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Towards sustainable data centres: Novel internal network technologies leading to sustainable cost and energy consumption in data centres in The Netherlands.

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Abstract

Information technology (IT), and in particular data centres, consume a huge amount of energy, which has negative influence on climate change. Therefore, it is important to look at the sustainability of data centres, especially in the Netherlands as one of the major location of these centres in Europe. In order to examine the extent to which data centres are sustainable and energy efficient, a comprehensive total cost of ownerships (TCO) analysis is undertaken to get better insights into the different costs components and technological opportunities for further reductions. Even if there are already a number of TCO studies on data centres, there have been none dealing with the effects of technological change on the networking part of data centres. However, this can be considered as a serious shortcoming of current research as technological change will have (cost-saving) effects on the networking part of data centres and data traffic will have an impact on the rack. After examining technological change by comparing different network technologies (ethernet, glass fibre, and plastic optical fiber (POF) in data centres, our TCO model studies improvements regarding costs, energy reduction, and improved sustainability of these three technologies. We conclude that the implementation of glass fibre or POF in a data centre can provide cost improvements amounting to about 1% per year. Looking at the energy consumption of the network part, a reduction of approximately 20% for glass fibre and 40% for POF can be reached. Therefore, the model demonstrated that changing current network technologies within the data centre will result in a decrease of energy consumption and total cost ownership.

1. Introduction

Global energy consumption has been rising over the past few decades (Akhmat et al., 2014) with information technology (IT) sector contributing a substantial part to overall consumption, especially with increasing integration of IT in daily lives (Røpke, 2012). Mingay (2007) stated that the IT sector is responsible for around two per cent of total carbon emission, which is estimated to be similar to the direct emission of the aviation industry (Whitehead et al., 2014). Global Action Plan (2009) proposed that the carbon emission could be reduce by roughly 15 per cent. Recently the term "green IT" has been introduced in the literature (Mingay, 2007; Erek et al., 2011; Brooks et al., 2012; Murugesan & Gangadharan, 2012 Tushi et al., 2014) to account for a set of technological innovations aimed at reducing the impact on the environment. In this context, green IT is considered as the systematic application of practices that enable the minimization of the environmental impact of IT, maximize efficiency and allow for company-wide emission reductions based on technology innovations" (Erik et al., 2011).

Within the (green) IT domain, data centres (DCs) are a main technological domain (Gu et al., 2013). In a recent study (Bawden, 2016), it has been shown that DCs consume globally roughly 3 per cent of all the electricity and are responsible for 2 per cent of the total greenhouse gas emissions (GHGs). In order to account for the energy consumption of IT, the European Commission has created a Code of Conduct (CoC) and the Dutch Government has implemented MJA (Meerjarenafspraken) to define the following steps in the development towards Green IT.

The study focuses on the Netherlands with Amsterdam as one of the most important region with respect to the location of DCs. In the Amsterdam area, currently 33 per cent of all the DCs in Europe are located. The reasons why many DCs are located in the Netherlands is based on the following characteristics: Firstly, access to high speed internet connectivity; secondly, top location with respect to affordable prices for business; thirdly, easy access to foreign businesses; fourthly, access to other parts of North Europe and Russia, and finally Amsterdam's location close to an Internet hub (Avgerinou, 2017; DDA, 2017; Gu et al., 2013).

In order to examine energy consumption and costs, many performance metrices for DCs are currently used ranging from basic to very extended studies (Wang and Khan, 2013). In order to develop a DC performance metrics, the analysis had to take the following issues into account (Wang and Khan, 2013): Firstly, study the extent to which energy consumption of a DC really is green; secondly, compare different products and services in and across DCs; thirdly, green performance need to be tracked; and finally, provide some guidance for engineers, managers, manufacturers to ensure future improvements of DCs. In order to achieve these objectives, a good understanding of the energy consumption and the related costs of DCs is required. A comprehensive total cost of ownership (TCO) metric allows to

identify the different components related to energy consumption, costs, and sustainability aspects of a DC (Cui et al., 2017).

In current literature on DC, TCO analyses have focussed on servers (Koomey et al., 2007; Kardis et al., 2009; Meisner et al., 2009; Vishwanath et al., 2009; Özer et al., 2010; Hardy et al., 2011; Grot et al., 2012; Hardy et al., 2013; Uchechukwu et al., 2016; Rokkas et al., 2017), the cooling elements (Patel & Shah, 2005; Moore et al., 2005; Witkowski et al., 2013; Ott et al., 2017; Cui et al., 2017), the software (Li et al., 2009; Beloglazov et al., 2011; Martens et al., 2012; Thanakornworakij et al., 2012), and scalability (Patterson & Loeffler, 2007; Marshall et al., 2009; Rasmussen, 2011). Surprisingly TCO calculations aimed at comparing different network technologies have not undertaken yet even in the light of the emergence of high performance servers (Gualbenzu, 2018). As these servers have an increased workload it is important that networking connections keep up with the improvements of servers. Therefore, it is relevant that networking equipment is taken into consideration. Furthermore, it has been shown (Greenberg et al., 2008) that the critical performance bottleneck is shifting from servers to the network part of DCs. In addition, the data traffic related to DCs is mostly generated within the racks (Cisco, 2016) and is accounting for approximately 58,8% of all traffic related to DCs. Finally, according to Amhdal's balanced system law, three resources (clock speed, capacity of main memory, and bit rate of in/output bandwidth) need to be in balance in order to achieve the optimal overall performance (Cohen and Petrini, 2009).

Although research has mainly focused on green IT and the TCO analysis of DCs, actual calculations and outcomes are mostly not available to the public (Gu et al., 2013). In addition, there is lack of studies calculating TCO of DCs. In this context, the research fills the gap related to the lack of data and conceptual foundations by determining the energy usage, sustainability and costs of DCs in the Netherlands. It contributes to existing studies in a variety of ways: First, it develops a generic and optimized TCO analysis to determine the energy usage, costs, and sustainability of DCs, based on best practices. Furthermore, it includes the option of technological change by comparing different networking technologies in DCs. Finally, the research utilizes three case studies of DCs and their energy consumption and related costs. The key question for the research was how much energy and cost savings an average DC in the Netherlands can achieve on a yearly basis looking if different energy-saving network technologies are deployed.

The remainder of this research is organized as follows. Section 2 explains the theoretical concepts that are used. Section 3 describes which methodology is applied. Furthermore, this section shows what kind of data is used and how this is collected. Section 4 shows the conceptual model that is derived from the literature and its assumptions are verified based on a number of interviews. Section 5 summarizes the argument and describes the actual results of the research. In Section 6, the conclusions are presented and the outcomes of the research are discussed.

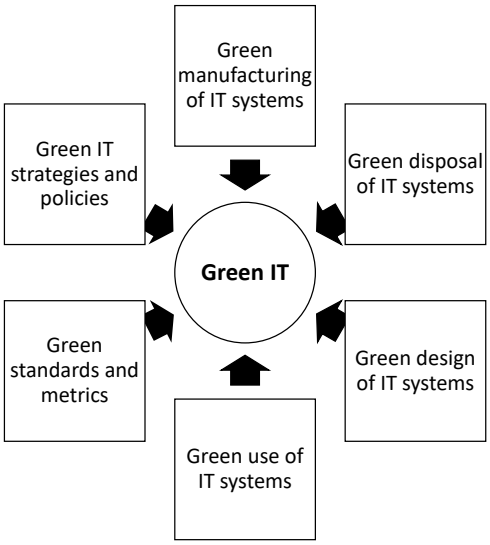
2. Sustainability and Technological Change in Data Centres

(In-)Sustainability of Data Centres

Sustainability has been considered as a key challenge facing the development of information technology in the near future (Røpke 2012, OECD 2009). Currently information technologies (IT) consume significant amounts of electricity, place a heavy burden on electric grids and contribute the greenhouse gas emissions. As Berners-Lee puts it (2011), a short email is adding about four grams of CO2 equivalent (gCO2e) to the atmosphere. The carbon output of hitting "send" on 65 mails is like driving an average-sized car a kilometre (Berners-Lee 2011). Data centres have a critical element in IT infrastructure having a major impact on energy consumption. To accommodate sustainability issues into IT infrastructure, the concept of green IT has been coined (Mingay, 2007), which focuses on the development, design and actual implementation of IT.

In order to examine green IT, a holistic approach divided IT into four different parts and two directions (Murugesan, 2008; Murugesan and Gangadharan, 2012) (see Figure 1): The first direction is the *green use* of the IT system. This direction focusses on the energy consumption reduction of computers and other information systems in a way that it is reducing negative effects on the environment. It focusses on the actual use and how people work with the computers. The second direction is *green disposal* of IT systems and refurbished and recycling of old computers. This path looks at what happens with computers and related (IT) equipment after people stopped using them. The third direction looks at the *green design* of components, computers, servers and cooling equipment. The goal is to design such parts that energy efficiency and environmentally friendly. The fourth direction focusses on *green manufacturing*. In this path the actual production of computers and related IT equipment are central. The goal of this path is to minimize the impact on the environment (Murugesan, 2008). The fifth direction is *green standards and metrics* by looking at the promotion, comparison and benchmarking of sustainable initiatives, products, services and practices. The focus is here at the way how companies compare their work method and performance with other firms. Finally, the sixth direction focusses on *green IT strategies and policies*. Strategies and policies need to be determined in order to set goals, with an actual step-by-step plan, to achieve benefits in the short-, mid-, and long-term. The green IT strategies and policies are part of the total business strategies and policies and can be seen as a key component of greening IT (Murugesan, 2008; Murugesan and Gangadharan, 2012). In the research, the focus is on the first direction (analysing energy consumption and cost components) and the fifth direction (comparing similar technologies to account for technological change).

