MENDEL UNIVERSITY IN BRNO
FACULTY OF BUSINESS AND ECONOMICS

Analysing and exploiting technology driven cost factors in long term IT operations in complex, mission critical operations centres

DISSERTATION

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1 INTRODUCTION

The purpose of this chapter is to create an understanding of the reader in regards to the purpose, aim and objective of this dissertation. In order to create this understanding, the actual context is outlined as well as the approach to the issue is explained, along with potential mitigation steps how to limit the impact of the key issues found.

1.1 Background of the dissertation

In recent years, the cost and complexity of IT undertakings is increasing – generally information technology plays a bigger role in everyday life but also in every product developed and service used. As the author sees the need for lowering costs and is very involved for a long time with IT systems in the space domain, the scenario of spacecraft operations is used as an example within this dissertation in order to determine an approach to achieving cost savings.

Unfortunately, in recent years, IT costs are also increasing due to increasing complexity on space missions.

Such increased costs and increased complexity within this domain is for example demonstrated by the finding of the "consultative committee for space data systems" in further named CCSDS. The CCSDS is an international organization consisting of eleven member space agencies like: ASI (Agenzia Spaziale Italiana/ Italian Space Agency), CSA (Canadian Space Agency), CNES (Centre National d'Etudes Spatiales / French Space Agency), CNSA (Chinese National Space Administration), ESA (European Space Agency), RFSA (Russian Federal Space Agency), DLR (Deutsches Zentrum für Luft- und Raumfahrt / German Space Agency), NASA (National Aeronautics and Space Administration), JAXA (Japan Aerospace Exploration Agency), UK Space Agency and other participants.

CCSDS has been founded in 1982 by major space agencies from all over the world as a multi-national forum for the development of communications and data systems standards for spaceflight.

Today, leading space communications experts from 26 nations collaborate in developing the most well-engineered space communications and data handling standards in the world." (CCSDS.org,2016)

In their publication "Report Concerning Space Data System Standards" as of December 2010, the finding has been:

"There is a general trend toward increasing mission complexity at the same time as increasing pressure to reduce the cost of mission operations, both in terms of initial deployment and recurrent expenditure." (CCSDS, 2016)

As demonstrated, the demand for information about the key factors contributing largely to cost has increased.

Currently, a significant amount of literature describing ways to reduce costs by optimizing spacecrafts themselves, mission duration, flying orbits, instruments and other parameters exists. Samples of such are established publications like "Space Mission Analysis and Design" (Larson,Wertz,2005), "Methods for

Achieving Dramatic Reductions in Space Mission Cost" (Wertz, Conger et al., 2011), "Reducing Space Mission Cost", (Larson, Wertz, 1996), "International study on Cost-Effective Earth Observation Missions" (Sandau, 2006) and others.

The previously described literature is reviewing mostly techniques and methods to apply to scientific missions, changing actual parameters of these. Unfortunately, in this literature, most of the parameters outlined are referring to the space segment.

On a scientific, planetary mission for example it may be possible to reduce the amount of orbit time required by using a higher resolution camera with a wider angle lens in order to capture the entire planet.

Further on, e.g. for constant services like satellite based television or on navigation services to be delivered, orbits can only be optimized up to a certain point as certain coverage is needed.

Unfortunately, rather than changing space based or scientific parameters or instruments, on long-term space missions, the main cost drivers are arising from ground operations during the duration of the mission – space based services and instrument data are typically pre-defined do normally not change over time. As the goal of long-term missions is to provide services for a long duration, missions cannot be shortened in order to optimize cost.

From these findings it becomes clear that ground operations costs should be reviewed in order to achieve lowered costs – such ground operations costs are typically driven by personnel cost and IT costs. As most missions are very automated already personnel cannot really be lowered any further, but maybe ground segment IT infrastructure can be reviewed in order to create further cost savings.

Unfortunately in literature, there is generally little information available on cost reduction with regards to the ground segment IT Infrastructure, based on fixed requirements.

Especially when it comes to missions delivering services, durations to be covered can be very long however, resulting in fixed requirements with regards to the ground segment versus changing technologies available.

Within the context of standard IT operations, IT originated costs are typically captured either as total number or in total cost of ownership model. Unfortunately, however, such TCO models and connected available data is typically looking only at IT-typical life cycles of three to five years, expecting IT equipment to be replaced after such a period (Koomey, 2007).

Further on, even in case TCO is considered, it is typically not complete and lacks certain elements: As we will see, especially in a long-term scenario, power consumption plays an important role.

According to a study by the European Commission, Austrian Energy Agency, University of Karlsruhe "Energy efficient servers in Europe" (Schäppi, 2009) the following has been found:

"Experts often do not consider TCO (Total Cost of Ownership or Life cycle costs) as a criterion and even if they do, energy efficiency is normally not included as a parameter. This leads to the fact that the purchasing prize clearly dominates the buying decision. TCO concepts including energy efficiency therefore should be promoted in procurement guidelines and information concepts."

While there are clearly also other approaches, other than TCO like for example a newer model looking at costs more from a lifecycle perspective, even these assume a lifetime of IT systems of three to five years as outlined in relevant publications like "Beyond TCO: Total Cost of Lifecycle as support to Planning and Argumentation, by Wolf-Dieter Mell of the Leibnitz-Institute" (Mell, 2003) and still ignore the fact of energy efficiency.

Further on in the context of long-term missions, little research was so far undertaken on how to reduce costs occurring with regards to the actual ground segment IT systems over long periods.

2 OBJECTIVES

While it is already possible from the title of the dissertation to estimate the primary objective, during research it turned out that there are secondary requirements which are to be fulfilled in order to make it possible to meet the primary objective in a way it is actually practically usable or to create acceptance for measures proposed to meeting such. In the following chapter, the primary objective will be described along with the secondary requirements to be addressed.

2.1 Cost in Space Operations and other mission critical long-term IT operations

Within the context of IT operations, it is an ever-existing demand to keep costs as low as possible, without actually compromising the quality and especially availability of the actual operation.

While the challenges are described here based on the specific example of spacecraft operations, most challenges are in-line and similar in other comparable scenarios which require a complex IT environment over a longer time (e.g. 15-20 years).

Examples here can be found along, but are not limited to the following: railway operations centres, nuclear power station control, national airspace control, missile approach warning systems and others.

This is in a clear contrast to the than the usual lifecycle of an IT system which will be explained later in this chapter.

During preliminary investigations it was found that actually space operations is among the most complex undertakings from the above, due to the large number of parameters as well as systems involved. Based on this input, it has been decided to actually investigate on cost and efficiency advancement primarily within this domain in order flow down the lessons learned to allow others use of the found information also within their potential other areas of applicability.

In order to find the point of most concern with regards to space IT operations, a short survey among 45 space IT infrastructure decision makers as well as spacecraft control IT operations engineers in six organizations was undertaken by the author.

The following points have been found to be of most concern in the order of frequency:

- High availability
- Good performance
- Low cost
- Long-term maintainability
- Short repair times

Even three out of these five points are actually directly adhered to costs, when undertaking further investigations, it can clearly be seen that also the requirement high availability, long term maintainability as well as short repair time is clearly a very driving factor for costs and requires all IT equipment to be at all times either under a service contract or to have an adequate number of spares to be available.

While the performance objective in the first place does not seem directly related to cost, it is however indirectly as well a driving factor for it.

In recent history, there are also quite a few examples of the top-level requirement for cost reduction. Within the space industry, the most known example of a top manager / politician asking for lowered costs may be the famous call to carry out space projects "faster, better, cheaper" by Daniel Goldin, as NASA Administrator General. He introduced the initiative with the same name to the entire NASA space programme in 1992 to several programmes; it is even today still known by the abbreviation “FBC”. (Goldin, 1992).

In 2010, a study on conclusions drawn on the FBC programme was undertaken by Lt.Col. Dan Ward bearing the title “USAF Faster, Better, Cheaper Revisited, Program Management Lessons from NASA, and conclusion was drawn from the overall programme”. Within this study, the short summary and outcome can be described as: “Success-per-dollar is a more meaningful measurement of achievement than success-per-attempt.[…]The important thing is not how much success we get out of 100 tries, but rather, how much success we get out of 100 dollars.”(Ward,2010).

Aimed even more closely at cost reduction is the investigation of Richard Holdaway, Director of Space Science of the Rutherford Appleton Laboratory in Oxford, UK, who described the required development as “As the capability of […] systems has risen, so has the percentage mission cost of ground system and operations. There is therefore a clear need to focus cost reduction techniques to the ground system and operations.” (Miau, Holdaway, 2000-2013)

With regards to IT operations in spacecraft control, information on cost and efficiency can be specifically of high value in the following typical situations:

- Purchase decision / implementation / design of a solution:

  When it comes to an implementation decision, information on cost of ownership and efficiency can help to select the “right” equipment to purchase. While it may look initially attractive to purchase the lowest price equipment, it is very important to investigate on the overall situation; it is specifically important to consider not only the initial purchase price, but to also carefully investigate the associated cots as well as potential life cycle steps in order to continue to keep costs low also in future. As identified previously by (Schäppi,2009), considering only the initial purchase price can easily lead to several orders of magnitudes higher costs in the long term.

- Service length / envelope of support periods:

  When considering implementing a new system within a spacecraft operation IT infrastructure, usually a service length or envelope of support is to be defined as well as maintenance decisions have to be taken. Due to the nature of spacecraft operations, usually missions can be rather long-term. While depending on several factors of like for example the type of satellite orbit or mission (for example, low earth orbit, medium earth orbit or geostationary orbit or deep space mission), usual lifetimes of satellite missions are in the range of several years to decades. As longest running mission so far, the mission “Voyager I” can easily be identified (Voyager, 2016). It was running for 37 years in 2014 and is expected to continue its mission until 2025, then having reached a lifetime of 48 years.

  While these numbers are rather large, even further investigation shows the contradiction between standard IT equipment life cycles and operational spacecraft IT lifecycles:

- System efficiency after a standard IT lifecycle / long term efficiency:

  While IT systems are following a certain market lifecycle, usually such a replacement cycle can be traced back to the standard catalog-offered warranty options of the biggest industry leading manufacturers. In the following table 1, according to the 2014 market analysis numbers from IDC a short overview of the biggest server manufacturers is given:

No.	Vendor	Revenue in Million USD	Market Share
1	Hewlett Packard	13.484	26,5%
2	IBM / Lenovo	9.280	18,2%
3	Dell	9.064	17,8%
4	Cisco	3.144	6,2%
5	Oracle	2.080	4,1%
6	Others	3.474	27,2%
	Total*	40.526	100%

Table 1 : Server Market Share in Q3/14 (Kuba, Matt et al., 2014)

According to investigations vendors 1-5 per default sell equipment with a support period of three years, have catalogue offerings for extended support of up to five years and support by the means of special contracts and high additional cost of up to seven years.

This is quite in drastic contrast to the usual life time in comparison to a typical required life-time for a long-term spacecraft IT system.

The author was involved with the ground segment system conception and development of the mission control systems of the missions Integral (Integral, 2002), Radarsat2 (Radarsat2, 2007), and Herschel/Planck (Herschel, 2009) and

Galileo (Galileo, 2011). The longest running of these missions so far is Integral, with an operational life of up to now (2017) of 14 years which has just been extended to 16 years (ESA Extension, 2016).

It has to be noted that none of the previously mentioned space missions has undergone a major and general mission control system IT infrastructure replacement.

During an investigation, on how to extend the useful life cycle of satellite missions, Owen D. Kurtin (Kurtin, 2013) has found that the useful lifetime of geosynchronous orbit satellites averages about fifteen years – a limit primarily imposed by the exhaustion of propellant aboard.

In future, it is even desired to keep satellites operating for longer times. Due to technological advancements with regards to transmitter technologies, satellites nowadays are ready for future applications as technology on-board can be reconfigured partially software wise to cope with data rates of tomorrow. Even re-fueling of satellites is a discussed topic (Bryan, 2014).

In addition to the actual operational lifetime of a satellite, there is also the development phase to be considered in terms of space IT operational life, which actually takes place before the launch of a satellite. Reason behind this is that usually it is required to develop and validate and test the relevant IT software on the same hardware it will be deployed on later operationally. Such a development phase in terms of duration is usually in the range of two to three years but can also be longer (Telespazio, 2013), (Trimble, 2014).

As it can clearly be seen from these numbers, service length and the envelope of support periods will take a significant impact on the actual cost of ownership and efficiency of IT systems in spacecraft operations.

Figure 1, based on findings during initial investigations, outlines the envelope investigated on within this dissertation, based on the variables “lifetime” as well as “complexity”.

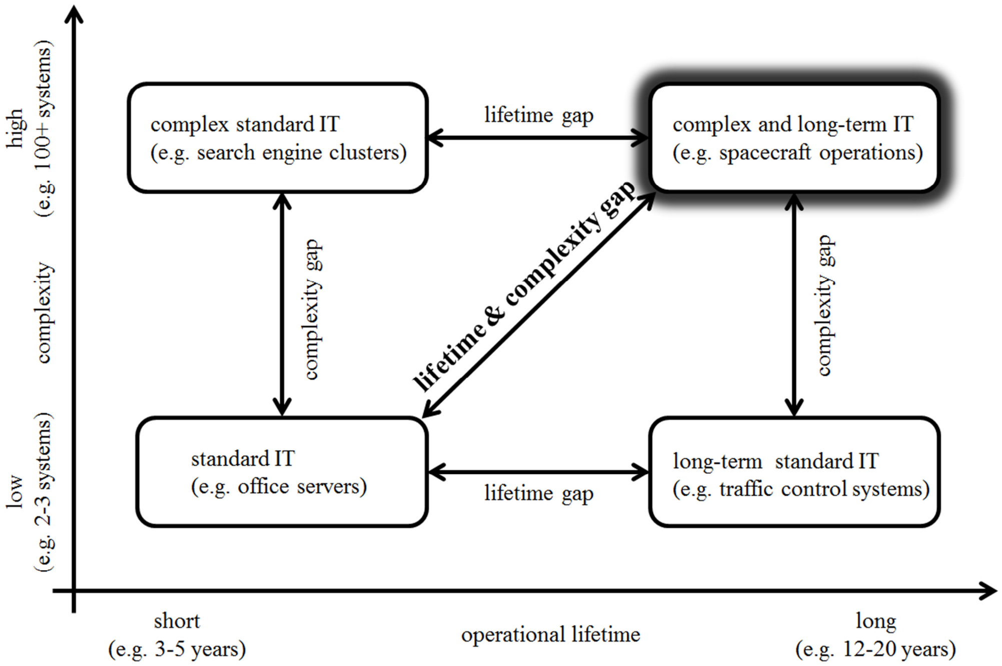

Figure 1 : IT infrastructure complexity and operational lifetime gap

It can clearly be seen that in comparison to other standard operational scenarios and setups, the lifetime as well as complexity is significantly increased. This leads to a **lifetime and complexity gap** in comparison to standard operational scenarios. As we will see in the later chapters, this has a significant impact on the financial factors as well as on all kinds of technological but also on secondary factors to be considered.

