the technology barrier for delivering new revenue-generating services at the edge thanks to providing a generic compute platform in the RAN unlike closed, vendor-proprietary physical RANs.

The most important potential source of revenue that is directly enabled by operators' new Open RAN clouds comes from the projected growth in enterprise spending on public edge cloud services. A wide range of use cases and services will need to deliver near-real-time responses and guaranteed reliability and privacy to users across various industry verticals including advanced industry 4.0 and 5.0 applications such as manufacturing automation, robotics and autonomous vehicles. Analysys Mason estimates that the revenue opportunity from these far edge services will grow at a CAGR of 103% between 2019 and 2030 to reach USD23.5 billion (Figure 22).[8] Having an open, flexible service platform that supports the deployment of vendor-agnostic network functions, IT and enterprise workloads and third-party partner and developer applications is a key enabler for operators to assert themselves in these new edge computing and MEC service value chains.

8 For more information, see Analysys Mason's *Implementing the vRAN cloud: strategies for success*.

Figure 22: Enterprise spending on public edge services at the far edge by vertical, and as a percentage of the total public edge spending, worldwide, 2019–2030



Source: Analysys Mason

6. Conclusions and recommendations

The results from our TCO study show that Open RAN can provide realistic TCO savings for operators to start implementing Open RAN today. However, this is only possible if operators adopt an Open RAN platform that consists of the right technology stack and ecosystem and they invest in the acquisition of required skills and capabilities. In the near term, we expect that these savings will be boosted with the introduction of innovations and developments across both hardware (RU, antenna, chipset, COTS servers) and software (cloud-native xNF and CaaS) layers, which will further improve the attractiveness of Open RAN business case.

We provide the following recommendations for operators that are evaluating Open RAN and/or want to achieve the optimal TCO and business case:

- **Start implementing Open RAN as soon as possible to benefit from the first-mover advantage for enterprise and MEC use cases.** Open RAN with the right technology and skillsets is economically feasible today. However, carrying out the necessary changes to people, processes and technology takes time and it will not be easy to catch up with the market leaders that have undergone this transformation. The competition in the 5G, enterprise and edge/MEC services is growing quickly with a diverse set of players entering and competing for a share of the same revenue pot. To implement Open RAN, operators should start their operational and organizational transformation early on to maximise their chances of success in these markets as first movers.

- **Choose a cloud platform that is capable of supporting the performance and cost-efficiency requirements of Open RAN.** Operators need a highly optimized and automated distributed O-Cloud platform that supports the stringent processing requirements of the 5G RAN today and in the future and which minimizes its deployment footprint and costs. The O-Cloud platform should also support all Open RAN architecture and deployment models flexibly as operators will probably experiment and adopt a combination of these different models.

- **Begin your Open RAN implementations with distributed architecture to minimize disruption but be prepared to evaluate and deploy more-centralized architecture in the future.** Adopting a distributed Open RAN architecture as the starting point provides the most realistic TCO savings in the near term. However, centralized architecture such as vDU/vCU pooling has the potential to deliver bigger benefits in the future as the availability of fiber and edge data centers increases. Operators should continue to explore and evaluate this option in order to be prepared for the transition when it becomes technologically and economically feasible.

7. Annex

This section provides details of the modeling assumptions and parameters of the TCO analysis.

7.1 Connections and traffic

Figure 23: Total number of 5G connections for modelled operator profiles

	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6
Tier-1 Western European	4 838 260	11 638 169	19 931 106	28 537 395	36 567 529	42 086 074
Medium-sized (developed market)	3 225 507	7 758 779	13 287 404	19 024 930	24 378 353	28 057 383
Tier-1 (emerging market)	5 106 748	8 528 571	11 900 104	15 558 912	19 663 181	23 194 907