Figure 1: Holistic approach towards IT based on Murugesan and Gangadharan (2012)



Structure of Data Centres

In the literature (Murugesan and Gangadharan, 2012), data centres are divided into two parts namely, the facilities infrastructure and IT infrastructure. IT infrastructure does have direct influence on the services that a DC provides. However, the facility infrastructure is needed in order to ensure that the IT infrastructure can operate (see Table 1).

Physical data centre infrastructure	
Facilities infrastructure	IT infrastructure
Power system • On-site generation plants (OSG) plants • Transformer, switch gear and transfer switch • Uninterruptible power supply (UPS) including el. Storage (batteries) • Power distribution units (PDU) and cables **Cooling system** • Chillers, cooling towers and economizers • Liquid cooling cycles (Pipelines, pumps, valves, th. storage, heat exchangers, and recovery units. • Computer room air conditioner / handler (CRAC/Hs) and direct expansion air handling units (DX AHU) • Raised floor, ductwork and rack containment **Other supporting systems** • Access protection and video control • Fire suppression and water protection • Building control and automation • Lightning • Other small power consumers	**Server system** • Mainframes and high performance computer • Standalone tower • Standard rack-optimizer servers • Multi-node, blade and micro slice servers **Storage system** • Controllers • Solid state drives (SSD) • Hard disk drives (HDD) • Tape and optical media **Network equipment** • Local area network (LAN) switches • Access distribution and core • Storage area network (SAN) switches • Wide area network (WAN) router • Other (gateways, firewalls etc.) **Other IT** • Telecommunication equipment • KVM switches • Desktop PCs, terminals, printers and monitors

Table 1: Physical infrastructure DC

As shown in Table 1, facility infrastructure and IT infrastructure are divided in more sub-components. The facility infrastructure consists of *power system, cooling system* and *other supporting systems*. The *power system* is essential for a DC. Losing power results in customers that cannot use the services of the DCs. The power system gets input from the power supply, that can be generated by three different sources: main grid, renewable energy supply, and emergency energy supply. In order to avoid disruption in the power supply, DCs have an uninterruptible power supply (UPS) and battery storages, in order to ensure that the output is always active. Power distribution units (PDUs) are connected after the UPSs. The PDUs convert the voltage to a lower voltage to ensure that the required amount of voltage is send to the servers and switches (Hill, 2009; Murugesan and Gangadharan, 2012). The *cooling system* takes care of the internal environment of the DC. The goal of this system is to ensure that the equipment does not overheat. In this way the DC can work in an optimal way, and is the DC prevented from damage due to failing equipment. The raised floor in a DC is divided into hot and cold aisles. This is done due to the fact that this ensures more efficient cooling (Murugesan and Gangadharan, 2012). In the cold isles, cold air is blown into the isles. The other isles contain hot air generated by the IT equipment. The hot air is gathered by cooling units that are positioned above the hot isles. The cooling units, computer room air conditionings (CRAC), gather all the hot air and cool it again and put this new cold air back into the raised floor, where it used again in the cold isles. Lastly, the other supporting systems are systems that have nothing to do with the power or cooling system. Supporting systems contain e.g. video control, fire control, and lightning.

The IT infrastructure systems do have direct influence on the delivered services of a DC. This part of the physical infrastructure of a DC is divided in four different sub-systems: *server, storage, network equipment, and other it systems*. "Server systems have as main goal to provide a service as a part bipartite communication between client and a server" (Murugesan and Gangadharan, 2012). The servers are packaged in cabinets or racks. Furthermore, each server consists of three different parts, the physical hardware, the operating system (OS), and the software service. Most of the DCs have headless servers, which means there is no mouse of screen connected. Servers are connected to each other, and humans do not operate at the services. Human intervention is only needed when there is maintenance, a failure, and need for replacement. Storage refers to the data storage of a DC and is a critical element of the DC design. Difference between different kind of storage solutions depend on how the servers manage the space of storage. Network equipment deals with the transportation of data inside a DC. The network consists of switches that are connected through cable with the servers or processing parts, based on a particular topology. Cables have a crucial role in DCs due to the transmission of data. Data rates in DCs differ between 1 Gbps and 100 Gbps. Currently, there are three different kind of cables used, but due to the increasing demand for speed MMF and SMF the percentage of Glass fibre cables is increasing (Gualbenzu, 2018; Appendix X). Therefore, Ethernet-based cables are replaced, even for the connection

of server and switches. Additionally, the network part of a DC consists of SFP (transceivers). Those SFPs are responsible from E/O and O/E conversion.

Categorizing DCs

In order to find out which DCs are used for the case study it is important to categorize DCs. On the one hand it is important to find out which functionalities the DCs have. On the other hand, it is important to find out how different DCs have influence on the relevant variables. Categorization of DCs is done in various ways such as, tier-levels, domains, function, floor size, racks, megawatts, business models, and topology. This sub-section shows different ways of categorizing DCs.

The categorization method that occurs most often in the literature is invented by Uptime Institute (2006). Their classification consists of four different tier levels with the goal to effectively evaluate the infrastructure of a DC mainly based on ability to be redundant. The classification is based on the following variables: power distribution, UPS, cooling delivery and redundancy. A higher tier-level is associated with an increase complexity and costs regarding the previous mentioned variables. Table 2 shows an overview of the different tier levels. Currently, especially in the Netherlands, nearly all DCs are located in Tier III and Tier IV (Barroso et al., 2013; DDA, 2018).

Table 2: Performance standard by Tier Level

	Tier levels			
Tier requirements	**Tier I**	**Tier II**	**Tier III**	**Tier IV**
Source	System	System	System	System
System component redundancy	N	N + 1	N + 1	Minimum of N + 1
Distribution paths	1	1	1 normal and 1 alternate	2 simultaneously active
Compartmentalization	No	No	No	Yes
Concurrently maintainable	No	No	Yes	Yes
Fault tolerance (single event)	No	No	No	Yes

Koomey (2012) divided the DC industry into four different domains: public cloud computing providers, scientific computer centres, co-location facilities, and in-house DCs. Public cloud computing providers are companies like Amazon and Google and are considered much more efficient than the other DCs due to economies of scale, diversity & aggregation, flexibility, and the possibility to easily avoid organisational issues (Koomey, 2011). Scientific computer centres, are centres that are owned by (national) laboratories and universities. Those centres are the only one that do not need to respond in real time. Co-location facilities are DCs that house servers owned by other companies. The last category, and the biggest one, are the in-house DCs. Those facilities do not have computing as their primary business, although these are owned and operated by those companies.

Horner and Azevedo (2016) invented a classification based on the classification of Patterson (2010). They state that it is difficult to put DCs into classes, due to the fact that they all differ in size and solution provider. They made a distribution, which is presented in Table 3. Generally, they say that the further you go down the list, quality, redundancy, size, and criticality increase. Nevertheless, the classifications are not qualitative and therefore the differences between the classes may be fuzzy (Horner and Azevedo, 2016). In addition, they mention that these different DCs can operate in different domains.

Table 3: Data centres ordered by function

Class	Explanation (Horner and Azevedo, 2016)
Server closets	Support small businesses or individual projects at larger companies. They may get some support from a corporate-level IT department but may also be configured and operated by non-experts.
Server rooms	Small DCs that support small businesses or special groups or projects of larger entities. They may be administered by central IT staff or "owned" by each project or division.
Localized DCs	Provide business-critical applications and have some power and cooling redundancy, though downtime is not catastrophic. Restoration of service on the order of hours is acceptable
Mid-tier DCs	Large-to-medium-size DCs used to host enterprise-wide applications in support of operations or human resources the data is critical, but incidental to the primary business line. Downtime lasting longer than a few minutes has significant impact on the business. These facilities are operated by the company's central IT department
Enterprise DC	Large facilities used, usually by non-ITC companies, in support of core business. These DCs are often in special-purpose facilities and operated under a separate business unit or division. Downtime is catastrophic, and these facilities have highly redundant infrastructure.
Hyperscale DCs	Very large DCs, usually constructed in their own physical plants, built by ICT companies with a primary business line focused on data (e.g., Google, Apple, Facebook, Amazon, et al.) and, increasingly, cloud-based services.

In the article of Oro et al. (2015) DCs are divided in three categories based on their business models. In their article they mention that most of the business models are based on ownership of the facility, IT equipment, and, software. The first category is *enterprises*. This category has a common ownership of all the three. Examples regarding this category are banks and universities. The second category, *co-location*, is characterized by separate ownership of the facility, compared to IT equipment and software. In this category the DC rents the infrastructure to somebody who can stall their IT equipment there. The last category is named *hosting*. In this category the ownership of the software is separate from the ownership of facility and IT equipment (Oro et al., 2015).

