Data collection for model inputs

The model inputs are grouped to (i) market and industry, (ii) technology, (iii) spectrum, and iv) cost as shown in Figure 1.

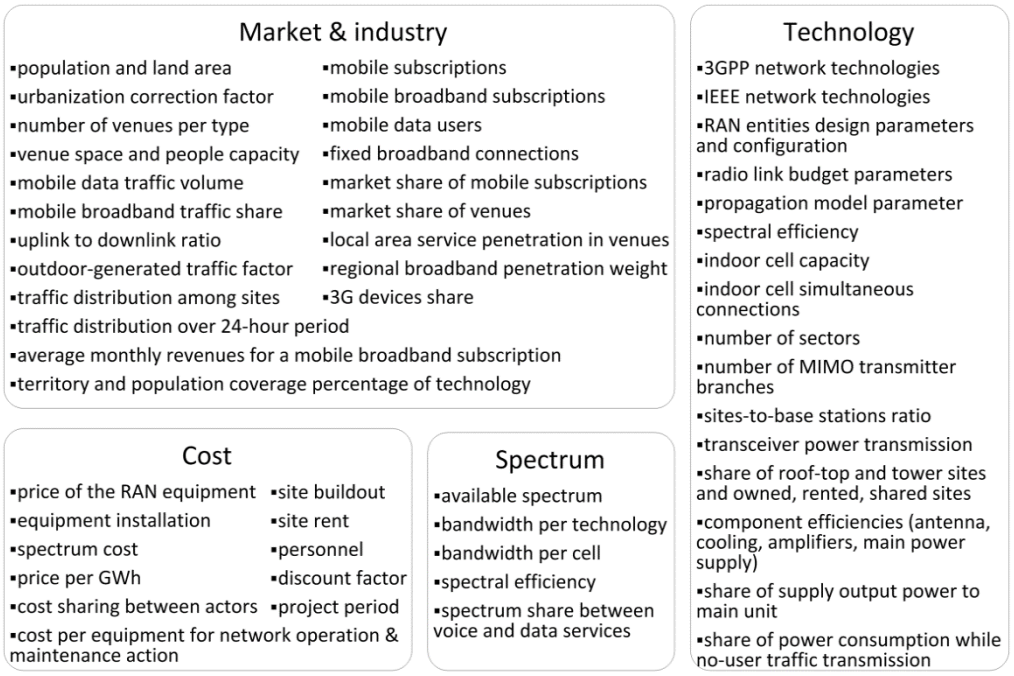


Figure 1: An overall model input classification.

The inputs variables are secondary data published by researchers, companies and governmental organizations, which is accessible over the web. For example, researchers publish information in journal and conference papers, doctoral dissertations, books and research projects' deliverables. Also, companies and industry associations, which aim to support their operation and industry, publish a variety of data in special publications, studies, reports, coverage maps, press releases and white papers. Finally, governmental and intergovernmental bodies (e.g., official statistics, regulatory authorities, OECD) provide essential information in publications, reports and press releases.