In recent times, not only to finance related economical aspects, attention is paid to, but also other factors are becoming increasingly important. As identified by (Wright, Kemp,Williams, 2011) the currently most important other factors to be considered are of environmental nature. In order to quantify gains in terms of environmental savings, by these authors it has been identified that gains should be based on measurements of CO_2 as well of CH4 gas emission volume. According to (EPA, 2016) the overall percentage of emission CO_2 volume by metric tons is the range of 81% of all greenhouse gas emissions with a global warming potential of 1. The other gas identified in this context is CH4 (Methane) where the percentage of emission is in the range of 11% with a global warming potential of 25.

Due to the operational scenarios outlined in the introduction, we can expect energy to be a main contributor towards this measure.

As identified in the EPA provided tool “Greenhouse Gas Inventory Data Explorer” (GGE, 2016), in the context of energy generation, the distribution of greenhouse gases is according to the following table as per the latest complete dataset available:

Electricity Generation	Latest Data (2014) [Mm^3]	Distribution
Carbon dioxide	2039,32	~ 99%
other greenhouse gases	20,02	~ 1%

Table 2 : Greenhouse gas distribution involved in electricity generation as per EPA in 2014

From this data, due to the significance, only CO_2 is selected as the by far largest indicator of environmental concern.

2.2 Main Objective

While many of the topics previously outlined can be objectives, as essence and central point of the found evidence, the main objective of this dissertation will be defined as:

"To give recommendations to exploit the lifetime and complexity gap existing within of complex long term operational IT infrastructure and leverage costs and CO_2 emissions caused by such."

As we have previously, during our initial survey, found that high availability and short repair times are considered to be important, as side condition, changes in these will need to be considered. Both topics can be consolidated within the topic of reliability; reliability will need to be reviewed in order to ensure that demonstrated findings can be used in real world applications.

Ideally, any of these steps towards lowering costs should provide a quick return on investment – they should reach break-even quickly and be self-paying within a reasonable short time-frame.

Further on, the initial survey undertaken has found that performance will need to be adequate and not worse the currently accepted solutions. So as additional ancillary condition, performance will also need to be considered.

2.3 Hypotheses

Based on this previously defined main objective to leverage and lower costs, the outcome of the undertaken research leads to the following hypotheses:

Hypothesis 1: It is possible in a long-term operational IT scenario to lower IT costs in a self-paying way without decreasing reliability.

The outcome of this hypothesis is two-fold: While the center of this hypothesis is the aim to verify that a break-even exists, the second variable in this context to be verified is changes to reliability introduced here. As the environment of application of this dissertation is very reliability sensitive, it is very clear that an aim to reduce costs can only be successful if reliability is not decreased. This could be achieved by the means new technologies leading to increased reliability and thereby reduced risk of loss of operational availability.

Hypothesis 2: By re-investing a significantly smaller, to be found percentage, in comparison to original IT budget, after a typical duration of an IT industry equipment lifecycle (e.g. 5 years), IT infrastructure with the same or better performance and with a significantly higher energy efficiency can be purchased.

Investigation on this hypothesis aims towards an answer how much reinvestment cost is actually needed after the duration of for example five years and how much less energy would be needed after taking such an upgrade step. Clearly, higher energy efficiency will lead to additional cost savings. Our research will also focus on measuring both the required financial but also on the power parameters.

2.4 Research questions

While there is not an absolute requirement for research questions in the context of a PhD-Dissertation, according to general research practice “It's absolutely essential to develop a research question that you're interested in or care about in order to focus your research [...].” (SUNY,2016)

As central questions during ongoing research, the following research questions have arisen:

- **RQ1: What does the exponential development in IT resources mean economically for long-term IT operations with fixed requirements?**

While interfacing with involved decision makers in different organizations, it became evident that only the demonstration of actual economic numbers will lead to a situation under which cost reduction strategies will be considered. For this reason, it was required to analyse and predict future developments and to find the most important factors contributing towards cost decrease.

During ongoing research, it became clear that technological trends have the biggest impact on operationally influencable costs (e.g. electricity, floor space usage etc.). In this context, the following question manifested:

- **RQ2: Does it pay off, within the context of some typical missions and with respect to previously defined criteria, to actually undertake the effort in order to migrate IT infrastructure in comparison to the “freeze and do nothing” approach?**

While further researching in this direction, it became clear that due to normally little changes undertaken on systems in a long-term operational scenario, in case adjustments of systems with regards to technological developments would be undertaken, such ones would actually create costs. In this context one important question to find an answer to is if there is actual return on investment.

In order to incorporate newer technology for existing tasks, it became clear that the only way to progress in this case would likely be updates and changes at the level of the IT systems platforms. However, such ones would only be acceptable if along with the other criteria previously mentioned as one of the points of most concern, system reliability and availability would not be negatively impacted. This criteria has lead to the following research question:

- **RQ3: Is the reliability of the systems negatively impacted by following the proposed “intelligent migration” approach?**

Further aim of the answer to this research question is to create confidence in the found proposed approach and to actually convince decision makers to adopt and implement the proposed approach.

In the following chapters, these research questions will form the central themes of the undertaken analysis.

During initial investigation, it became clear that the besides economical aspects, also ecological aspects could be enhanced automatically along with the efforts to reduce resource requirements. As previously outlined, quantification could be based in this field on CO2 emission as well as on energy usage. This leads to the following final research question:

- **RQ4: How much energy and CO_2 emission caused by energy usage can be saved and when following an upgrade interval of e.g. 5 years during a mission lifetime of 20 years?**

Being not only ultimately only of financial concern, the answer to this question becomes more and more important, as industrial users also to pay attention to environmental matters (King, Lenox, 2001) The aim of the author is also to measure and quantify environmental aspects involved with this research.

3 METHODOLOGY

As previously found, this dissertation will aim at lowering costs through leveraging technological advancement over a long time (e.g. 15-20 years). Figure 2 outlines the methodology used in the further progress of this dissertation.

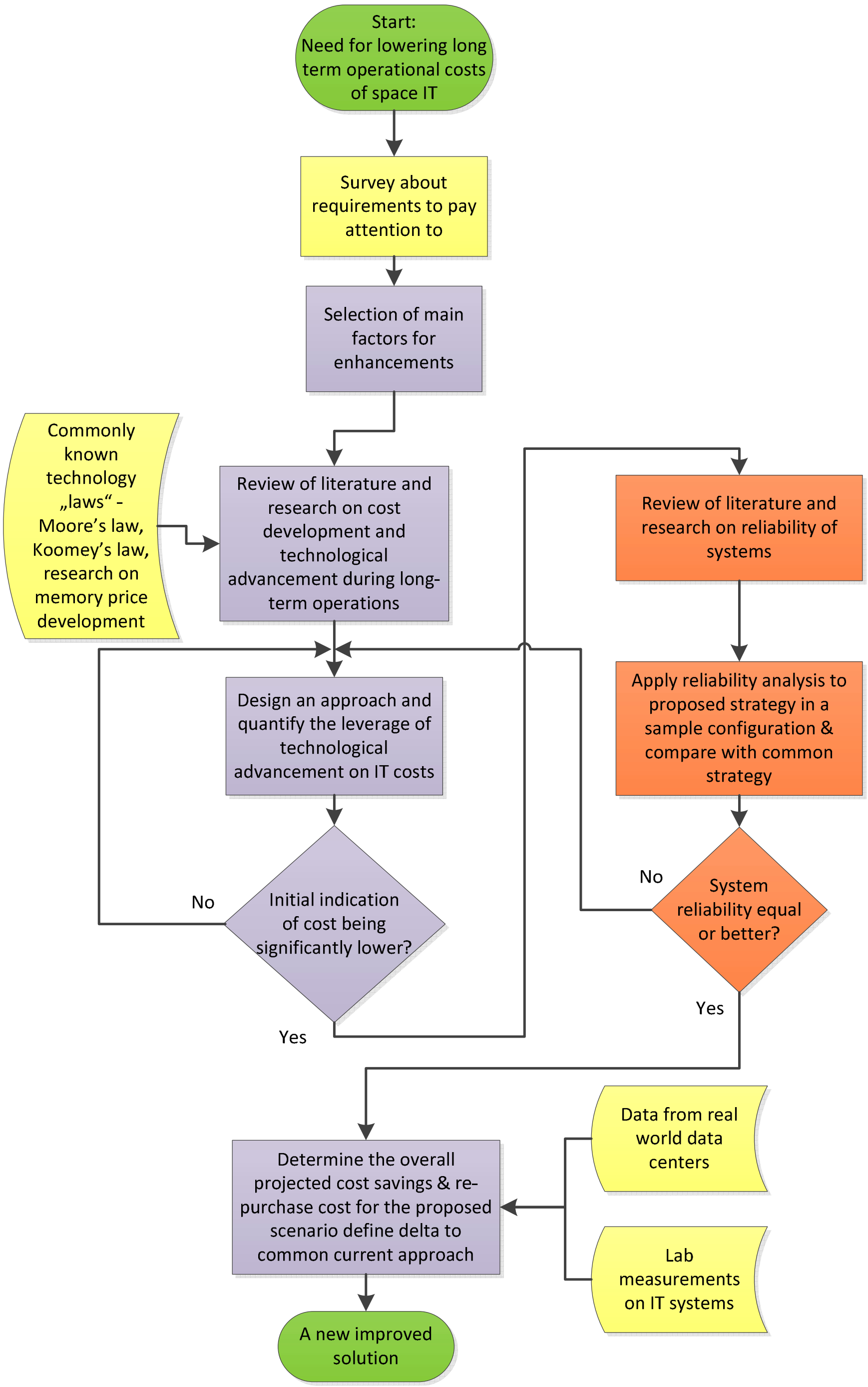

Figure 2 : Research methodology used in this dissertation

The initial trigger for the research undertaken is the need for lowering long term operations costs of space IT.

As first input towards optimizing IT costs, a short survey among 45 persons from six organizations, consisting of IT infrastructure decision makers as well as spacecraft control IT operations engineers was undertaken by the author. Based on this survey, important requirements have been derived and in the following, the main factors to be optimized have been selected, based on the order of their frequency.

In order to understand cost development and technological development in the course of time, literature has been reviewed in order to find the driving factors behind such. Information with regards to chip complexity is described for example by Moore's law (Moore, 1965), while the development of chip efficiency is described by Koomey's law (Koomey et al, 2009). Information in regards to memory pricing development is based on own research as well as on input from other researchers.

Based on these findings, the author will then design an approach and try to quantify the leverage of technological advancement on IT costs.

If the outcome of this approach does not initially indicate significantly lowered costs, a re-iteration of the approach would be needed.

If however the outcome of this approach initially indicates significantly lowered costs, then this approach would be followed further.

Based on the initial survey, one very important factor which has been found is reliability. In case one wants to successfully suggest approaches towards lowering costs, such approaches also need to closely pay attention to ensure a high enough IT reliability resulting from of the proposed changes is achieved.

Therefore, literature will be reviewed and research on reliability of systems will be undertaken.

During this research, a comparison between the existing approach and the proposed approach in terms of reliability will be undertaken. If the outcome is that the proposed approach is at least on the level of the existing approach it would become clear that the proposed approach would satisfy reliability requirements and could be followed. If the outcome here is negative, then the designed approach would need to be re-evaluated.

Based on findings during research, it becomes evident, that in order to make use of technological advancement, IT infrastructure migration(s) must take place. While following technological advancement sounds logical in the first place, there are quite a few issues which need to be covered with specific resolutions like for example technical incompatibilities of future IT hardware with current software and platforms, this dissertation will show ways to mitigate such issues. Due to the long-term perspective taken within the dissertation, as main input to on the cost side and efficiency measure, electricity usage is used. During the progress on research, it also became evident that data center floor space usage also significantly contributes towards IT costs. This dissertation also therefore aims at investigating on indications how far leveraging technological advancement can also help towards lowering data center floor space usage.

3.1 Operational strategies

Up to now, most space missions follow a strategy which makes use of the same IT equipment during the entire mission life time.

In order to demonstrate further research findings, based on this undertaken analysis, the dissertation takes this commonly existing strategy and compares it to the new approach.

The strategies compared therefore are the following

- Strategy I (existing): Assuming a frozen space IT infrastructure during the whole IT lifecycle.
- Strategy II (proposed): Leveraging technical advancement by introducing migration steps in order to bring the space IT infrastructure in line with current IT developments.

Once this step has been finished and a preliminary design is determined, we will need to apply the previous findings on reliability onto this design and undertake a reliability analysis in order to find out about whether the reliability of the IT system has not been made worse by the author’s proposed cost reducing changes. In case the projected reliability would be significantly worse, the author would need to go back to step of re-designing the suggested approach and tweak parameters having an impact on reliability.

If findings show reliability at least equal to or better than the original scenario without changes, then further progress can be made without further evaluating if the impact of the proposed changes in terms of reliability is too high to justify proposed changes.

In the next step, the author will determine the overall projected cost savings. With regards to the cost side of technological migrations, this dissertation will try to determine the cost of investment required in order to migrate a given IT system to an up-to-date solution at certain times during the operational lifetime.

In order to reach this result, data will be used from three real world data centers of larger space missions considering the mission control system as well as first level payload data processing. In addition, research is also making use of data from measurements of different IT systems in a lab environment.