Technological Change towards Sustainability in Data Centres

Technological change in data centres in the network part has rather been slow. Ethernet and fibre technologies have mostly been used as networking technologies within racks. Ethernet is still the leading technology due to the fact that this technology is less expensive (compared to fibre) and meets the current speed requirements within the rack. However, as some customers need speeds up to 10G, fibre technologies are also used.

POF technologies are currently not used in DCs, even if this technology has advantages (Lannoo et al., 2011) compared to ethernet and fibre technologies. First, POF has less initial costs than ethernet and fibre technologies. Secondly, labour costs are much lower due to fast installation time. Thirdly, switches that are based on POF consume less energy per port. Fourthly, compared to ethernet, POF has a greater scope for CO2 reduction (Liburdi, 2013). Due to account for technological change in networking technologies, it seems highly relevant to compare these different technologies in their effects on energy consumption.

3. Conceptual Model and Methodology

3.1. Case Study Design and Conceptual Model

A convergent parallel mixed method design is used in order to conduct this research (Creswell, 2013). With this method qualitative and quantitative data is merged and combined together. Gathering the information is done via a systematic literature review, desktop research, semi-structured interviews, and multiple case studies. In this case quantitative data is used in order to build the conceptual model and to find numbers that could be used for the case studies. Qualitative research, focusses on the verifying the results found in the quantitative part.

In order to gain initial knowledge regarding TCOs related to data centres, a systematic literature review was conducted. Science direct, Scopus, and Google Scholar were used in order to get relevant literature. Many different search terms were used in order to get the right articles. Main terms or related terms that are used are: Total cost of ownership, CAPEX, OPEX, Data centre, sustainability, green performance indicators, green performance measures, PUE, energy efficiency, calculation, IT equipment, and network.

In order to generate a conceptual model quantitative data is used from different sources. In this way weighted averages are calculated. For calculating the servers, for example, 159 servers are averaged out. Similar calculations are made for switches, storage, SFPs, and the energy consumption of switches.

Besides, also Dutch statistic companies are used in order to get relevant information regarding financial, housing, and energy prices.

Participants that are used for the interview, interviewees, are experts in their field and can therefore deliver inside information regarding their specialized topic. After interviewing the co-location data centres (5), it became clear that the network equipment is initially purchased by the customers of those data centres. Therefore, to get a more in-depth look, four customers were interviewed. Lastly, a research institute regarding green IT was interviewed.

Creswell (2013) states that case studies are mainly used for evaluation, in which an in-depth analysis of a particular case is provided. Multiple case studies are used for comparing different network technologies. According to Yin (1984), one major concern regarding case studies is the fact that case studies provide only a basis for scientific generalization. However, due to the fact that in this research a multi case study is performed, this concern is overcome.

3.2 Conceptual model: TCO methodology applied to data centres

In order to get a full overview regarding the energy, costs, and sustainable aspects of DCs, a TCO metric is chosen as green performance metric. The concept of total cost of ownership (TCO) was introduced in 1987 by Gartner. Since then the TCO is heavily discussed in the literature. According to Ellram et al. (1993) TCO can be defined as: "*all costs associated with the acquisition, use, and maintenance of a good or service*". Gartner sees the TCO as assessment for IT or other costs across enterprise boundaries over time. TCO is helpful when people have to make a judgement regarding two or more different technologies. The main goal of the TCO is to look at the total costs compared to just looking at the initial purchase price. In addition, it is possible compare the energy consumption of different parts and technologies. Compared to other costing techniques TCO has many benefits. First, TCO is a good technique to measure the overall performance. Secondly, TCO enables with decision making. Thirdly, it helps during communication, since costs are clarified in a standard way. Fourthly, it helps with continuous improvement. Due to the cost breakdown people have insight in how their costs are divided Ellram et al. (1993). Fifthly, a baseline is determined with the TCO. Sixthly, TCO generates a widespread understanding of all the costs related to a particular investment (Bailey & Heidt, 2003). TCO is divided in capital expenditures (CAPEX) and operational expenditures (OPEX). According to Cui et al (2017), the total cost of ownership plays a significant role in the development of DCs. When comparing different technologies (new versus current) TCO gives a critical judgement about the total costs of ownership. Although a certain technology may cost less money during the investment (CAPEX), the technology may consume much more energy during his life cycle (OPEX).

Over the last 10 years many authors identified the TCO of DCs in different ways, which often resulted in complex and difficult metrics for determining the TCO. In addition, most of the metrics were very focussed on very specific DCs or markets. Therefore, it seems relevant to modify certain metrics to make it more generic. To the best of our knowledge are Patel & Shah (2005) the first who came up with a metric to calculate the TCO for DCs. They exposed the necessity of determining the different costs associated with DCs. Not only because of the complexity of DCs, but also because tremendous growth of DCs all over the globe. Their initial goal was to introduce a cost metric for building and operating a DC. In addition, they did some suggestions regarding smart design in DCs. In 2007, Koomey et al. (2007) released a working spreadsheet with which the TCO could be calculated. In comparison with the other authors this working sheet was much easier to apply and accessible. One of their major findings was that site infrastructure capital costs are much higher as expected before compared to the capital costs of IT hardware (based on the DC they used in their case study). Patterson et al (2007), in name of Intel, also published a white paper regarding the TCO of DCs. In their study they compared DCs with high-density spaces compared to low-density spaces. The outcome of their study proved that high-density DCs reduce the TCO compared with a low-density DC. Hardy et al. (2011) proposed a TCO estimation was calculated based on four different costs. By adding up the costs of acquisition, servers, power, and maintenance the TCO can be determined. In addition, they took a look at hot and cold spares, which estimates cold spares needed for the server failures and the impact of ambient temperatures. Grot et al. (2012) determined the TCO of a DC and compared this TCO among various processors. Therefore, they can be considered as the first one who compared different technologies and the influence on the TCO. In 2013 Hardy et al. elaborated further on the metric they started with in 2011. Compared to their earlier metric they add an additional cost aspect, networking equipment cost expenses. Those costs include money spent on buying network equipment. Furthermore, they compared their metric with two other metrics to validate their results. Since the other metrics did not include all the variables similar to the ones from Hardy et al. (2013), it was difficult to compare the outcomes. Similar to Grot et al. (2012), Hardy et al. (2013) compared two different server configurations. An extra dimension they add to their paper is the fractioning of the different costs from the server (processors, DRAM, disks, power supply, board, and fans) and taking into account the mean-time-to-failure (MTTF). Yang et al. (2017) were the first who looked at the TCO in DCs taking in consideration storage devices (SSD) and their amplification degree. Their metric took into account the workload characteristics of flash storage devices. Their experiments showed that the minimum TCO can reduced the TCO while holding high throughput. Cui et al. (2017) stated to save energy consumption and reduce power costs, and to compare different technologies a comprehensive TCO is needed to get insight in the different costs and possible reductions. Cui et al. (2017) used the similar cost aspects as Hardy et al. (2013). However, their break-down of costs is easier to work with. In addition, their TCO metric is based on dollars per month, since this is a time period in which companies often operate. Based on their built TCO, Cui et al. (2017) did three case studies. The following aspects are included: direct liquid cooling

solutions, high efficient power delivery using 48VDC, and IDEC. By studying those case studies, they tried to connect power consumption directly to IT performance and the total performance of a DC. Ott et al. (2017) conducted research on the ROI and TCO of adsorption chillers in DCs. Although they proved that DCs can achieve a significant amount of money when using a different kind of cooling solution, their metric is not well described in their paper. To the best of our knowledge Rokkas et al. (2017) has the most recent TCO metric regarding DCs. In their study they focussed on the cost reduction that can be generated due to virtualization. They proved that cost savings between 13% and 25% can be reached due to lower IT investment and power consumption. Another important outcome of the study is that economies of scale can achieve a significant energy reduction and therefore energy consumption. The metric they built is similar to the one from Hardy et al. (2013) and Cui et al. (2017), but they divided the costs due to power consumption in power used for IT equipment and power used for cooling.

3.3. TCO model for Data Centres in the Netherlands

Due to the fact that Koomey et al. (2007) created a very clear and practical metric, this metric is chosen as the foundation. Since the model is over a decade old different modifications are made. In addition, modifications regarding the network equipment is are, since this is the IT component where this research focusses on. As mentioned before, the TCO in this paper is determined by the OPEX and CAPEX costs. An explanation of the variables and formulas related to the variables can be found in Appendix A. U is a fixed space in a rack. # is a number. E is the energy consumption.