Figure 24: Annual 5G data traffic (PB) for modelled operator profiles

	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6
Tier-1 Western European	1344	3971	8276	13 889	20 096	26 079
Medium-sized (developed market)	896	2647	5517	9259	13 398	17 386
Tier-1 (emerging market)	813	2016	3565	5470	7746	10 218

7.2 Network design

Figure 25: Tier-1 Western European operator's RAN geo-types and number of sites

Geotypes	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6
Dense urban	947	1326	1705	1856	1892	1892
Urban	141	281	481	765	1078	1383
Suburban	-	34	90	157	268	313
Rural	-	-	16	153	383	689
Very rural	-	-	-	-	204	1016
Total sites	**1088**	**1641**	**2292**	**2931**	**3825**	**5293**

Figure 26: Mid-size developed market operator's RAN geo-types and number of sites

Geotypes	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6
Dense urban	711	995	1279	1392	1419	1419
Urban	106	211	361	510	719	922
Suburban	-	26	67	118	201	235
Rural	-	-	12	115	287	517
Very rural	-	-	-	-	153	762
Total sites	**817**	**1232**	**1719**	**2135**	**2779**	**3855**

Figure 27: Tier-1 emerging market operator's RAN geo-types and number of sites

Geotypes	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6
Dense urban	231	432	720	1008	1296	1411
Urban	-	59	157	268	409	554
Suburban	-	-	-	20	52	90
Rural	-	-	-	-	10	92
Very rural	-	-	-	-	-	-
Total sites	**231**	**491**	**877**	**1296**	**1767**	**2147**

Figure 28: Spectrum related parameters

Spectrum band	Total amount of spectrum	Carrier size
700MHz	2×10MHz	2×10MHz
3.5GHz	100MHz	40MHz

- Sites in urban areas have 700MHz **and** 3.5GHz carriers.
- Sites in rural areas all have 700MHz carriers but not all do have 3.5GHz carriers.

Figure 29: 5G RAN related parameters

Parameter	Value
Sector non-homogeneity factor	75%
Maximum utilization of carriers	75%
Sector per carrier	3
5G spectrum efficiency (Mbit/s/MHz)	1.75 – 2.03 (Year 0 – Year 10)

7.3 Cost parameters

- The costs for training and OSS/BSS integration for RAN components are excluded in all scenarios.
- The costs for passive assets (for example towers, poles etc.), RIC and packet core are excluded in all scenarios
- Transport network costs (xHaul) are assumed to be incremental costs over existing fiber, leased line and microwave links based on the traffic profiles shown in section 7.1.
- Traditional physical RAN costs are normalized and averaged from various vendor price benchmarks used in Analysys Mason's consulting projects and regulatory models.
- Open RAN RU, antenna and COTS hardware costs are collected and normalized from various internal sources including Analysys Mason's consulting projects, regulatory models and operator surveys as well as external sources such as the FCC's "Final catalog of eligible expenses and estimated costs".
- CaaS software costs are estimated based on Wind River's guidance.
- All hardware and software costs for the emerging market operator profile are discounted by 20%.
- The lifetime of traditional physical RAN equipment (gNodeB) is assumed to be 5 years and COTS servers' lifetime is assumed to be 3 years.
- Site installation and provisioning costs are assumed to be 20% of total hardware and software costs per site.
- System integration costs for Open RAN elements are assumed to be 30% of total hardware and software costs.
- Support and maintenance costs for all RAN hardware elements are assumed to be 5% of the equipment cost.
- Support and maintenance costs for all RAN software elements are assumed to be 20% of the software license.