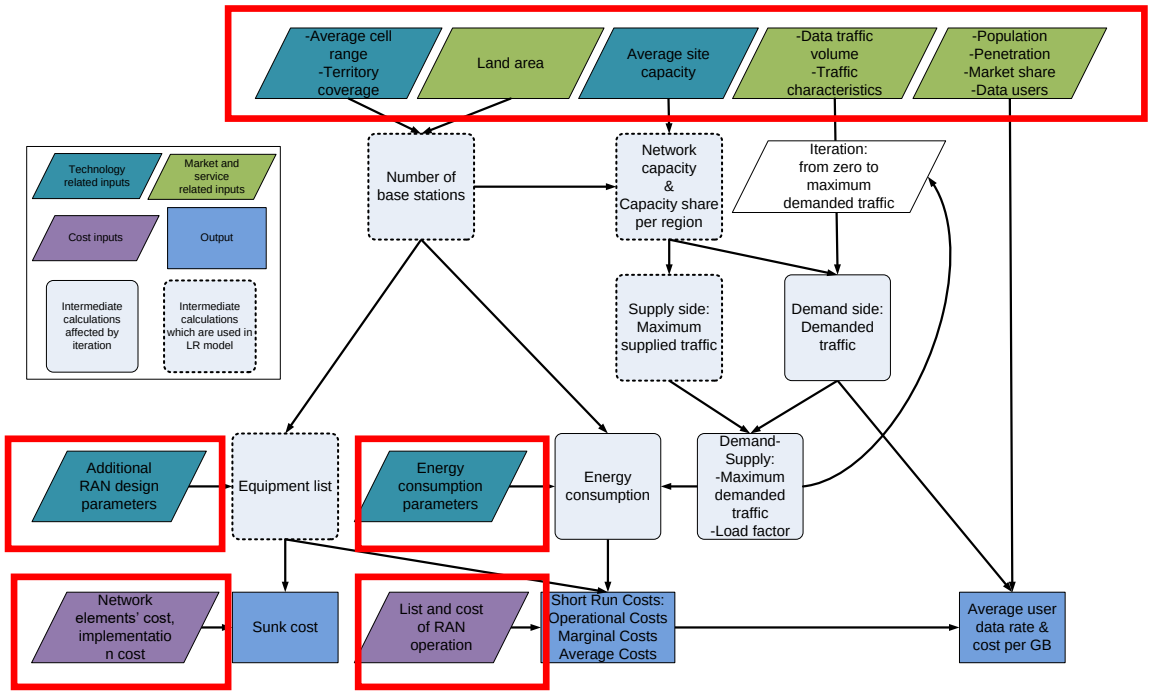


Figure 2: The short-run model

Market and industry model inputs

Basic demographics (2015)		
Finland	Land (km^2)	303900
	Population	5487308
	Population density	18.06
Studied region	Land (km^2)	9
	Population	66449
	Population density	7383.2
	Territory percentage (%)	0.003
	Population percentage (%)	1.21
Mobile market (1H/2016)		
Mobile penetration		172.7 %
Total mobile data traffic volume (in TB, country level, UL and DL)		465269
Mobile operator's market share		39 %
Proportion of mobile data users		85.1 %
Mobile network users (calculated)		44755
Mobile data users (calculated)		38087
Mobile data traffic (service) characteristics		
Traffic distribution among sites		0.3 [a]
Traffic distribution for busy hour (over 24-hour period)		0.15
Uplink to downlink ratio		0.1

a. 15% of traffic is carried by the 50% of the sites

Figure 3: Studied region (central Helsinki)

Market and industry model inputs	Reference
Population structure	(Stat 2016a-f) www.paikkatietoikkuna.fi
-mobile penetration **-market share** **-proportion of mobile data users (calc. mobile users)** **-total mobile data traffic volume**	(Stat 2015a; FICORA, 2016a) (FICORA, 2016c) (FICORA, 2016a, 2016d) (FICORA, 2016b)
-uplink to downlink ratio **-traffic distribution for busy hour** **-traffic distribution among sites**	(Plum, 2011) (Holma and Toskala, 2009) (NSN, 2010)

Technology and spectrum model inputs

Network technology configuration and spectrum assumptions per region

List of current network technology configurations: 1. GERAN@900, GSM/EDGE 2. GERAN@900, GSM/EDGE (refarming) 3. GERAN@1800, GSM/EDGE 6. UTRAN@2100, DC-HSPA+, R8, 64 QAM, 42 Mbps 17. UTRAN@900, HSPA+, R7, 64 QAM, 21 Mbps 20. E-UTRAN@2600, LTE, R8, 20 MHz, 64 QAM, 2x2 MIMO, 172 (150) Mbps 24. E-UTRAN@800, LTE, R8, 10MHz, 64 QAM, 2x2 MIMO, 86 (75) Mbps CA#1. E-UTRAN@2600+1800, LTE-A, R11, CA, 20+20 MHz, 64 QAM, 2x2 MIMO, 344 (300) Mbps CA#6. E-UTRAN@2600+2100+1800, LTE-A, R13, CA, 20+20+20 MHz, 256 QAM, 2x2 MIMO, 690 (600) Mbps				
Site config.	Cell spectrum (Mhz) / Spectral efficiency (bps/Hz)	Average cell range (km)	Territory coverage (%)	Typical 3sectored site capacity (Mbps)
1	-	0.4	50	0.98
2	-	0.4	50	0.54
3	-	0.25	100	1.22
6	9.9/1.05	0.23	100	29.74
17	4.95/1.05	0.4	50	12.75
20	20/1.56	0.2	40	89.26
24	10/1.56	0.5	40	44.63
CA#1	40/1.56	0.2/0.25	39/60	178.53
CA#6	60/2.1	0.2/0.23/0.25	26/34.4/40	360.49