3.3.1 OPEX

In the model, first the OPEX costs for the IT equipment are calculated. Based on the number of racks, the distribution of IT equipment (Servers, storage, and, networking), Us per rack, the percentage of filled racks, and the number of filled U per IT sub-system is calculated:

(1) $$U_{Server} = (\#_{racks}) * (\%_{server}) * (\#Us) * (\%_{rack\ filled})$$
$$U_{Storage} = (\#_{racks}) * (\%_{storage}) * (\#Us) * (\%_{rack\ filled})$$
$$U_{Network} = (\#_{racks}) * (\%_{Network}) * (\#Us) * (\%_{rack\ filled})$$

The energy use per sub-system is than calculated based on the energy used of an average server, average storage device (Based on kW per GB), and average networking device (Switch, SFP and cable):

(2) $$E_{Servers} = U_{Servers} * E_{server}$$
$$E_{Storage} = U_{Storage} * E_{storage}$$
$$E_{Network} = U_{Network} * E_{server}$$

Afterwards the energy used for cooling and auxiliaries are calculated. This is done based on the median Dutch PUE (DDA, 2018) and the breakdown of the cooling and auxiliaries costs. Equations regarding the energy used regarding cooling and auxiliaries are described below. A full breakdown of the equations are described in order to give a full understanding of the energy consumption regarding the cooling and auxiliaries.

(3) $E_{servers + cooling + auxiliaries} = E_{Servers} + (E_{Servers} * (PUE - 1))$

$E_{Storage + cooling + auxiliaries} = E_{Storage} + (E_{Storage} * (PUE - 1))$

$E_{Network + cooling + auxiliaries} = E_{Network} + (E_{Network} * (PUE - 1))$

(4) $E_{cooling + auxiliaries} = E_{Servers/storage/network} * (PUE - 1)$

$E_{cooling} = E_{Servers/storage/network} * ((PUE * 0.7) - 1)$

$E_{auxiliaries} = E_{Servers/storage/network} * ((PUE * 0.3) - 1)$

(5) PUE = Total used energy / IT equipment energy

Based on the electricity use, the total electricity consumption is calculated. The electricity use is multiplied by the hours per year and the percentage of operational time per Tier Level (Tier 1 = 99,671%, Tier 2 = 99,749%, Tier 3 = 99,982%, Tier 4 = 99,995%). In order to calculate the total OPEX costs for the IT load, cooling and auxiliaries, the electricity consumption is multiplied by the price per kWh:

(6) $Year\ E_{servers + cooling + auxiliaries} = E_{servers + cooling + auxiliaries} * \#_{Hours} * \%_{Uptime}$

$Year\ E_{storage + cooling + auxiliaries} = E_{storage + cooling + auxiliaries} * \#_{Hours} * \%_{Uptime}$

$Year\ E_{network + cooling + auxiliaries} = E_{network + cooling + auxiliaries} * \#_{Hours} * \%_{Uptime}$

(7) $OPEX_{servers} = Year\ E_{servers + cooling + auxiliaries} * €/kWh$

$OPEX_{storage} = Year\ E_{storage + cooling + auxiliaries} * €/kWh$

$OPEX_{Network} = Year\ E_{storage + cooling + auxiliaries} * €/kWh$

Other OPEX costs that need to be taken into account are: network fees, staff, maintenance, janitorial and landscaping, security, and property taxes. Network fees are calculated based on the net DC surface multiplied by network fees per m2 (Koomey et al, 2007). Staff costs consists of two different components; number of employees and the price of an employee. The number of employees and price are calculated based on interviews with DCs. The net DC surface is divided by the m2 per FTE, which results in the number of FTE for a particular DC. Afterwards this number is multiplied by the cost of an FTE. The maintenance costs are calculated based on an estimation done by O'Brien (2014), a maintenance expert regarding DCs. O'Brien (2014) states that maintenance costs can rise up to 2% of

the DC annual budget. This percentage is taken from the annualized capital costs. Janitorial and landscaping costs (€/m2) are averaged out from different sources and multiplied by the number of m2. Security is calculated in a similar way as in Koomey et al. (2007). Three shifts a day are multiplied with the yearly income of a security guard. Property taxes are calculated based on 1% of the total installed capital costs of the building (not including IT costs).

3.3.2. CAPEX

For the CAPEX costs the IT costs are calculated as well. First, the number of watts per € are calculated, by dividing the average watts for servers, storage devices, and network devices, by the average costs that are found. Than those costs are transformed to costs per filled U and rack. Lastly, for the IT CAPEX, the total IT costs are calculated. In order to calculate the total IT costs, the costs per filled U are multiplied with the number of filled Us

(8) $$CAPEX_{servers} = (W_{server} / €_{server}) * U_{Filled}$$
$$CAPEX_{storage} = (W_{storage\ device} / €_{storage\ device}) * U_{Filled}$$
$$CAPEX_{network} = (W_{network\ equipment} / €_{network\ equipment}) * U_{Filled}$$

Secondly, the costs related to the racks are calculated. Based on Koomey et al. (2007) rack costs are €3.000 per rack. In addition, they made an estimation that the external hardwired connections and rack management hardware are €5.000 and €3.000 per rack. In order to calculate the CAPEX costs for racks, the rack costs, external hardwired connections costs, and rack management hardware costs are multiplied by the number of racks:

(9) $$CAPEX_{rack} = (€_{Rack} + €_{external\ hardwired\ connections} + €_{rack\ management\ hardware}) * \#_{racks}$$

The cabling costs are based on Koomey et al. (2007) and the DC surface. A fixed number is multiplied with the DC surface. The kW related infrastructure costs and area facility costs are based on a model built by Turner and Seader (2006). Those costs cover the power and cooling engine costs and varies between size and tier level. The power related and area related costs have taken into account inflation and the currency change from dollar to euro ($1 = € 1, inflation = 24,99% (IEX, n.d., in 2013 Dollars, n.d.)). A full list of the different tier levels can be derived from Table 4. In order to calculate the kW related infrastructure costs and area facility costs, the total number of energy consumed for IT needs to be multiplied by the power related costs and the area surface needs to be multiplied by the area related costs.

Table 4 kW and area costs

Tier level	kW related infrastructure costs	Area facility costs
1	€ 10.625 / kW	€ 2.550 / m^2
2	€ 11.685 / kW	€ 2.550 / m^2
3	€ 21.250 / kW	€ 2.550 / m^2
4	€ 23.375 / kW	€ 2.550 / m^2

Interest during construction is calculated based on numbers of the Netherlands Bureau for Economic Policy Analysis (CPB) (CPB, 2015). For calculating the interest during construction, kW related infrastructure costs and area facility costs need to be multiplied by the real interest rate of 5,5%. Land costs are the costs related to the surface area where to DC is located. According to the Dutch Kadaster, building land is worth €500.000 per ha. Multiplying the costs per ha with the number of ha gives the total costs for land. Architectural and engineering fees are estimated as 5% of kW related infrastructure costs plus other facility costs (electrically active). Costs for inert gas fire suppression based on Koomey (2007) and are approximately €570,00 per m2.

3.3.3 Input variables

For using the conceptual model, a couple of variables need to be filled in. The model passes on the incoming values and calculates the TCO and other relevant outcomes. Table 5 provides an overview of the variables that are the input variables.

Table 5 Input variables

Variable	Explanation
Data centre net surface (m2)	Surface of DC used directly for IT related processes.
PUE	Ratio between the total facility and the IT equipment energy.
Price per kWh (€)	The price that is payed per kWh.
Percentage of racks filled with servers equipment (%)	Percentage of rack space filled with servers.
Percentage of racks filled with storage equipment (%)	Percentage of rack space filled with storage equipment.
Percentage of racks filled with networking equipment (%)	Percentage of rack space filled with networking equipment.
Percentage of rack filled with IT equipment (%)	Percentage of rack space filled.
Number of GB in a U (#)	Number of stored GBs per U.
Tier level	Classification metrics for DCs
Yearly operational time (%) (based on Tier-level)	Yearly uptime hours.
kW components by desired level of functionality (€/kW)	Variable that determines related costs to every kW consumed.
Number of ports per switch (#)	Number of ports per switch installed.
Depreciation rate IT equipment (Years)	Devaluation time of the IT equipment.
Depreciation rate in years for site infrastructure equipment	Devaluation time of the site infrastructure equipment.

Compared to the model created by Koomey et al. (2007) there are several differences. The main difference are the different IT equipment components that are taken into account. While Koomey et al. (2007) as tape storage as a component, it is left out for this conceptual model, due to the fact that tape storage is used very sporadic (based on interviews). In addition, the distribution within the racks and the energy consumption per IT component. These numbers are updated based on market numbers that are currently available.

3.3.4. Limitations of the Model

Some variables (that other authors took into account) are left out in the conceptual model. In order to avoid confusion those aspects are explained in Table 6. In addition, some other clarifications are made to ensure the understanding of the conceptual model.

Table 6 Variables that are left out of the model

Variables	Reason
MTBF	Although this variable is influenced when using different technologies, nearly no information is available about the MTBF.
MTTR	Although this variable is influenced when using different technologies, no information is available regarding the MTTR.
MTTF	Although this variable is influenced when using different technologies, nearly no information is available about the MTTF.
PoE switches	PoE switches are not considered in this research, since electricity is calculated separately in this metric.
10G cables	Currently, 10G cables are available for Ethernet and fibre cables. In addition, research is done to improve the speed POF cables. Although rates up to 13G are achieved, 1G is still the standard. Therefore, this thesis only compares 1G connections.
MMF vs SMF	There is not difference made between MMF and SMF, due to time constraints.
Extraction of raw materials	IT components are used as fixed components, without looking at the initial raw material extraction. Therefore, this research does not look at cradle-to-cradle cycle before the usage of products.
Recycling	Recycling is not taken into account due to the scope. Therefore, this research does not look at cradle-to-cradle cycle after the usage of products.