The author then compares the cost results based on his refinement ideas with the commonly used „Strategy I“ as previously described.

As final step, outcomes from the research undertaken will be summarized and final conclusions will be drawn from the data found.

3.2 Lab power measurements

As outlined in the previous section, in order to calculate the total power usage of typical systems used in spacecraft control, it is required to get access to data of such ones. While quite a bit of data is available via different power modeling tools (PowerAdvisor, 2015) provided by different server manufacturers as outlined in table 1, such data does not necessarily represent the a real world environment. The author had access to a lab containing duplicates of real systems used in spacecraft control which also had real-world spacecraft control software deployed. Within this lab, tests of real operational missions were continuously running, allowing undertaking further evaluation with meaningful, real data.

In order to gather the basic numbers for electricity usage, figure 3 describes the setup used in order to collect such data on a system level. In total, within the lab setup investigated on, there were six racks monitored.

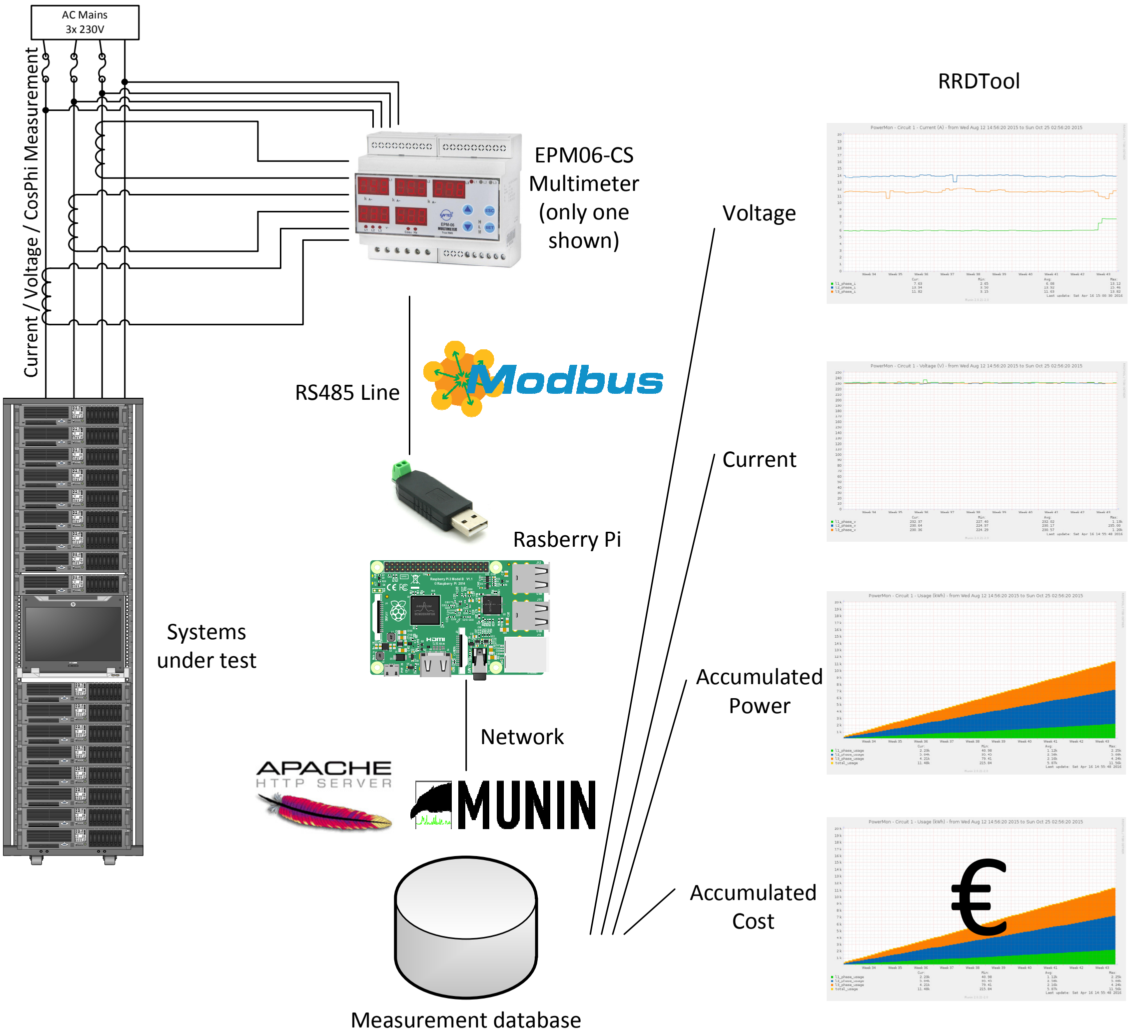

Figure 3 : Setup used to collect operational power data at system level

Relevant systems under test, housed in server racks, are connected to the relevant measurement equipment. All measurement equipment is housed in the instrument box shown in figure 18.

Starting from the building power supply, the AC mains power is connected to fuses which then again connect via current transformers and voltage dividers to four power-distribution box mounted **multimeter** which constantly undertake measurements of **current, voltage as well as CosPhi**.

This collected data is then read via a **RS485** (Soltero, 2010) line into a **Rasberry Pi** (Raspberry, 2015) mini computer. This mini computer then passes the read data onto the monitoring and data collection open-source software „**Munin**“ (Munin, 2014) which is storing them in a **MySQL measurement database** (MySQL, 2016) and is allowing access to the data connected via an IP network connection to the data via **RRDTool** (Oetiker,2016) by making use of an **Apache web server** (Apache, 2016).

From these measurements, the power used by the systems can then be calculated for further analysis.

4 SURVEY OF LITERATURE AND DESK RESEARCH

Initially, existing literature and journals as well as conference papers and white papers of different manufacturers with relevance to the topic have been reviewed.

In the further context, the actual cost side of long-term IT operations will be investigated into.

As initial area of interest, existing approaches to determine IT cost distribution will be reviewed.

In the following, the author will review existing, practically used results on real world cost distribution based on the typical 3-5 year IT cycles.

Due to the missing existence of theoretical background and information on long-term IT infrastructure in the range of 15 years, the author will then extrapolate the costs in order to understand the main cost drivers in long term operations, based on a frozen IT scenario.

The then found main cost driver "electricity" will be investigated into deeper - further on, efficiency and their measurement of data center infrastructures will be reviewed. In the context of such measurement indicators, also their issues will be identified.

To classify the power consumption of IT infrastructure in general, a short projection on the country of Germany will be undertaken.

In the further, technological drivers for power consumption and efficiency as well as memory pricing over time will be reviewed and generalized in order to apply these finding later in our solution. Aim is here to apply the findings in order to determine the impact on the cost side.

As reliability is very important in the reviewed context, the author also needs to consider such; any change on IT infrastructure will also lead to changes on reliability. For this reason, reliability calculation background is presented.

4.1 Cost distribution according to ITIL

One widely used methodology for dividing IT costs into different categories is the one developed by ITIL (ITIL, 2011). The ITIL methodology has been developed initially by the British Cabinet Office and is now managed and kept up to date by AXELOS Ltd, a joint venture between HM Cabinet Office and Capita Plc. (a private company).

In this context, the relevant ITIL discipline is outlined as "Financial Management for IT Services". One of the main aims of this discipline is "Effective Financial Management for IT Services results in cost-effective IT services that carry in them the potential for a positive ROI.“ (Persse, 2014).

Categorization of the different areas of costs according to the ITIL model is shown in Figure 4 (Osatis, 2014)

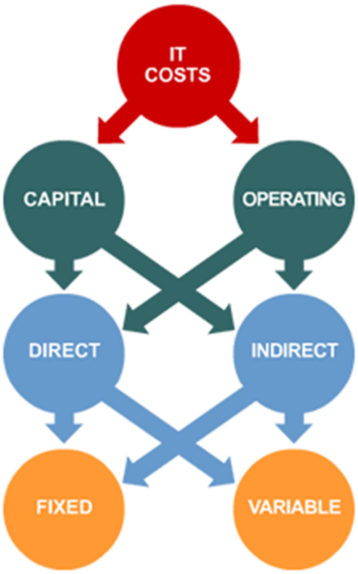

Figure 4 : IT Cost distribution according to the ITIL Model

The different areas of cost are described in the ITIL model according to the categories outlined in the model above. In this model, each cost is further categorized into two different further categories until the lowest layer is reached. Projected on to long-term spacecraft operations, sample costs for each category are among the following (Osatis, 2014, adjusted):

- Costs depending on the time horizon:
  - Cost of capital: deriving from the repayment of fixed assets or long-term investments.
  - Operating costs: costs associated with the day-to-day functioning of the IT organisation.
- Costs that may be attributed directly or indirectly to the delivery of the service or manufacturing of the product:
  - Direct costs: In this category, costs are falling, which are specifically related to a single product or service. Such ones can be for example:

cost for IT hardware, direct costs for specific servers or also service contracts being related to specific equipment

  - Indirect costs: Within this category, all costs are to be found which are not specifically related to a single service but represent rather a shared cost base. Such ones can be for example costs for external connectivity, power or facilities. During daily operation, these costs are more difficult to determine and are generally spread, pro rata, across the various services and products. Nevertheless, such costs should be paid careful attention to as they can easily reach significant volumes.

- Other associated costs, volume based of fixed:
  - Fixed costs: these are independent of the volume of production and are normally related with the costs of fixed assets. Staying with the example of external connectivity here, an example can be the monthly basic fee for WAN (wide area network – network to share data within a limited number of users, not necessarily internet connectivity) connectivity for the provision of the line.
  - Variable costs: These include those costs that depend on the volume of use. Examples here can be here for example fees per gigabyte of transfer on internet lines, consumables like toner for printers, etc.

While ITIL offers a way of categorizing costs and generally offers a model how to operate a service, it does not directly offer possibilities of reducing costs. In fact, certain sources even see ITIL causing the opposite – to increase costs (Pauli, 2008).

4.2 Known generic approaches to achieve cost reduction

Clearly, the spacecraft operations scenario investigated on is bringing along some rather specific characteristics like for example not following the normal industry standard IT lifecycle of 3-5 years. Most existing cost savings approaches assume a replacement of IT infrastructure within such cycles. Regardless of this fact, the author wants to present some of such existing approaches and explain their potential transferability also to the long-term mission critical scenario.

One research paper here was published by Jay E. Pultz 2009 (Pultz, 2009). The following points have been found:

- Renegotiate major contracts such as telecommunications contracts
- Defer non-critical key initiatives other than consolidation and upgrade of legacy systems
- Consolidate infrastructure and operations
- Reduce power and cooling needs
- Control data storage growth
- Lower IT support costs by pushing support down to the 1st level
- Streamline repeating IT processes
- Implement IT equipment asset management

- Consider multi-sourcing of equipment and services

In addition to this source, (Dholakiya, 2015) has found some further points to reduce costs by using technology:

- Automate wherever possible
- Move IT infrastructure to the cloud
- Opt for free apps and tools
- Invest in green technology

While many of these points sound generally like a good idea to follow, a check is needed how far these are applicable to spacecraft operations; based on past and current experience of the author, to each of these points, generalized experience is outlined, also in order identify areas and approaches containing cost savings potential:

Renegotiate Major contracts such as telecommunications contracts:

Due to most spacecraft operators being either large state, intergovernmental or larger professional commercial organizations, telecommunication contracts are typically automatically renegotiated after the contracted period. Typically, contract management is ensuring to fulfill such requirements by having public tenders, sometimes even posting globally applicable invitations to tender. Especially organizations like NASA, ESA etc. are required, in order to allow fair competition, to publicly announce such contracts and then selecting the most economical bidder from industry. Due to the fact that this contract renegotiation is taking place per default in defined intervals, further large cost saving potential is exhausted already.

Defer non-critical key initiatives other than consolidation and upgrade of legacy systems:

Clearly, typically in spacecraft operations, once a mission is launched, few changes are done to existing hardware – consolidation normally never takes place. Mainly, this approach is typically chosen to reduce risk. Especially using the time and complexity lever could allow for efficient consolidation. Clearly, this area can contain a high potential for lowering costs.

Consolidate infrastructure and operations

Similar to the previous point, infrastructure is typically not changed and if at all also rarely moved and almost never consolidated components. As previously outlined in spacecraft control, typically the number of computers is high – so if consolidation would be possible, there could be a very high potential for lowering costs.

Reduce power and cooling needs:

Again, due to almost never changing infrastructure, power usage, by this definition, in a classical spacecraft operations scenario, typically stays constant. For the same reason, cooling needs to stay constant. Without changing the infrastructure, the only possibility imagined is installing a higher efficiency cooling system. Finding a way to reducing the power and cooling needs would definitely be resulting in significantly lowered costs.

Control data storage growth:

As the Gartner research results are mostly applicable to end-user used IT infrastructure, controlling data storage growth is definitely an option to save disk space and therewith cost; in spacecraft operations, data storage growth is typically driven by the volume of data and commands uplinked to and downlinked to and from spacecraft. Unfortunately, this parameter is unlikely possible to be changed. As well, typically, storage cost is not the largest driving IT cost factor in the context of spacecraft control systems.

Lower IT support costs by pushing support down to the 1st level:

While Gartner focuses here on an operational scenario where there are many end-user requests during IT operations, within spacecraft control, IT support is normally delivered mostly by contracting companies according to pre-defined procedures. Clearly, lowering costs by having the first level of support taking over of more actions from 2nd level support could be a possibility. Typically applicable average hourly rates (as of 2017, Germany) of ~40 € per hour for 1st level support staff as well as ~55 € per hour for 2nd level support can be used for a quick verification: If a team of 5 persons operating 8x5 is able to hand down 25% of the requests to 1st level support, one could save based on the delta of ~ 15 EUR per hour per year approximately 39k€. Clearly, over a period of 15 years, a sum of 585k€ could accumulate. While this should be kept in mind, the author assumes that other possibilities could enable larger savings.

Streamline repeating IT processes:

As outlined in the previous point, IT processes are typically streamlined within spacecraft operations to the level of having a procedure for almost every repetitive task. A high degree of streamlining has been achieved already.