Additional Radio Access Network design parameters

type of sites shares	Share of tower	0.1
	Share of rooftop	0.9
	Share of owned tower (out of tower sites)	0
	Share of owned rooftop (out of roof-top sites)	0.1
	Share of rental tower (out of tower sites)	1
	Share of rental rooftop (out of roof-top sites)	0.90
	Share of shared rental tower (out of rental tower sites)	0.2
	Share of shared rental rooftop (out of rental roof top sites)	0.2
Sites to base stations ratio		0.4
BSC	Transceivers per BTS	18
	BSC capacity (TRx per BSC)	2048
PCU for GPRS/EDGE	BTS per PCU	32
RNC	RNC capacity (NodeBs per RNC)	384

```
% It is assumed that the existing etwork has been built to cover the demanded traffic plus
e.g.,10%
caproom = 0.1;
```

Energy consumption parameters

Base station type	Maximum power (Watt)	Power share at idle mode
BTS	2145	60%
NodeB SC/DC/TC/QC	1450/1500/1550/1600	55%
eNodeB single/2CA/3CA/4CA/5CA	1000/1500/2000/2500/3000	50%

Technology and spectrum model inputs	References
network technologies and entities description	(3GPP, 2016)
territory and population coverage percentages	(DNA, 2017a, 2017b; Elisa, 2017a, 2017b; Sonera, 2017a, 2017b; Stat 2016a-f)
typical spectrum efficiency per technology (calc.average cell capacity)	(Holma and Toskala, 2011, Real Wireless, 2011, 3GPP, 2007; Rysavy, 2016)
average cell range	(Holma and Toskala, 2011)
assumptions about additional design parameters e.g., types of site share, site-to-base station ratio, number of TRx, RNC capacity, BSC capacity	(NPT, 2013; PTS, 2011; Ofcom, 2010)
Power consumption parameters for each base station type	(Conte, 2012;Katsigiannis and Hämmäinen, 2014)
spectrum availability	(ECO, 2013)

+assumptions about the current network configuration and coverage rollout

Cost model inputs

Cost of radio access network elements (CAPEX)

Radio access network equipment and site types		Unit cost (€ '000)
GERAN	BTS	30
	BSC	350
	PCU	100
UTRAN	NodeB	50
	NodeB upgrades (carrier/software)	10
	RNC	1000
E-UTRAN	eNodeB & new antenna system	60
	eNodeB CA upgrades (carrier/software)	10
Site types	owned tower site	50
	owned roof-top site	25
	rental tower site	50
	rental roof-top site	25
	shared rental tower site (3 MOs)	16.7
	shared rental roof-top site (3 MOs)	8.3

Implementation cost (IMPEX as part of CAPEX)

Network implementation actions	Action cost (€)
Site buildout (€/site buildout)	35000
NodeB and eNodeB upgrades (€/upgrade)	200
Other installation of components (€/ installation)	500

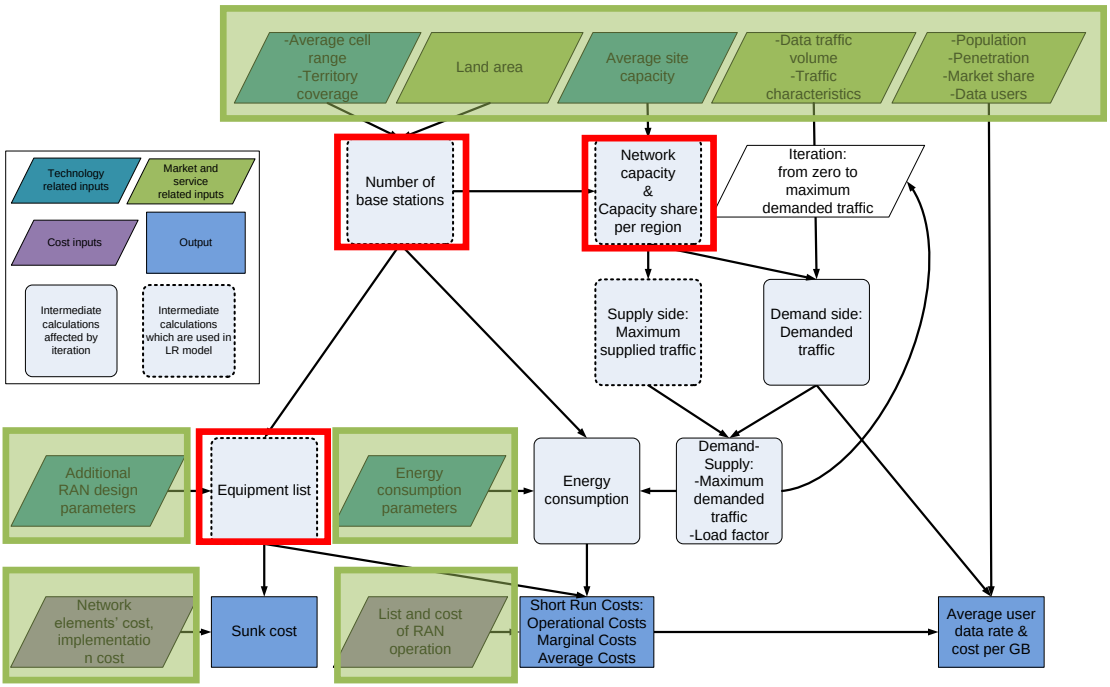
Operational cost of radio access network (OPEX)