4. Results of TCO analysis of Data Centres

4.1. Classifying Data Centres in the Netherlands

This section elaborates on the results of the empirical analysis. The three different cases are applied on the conceptual model. First, the different cases are explained in order to ensure the relevance of the

cases. Secondly, assumptions are described, on which the model is built. Thirdly, the results of the different cases are presented.

The Dutch Data Center Association (DDA) classifies DCs according to three different variables, space (in square meters), number of racks, and the amount of electrical power that is used (in megawatts (MW)) (DDA, 2017). Table 6 shows the classification of DCs done by the DDA. As can be derived from Table 6, each variable is divided in nominal values. Since the DDA did not give names to the different levels, those are added. For this research this distribution of DCs seems interesting, due to the fact that nearly all the data is available of DCs located in the Netherlands. In this way it is easy to take a look to which category most DCs belong. However, there are also a disadvantage. Sometimes DCs are located in multiple categories. The space of a particular DC may fall in the category small, while the amount of racks is still between.

Table 1: Categorization of DCs by DDA

	Categorization			
Variables	Small	Medium	Large	Very large
Space (M^2)	0 – 1.000	1.000 – 2.500	2.500 – 10.000	10.000+
Racks	0 – 200	200 - 500	500 – 1.000	1000+
Power (MW)	0 – 1	1-10	10 - 20	20+

For these case studies a generalized DC is used in order to show the differences regarding TCOs between the different technologies. In order to get a representative outcome, the input numbers are based on averages in the Dutch DC market, interviews or estimations. Table 7 gives an overview of the input variables. The other variables that are used in the spreadsheet are either fixed or are passed on based on the variables in Table 7.

Table 7 Case study input

Variable	Case study values	Source
Data centre net surface (m2)	1370	RVO (2016), DDA (2017)
PUE	1.3	DDA (2017)
Price per kWh (€)	€ 0,07	Interviews
Percentage of racks filled with servers equipment (%)	45	Interviews
Percentage of racks filled with storage equipment (%)	45	Interviews
Percentage of racks filled with networking equipment (%)	10	Interviews
Percentage of rack filled with IT equipment (%)	75	Koomey (2007)
Number of GB in a U (#)	10.000	Interviews
Tier level	3	DDA (2018)
Yearly operational time (%) (based on Tier-level)	99,982	Turner and Seader (2006)
kW components by desired level of functionality (€/kW)	21.250	Turner and Seader (2006)

Number of ports per switch (#)	24	Estimation
Depreciation rate IT equipment (Years)	3	Koomey (2007), Hardy et al. (2013)
Depreciation rate in years for site infrastructure equipment	15	Koomey (2007) Hardy et al. (2013)

Based on papers from the RVO (2016) and DDA (2017) is the average DC net surface calculated, which is 1370 m2. Although figures presented in those papers are 1 and 2 years old, the estimation is made that the average surface still holds nowadays. The median PUE of Dutch DCs is 1.3, based on a paper from the DDA (2018). The racks that are used in the case studies are filled with 45% servers, 45% storage, and 10% networking equipment. Those numbers are derived from interviews with experts in the field (DC owners and co-location customers). Racks are filled on average for 75% (Koomey, 2007). In order to calculate the OPEX and CAPEX costs for the storage devices, based on an interview, the number of GBs per U is estimated on 10.000 (Interviews). The median tier level regarding Dutch DCs is 3, with a corresponding yearly operational time of 99,9982%. The kW components by desired level of functionality, based on Turner and Seader (2006) for a tier 3 level is €21.250 per kW. The number of ports per switch is determined on 24 ports. Lastly, the depreciation rates of the IT equipment and the infrastructure equipment are, based on Koomey (2007) and Hardy et al. (2013), estimated to be 3 and 15 year.

Based on the conceptual model three different in-rack network technologies are compared with each other, looking at the TCO and related energy consumption. Ethernet (1G), Glass fibre (1G), and POF (1G) are compared to each other. In the paper written by Lannoo et al. (2011), a TCO was calculated regarding in-building network bandwidth for 5 different technologies. In this case study, those 5 technologies are merged into 3 technologies; Ethernet (CAT 5 and 6), Glass fibre (SMF and MMF), and POF.

4.2. Results of TCO analysis

Technological change has affected data centres by using variety of network technologies like ethernet (base case), fibre and POF technologies. First, the energy consumption of the networking equipment is presented with the cooling and auxiliaries. In addition, the CO2 emissions are shown. Secondly, a breakdown of the annual costs are described. This is done to find out what the influence is on changing the networking equipment as part of the TCO. Furthermore, the TCO and the cost reductions for the different scenarios are described. Lastly, a sensitivity analysis is conducted.

Figure 1 gives an overview of the costs for electricity for the network part of the IT equipment. The left Y axis shows the costs related to the energy consumption of the network part. The right Y-axis shows the difference compared to the baseline (Ethernet). The scenarios are calculated based on the input variables described in the beginning of this section. As can be derived from Figure 1, when looking at Ethernet as a technology, costs are approximately €100.000 looking at kWh for the networking part.

Networking costs related to kWh for glass fibre are approximately €80.000 and for POF approximately €60.000. These results reveal that the savings regarding kWh costs for the networking part are 24% for glass Fibre and 37% for POF.

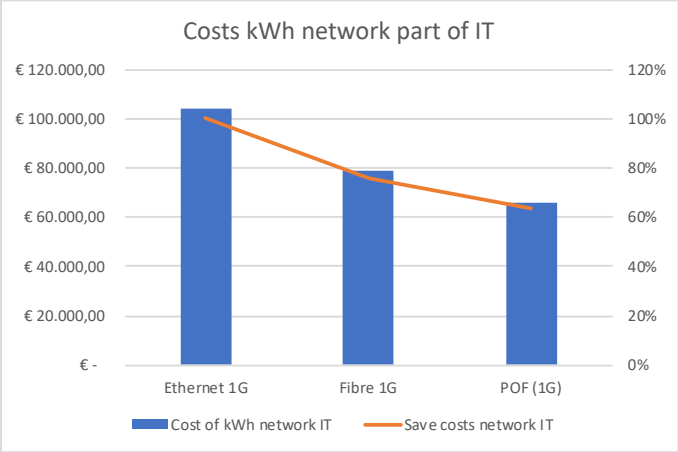


Figure 1 Costs kWh network part

Figure 2 gives an overview of yearly CO2 emission for the network part of the IT equipment. The left Y axis shows the annualized yearly CO2 emission for the network part. The right Y-axis shows the savings compared to the baseline. As can be derived from Figure 2, does Ethernet as a technology in a DC has a CO2 emission of just over 500.000 KG. Compared to glass Fibre and POF, the CO2 emission of Ethernet is much higher, Glass fibre and POF have CO2 emission of approximately 400.000 KG and just over 300.000 KG. Similar to savings regarding money spent on kWh, a 24% reduction with glass fibre and 37% reduction with POF can be achieved compared to Ethernet.

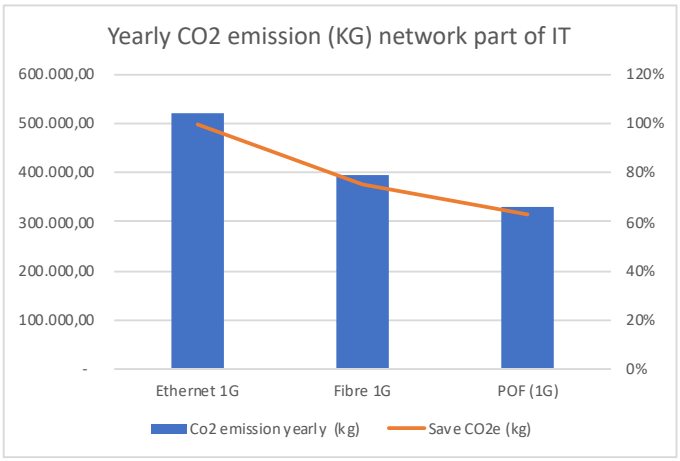


Figure 2 Yearly CO2 emission network part

Table 8 gives an overview of the related costs, that are influenced by the networking components. As can be derived from the table, there are OPEX and CAPEX costs influenced by changing the network equipment. OPEX costs that change are related to cooling and auxiliaries. Regarding the CAPEX costs the initial purchase costs differ, as well as the kW related infrastructure costs, interest during construction, and architectural and engineering fees. Compared to the baseline glass fibre can save up

to € 173.000. Those savings are even higher for POF, € 232.000. Changing this into percentages, for glass fibre and POF, indirect costs savings are approximately 1.8 and 2.4%.