Implement IT equipment asset management:

Due to the critical nature of spacecraft operations, typically every piece of IT equipment is not only covered by asset management, but is typically also monitored individually on a 24/7 basis. For this reason, one should not expect major cost savings to be resulting from this recommendation as it has been implemented already widely.

Consider multi-sourcing of equipment and services:

As already previously described, equipment and services are typically procured in larger spacecraft operating organizations via public tender processes. This point has already been implemented widely.

As we can see, the areas identified by (Pultz, 2009) confirm that the author's initially found idea to leverage on costs via technological advancement could likely be successful.

In the following section, an assessment is performed how far the findings of (Dholakiya, 2015) are applicable to spacecraft operations.

Automate wherever possible:

In spacecraft operations, a high degree of automating operations is already in place. In a longer past decade, significant budget has been spent not only to automate operations themselves, but also to operate the management and administration of systems. Simply by reviewing the schedule of larger space conferences like the largest and renowned conference “SpaceOps” in the year 2016 (SpaceOps, 2016) where the author of this thesis also presented a paper, reveals four parallel presentation sessions on the topic of automation. However in 2016, the largest easily achievable potential from mission operations automation has already been exhausted.

Move IT infrastructure to the cloud:

While for commercial IT operations, moving such to the public cloud (meaning effectively the internet) may be an option to reduce costs, in spacecraft operations dependencies on external services such as internet connectivity or remotely operated data centers is seen as unacceptable risk, both in terms of availability but also in terms of security. While using a public cloud may not be possible due to these limitations, one could think of a scenario of a physically locally located cloud. The author can very well see possibilities of such one bringing benefits towards the reduction of IT costs.

Opt for free apps and tools:

Unfortunately, while there are very few by the definition free software apps and tools available for spacecraft operations, many spacecraft operators very well make largely use of free tools in their spacecraft operations IT infrastructure. As example of such, ESAs mission control system SCOS-2000 (SCOS, 2013) is based on linux and other open source products and makes extensive use of such existing free apps and tools. Due to the specifics, one won’t likely find the software product desired as such a free tool itself, but lowering costs is already achieved here by using free, open-source software. For this reason this approach can be seen as already successfully implemented.

Invest in green technology:

As the primary aim of this thesis is to lower costs in long term IT operations in complex, mission critical operations centres, investing in green technology is likely only going to be successful if overall cost savings are achieved. From the previous point “Reduce power and cooling needs” such investment in green technology is already covered. The author will in this thesis however keep track of the “green technology” factor and it’s outcome and impact on environmental indicators.

4.3 Real cost distribution

While the research results by (Pultz, 2009) together with the experience of the author indicate already potential areas for lowering costs, however such qualitative analysis does not help directly with regards to finding the area with the biggest potential for cost savings in terms of financial quantities. We are interested in real-world costs and their distribution in order to lower such. Unfortunately, neither (Pultz, 2009) nor the ITIL model does not deliver this input. However, industry leading research organizations regularly undertake research into how data center costs are distributed.

In real-world scenarios researched into by again by e.g. Gartner Research, the typical internal cost distribution to be expected across data center operations is described by the following figures (Gartner, 2009):

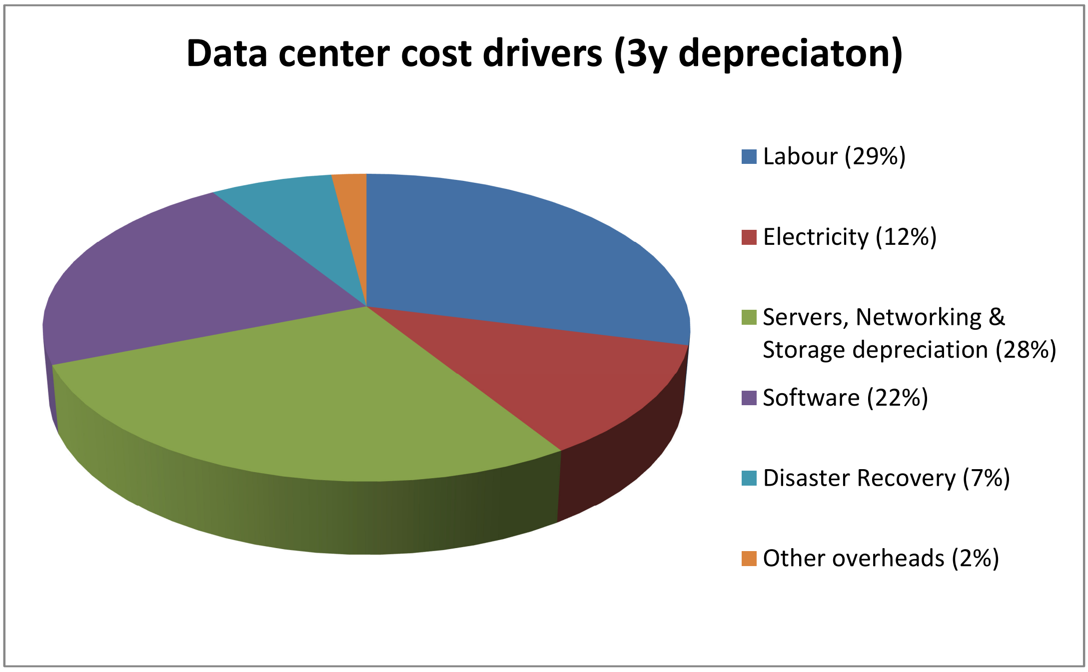

Figure 5 : Sample Cost Distribution in Datacenter Operations (Gartner, 2009)

When considering other sources than Gartner (see following table), it can be seen that their analysis outcome are differing slightly. Clearly, every operational scenario is different and therefore also has different factors of influence. The aim is to identify an average set.

Although being difficult to find generalized material on cost distribution, desk research has led to finding selected sources outlined in the following table:

Source Type	(Storage Craft, 2016)[1]	(Uptime, 2006)[2]	(Gartner, 2009)[3]	(Hamilton,2011)[4]	(UCSD, 2012)	Average
Electricity	20%	10%[5] -> 14,3%	12%[6] -> 16,1%	13%+ 14,8% -> 27,8%	19,75%	19,59%
HVAC Equipment[7]	6%	43% (Site Infrastructure Cost)	-	3,2%	3,25%	4,15%[8]
Engineering & Installation Manpower	18%		29% (Labour)	65% (Server and Networking Equipment and facilities)	11,95%	24,5%[9] (Labour)
Facility Space	15%		28% (Servers, Networking and Storage)		12,53%	43,63% (Servers, Networking and Facilities)
Rack Hw	2%				Included in other positions	
Service & Maintainance	15%					
Power Equipment & Server Equipment	20%	35% (IT Cost)			40,64%	
Project Management	5%	12% (Other operating expenses)	(included in Labour)	4% (Other Infrastructure)	-	
System Monitoring	1%				-	
Software	-	-	22%	-	-	
Disaster Recovery			7%		-	
Other			2%		11,88%	8,13%

Table 3 : Different sources of IT data center cost distribution

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[1] Distribution figures missing software costs, disaster recovery potentially incl. service cost

[2] Same as Footnote 1

[3] Gartner provides the only distribution including software costs

[4] Same as Footnote 1

[5] Electricity costs assessed in 2006, According to (EIA, 2016) and (DOE, 2006), costs have increased by 82% in total or 43% after inflation-adjusted (Calculator, 2017) in totals from 5,54 US cents/kWh to 10,08 US cents/kWh therefore, percentage should increased accordingly

[6] Electricity costs assessed in 2009, According to (EIA, 2016) & (DOE, 2010), costs have increased by 46% in total or 34,5% after inflation adjustment (Calculator, 2017) from 6,87 US cents/kWh to 10,08 US cents/kWh;Percentage should be adjusted accordingly to 16,1%

[7] Heating, Ventilation and Air Condition Equipment (HVAC)

[8] Average of only Storagecraft, Hamilton and UCSD

[9] Average of Storagecraft (E&I Manpower, Service &Maintainance with 33%), Gartner and UCSD

As average results from (Storage Craft, 2016), (Uptime, 2006),(Gartner, 2009), (Hamilton,2011) and (UCSD,2012) one gets to the following distribution:

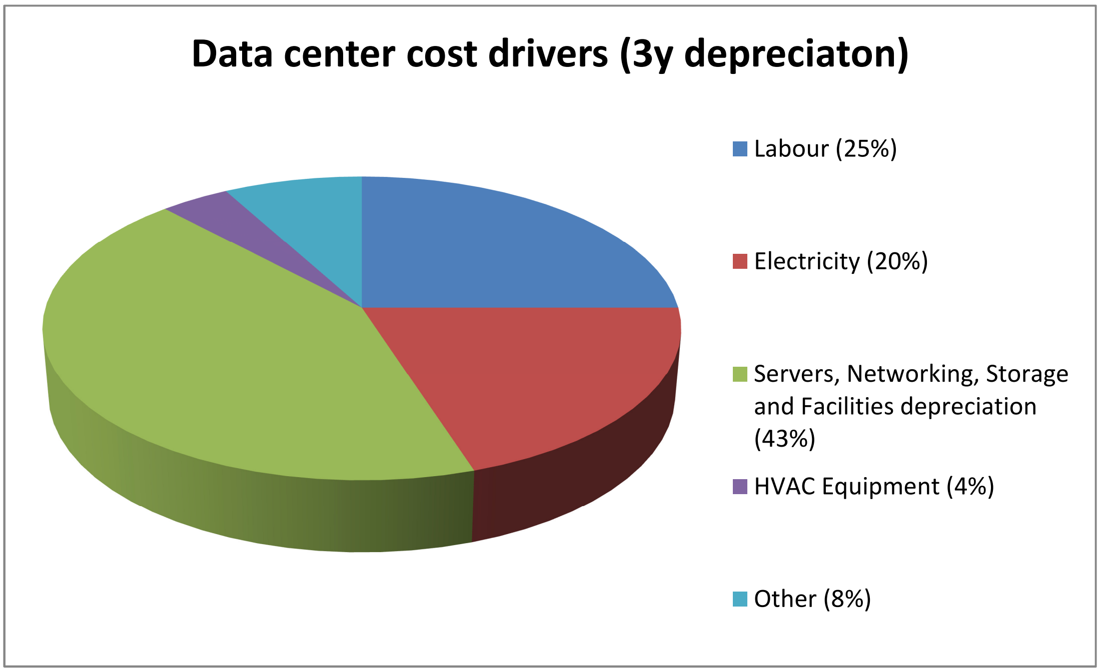

Figure 6 : Average Cost Distribution from different sources (Storage Craft, 2016),(Uptime, 2006),(Gartner, 2009),(Hamilton,2011) and (UCSD,2012)

From the figures demonstrated here an impression could be generated that actually the biggest main drivers are depreciation of hardware (43%) and labour (25%) – however, as the numbers presented here refer to a 3 year write-off scenario in terms of computing equipment, in long-term, complex IT operations the accumulated cost distribution actually is expected to be different.

Based on a period of for example 15 years in combination with the previously described „Strategy I: Assuming a frozen IT infrastructure during the whole IT lifecycle“ the actual cost distribution is however significantly different.

In order to estimate the impact and guide further research, based on the described scenario, the actual numbers from the previous diagram need to be been extrapolated towards a 15 year period in order to achieve a weighting which kind of research should be important.

Unfortunately, due to the unavailability of primary data related to cost in a long-term operational scenario of 15 or more years, other ways for choosing the main cost drivers will need to be explored.

It is clear, that such an extrapolation can never be accurate in terms of down to a single percent; however for the use as orientation in terms of further research direction, the delivered accuracy should be sufficient.

As a result from including the above presented thoughts, an extrapolation results in the following side conditions:

- **Labour:** While labour is also a large contributor, we assume in the further of this dissertation that labor after initial installation mainly takes place on a software level and in order to fulfill preventive administration tasks. As it was set that software will remain unchanged and systems will only be operated according to the initially designed specifications, clearly little maintenance is required on systems during the routine operations phase. In a long-term operational scenario, labour clearly has less of an impact in terms of operating a data center in comparison to a scenario where there is a lot of equipment replacement undertaken constantly. In order to be very conservative as the aim is only to find easiest changeable cost factor, assuming that 50% of the labour is accumulated during initial installation and 50% of the labour is required for ongoing operations and maintainance. Clearly, labour accumulates over time. Estimating 50% of labour required during long-term operations is not very satisfying, but according to practical experience in such undertakings, the number should be approximately right or even on a the high side of estimation. Unfortunately only approximate operational data could be accessed, no exact primary data was available on such a scenario. For this reason, labour will be scaled upwards to 180 months in terms of time by using 50% of the estimated 25% of labour.
- **Electricity:** Usage remains constant during the entire period; therefore cost for energy accumulates in a linear way during the 15 year period – therefore, the total amount of energy is scaled up. According to (EU, 2013), energy prices should only increase on average by a total of 2% until 2035 in the entire period. Therefore, no additional weighting of energy prices was undertaken.
- **Servers, Networking, Storage and Facilities depreciation** is set at the 15 years operational scenario – in the initial scenario looked at, there is no hardware replaced. Occuring costs here are scaled over 180 months instead of over 36 months / 120 months respectively.
- **Heating, Ventilation and Air Condition Equipment (HVAC):** This equipment and depreciation is treated in the same way as servers and scaled over 180 months.
- **Other Overheads:** Other running costs actually accumulate over time, therefore there is a multiplier used with the factor of the relevant number of months added.

Based on the previously outlined information, when creating a relevant calculation baseline, the following diagram can be generated.