Category	Cost (€)	Additional info
rental tower site	500	- Site rental - €/month/site
rental roof-top site	600	
shared rental tower site	167	
shared rental roof-top site	200	
Employees and salary	4000	-2 employees - €/month
Network operation & maintenance	1	- sum of network components (excl. sites) - €/month/component
New spectrum acquisition and auction price[a]	0	- spectrum in 800 MHz (2x10 MHz) = 15000 €/month/MHz (3,600,000 euro/MHz / 20 years of possession / 12 months) - new spectrum in 700 MHz (2x10 MHz) = 9167 €/month/MHz (2,200,000 euro/MHz / 20 years of possession / 12 months)
Energy	40000	€/GWh

a Usually, the license costs are categorized under OPEX. However, it can be deemed as CAPEX. Nevertheless, the spectrum cost is considered as a fixed cost

Cost model inputs	**Reference**
-the list and the price of the radio access network equipment and sites **-the network implementation actions** **-operational expenditures**	(NPT, 2013; PTS, 2011; Ofcom, 2010, Lavender, 2013)

Short-Run Intermediate Calculations



List of current network technology configurations:
1. GERAN@900, GSM/EDGE
2. GERAN@900, GSM/EDGE (refarming)
3. GERAN@1800, GSM/EDGE
6. UTRAN@2100, DC-HSPA+, R8, 64 QAM, 42 Mbps
17. UTRAN@900, HSPA+, R7, 64 QAM, 21 Mbps
20. E-UTRAN@2600, LTE, R8, 20 MHz, 64 QAM, 2x2 MIMO, 172 (150) Mbps
24. E-UTRAN@800, LTE, R8, 10MHz, 64 QAM, 2x2 MIMO, 86 (75) Mbps
CA#1. E-UTRAN@2600+1800, LTE-A, R11, CA, 20+20 MHz, 64 QAM, 2x2 MIMO, 344 (300) Mbps
CA#6. E-UTRAN@2600+2100+1800, LTE-A, R13, CA, 20+20+20 MHz, 256 QAM, 2x2 MIMO, 690 (600) Mbps