Table 8 Comparison indirect costs for different technologies

	Variable	Ethernet	Glass fibre	POF
OPEX	Cooling for network equipment	€20.000	€17.000	€14.000
	Auxiliaries network equipment	€ 9.000	€ 7.000	€ 6.000
CAPEX	Network IT equipment	€ 560.000	€ 470.000	€ 460.000
	kW related infrastructure costs	€ 8.350.000	€ 8.280.000	€ 8.240.000
	Interest during construction	€ 477.000	€ 473.000	€ 470.000
	Architectural and engineering fees	€ 434.000	€ 430.000	€ 428.000
	Yearly costs influenced by changing the network equipment	€ 9.850.000	€ 9.677.000	€ 9.618.000
	Difference compared to baseline (absolute)	**€ 0**	**€ 173.000**	**€ 232.000**
	Difference compared to baseline (percentage)	100%	98.2%	97.6%

Figure 3 presents the TCO savings on a yearly basis for two different scenarios compared to the baseline. The left Y axis shows the annualized costs in million euros. The right Y-axis shows the savings compared to the baseline (Ethernet). As can be derived from Figure 3 are the total annualized costs from the three different scenarios all between 32 and 32.6 million euro a year. The difference between Ethernet and glass fibre is nearly €230.000. Between Ethernet and POF the annual difference in TCO is over €300.000. Looking at glass fibre, the TCO on an annual base dropped just over 0.6% looking at the costs. For POF, the annual costs dropped even more to nearly 1%. The reason why the TCO dropped was caused by multiple reasons. First, for both glass fibre and POF, the energy consumed during operation is lower. Therefore, less kWh were consumed which results in less money spent on energy. Secondly, due to lower energy consumption, less energy is as well needed for cooling and auxiliaries. Thirdly, looking at the CAPEX differences glass fibre and POF is mainly caused by the fact that those components are much cheaper on their initial purchase. Fourthly, the kW related infrastructure costs drop significantly with nearly 1 million euro from Ethernet compared to POF. Fifthly and sixthly, interest during construction and architect costs are lower compared to Ethernet.

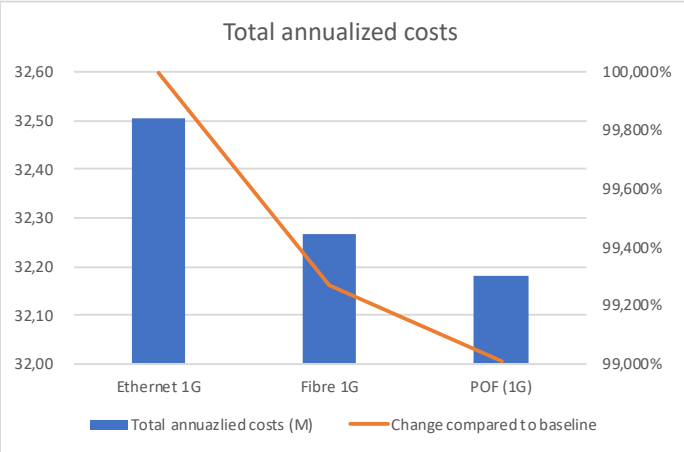


Figure 3 Annualized TCO

Table 9 gives an overview of a breakdown of the annualized costs. As can be derived from the Table, several costs, as part of the total TCO, stay similar when changing the network equipment. Energy costs servers, energy consts storage, IT captital costs for servers and storage, and IT capital costs rack maangement hardware total stay similar. Those variables are not influenced when parts of the network equipment is changed. On the other hand there are variables that are influenced when the network part changes. As can be derived from Table 9, Energy costs networking, other operating expenses, IT capital costs networking, and other infra costs reduce as part of the total TCO. Energy cost networking drop with respectively 0.1% and 0.15% for glass fibre and POF. Other operating expenses drop with a small percentage, namely, 0.05% for glass fibre and 0.07% for POF. Regarding the IT capital costs regarding networking there is an decrease in the TCO of 0.28% and 0.33% for glass fibre and POF. Other infrastructure costs also drop significantly when different networking equipment is used. Compared to Ethernet, there is a reduction of 0.28% reduction for glass fibeibre and a 0.42% reduction regarding POF.

Table 9 Breakdown annualized costs

Annualized costs	**Ethernet**	**Glass fibre**	**POF**
Energy costs servers (including cooling + auxiliaries)	7,16%	7,16%	7,16%
Energy costs storage (including cooling + auxiliaries)	3,41%	3,41%	3,41%
Energy costs networking (including cooling + auxiliaries)	0,43%	0,33%	0,27%
Other operating expenses	8,89%	8,84%	8,82%
IT capital costs servers	36,66%	36,66%	36,66%
IT capital costs storage	7,32%	7,32%	7,32%
IT capital costs networking	1,78%	1,50%	1,45%
IT capital costs Rack management hardware total	1,94%	1,94%	1,94%
Other infra costs	32,41%	32,13%	31,99%
Total	**100%**	**99,27%**	**99,01%**

4.3. Sensitivity analysis

To better estimate which variables, influence the TCO of DCs a sensitivity analysis is performed. This section first presents an overview of which variables are changed to the earlier case studies. Secondly, the sensitivity analysis is conducted.

Due to an increase of DC surfaces over the past years (DDA, 2018) this variable is taken into consideration for the sensitivity analysis. Since the other variables are also changed in a positive and negative way, this similar done for this variable. Furthermore, due to continuous improvements, different PUEs are considered (retrieved from interviews). The PUE in the first case study was estimated to be 1.3. Since it is practically nearly impossible to have an PUE of 1.0 or below, those numbers are left out. Moreover, the costs of the network equipment is used in this sensitivity analysis, as well as the power consumption of the network equipment. Lastly, the costs per kWh are put into the sensitivity analysis.

Figure 4 gives an overview of the sensitivity analysis for POF for the above described variables. The x-axis shows the modifications of the variables between -20% of the initial value and +20% of the initial value. The y-axis shows the sensitivity changes that are the output of changing the input variables. As can be derived from Figure 4, the data centre surface has the largest influence on the total TCO. When expanding the data centre surface with 20% the TCO only rises with 0.2% compared to the surface area from the case studies in the previous section. A similar sensitivity analysis is conducted for the number of ports per switch, see Figure 5. However, another scale is used due to market standards other modifications are done. The baseline model has 24 ports per switch, while for the sensitivity model the number of ports are increased to 48, 96, 128, and 265.As can be derived from the picture, does the TCO for POF hardly increase while ports almost 10 fold. Similar counts for glass fibre although this number is around 50% higher compared to POF. For Coper the increase in TCO, when increasing the number of ports, is the highest.

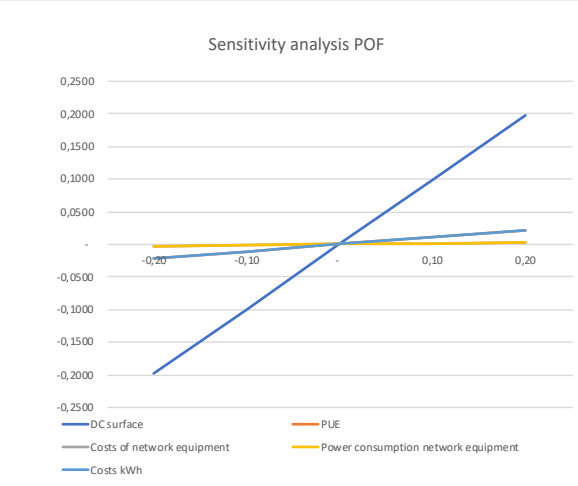


Figure 4 Sensitivity analysis POF

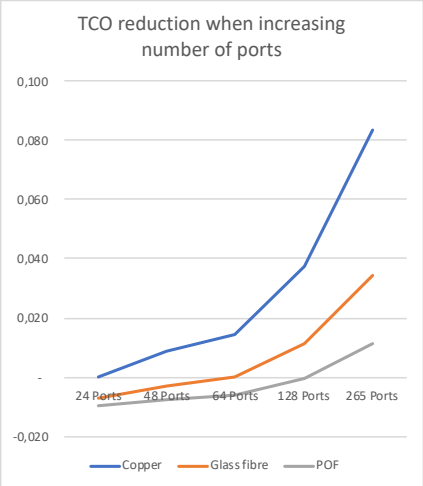


Figure 5 Sensitivity analysis POF ports

5. Conclusion and discussion

This section focusses on the conclusion and discussion of this research. First, an explanation of findings are presented, which focusses on answering the main- and sub-questions of this research. The goal of this study was, looking at the network infrastructure of DCs, how much energy an average DC in the Netherlands can save on a yearly basis. Additionally, managerial and theoretical contributions are explained. These sub-sections elaborate on how managers can use this research for doing business and how this research contribute to relevant literature. Furthermore, societal implications are discussed. Lastly, limitations and future research is suggested.

As can be derived from the different case studies, there is a difference between annual TCOs when using different network technologies. Looking at the annual TCO for the different technologies the following TCOs are calculated: €31.410.000 for DCs with Ethernet solutions, €31.190.000 for DCs with glass fibre solutions, and nearly €31.110.000 for DCs with POF solutions. Therefore, POF can be considered as the least expensive solution for DCs.