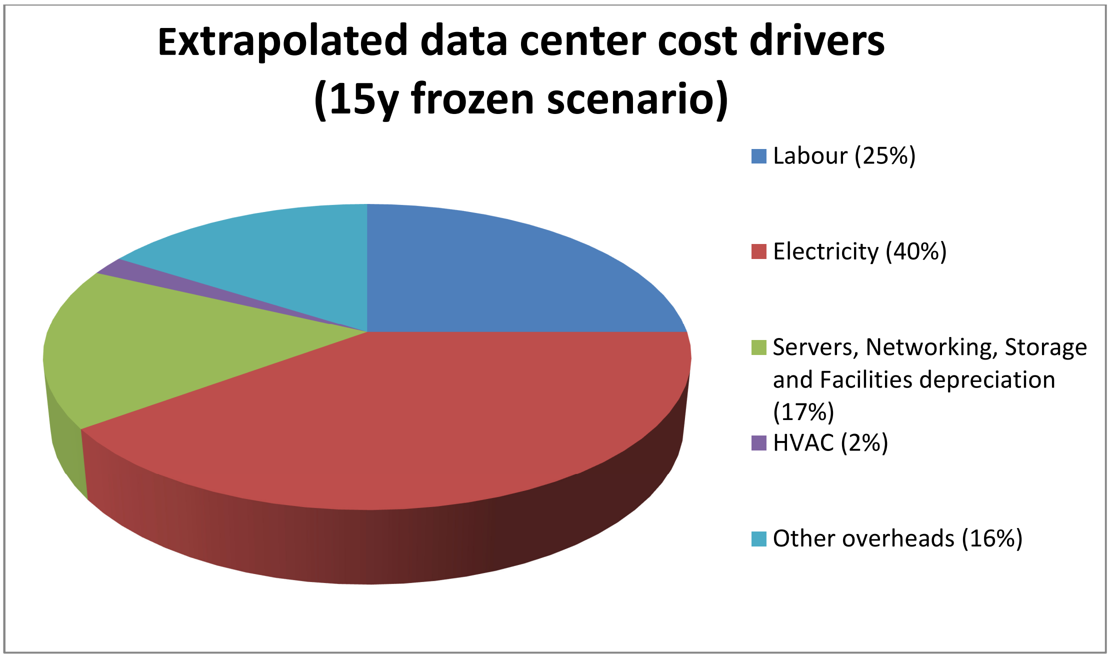

Figure 7 : Cost Distribution in Datacenter Operations within 15 years, extrapolated, based on a frozen scenario using average data found from sources (Storage Craft, 2016),(Uptime, 2006),(Gartner, 2009),(Hamilton,2011) and (UCSD,2012)

From this result it becomes clear that the largest gains in terms of cost reduction could potentially be found in the area of saving electricity during operations. Due to this reasoning, electricity usage / power consumption will be the focus area of research.

The second largest single contributor here is then labour, followed by hardware, networking, storage and facilities depreciation and other overheads.

Reducing labour costs is always up to individual measures on the specific scenario. As the aim of this research is to find generally applicable measures towards reducing costs in long-term operational scenarios, such measures would need to be looked into on a case by case basis. When looking at spacecraft operations as an example, reducing labour can not easily be achieved without changing pre-defined procedures which have been implemented and trained over long periods of time. For this reason, the thesis will in the further focus only on the largest found factor “electricity” or “power”.

4.4 Power

In literature, there are several approaches towards an evaluation of power / electricity parameters in IT operations centres.

Ultimately, the goal is in IT to use as little power as possible to achieve the desired output which could be for example calculations. The more detailed specification what is actually measured as output will follow later in this chapter.

While it can be one method to actually evaluate CPU performance in terms of calculations per unit of energy, reality is a little more complex:

Usually, when looking at larger installations and especially mission critical systems, computers are not just operated in a normal office on or below a desk. In fact, to operate such equipment as standard today, highly sophisticated facilities named datacenters are being used. Unfortunately, actually operating a datacenter adds further costs and overheads to IT operations – however, such additional overhead is not avoidable in the case of serious and safe IT operations.

In the following paragraphs, common metrics applied to datacenters will be discussed. In addition existing actual gaps in such commonly used metrics will be identified.

4.4.1 Power Usage Effectiveness

One of these commonly used metrics is the so called PUE (Power Usage Effectiveness) (Belady,2008).

PUE is defined as:

$$P_{ue} = \frac{Total\ Facility\ Power}{IT\ Equipment\ Power}$$

Equation 1 : Power Usage Effectiveness (Belady, 2008)

The PUE Value is actually describing the relation between the total energy used in a datacenter and the power finally used for IT equipment. By running an analysis of the PUE Value of a Datacenter, it is actually possible to get a metric about the efficiency of the energy used for the actual IT Equipment.

The following table 4 gives an overview sample PUE values at the date of 2011-2014, Data for this table has been taken from various sources stated in the footnotes below:

PUE Value	Benchmark	Description / Examples
3,0 or higher	Lowest end of scale, not optimized	Completely not optimized datacenter with inefficient cooling
2,8	Below state of the art	Average PUE in North America 2012[10]
2,6	See above	Average PUE in Europe 2012[11]
2,5	See above	Average PUE in Asia-Pacific 2012[12]
1,9	Set by EPA[13] as Trend in 2007 for 2011	-
1,7	Improved Operations defined by EPA in 2011	-
1,45	Better than average	Amazon Web Services in 2011[14]
1,4		EBay Facility in Jordan, Utah, USA
1,2-1,3	Best practices	Portugal Telecom Datacenter in Covilhã[15]
1,08-1,18		Main Google Datacenters Worldwide[16]
1,0 or lower	Future Trends	Only possible via on-site energy generation - e.g. solar power

Table 4 : Selected PUE levels

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[10] (Research Trust, 2012)
[11] ibidem
[12] ibidem
[13] (EPA, 2009)
[14] (Hamilton, 2011)
[15] (Dynamics, 2013)
[16] (Google, 2014)

4.4.2 Data Center Infrastructure Efficiency

Another very similar metric commonly used for identifying Data Center Infrastructure Efficiency is actually just called DCiE (Data Center Infrastructure Efficiency) (Belady, 2008).

DCiE can be derived directly from PUE – it is defined as:

$$DCiE = \frac{1}{PUE * 100}$$

Equation 2 : Data center infrastructure, efficiency derived from PUE

and

$$DCiE = \frac{IT\ Equipment\ Power}{Total\ Facility\ Power} * 100$$

Equation 3 : Data center Infrastructure, efficiency by distribution

As it can be seen by the definition, while DCiE is usually given in percent – other than this, DCiE is the inverse of PUE. In terms of data center efficiency description, the use of DCiE is generally less common than the use of PUE.

For example, the Amazon Web Services Data center described previously to have a PUE of 1,45 will result in a DCiE of ~69% (Hamilton, 2011).

Due to the calculation in standard cases where facilities are not actually producing energy by other means, DCiE numerical values are by definition between zero and one hundred percent with the later one being the ideal case.

In certain cases where facilities actually are producing more energy than they are consuming, it is possible for DCiE to reach values over 100% - this can be the case where a data center would generate electricity out of solar power with an amount being larger than the facility overhead losses. Re-using the Amazon Web Services example, a minimum of additional 31% of all consumed power would need to be generated from solar power to reach a DCiE of 100% or higher.

4.4.3 Issues with PUE and DCiE and mitigations

Unfortunately, while the usage of PUE and DCIE is actually providing at least an initial approach in order to assess the energy situation of a data center, there are several small problems with the details of gathering, measurement, interpretation and inclusion of data:

Gathering of data

While the “green grid” (a non-profit organization for IT professionals) has initially proposed PUE and DCIE and it effectively has become the most commonly used metric, there are no clear definitions and requirements how the data is actually generated. In certain cases, it is possible that actually only results from theoretical analysis are used to describe the data center efficiency. Real operations actually can reveal significant differences to the mathematical model used. (Fortrust, 2015).

As mitigation, it should be a fixed requirement to use only measured data under real operations. In addition, the measurement methods should be clearly outlined and described, both in terms of accuracy as well as type of measurement to be used.

Time and duration

Further on, in the definition of PUE and DCiE, there is no specific timeframe outlined during which the actual determination of PUE and DCiE has to take place. For example, under certain circumstances it is possible in cold times for data centers to actually use outside air cooling only. In case this is being true when the measurement results are taken, it may not be fully representative (Datacenter, 2013).

As mitigation, it should be required to gather the data during a full year; even doing so, there is still some uncertainty in the gathered data remaining, as there may be colder or warmer years which can take significant influence on power usage.

Inclusion and exclusion of figures of other energy sources

In case for example, the data center is operating a combined heat and power system (CHP) or so called cogeneration system or even a combined cooling, heat and power system (CCHP) which uses trigeneration, then PUE and DCiE in their standard definition still only consider the actual electrical input of the facility. The actual energy generation flow of a CCHP system can be found in the figure 8.

While the use of a cogeneration or even trigeneration system is generally a good idea for datacenters especially in combination with the provision of either local building or district heating, PUE as well as DCiE should also consider the use of other energy within its efficiency model. While it is clear that in such a case, not the entire heating capacity of the used fuel (often gas, but also biomass as well as diesel) could be considered in an enhanced PUE and DCiE model, as otherwise the use of more efficient energy systems could actually make the energy balance look worse than without the use of such efficient systems.

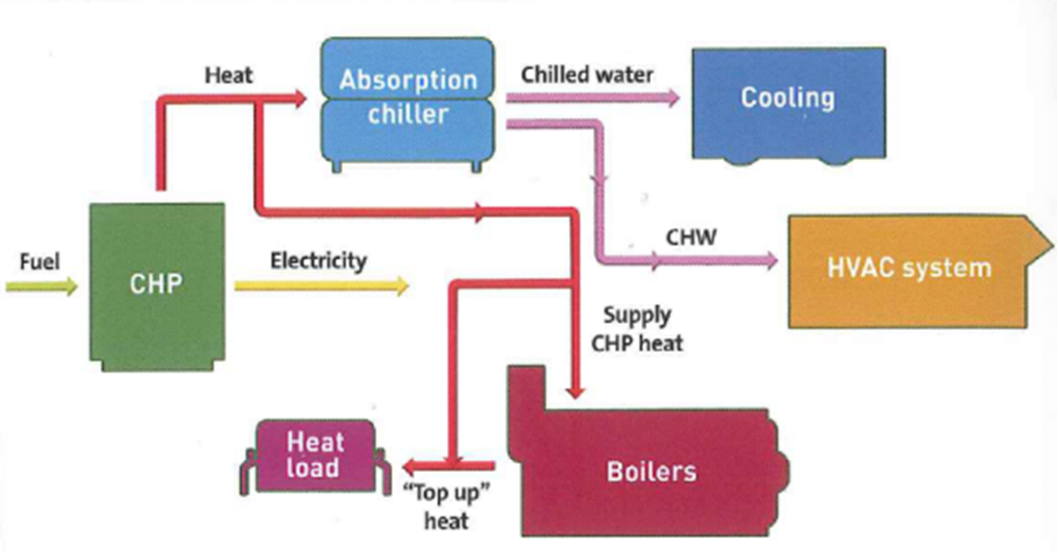

Figure 8 : Combined cooling, heat and power system – CCHP (Veolia, 2014)

Supply Voltage and transmission losses or where to start the measurement (Tamburini, 2015):

While there are different mains voltages available to data centers, unfortunately neither PUE nor DCiE define where to start the measurement of the consumed power. While ultimately in the end no server components will run on voltages higher than 230 V AC in Europe, respectively 208V AC in the US, on larger data centers with loads starting from 100 kW, it is common to actually inject the power into the data center at a level of 1-40 kV and then to transform the voltage down locally. While it is generally a good idea to use higher voltages for longer distances especially at high loads, neither PUE nor DCiE define clearly if the transformation losses should be included in case of on-premises transformer substations or not. Generally, the PUE and DCiE model should define a clear policy here if transformation losses should be included or not. Better suited seems the scenario where transformation losses are excluded as otherwise data centers with external, unmeasured or immeasurable transformation losses would have competitive advantages without actually being more efficient.

Efficiency only of the data center power consumption, not of the actual output:

As per definition, DCiE and PUE only define how much energy actually reaches computer systems, but not how many computations are undertaken per energy unit.

While DCiE and PUE are a measure on the overhead of data centers or in other words on the waste of energy through data centers, these numbers are not representative on how high the output of actually used energy is. In case very old computers are used, a data center still could have very good values in terms of DCiE and PUE without actually being efficient. Clearly, both the energy efficiency of the data center itself as well as of the computers deployed in combination together is important.