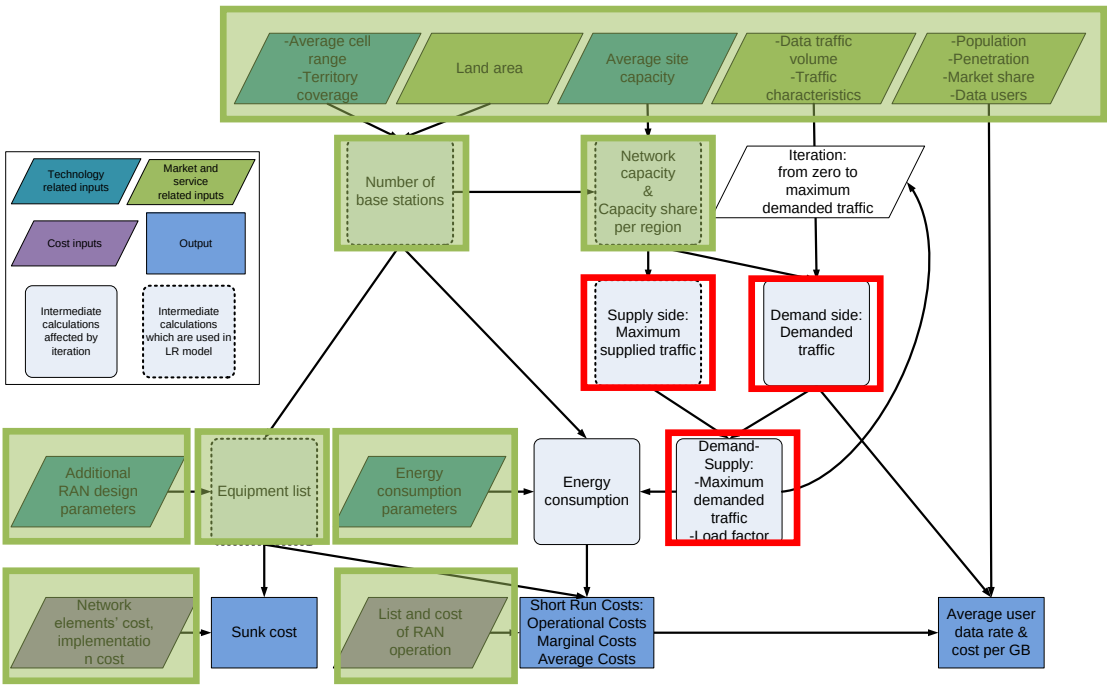
Site config.	Number of base stations	Network capacity (Mbps)
1	15	14.76
2	15	8.1
3	0	0
6	88	2617.14
17	15	191.19
20	47	4195.4
24	8	357.1
CA#1	45	8033.75
CA#6	30	10814.67
Total	263	26232.1

The capacity of existing network could indicate the current demanded traffic per region. It is assumed that MNOs deploy the network to handle the demanded traffic in busy hour. Thus, a parameter which shares the supply traffic among regions (capacity share per region c_r) is used also to show the demanded traffic share per region. The capacity share for other region

is roughly the max supplied traffic in region to country data traffic volume. Capacity share for the studied region is 0.024.

Current Radio Access Network equipment list for a Mobile Operator

		Total
sites	owned tower site	0
	owned roof-top site	9
	rental tower site	9
	rental roof-top site	68
	shared rental tower site	2
	shared rental roof-top site	17
	Total sites	105
GERAN	BTS	30
	BSC	0
	PCU	1
UTRAN	NodeB	103
	NodeB upgrades (carrier/software)	0
	RNC	1
E-UTRAN	eNodeB & new antenna system	130
	eNodeB upgrade for CA	0



The (maximum) supplied traffic S (in bps) is the regional macro network capacity in downlink and is calculated by multiplying the number of base stations N_{BS} in a region, the number of sectors N_s and the average cell capacity $\bar{R}_{cell}$ (in bps). The average cell capacity depends on the bandwidth per cell BW and the spectrum efficiency of the technology SE:

$$S = \bar{R}_{cell} N_s N_{BS}, \quad \text{where } \bar{R}_{cell} = BW\,SE \tag{1}$$

Also, the supplied traffic S is converted to e.g., TB/month and TB/hour for comparison with the corresponding values of the demanded traffic.