Looking at the energy consumption for the different solutions, the kWh usage of the different technologies are compared with each other. Looking at the network equipment, regarding Ethernet, annually, 1.930.000 kWh is used. Compared to glass fibre this number is 470.000 kWh higher, since for glass fibre the electricity usage is calculated at 1.460.000 kWh. For POF this number is even lower with an annual electricity usage of 940.000 kWh. The electricity consumption of the POF solution is less than 50% of the electricity consumption with the Ethernet solution. The total difference in kWh is 990.000 kWh. As we multiply this number with the number of commercial DCs in the Netherlands, which is proximately 205 (DDA, 2018), the total savage of kWh for nearly all the DCs in the Netherlands is around 202.950.000 kWh every year, which is equal to 0.2 TW. Although, the initial savings for a single DCs may only be around 1% of the TCO, the total energy savage that can be made by combining all savages of all the DCs a substantial amount of energy can be saved. Translating the annual kWh savings into Kg CO2e a reduction of 71.349.102 Kg CO2e can be achieved.

Managerial contributions

The theoretical framework and empirical results shows a generic way for determining the TCO for DCs and how this TCO differs between different network technologies. Therefore, this research is useful for DC owners, DC customers, the government, and network equipment suppliers. This sub-section elaborates on how the above described stakeholders can benefit from this research.

First, DC owners let customers pay for rack space and additionally customers pay a fee for the electricity they use during operation. As mentioned before, the energy consumed for cooling and auxiliaries is influenced by the energy consumed by the IT equipment. If DCs choose to only let in IT equipment with particular specifications other costs of DCs would decrease as simultaneously. Many of the DCs say that this would result in outcompete by other DCs. But by creating an incentive for customer

of DCs to become more energy efficient, also less costs in the operation are generated. In this way DCs can offer less expensive rack space and the monthly electricity bill also decreases. Additionally, when a couple of DCs would change to this strategy, other DCs will be outcompeted due to price. Other DCs will become less attractive while offering the same functionalities.

Secondly, this TCO model focussing on networking equipment can be beneficial for DC customers. By giving them insight in the electricity consumption, and the possible reduction they can achieve. Due to the fact that they will look at the whole picture, instead of only CAPEX, their view might change. In addition, as mentioned above, energy reduction in the IT part will also result in less energy consumption in other parts of the DC. Due to these two aspects, monthly costs will decrease while customers can keep the same stability and uptime as before.

Thirdly, this research contributes to the understanding of DC energy consumption for the government. It gives insight in how much energy is consumed on average in DCs and how much DCs can save with different technologies. Therefore, it is easier for the government to control the energy consumption within DCs. In addition, they can steer DCs in the right direction or control them while looking at their energy consumption. More about governmental implications can be found in section 6.4 societal implications.

Lastly, this research is beneficial for network equipment suppliers, especially for the ones who are operating in glass fibre or POF market. Since the TCO of both technologies is much lower compared to the conventional Ethernet technology, while having the same specifications, they can use this research as a selling argument. With proved data, and a data sheet they can support their selling strategy with empirical evidence. In this way they can convince people to shift from one to another technology.

Theoretical contributions

This research contributes to existing theory in several ways. First, this research provides a generic TCO that can be used by DCs in order to determine their costs and energy consumption related to all the different sub parts. Other TCO models that are described in the literature are mainly focussed on particular DCs or DCs in a specific sector, while this TCO model is made much more generic. Furthermore, this model passes on many mathematical equations based on some input variables. Therefore, based on only a few input variables, outcome variables are determined. This makes it possible to easily handle the TCO and interpret the outcomes.

Secondly, this is the first research in which a TCO model is tested with case studies regarding in rack network equipment. Although other papers already compared different technologies in DCs, none of them focussed on network equipment. The following papers focussed on following technologies or variables: servers (Koomey et al., 2007; Hardy et al., 2011; Grot et al., 2012; Hardy et al., 2013; Rokkas et al., 2017;) cooling (Patel & Shah, 2005; Ott et al., 2017; Cui et al., 2017), and scalability (Patterson & Loeffler, 2007; Rasmussen, 2011). With comparing different networking technologies this research contributes to a new aspect of DCs. In addition, this research, is besides Rokkas et al. (2017)

the only one who takes into consideration sensitivity (or scaling). This gives a more in-depth insight in the changes that might appear when certain variables are changed. With this insights it is possible for managers and other users to determine how and how much scaling is needed (See section 6.2).

Societal implications

Besides managerial and theoretical contributions, there are also societal implications regarding this research. The results of this study have implications for potential positive social change on the individual level, organizational level, and at the societal level.

On an individual level, it this thesis may change the view of people regarding IT equipment and their energy consumption and pollution. By making people aware of the side effects of particular technologies, and the possible savings they can achieve pollution may decrease.

On an organization level, this thesis may help companies to become more aware of their footprint. By proving how changing particular IT equipment also effects other parts of the DC, an incentive could be created for DCs to only work with sustainable IT equipment. Therefore, the environmental impact is lowered.

On a societal level this thesis may contribute to the overall discussion regarding energy consumption of IT. As can be derived from Røpke (2012), the integration of IT was, is and will increase into our daily lives. Therefore, while people know IT is not sustainable, the usage of IT will do not decrease in the coming years. Therefore, similar to Røpke (2012), the question is if IT can become sustainable. It might just be that IT is a given phenomenon and that people have to try to decrease the pollution regarding IT. Therefore, this research may make people aware of the possibilities for DCs to decrease energy consumption. While decreasing energy consumption, and therefore also energy costs, the awareness can be created to become more sustainable. In addition, this will also help to lower the CO2e and other pollution.

Limitations and future research

Although this study has contributed on managerial, theoretical and societal level, it has limitations that create possibilities for further research. The limitations of this research and recommendations regarding future research are discussed in this sub-section.

Looking at the shift towards green IT, for future research, a deep green approach (Murugesan (2008) can be investigated. This research only looked at the OPEX and CAPEX costs for different network technologies, due to the scope. However, to get a full overview of all the costs and energy consumption the full chain needs to be investigated. Therefore, looking at a deep green approach, seems most appropriate for future research. With this approach also other variables are taken into account, such as, the usage of green energy, cradle-to-cradle technologies, and the use of renewable energy. Especially looking at cradle-to-cradle seems very relevant. POF for example is only made of plastic which can be

re-used, with a chemical process, while Ethernet based networking technologies are much harder to re-use.

Furthermore, in this study only cables with a speed of 1Gbit are considered, while connections with 10Gbit are appearing fast. Ethernet cables and glass cables with 10Gbit are already available, however information about POF cables with 10Gbit is not available. A company in the south of Germany is already testing with POF cables that can handle 10 Gbit (up to 13 Gbit). However, there is currently no information available about the specifications and therefore cannot be compared yet to other technologies.

Ethernet, glass fibre, and POF do all have different manners to connect them to a switch. In addition, cables may have different life cycles. In this study, mean time to repair, mean time between failure, and mean time to failure are not taken into consideration, but they could be helpful for understanding all the different costs related to implementation and maintenance (See section 4.3, scope conceptual model). In addition, the lifecycle between the cables also differs. Therefore, it is interesting to look at the mean time between failure in order to get a full understanding of the different technologies.

As described in the societal implications, governmental regulations may help to steer data centres towards a more sustainable way of thinking and operating. How this process should take place is an incentive for further investigation. There are many ways how control particular innovations with regulations, such as, taxes, subsidies, and laws.

This research focusses on the networking equipment data centres use within racks. Other researches focussed on many other parts of data centres, and how innovations in those parts would be beneficial for the TCO. However, there are still some parts of data centres that are undiscovered. Currently there are papers available regarding servers, cooling, scalability, and networking (Koomey et al., 2007; Hardy et al., 2011; Grot et al., 2012; Hardy et al., 2013; Rokkas et al., 2017; Patel & Shah, 2005; Ott et al., 2017; Cui et al., 2017; Patterson & Loeffler, 2007; Rasmussen, 2011) . Therefore, it is recommended that the following topics should be investigated to achieve more sustainable data centres: software, air management, and power provisioning. Those topics are not yet described in the literature and therefore seem relevant for future research.

Despite these limitations, the conceptual framework and findings have proved added value to the data centre market and their related energy consumption. We hope that with this thesis stakeholders become aware of the possible improvements that can be made regarding data centres and that this thesis contributed to new insights regarding the determination of the TCO.