4.4.4 Typical Scenario at a level of PUE of 2,0

An example of the typical distribution of Power in a Datacenter with a PUE of 2,0 can be found below (Neudorfer, 2012):

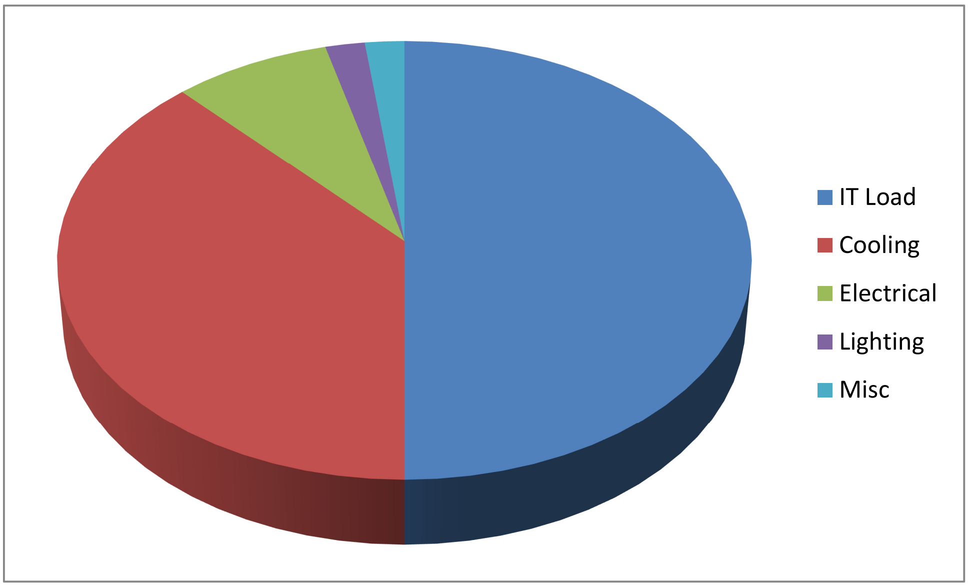

Figure 9 : Typical power usage at PUE 2,0

Within this Power Usage, the loss of energy becomes even clearer when looking only at the facility portion; The following graphic illustrates the distribution of solely facilities (Neudorfer, 2012):

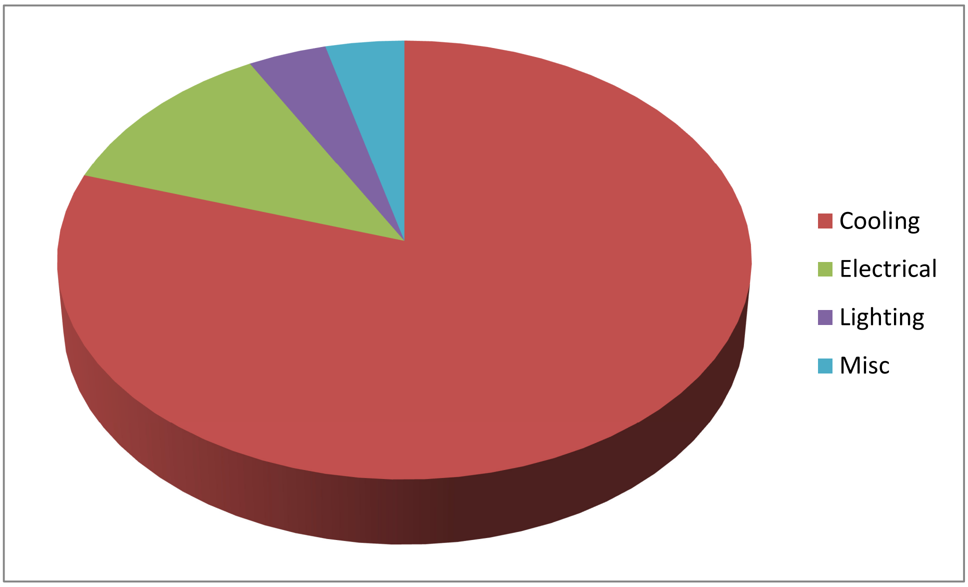

Figure 10 : Typical infrastructure power distribution on facility power at PUE 2,0

As it can be seen from this measured and acquired statistical information, the largest portions are actually the IT load itself as well as the cooling required for the equipment, then followed by losses in electrical conversion and equipment.

In terms of total numbers, the distribution is described in table 5

Percent	Load Type
50	IT Load
38	Cooling
8	Electrical
2	Lighting
2	Misc

Table 5 : Percentage of infrastructure power distribution at PUE 2,0

4.4.5 Projection on a national level to the country Germany

In order to understand the overall volume of IT equipment used on the scale of a country, some desk-based research was undertaken in this direction. As example country, Germany is used in this dissertation; research was undertaken how large the overall power consumption of IT is within Germany.

According to a study of the Federal Environmental Protection Agency of Germany in 2010/2011, updated with numbers of a study of the Federal Association for Information Technology ("Bitkom") (Hintemann, Clausen, 2014) the overall German national data center infrastructure can be outlined by the following numbers (Fitchner, Hintemann, 2011)

Type of Installation	Number of installations	Number of Servers	Area used	Power Usage including additional Equipment[17]	Total Servers	Total Power
Server Rack	30500	3-10 (Avg.:4,8)	5m^2	3,2 kW	146400	96,6 MW
Server Room	18100	11-100 (Avg.: 19)	20m^2	16,3 kW	343900	295 MW
Small Datacenter	2150	101-500 (Avg.: 150)	150m^2	145,5 kW	322500	313 MW
Medium Datacenter	280	501-5000 (Avg.: 600)	620m^2	474 kW	168000	133 MW
Large Datacenter	70	5001- (Avg.: 6000)	5800m^2	4320 kW	420000	302 MW
						1139,6 MW

Table 6 : Datacenter infrastructure outline within Germany

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[17] Corrected according to contact with updated numbers according to Dr. Ralph Hintermann and Prof. Dr. Klaus Fichtner in conjunction with industry average server power consumption of ~ 270W and a PUE of 1.7-2.6 depending on data center type and avg. age

As it can be seen from the table above yearly power consumption corresponds to 9983204352 kWh or to 9983 GWh or simply 10 TWh.

According to the data collection of the federal environmental protection agency of Germany, the constant electric load here is about ~ 1100 MW which is approximately the output of a larger commercial nuclear reactor (BUMB, 2015).

Within one additional study undertaken on consolidation, colocation, virtualization and cloud computing by the Borderstep institute, the development on total electricity used by data centers within Germany has been found as visualized in figure 11 (Hintemann,2014).

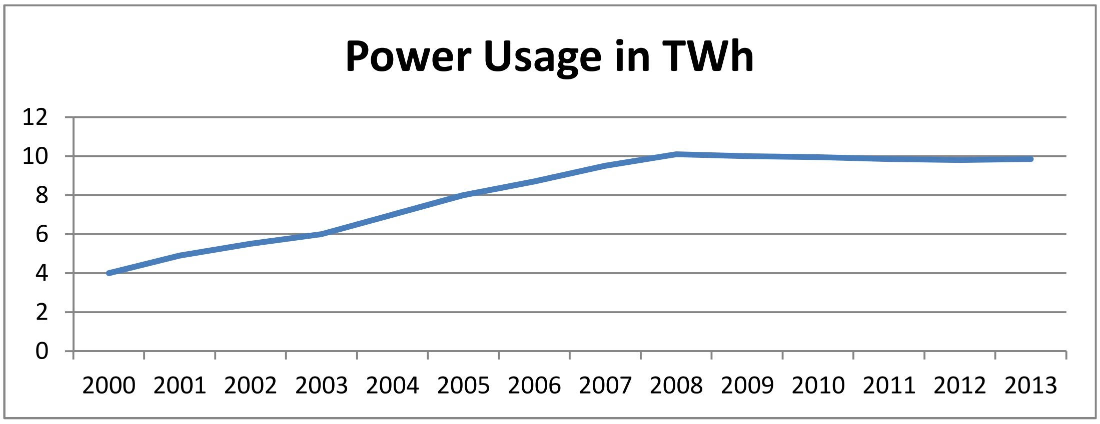

Figure 11 : Power usage by significant computing infrastructure within Germany

As outlined in the figure above, a rising trend until 2008 with a flat tendency since then can be clearly seen.

In 2014, in terms of comparability to a household electricity usage of 2200 kWh per 2 persons, this corresponds to approx. 4,5 Mio. Households.

Starting from approximately 250 MWh per year, the cost for electricity starts to be dramatically lower compared to lower usage. This is mainly caused by the government dropping taxes and other charges in order to keep power intense industry within the country.

Considering the cost for electricity of approx. 26,1 EUR/cents for sizes of up to a server room and industry prices of approx. 8,47 EUR/cents per kWh for small data centers and up, the total monetary cost for electricity can be estimated to be in the range of 1450 Mio. EUR or 1,5 Bn EUR.

In terms of national electricity usage, Germany has a base electrical load of approximately 45 GW as of 2012 (Gründwald, Ragwitz et al, 2012).

As it can be seen from the data above, the overall power consumed by data centers which lies in the area of the base load as it is existing 24/7, can be estimated to cause approximately 2,5% of the German national base load capacity.

In the overall, operation of IT within Germany generates a total of 5490762 Tons of CO_2 per year[18].

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[18] On average, 0,55 kg CO_2 per kWh, according to the German Federal Office for Environmental Protection

As the numbers outline here, saving on electricity of IT definitely has a large impact both in terms of absolute cost but also in terms of environmental issues.

Clearly, as the main focus of this dissertation is space operations, one cannot conclude that all IT power usage is caused by long-term operational scenarios, an identification of the range here would be subject to a further study on the distribution of long-term IT on a national level.

4.5 Efficiency considerations

While efficiency in terms of IT systems can be measured mainly in terms of computations per unit of electrical power consumed by central processing unit (CPU), there are also other factors which take influence on system efficiency as a by-product of IT systems.

Clearly such factors are by-products of the productive goal of IT systems in this case – which aims mainly at achieving maximum computations per power – but still such ones need to be considered.

IT systems consist typically of more than CPUs, a computer internally typically also contains a single or dual power supply, memories, hard disks, network components, graphic chips and other components. Such ones on one hand contribute towards achieving the goal of undertaking the relevant calculations and achieving the required functions, but on the other hand, they create power losses themselves. It is important to understand the degree of such power losses, as we will not be able to eliminate such ones generally also in future proposed solutions. Clearly, if a solution involves a reduction in terms of machine count, also such power losses will be reduced, however it will not be possible to completely eliminate such but only to lower the level.

In table 7, typical power losses of IT systems are presented.

Data presented in this table is either based on own measurements or on manufacturer's data which was independently confirmed.

Component	Power loss	Typical power loss in W
Server Power Supply @ typical 95% efficiency[19],[20],[21]	~5%	12W
Hard Disks (mechanical, 2,5” size, 10k RPM)[22]	~2,5-3% per piece ~15-21% Total per server, based on 6 HDDs	6-8W per piece. Typical: 36-50W per Server
RAM[23],[24]	~1-1,5% per piece ~3,5-10% total per Server, based on 4-8 modules	2-3W per piece. Typical: 8-24W per Server
Mainboard, including onboard video card, chipset, network cards, CPU voltage converters and fans[25]	~21-34%	50-80W
CPU at 50% usage[26]	~50% for a two CPU server	120W (60W per CPU)

Table 7 : Typical power losses within computer systems

As we can see from the above, most of the power is in fact consumed by the CPU. In further research, main focus will be on the CPU output, as this will be the main factor to drive efficient consolidation.

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[19] (HP, 2016)

[20] (Lenovo, 2016)

[21] Own measurements on different PSUs from manufacturer „HP“

[22] (Schmidt, Roos, 2009)

[23] (Intel, 2009)

[24] (Angelini, 2014)

[25] Remaining power consumption, reversely calculated from total consumption at PSU output after deduction of all components

[26] Average of several measurements, taken in Lab-Setup with the Intel Power Monitoring Tool (Intel, 2016)

4.6 Development in future IT efficiency

As we have seen in the previous chapters, especially with regards to overall IT power usage, the power used for computation does not constantly increase, but for example on the national projection on the country of Germany stays more or less since 2007 constant, one may ask the question why even the use of computes becomes more and more wide-spread and the complexity of IT systems is constantly increasing, the power usage does not increase as well. For example, during a 20 year period, usual operating systems were going from 4,5 million lines of code in 1993 (Windows NT 3.51) to about 85 million lines of code (Mac OS X Tiger) in 2014 (McCandless, 2015) – which is an increase in terms of lines of code approximately factor 19. The answer here lies in the nature of physics with regards to silicon manufacturing advancement. In particular with regards to complexity as well as with regards to efficiency, Moore and Koomey have found scientific proof through market analysis of complexity as well as efficiency doubling approximately every 18 to 24 months.

4.6.1 Moores Law

Dr. Gordon Moore, co-founder of the Intel Corporation, researched into chip complexity increases. Already in 1965, he described his observation of chip complexity doubling approximately every two years (Moore, 1965). As indicator, he used the number of transistors within the integrated circuit. Even though, the outline given by Dr. Moore was based initially on an observation in the time duration between 1959 and 1965, the projection has stayed fairly accurate until today. The following graphic outlines the actual development in the time-frame between 1971 and 2011:

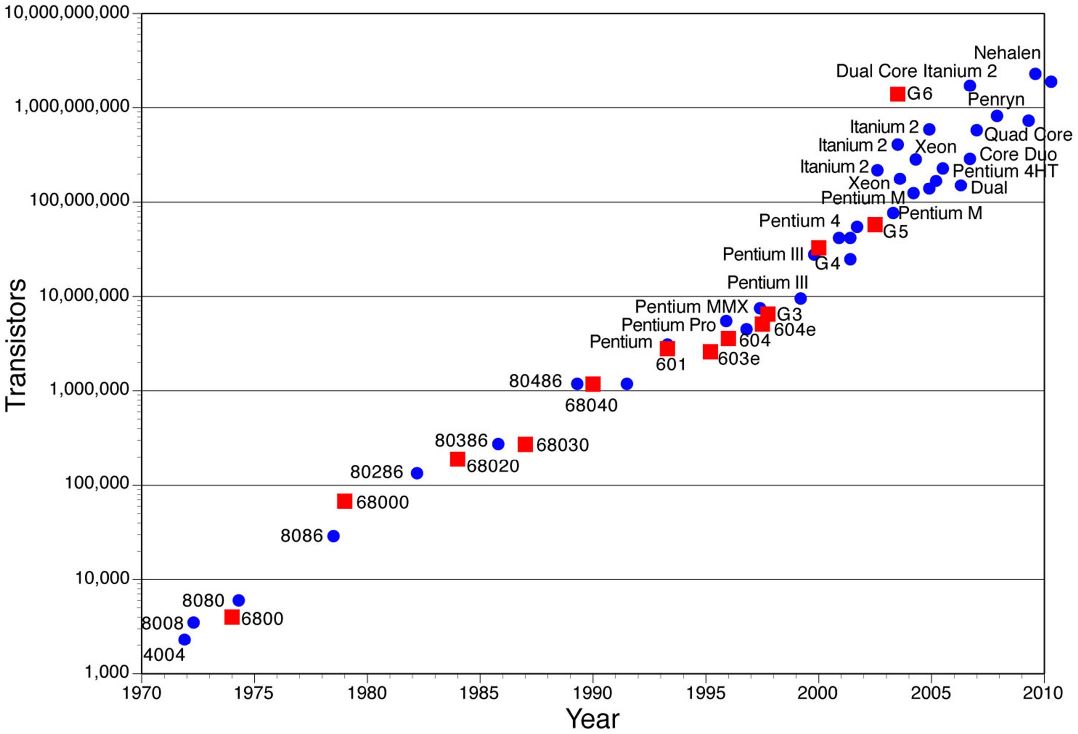

Figure 12 : Complexity increase in electronic circuits over time with logarithmic scale (Penn State University, 2013)

As it can be clearly seen, the increase in transistors per circuit is exponential, considering the logarithmic scale on the y-axis.