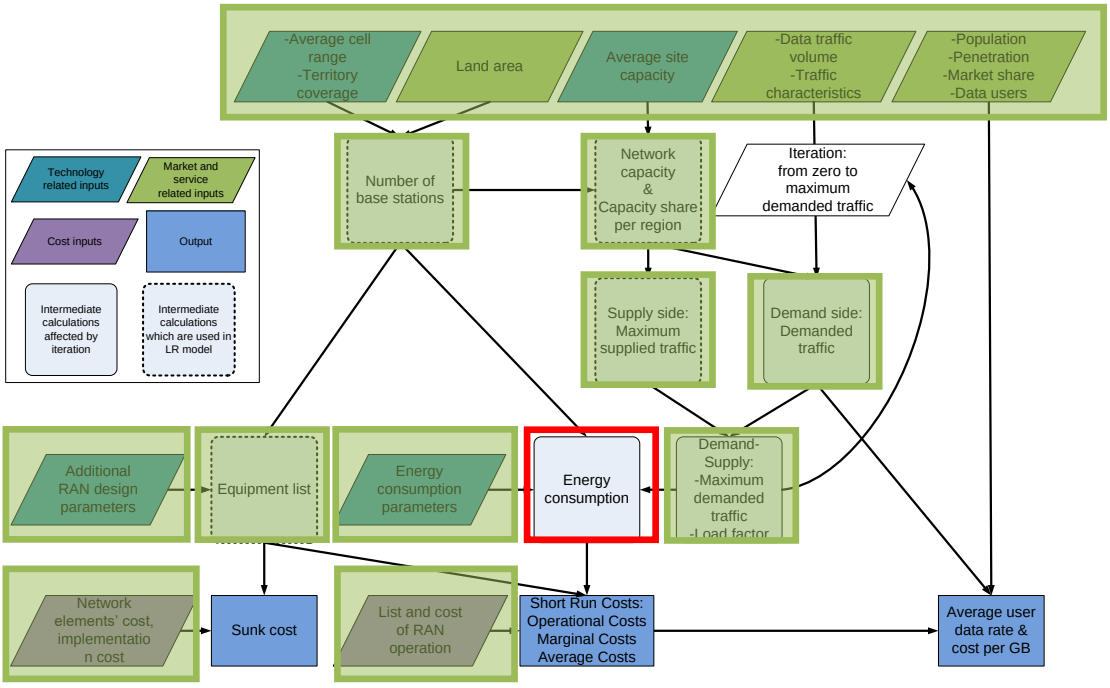
The demanded traffic D is the downlink mobile data traffic volume which is carried by a regional network of a MNO. The total mobile traffic volume in the country V and the MNO's market share m give an approximation about the demanded traffic carried by MNO's network (e.g., in TB/month). The capacity share per region c_r splits this traffic to each region, and the uplink to downlink ratio $r_{UL/DL}$ separates the traffic to uplink and downlink traffic. Furthermore, the regional demanded downlink traffic is not evenly distributed over time and space (geographical area). Traffic characteristics, such as the traffic distribution over a 24-hour period (share of daily traffic in busy hour T_{Dtime}) and the traffic distribution among sites (share of traffic conveyed by some share of cells T_{Dspace}), are considered. Thus, the demanded traffic under these conditions (e.g., in TB in busy hour) is given by (4), and is mainly used in network dimensioning process.

$$D = \frac{V\,m\,c_r}{(1 + r_{UL/DL})} \tag{3}$$

$$D_{BH} = \frac{D}{30} \frac{T_{Dtime}}{T_{Dspace}} \quad (4)$$

The average load factor of the site L is defined as the ratio of the demanded downlink data traffic to the network capacity (dimensionless):

$$L = D / S \quad (5)$$

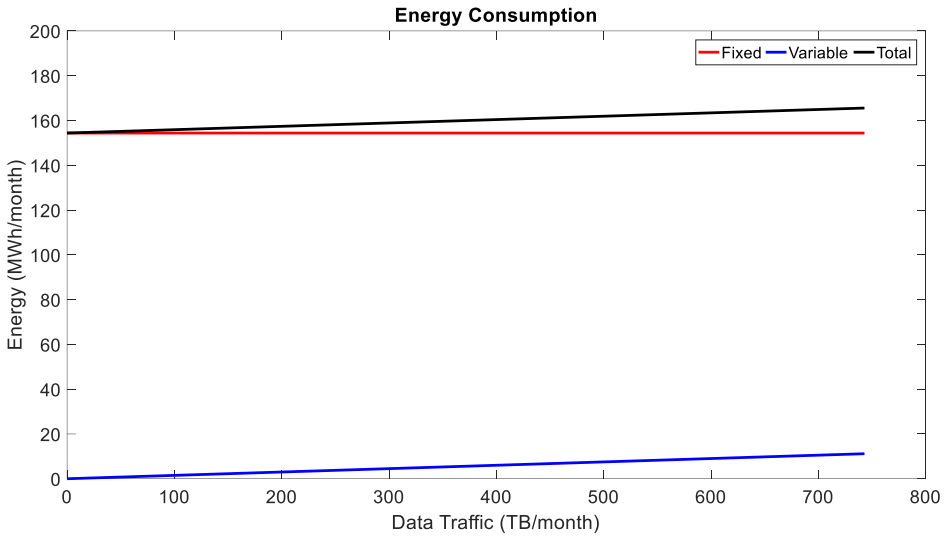


A site consumes power (i) while user traffic transmission (variable), and (ii) while no-user traffic transmission (fixed, i.e., the site is at a state other than user traffic transmission). The average power consumption of a site `Psite` is the sum of a variable component, represented by `(Pmax-Pmax.*po)*AvL` and a fixed component, representing by `Pmax.*po`. The varied demanded data traffic is included in the average load factor. Thus, the average power consumption of a site depends on its maximum power consumption, its average load factor, and the percentage p_o which determines the level of consumption while no-user traffic transmission (control channels are included in this parameter):

```
Psite_idle_mode = Pmax.*po*(1-AvL);
Psite_load = Pmax*AvL;
Psite = Psite_idle_mode+Psite_load;
```