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Appendix A - Explanation variables TCO

No	Explanation
1	Fraction of racks allocated to different parts of IT part
2	Number of racks in a particular DC, based on the nett floor size
3	Number of U in a rack, standard 42
4	Percentage of a rack that is filled
5	Number of Us filled with particular IT equipment
6	Average usage per U, based on the most common market used IT equipment
7	Energy use per rack is the product of the total number of Us filled times watts per installed U
8	Total direct IT energy use is the product of watts per rack times the number of racks of a given type
9	Total direct IT energy use is the product of watts per rack times the number of racks of a given type
10	Cooling electricity use, as part of IT load
11	Auxiliaries electricity use, as part of IT load
12	Total electricity use = sum of IT, cooling, and auxiliaries use.
13	Electricity intensity is calculated by dividing the power associated with IT load divided by the total electrically active area of the facility.
14	Electricity intensity is calculated by dividing the power associated with cooling divided by the total electrically active area of the facility.
15	Electricity intensity is calculated by dividing the power associated with auxiliaries divided by the total electrically active area of the facility.
16	Electricity intensity is calculated by dividing the power associated with total electricity use divided by the total electrically active area of the facility.
17	Total electricity consumption (IT load) is calculated using the total power, a power load factor(based on tier level), and 8766 hours/year (average over leap and non-leap years).
18	Total electricity consumption (Cooling) is calculated using the total power, a power load factor(based on tier level), and 8766 hours/year (average over leap and non-leap years).
19	Total electricity consumption (Auxiliaries) is calculated using the total power, a power load factor(based on tier level), and 8766 hours/year (average over leap and non-leap years).
20	Total electricity consumption (total electricity use) is calculated using the total power, a power load factor(based on tier level), and 8766 hours/year (average over leap and non-leap years).
21	Total energy costs for the IT load, electricity consumed times energy price
22	Total energy costs for the cooling, electricity consumed times energy price
23	Total energy costs for the auxiliaries, electricity consumed times energy price
24	Total energy costs, electricity consumed times energy price
25	Watts per K€, based on market research (internet) and interviews with customers of co-locators
26	Costs per filled U. Power per filled U / (power / K€). Numbers are based on market research and interviews with customers of co-locators
27	Cost per filled rack is the product of the cost per U and the total # of Us per rack (42).
28	Total IT costs are the product of the number of filled Us and the cost per filled U.
29	Rack costs are the costs of the rack structure based on Koomey (2007)
30	External hardwired connections costs based on Koomey (2007)

31	Rack management hardware costs based on Koomey (2007)
32	Total costs for racks is the product of the cost per rack and the number of racks.
33	Total costs for hardwired connections is the product of hardwired connections and the number of racks.
34	Total costs for rack management hardware is the product of rack management hardware and the number of racks
35	Total cabling costs based on Koomey (2007)
36	kW related infrastructure costs based on Turner and Seader (2006), inflation taken into account
37	Other facility costs based on Turner and Seander (2006), inflation taken into account.
38	Interest during construction estimated based on total infrastructure and other facility capital costs assuming a 5,5% real interest rate for one year.
39	Land cost based on €68,000 per ha
40	Architectural and engineering fees are estimated as 5% of kW related infrastructure costs plus other facility costs (electrically active). Cost percentage is based on personal communication with Peter Rumsey of Rumsey Engineers, 9 July 2007. Cost for inert gas fire suppression are Uptime estimates ($50/sf of electrically active floor area).
41	Cost for inert gas fire suppression based on Koomey (2007)
42	Total installed capital costs
43	Capital costs with three year life include all IT equipment costs
44	Capital costs with 15 year lifetime include all capital costs besides IT costs (these costs also include rack, cabling, and external hardwire connection costs).
45	Capital costs are annualized with the capital recovery factor calculated using the appropriate lifetime (three or 15 years) and a 5,5% real discount rate.
46	Total energy costs, electricity consumption times energy price (same as 24)
47	Network fees based on Koomey
48	Costs of staff based on FTE per m2 times salary costs (determined by interviews DC + Patel & Shah (2005))
49	Total installed capital costs times 2% maintenance costs (http://www.datacenterjournal.com/datacenter-facilities-maintenancen time-change-culture/)
50	Janitorial and landscaping costs are € / m2 / y times m2 (based on literature)
51	1 security guide with 3 different shifts per day
52	Annual property taxes estimated as 1% of the total installed capital cost of the building (not including IT costs).
53	Total operating expenses include electricity costs, network fees, and other operating expenses.
54	Total operating expenses include electricity costs, network fees, and other operating expenses.
55	Total annualized costs include capital and operating costs.
56	Costs per square foot per year are calculated by dividing total annualized costs by the total electrically active floor area.
58	Costs per server are calculated assuming that all servers are 1U Volume servers and by dividing total annualized costs by the number of Us occupied by servers.
59	Costs per storage are calculated assuming that all storage are 1U Volume storage and by dividing total annualized costs by the number of Us occupied by storage.
60	Costs per networking are calculated assuming that all networking are 1U Volume networking and by dividing total annualized costs by the number of Us occupied by networking.

Appendix B – Guidelines conceptual model

Regarding the current metrics many challenges are mentioned and discussed in section 2. Those challenges regarding current metrics are tackled in order to create an improved metric. In addition, Newcombe (2009) and Wang & Khan (2013) made different goals and criteria for determining green performance metrics. Those goals and criteria are followed to ensure the usefulness and applicability of the metrics.

Table 1 gives and overview of the goals of green performance metrics. Newcombe (2009) initiated 9 different goals that need to be reached in order to get a suitable metric. Goal 1 and 2 focus on the understanding what is measured (the result) and how this result can be measured. Due to the framing of the main- and sub-questions a clear view is generated regarding those goals. The output measure of the conceptual model is determined in TCO, kWh and, a percentage difference between the three technologies (with one technology as baseline). Goal 3 focusses on the networking function of the IT services. For this goal the following aspects are taken into account: switch, SFPs and cabling. Goal 4 is achieved by initiating an input sheet. Only a few variables can be changed that affect the outcome. Goal 5 and 6 are completed due to combining different technologies, and the possibility for users to change particular variables. Due to an output sheet with a comparison of the different technologies, goal 7 is achieved. By changing one of the current technologies that is used as an input, the other mathematical equations regarding the model change automatically, which results in achieving goal 8 and 9.

Table 1 Goals of green performance metrics.

	Goal (Newcombe, 2009)
1.	*Provide a clear, preferably intuitive understanding of the measure*
2.	*Provide a clear, preferably intuitive direction of improvement*
3.	*Describe a clearly defined part of the energy to useful work function of the IT services*
4.	*Be persistent, i.e. the metrics should be designed to be stable and extensible as the scope of efficiency measurement increases, rather than confusing the market with rapid replacement*
5.	*Demonstrate the improvements available in a modern design of facility*
6.	*Demonstrate the improvements available through upgrade of existing facilities using more efficient M&E systems*
7.	*Provide a clear, preferably intuitive understanding of the impacts of changes*
8.	*Be reversible, i.e. it should be possible to determine the energy use at the electrical input to the DC for any specified device or group of devices within the DC*
9.	*Be capable of supporting 'what if' analysis for IT and DC operators in determining the energy improvement and ROI for improvements and changes to either the facility or the IT equipment it houses*

As can be derived from Table 2, Wang & Khan (2013) defined different criteria for building a metric. Wang & Khan (2013) identified 5 different criteria that should be taken into consideration. Due to the possibility to change DC characteristics such as, surface size, tier level, and the distinction between

fulfilment of the racks, it becomes possible to apply the metric on various DC types. Due to comparing different metrics there is sought to do not overlook components of the DC. In addition, modifications regarding other models are made to give a more in-depth look into the costs regarding the DC. Some other metrics put in fixed numbers, while this conceptual model tries to make variables more variable. The evaluation of all the features are achieved by interviewing DCs and customers of DCs. In this way is tried to get a realistic overview of actual DCs. Variables that confirmed by DCs are: distinction between fulfilment of the racks, percentage of racks filled, and the number of storage GBs per U. Since only a couple of variables can be changed it is not difficult to implement this model. After changing the variables, a fixed number of tables is generated with all the relevant information needed, which fulfils the criteria of low cost implementation and ease of use.

Table 2 Criteria green performance metrics

	Criteria green performance metrics
1.	*Technically sound: The metrics should be adaptable to various DC types, including internal DCs and outsourced DCs multi-tier DCs and DCs with redundancy.*
2.	*Holistic and balanced system evaluation: A green performance metric should evaluate the whole DC system, without overemphasizing or overlooking any components of a DC.*
3.	*All-featured evaluation: Green performance metrics should be able to capture a data centre's behaviour at typical workloads and operation modes.*
4.	*Low cost to implement: Complex and expensive implementation of performance metrics may circumscribe its wide adoption.*
5.	*Ease of use: Data center management staff and users would be glad to adapt to some metrics, which are easy to use and intuitive to understand.*

Table 3 gives an overview when and how to use the conceptual model that is presented in section 4.2. Since one of the problems of many metrics is that people do not know when to use a particular metrics, it is important to elaborate on this.

Table 3 How to use the conceptual model

When to use?	The metric should be used when DCs, DC customers or other people related to DCs want to get insight in the current energy consumption and costs related to networking. In addition, this metric compares different technologies and therefore enables to possibility to find out which networking technology is most suitable for someone.
How to use?	The usage of the metric should be done via the worksheet that is built. There are input variables that need to be filled in. The spreadsheet calculates the outcomes based on the input variables and graphs change automatically
How often to use?	The metric should definitely be used when people want to have a baseline of their energy consumption and costs regarding network equipment. Therefore, it is important for all DCs and customers to use this model to create this baseline. Furthermore, this metric can be used every time new network equipment is purchased. In this way, in a consistent way,

	calculations can be made for every new investment. Additionally, this metric can be used as well when DCs purchase new infrastructure related products, since this influences as well.
How to interpret the results?	Results should be interpreted from the output spreadsheet. Fixed outcome variables are calculated. Therefore, the output variables are similar every time calculations are done. This avoid the people who use the model from indistinctness.