Central finding: **Since approximately 1970, per decade, the chip complexity increases by factor ~32.**

4.6.2 Koomeys Law

Based on the research and findings by Dr. Moore and with the addition of significant own research, in 2010, Dr. Jonathan Koomey along with other researchers, published a paper with the title "Implications of Historical Trends in the Electrical Efficiency of Computing" with the IEEE as well as already in 2009, the paper "Assessing trends in the electrical efficiency of computation over time" (Koomey, et al, 2009).

Main finding of his research and paper has been computations per unit of energy doubling approximately every 1,57 years or 19 months with a R-Square of approximately 98% since 1950 (ibidem).

As outcome of further current and previous research, Koomeys law can be expected to be effective until 2048. Reason here is the implication of Landauers principle described for the first time described in 1981, published 1982 (Landauer, 1982). Landauer describes, through theoretical research into thermodynamics as well as statistical physics, a lowest limit of power consumption possible for computations.

The following figure describes the development of computations per kWh being possible over time and is based on the original publication by Dr. Koomey.

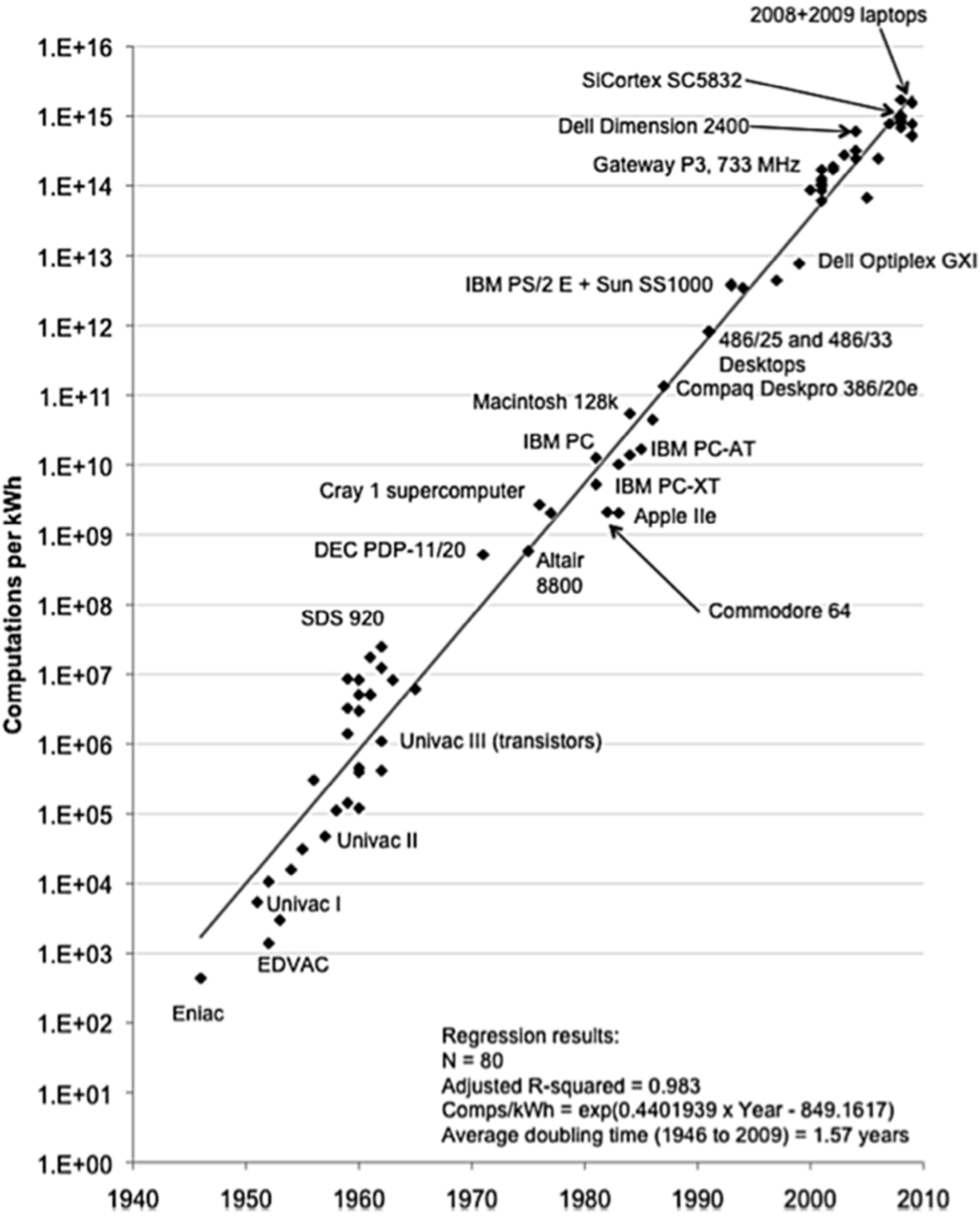

Figure 13 : Computations per kWh vs. year of computer release to market (Koomey et al, 2010)

As it can be clearly seen, the increase in computations per kWh is exponential, considering the logarithmic scale on the y-axis.

Central finding: **Since approximately 1955, per decade, the computation efficiency increases by factor ~82.**

4.6.3 From FLOPS / kWh to FLOPS / CPU

Koomey's law describes the chip efficiency increase over time. In order to derive physical sizes (and required floor space) from chip efficiency models, additional information is needed. Nowadays, standard servers in space operations typically host two CPUs. Knowing the number of CPUs per machine already allows to roughly estimate the development of processing power. However, in order to conclude meaningful performance numbers, the input variable "power per CPU" is needed:

In order to estimate the processing power per server, we need to understand know which development of power dissipation to expect. From statistical data obtained for the years 2000 to 2015, it is clear that typical maximum power dissipation figures per CPU – also called Thermal Design Power (TDP) - are more or less constant. The TDP in the years 2007 to 2015 was in the range of 130W +/- 25% (Rupp, 2014).

From this finding, one can easily derive the implications on chip efficiency:

As the maximum TDP remains almost constant and thereby the maximum power per CPU remains constant, the exponential FLOPS / kWh finding can directly be transferred into an exponential performance per machine performance development.

4.6.4 Memory price development

As one input to long-term computer cost development, a view at memory prices is also of significant interest.

While there is quite a bit of information about memory prices to be found in short-term periodical publications like for example newspapers, the information to be found here includes statements like the following:

- "RAM prices will continue to climb - last year's (2012) rock-bottom prices will probably never return"(Hruska, 2013)
- "China factory fire sends memory chip prices to three-year high (2013)"(Garside, 2013)
- "Memory prices to fall this year after stabilizing in 2014"(Shah, 2015)

Unfortunately, such publications seem to rather play with reader's interest than actually represent long-term development.

In order to analyse the cost of memory over time, literature research was undertaken in order to measure how the cost of memory over time developed.

In order to achieve this, memory prices were gathered from different sources (McCallum, 2015), (Stengel, 2015), (Schembri, Boisseau, 2015), (Newegg, 2012), (Pcmag, 2015), (Byte, 1975-1998) partially through information currently on-line but also from information retrieved via the internet archive (Archive, 2016) and broken down to the cost per MB of memory storage in United States Dollars.

As basis for this research, the following definitions have been used:

- Megabytes calculated are based on base 2, resulting in 1 MB being 1 048 576 bytes

- US Dollars are based on uncorrected Dollar rates applicable at the time
- Inflation has not been calculated into pricing
- Prices used were where available market prices
- In the case of older price information (approximately before year 2000), list prices were used

While it turned out to be rather difficult to find memory prices for the pre 1980 era, the detail and amount of data available from 1980 is much more dense. Pre 1980, sometimes unfortunately longer gaps exist in the analysis as computer usage and price information could not be found in closer intervals (e.g. on a yearly basis). As it can be seen however later in the analysis, this does not actually create a larger issue – the general trend is still clearly visible.

As outcome of this research, quite an interesting development of memory pricing over time could be found. As prices declined rather quickly, it was required to scale the cost axis in a logarithmic way in order to still produce a meaningful and useable graphic representation. The summary of the information can be found in the following figure.

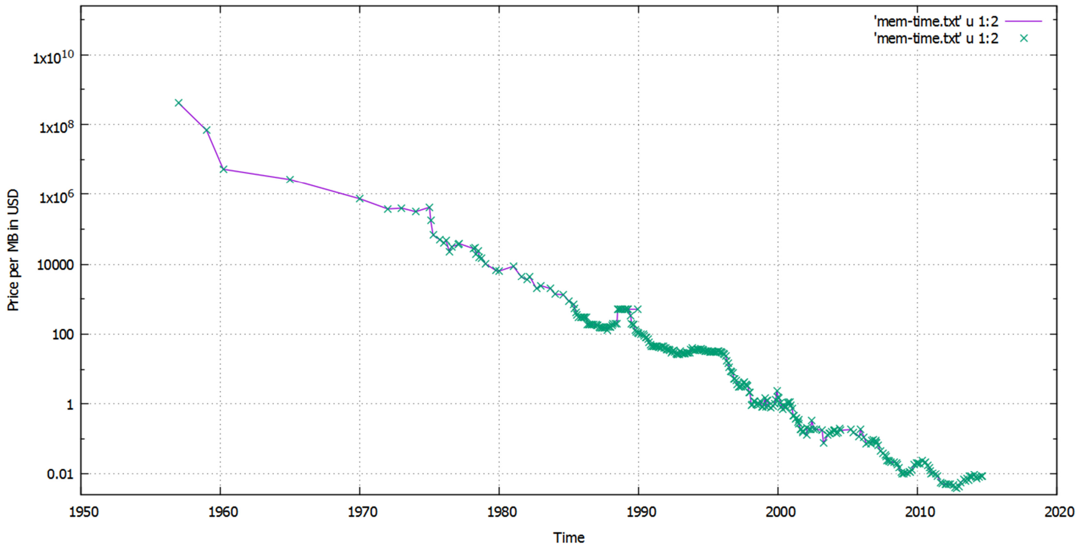

Figure 14 : Memory price in USD / MB vs. time[27]

As it can be clearly seen, the price drop is exponential, considering the logarithmic scale on the y-axis.

Central finding: **Since approximately 1955, the price per MB of memory drops, per decade, by factor 100.**

Such a development is quite significant, as the applications looked into in terms of long-terms IT operations are usually static – so the memory consumption of the application does usually not increase over time in comparison to the free market, where performance required running up to date software increases.

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[27] Data from sources (McCallum, 2015), (Stengel, 2015), (Schembri, Boisseau, 2015), (Newegg, 2012), (Pcmag, 2015), (Byte, 1975-1998) and own research

In the area of memory, in case an easy mechanism is found for taking advantage of the price drops in memory without endangering the application software or generating huge migration costs, it is possible to take advantage of an exponential price drop.

4.6.5 Calculation background

The technological development (e.g. chip transistor count increase) according to Moore’s law, with regards to transistor count, is described by Siegel (2012) as follows:

$$N(t) = X(0) * \ 2^{\frac{t}{2}}$$

with

$$N(t) = number\ of\ transistors\ at\ time\ t$$
$$X\ (0) = \ start\ count\ or\ rlative\ factor,$$
$$t = time\ in\ years$$

Equation 4 : Calculation of exponential growth according to Moore’s Law

The development of chip efficiency measured in FLOPS per kWh is described by the following equation, derived from Koomey (2009):

$$N(t) = X(0) * \ e^{\mathrm{k}*t}$$

with

$$N(t) = number\ of\ FLOPS\ per\ kWh\ at\ time\ t$$
$$X\ (0) = \ initial\ FLOPS\ per\ kWh\ at\ time\ t = 0$$
$$k = growth\ factor \text{ and } t = time\ in\ years$$

Equation 5 : Calculation of exponential FLOPS / kWh growth

The average growth-factor has been empirically found to be k = 0.4401939.

With regards to the USD / MB price degradation of memory, the following equation is derived from the data of Figure 4:

$$N(t) = X(0) * \ b^{-t}$$

with

$$N\ (t) = \ memory\ price\ per\ MB\ at\ time\ t,$$
$$X\ (0) = \ memory\ price\ per\ MB\ at\ time\ t = 0,$$
$$b = degradation\ factor \text{ and } t = time\ in\ years$$

Equation 6 : Calculation of memory price decrease

The average degradation factor has been calculated as b=1.584893192. The numeric coefficients have been found by calculation from the base data.

4.7 Availability aspects

In terms of availability, any change to an existing system will have certain influence on availability. In order to understand the potential impact of the latter on proposed changes, we will need to compare the influence of the changes with the current approach and check if the situation is not made worse or the impact is below an acceptable threshold in comparison to the current scenario. If proposed changes will in fact make availability worse, then it is required to look at the level of a threshold – otherwise, no threshold will be required.

As previously described during the short survey among spacecraft operations decision makers and spacecraft operations engineers, high availability was raised as major concern.

In order to understand what availability means, a definition of the calculation methods for availability will need to be created. While the time of the occurrence of a specific failure cannot easily be predicted, methods have been developed to predict general availability of systems. In general in literature availability is usually closely interconnected with mean time between failures - abbreviated MTBF as well as mean time to repair – abbreviated MTTR and mean time to failure - abbreviated MTTF.

The following graphic (Doeben, 2006 with own additions) illustrates the relevant states of a system and the determination of the TBF, TTR and TTF.