(6)

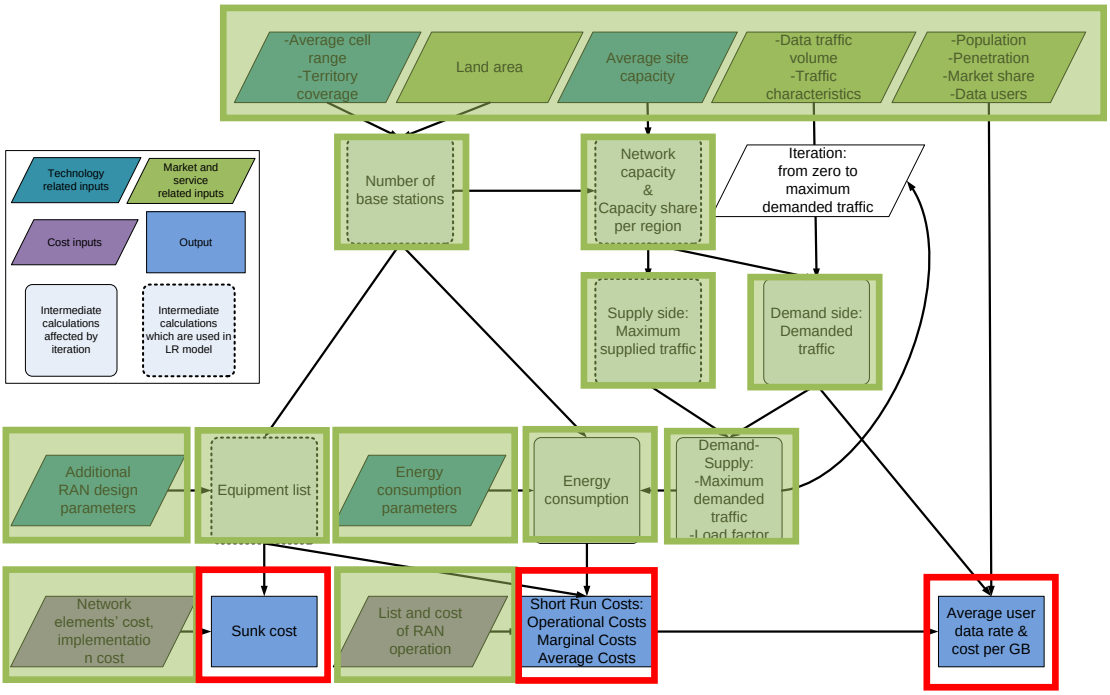
```
Psite_fixed = Pmax.*po;
Psite_variable = (Pmax-Pmax.*po)*AvL;
```