Figure 30: Summary of labor costs for the modelled operator profiles

Parameter	Value
Hourly cost of labour (USD) – developed market	130
Hourly cost of labour (USD) – emerging market	65
Cost trend of labour	2.0%
Number of working hours per year	1725

Figure 31: Summary of floorspace cost parameters

Parameter	Value
Rack units per standard rack	45
Rack floorspace (sqm/rack)	4
Cost trend of floorspace	3%
Annual floorspace cost (USD/sqm) – emerging market	3000

Parameter	Value
Annual floorspace cost (USD/rackspace) – emerging market	12,000
Annual floorspace cost (USD/sqm) – emerging market	1,500
Annual floorspace cost (USD/rackspace) – emerging market	6,000

Figure 32: Summary of power cost parameters

Parameter	Value
Power (at a consumption of 48V per kWh) (USD) – developed market	0.10
Power (at a consumption of 48V per kWh) (USD) – emerging market	0.05

7.4 TCO breakdown for the mid-size incumbent operator in a developed market

Figure 33: TCO breakdown for the mid-size incumbent operator in a developed market

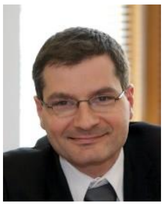
TCO component	Scenario 1 Traditional physical RAN	Scenario 2 Open RAN – distributed	Scenario 2 compared to Scenario 1	Scenario 3 Open RAN – vCU centralized	Scenario 3 compared to Scenario 1
Capex					
RAN hardware and software	USD51 347 107	USD39 658 010	–23%	USD39 581 439	–23%
Backhaul and other	USD1 393 499	USD1 393 499		USD1 393 499	
Total capex	USD52 740 607	USD41 051 510	–22%	USD40 974 939	–22%
Opex					
Supplier support and maintenance	USD13 823 159	USD7 301 779	–47%	USD6 868 751	–50%
Additional FTE costs		USD2 058 884		USD2 058 884	
Power costs	USD8 562 127	USD9 767 729	+14%	USD10 133 636	+18%
Rack space costs		USD3 297		USD178 022	
Total opex	USD22 385 286	USD19 131 690	–15%	USD19 239 293	–14%
TCO (3-year)	**USD75 125 893**	**USD60 183 199**	**–20%**	**USD60 214 232**	**–20%**

8. About the authors

Gorkem Yigit (Principal Analyst) is the lead analyst for the *Cloud Infrastructure Strategies* and the *Edge and Media Platforms* research programmes. His research focuses on the building blocks, architecture and adoption of the cloud-native, disaggregated and programmable digital infrastructure and networks that underpin the delivery of 5G, media and edge computing services. He also works with clients on a range of consulting projects such as market and competitive analysis, business case development and marketing support through thought leadership collateral. He holds a cum laude MSc degree in economics and management of innovation and technology from Bocconi University (Milan, Italy).

Caroline Chappell (Research Director) heads Analysys Mason's Cloud research practice. Her research focuses on service provider adoption of cloud to deliver business services, support digital transformation and re-architect fixed and mobile networks for the 5G era. She is a leading exponent of the edge computing market and its impact on service provider network deployments and new revenue opportunities. She monitors public cloud provider strategies for the telecoms industry and investigates how key cloud platform services can enhance service provider value. Caroline is a leading authority on the application of cloud-native technologies to the network and helps telecoms customers to devise strategies that exploit the powerful capabilities of cloud while mitigating its disruptive effects.

Audrey Bellis (Manager). Audrey's work to date includes in-depth analysis of spectrum, regulatory and competition issues in the telecoms, internet and media markets. She has significant experience of spectrum valuation, including advising on spectrum use and modelling of technical, commercial and strategic value, as well as experience in the socio-economic impacts of digital advertising, and performing strategic ICT market review



Gilles Monniaux (Principal) is based in Analysys Mason's Cambridge office. He joined Analysys Mason in 2007 and specialises in network economic cost modelling, spectrum valuation and regulatory analysis. Gilles has significant cost modelling experience, having been involved in the cost modelling of fixed and mobile networks in Ukraine, Norway, France (including overseas departments), the UK, Belgium, French Polynesia, Brazil, Malta, Mexico, New Zealand and Australia. Gilles has presented techno-economic cost modelling issues in open industry and operator meetings during these projects.