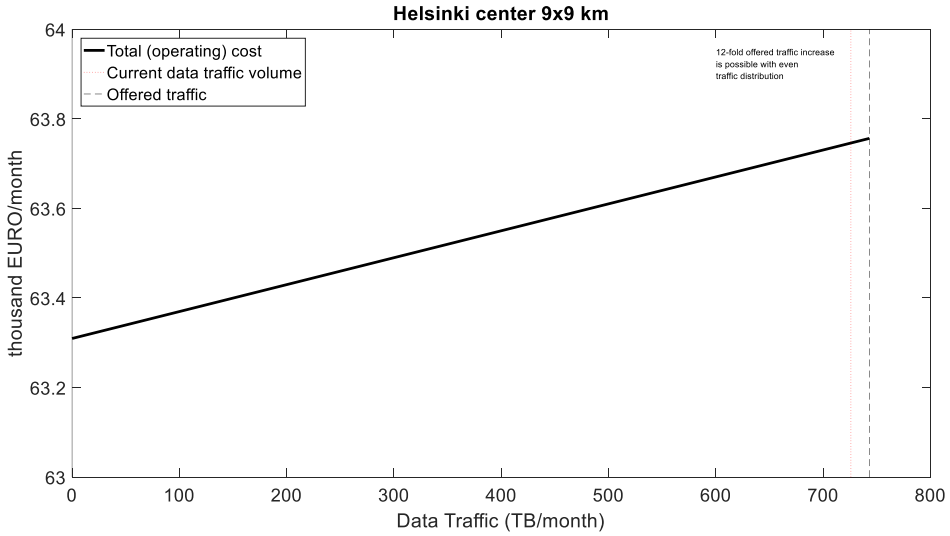


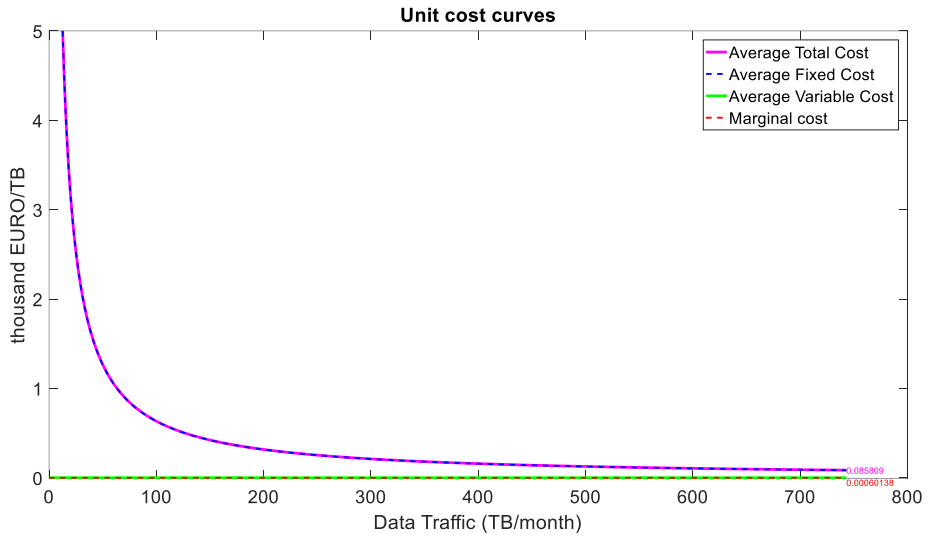
Energy consumption of radio access networks for a mobile operator

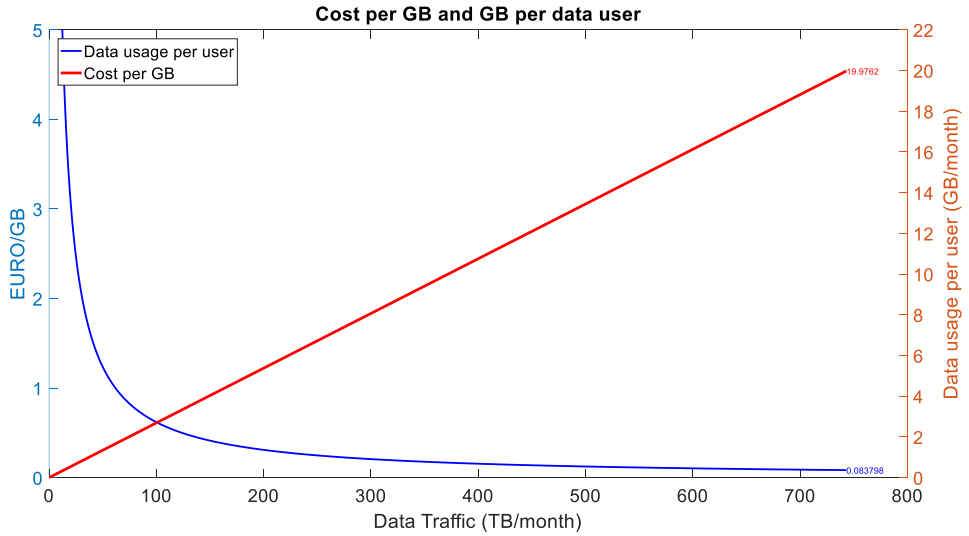
Energy consumption at the maximum data traffic the network can carry	MWh/month
Total	165
Fixed component	154
Variable component	11
While the sites are at other state than transmitting user data	142
Based only on user data traffic	23

Short-Run Results









Other numerical results for important parameters

Sunk cost (€)	21389462
Average load factor of site in busy hour and considering the traffic distribution in space	97.69 %
Average load factor (L)[a]	8.64 %
Average cost per site[a] (€/site/month)	606
Energy cost share[a]	10.39 %

a. At maximum data traffic the current network can carry

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