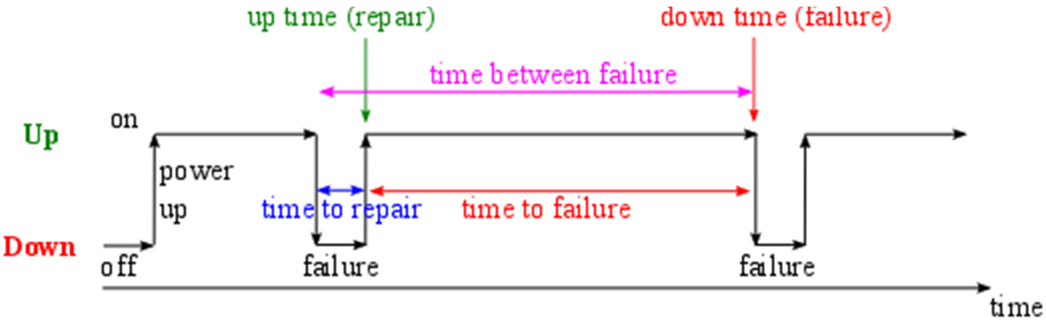

Figure 15 : Operational States of a System, TBF, TTR and TTF (Doeben, 2006)

While the investigation of a single failure does not allow concluding from the single failure to all failures, the mean time – so average time between a failure is the number of interest. While it is clear that the single time of a failure cannot be predicted precisely, the goal of highest availability is reached by achieving a large average mean time between failures also called MTBF. Therefore, MTBF is therefore defined as it follows (Doeben, 2006),(Joseph,2013):

$$Mean\ Time\ Between\ Failures\ (MTBF) = \frac{\sum\ (down\ time - up\ time)}{number\ of\ failures}$$

Equation 7 : Formula for the calculation of MTBF

4.7.1 From MTBF to Availability

While actually, the MTBF measure is a good indicator of a reliable or unreliable system, not only the time between failures is relevant, but especially also how long it takes to actually be back to an operational state “Up” again. Therefore, another measurement for the indication about the mean time to repair is required – the “Mean Time To Repair” or MTTR. When combining MTBF with MTTR, the following formula can be used to calculate “Availability” (Joseph, 2013):

$$A = \frac{MTBF}{MTBF + MTTR} * 100$$

with

$A = Availability\ in$ %
$MTBF = Mean\ Time\ between\ failures$
MTTR = Mean Time to repair

Equation 8 : Formula for the calculation of Availability

As it can easily be seen from this formula, also the time to repair has got a very significant impact on the availability. While manufacturers specify typically the MTBF, we must also undertake the required effort to reduce the MTTR. In an ideal case, the repair shall only take a few minutes rather than days in terms of absolute numbers.

While the described formulas focus only on a single system, as previously described, the focus are systems consisting of a large number of components. In this context, it is important to understand how the different organizations of components are impacting availability.

In this context, it is also important to understand that we are dealing here with the case, where failed components can and will be repaired. Depending on the state of deployment, this may not be the case – e.g. on a spacecraft, no repair can typically be undertaken except in very specific circumstances. It is herewith clarified that the author’s research only covers cases with repair.

Typically, further in the context of this dissertation, there are only two cases which we need to deal with for performing a MTBF calculation. These cases are explained in the following.

4.7.2 Serial connection of systems

Typically, a functional element does not necessarily consist only of a single system. As we will see when investigating on a typical ground segment system, usually, the function of several serialized systems is required in order for such a functional element to perform its duties. Unfortunately, serialization of systems means in terms of availability or MTBF a decrease but is not avoidable without changing to-be-used software drastically.

The following graphic describes the serial connection of systems scenario here:

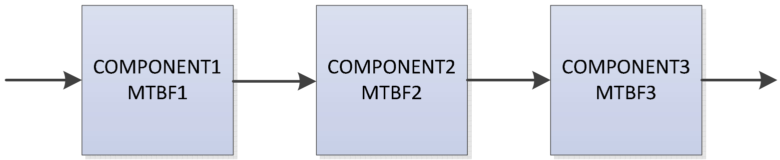

Figure 16 : Serially connected systems (Propst, 1994)

According to research undertaken by John Propst and published in the paper "Calculating Electrical Risk and Reliability" (Propst, 1994), the availability of serially connected components or systems can be described by the following formula:

$$A_{compl} = \prod_{i=1}^{n} A_i$$

with

$$A_{compl} = Total\ Availability$$
$$A_i = Availability\ of\ each\ component\ with\ index\ i$$

Equation 9 : Formula for the calculation of serial availability (Propst, 1994)

In this specific example, this results then to:

$$A_{compl} = A1 \cdot A2 \cdot A3$$

with

$$A_{compl} = Total\ Availability$$
$$A_{1,2,3} = Availability\ of\ each\ component$$

Equation 10 : Specific formula for the calculation of serial availability (Propst, 1994)

Projected on to the MTBF-case, this then resulting calculation is the following:

$$MTBF_{compl} = \frac{1}{\sum_{i=1}^{n} \frac{1}{MTBF_i}}$$

with

$$MTBF_{compl} = Total\ MTBF$$
$$MTBF_i = MTBF\ of\ each\ component\ with\ index\ i$$

Equation 11 : Formula for the calculation of serial MTBF (Propst, 1994)

In this specific example described by the above figure, this results then to:

$$MTBF_{compl} = \frac{1}{\frac{1}{MTBF_1} + \frac{1}{MTBF_2} + \frac{1}{MTBF_3}}$$

with

$$MTBF_{compl} = Total\ MTBF$$
$$MTBF_{1,2,3} = MTBF\ of\ each\ component$$

Equation 12 : Formula for the calculation of serial MTBF (Propst, 1994)

4.7.3 Parallel connection of systems

Contrary the above described serial connection of single systems, especially for mission critical systems it is typical to make use of redundant systems in order to significantly increase the reliability.

While the systems described before are cascades serially, parallel systems are one possible way to be used to increase availability again, resulting from unavoidable serial constructions.

As for example military users got a significant interest, there was significant research undertaken by the so called Rome Laboratory of the US air force. One publication covering a large field of this topic is for example the book written by Anthony J. Feduccia, The Rome Laboratory, Air Force Materiel Command (AFMC), Griffiss AFB, Reliability Engineer's Toolkit published in April 1993 (Feduccia, 1993). Another publication in the area was undertaken by Don L. Lin, Ph.D., Reliability Characteristics for Two Subsystems in Series or Parallel or n Subsystems in m_out_of_n Arrangement, Bell Laboratories, 2005 (Lin, 2005).

The following graphic describes the parallel, redundant connection of systems scenario here:

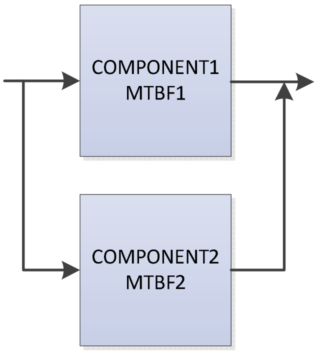

Figure 17 : Parallel connected redundant systems (Propst, 1994)

According to Lin (2005), based on the assumption the MTTR vs. the MTBF is small and repair is undertaken quickly, the equation 13 describes the availability in this scenario.

$$A_{compl} = A1 + A2 - A1 \cdot A2$$

with

$$A_{compl} = Total\ Availability$$
$$A_{1,2} = Availability\ of\ each\ component$$

Equation 13 : Formula for the calculation of parallel availability for two subsystems (Lin, 2005)

For the calculation of the availability of several subsystems in parallel, equation 14 can be used:

$$A_{compl} = 1 - \frac{n!}{m!\,(n-m)!} \cdot (1-A)^m$$

$$A_{compl} = Total\ Availability$$
$$A = Availability\ of\ each\ identical\ component$$
$$n = Total\ number\ of\ identical\ parallel\ systems$$

m = system fails if m or more subsystems fail

Equation 14 : Formula for the calculation of parallel availability for multiple identical subsystems (Lin, 2005)

With regards to MTBF, the calculation can be undertaken by using the following formula:

$$MTBF_{compl} = \frac{MTBF_1 \cdot MTBF_2}{MTTR_1 + MTTR_2}$$

with

$$MTBF_{compl} = Total\ MTBF$$
$$MTBF_{1,2} = MTBF\ of\ each\ component$$
$$MTTR_{1,2} = MTTR\ of\ each\ component$$

Equation 15 : Formula for the calculation of parallel MTBF for two subsystems (Lin, 2005)

In a scenario with n identical subsystems in parallel with each of them having the same MTBF and MTTR, this results in the following:

$$MTBF_{compl} = \frac{MTBF^{m}}{\frac{n!}{(n-m)! \cdot (m-1)!} \cdot MTTR^{m-1}}$$

with

$MTBF_{compl} = Total\ MTBF$

MTTR = Mean Time to Repair for each system

$n = Total\ number\ of\ identical\ parallel\ systems$

m = system fails if m or more subsystems fail

Equation 16 : Formula for the calculation of MTBF for multiple identical parallel systems (Lin, 2005)

4.7.4 Advantages and disadvantages resulting from parallel systems

As it can been seen from the previous diagrams and formulas, unfortunately, higher availability comes at a certain price: The systems which need an increase in reliability will need to have systems added in order to increase in reliability which will result in an overhead in terms of systems which are added without direct benefit to the overall system performance other than increasing reliability. Adding parallel systems in other words will consume actually energy without producing output, thereby increasing significantly reliability at the price of halving energy efficiency.

Unfortunately, parallelizing systems in order to increase reliability cannot be avoided in the scenario investigated upon as leaving parallel systems out could endanger reaching the overall computing system goal in order to keep a mission critical system running.
Also financially, having redundant systems deployed increases hardware purchase and deployment cost typically by factor two. One of the goals of further analysis should therefore be to decrease the number of parallel systems required in an intelligent way, without compromising system availability.

5 RESULTS

In the following chapter, the previous findings are applied to a real existing scenario. First, a look at the setup in the lab will be taken and power measurement results will be discussed. From here onwards, an analysis of the impact of the proposed changes on reliability will be undertaken. As final steps, a projection in terms of the development of costs for power and upgrades in a long-term scenario will be created.

5.1 Lab Measurements

As previously described, for analysing real existing power usage, measurements have been undertaken according to the previously in figure 3 presented circuit.

The following picture gives an impression of the actual multimeter setup in the power distribution box having been used:

Figure 18 : Current measurement setup (only Instruments shown)

As previously described, four multimeter, each measuring three phases both in voltage and current are used which will be used for collecting power usage data in order to further analyse power consumption of the systems.

In the further of this section, the lab measurement results are presented and interpreted.

Overall, the author has measured power consumption of 60 to 72 Systems in six racks together with two air condition units for duration of ~ 2 years. Due to system changes however taking place in terms of arrangement in the lab setup, only a timeframe of approximately 2 months could be found under which a constant, non-changing usage profile took place. The systems presented here were used to run tests for a spacecraft control system, comparable to a real usage profile. Later presented graphics will show that, there is little influence in any case caused by the usage profile towards the power consumption under this scenario.

Starting with Chapter 5.1.1, you can find the relevant measurement results from the representative time frame of approximately 2 months.

Rack No.	Number of servers in rack	Count and type of CPU per server	Benchmark per CPU (Passmark)[28]	Purchase Date (Quarter/Year)
1	5 (CPU)	2 CPUs of type: Intel E5-2650v2	13089	Q3/2013
2	14 (CPU)	2 CPUs of type: Intel Xeon 5160	1981	Q2/2009
3	16 (CPU)	2 CPUs of type: Intel Xeon 5160	1981	Q2/2009
4	16 (CPU)	2 CPUs of type: Intel Xeon 5160	1981	Q2/2009
5	6 (CPU) 4 (STORAGE)	2 CPUs of type: Intel X5670 2 Storage Units[29]	8126	Q3/2012
6	11 (CPU)	2 CPUs of type: Intel X5670	8126	Q3/2012

Table 8 : Systems in racks overview

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[28] CPU Benchmark as per http://www.cpubenchmark.net/

[29] Excluded from final calculation by making use of data of rack6 and reverse power calculation

5.1.1 Voltages of test setup

The electricity to the system was supplied by three phases which were commonly shared between all equipment. Differences in voltage due to extended cable lengths can be neglected as cabling is in line with current best practices and cable lengths are below 10m.

First, let’s start with the voltage measurement taken.

As described, the phases are shared across all equipment.

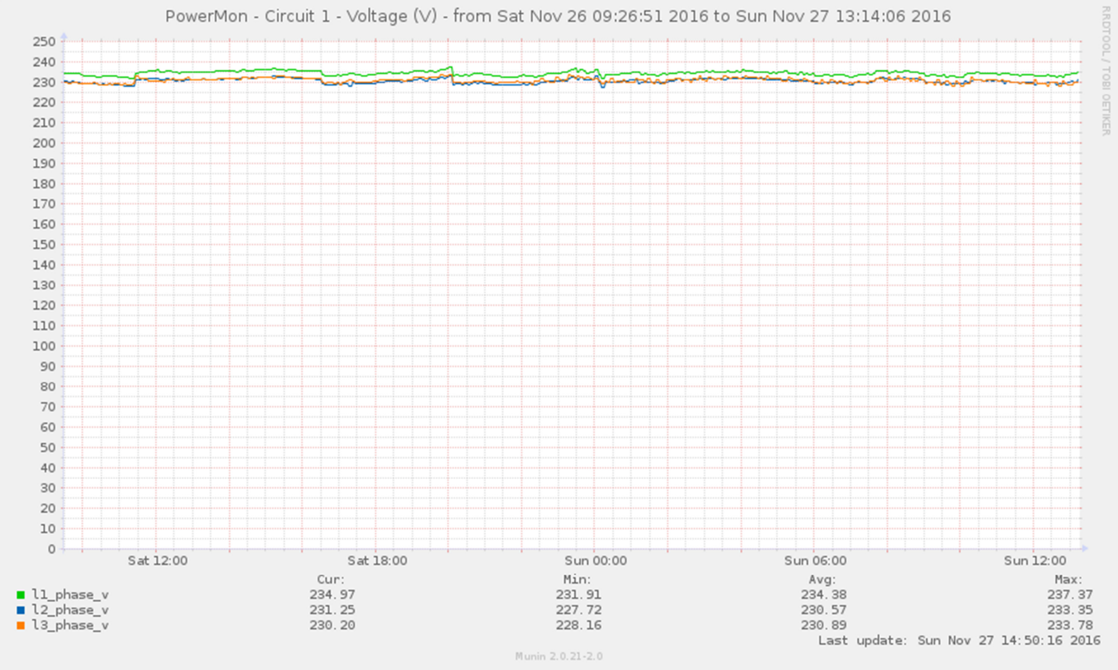

Figure 19 : Measured voltage on L1,L2,L3

As it can be read from the figure above, the voltage in the reviewed time frame was rather constant, averaging to the following values for each individual phase:

Phase	Average Voltage
L1	234,38 V
L2	230,57 V
L3	230,89 V

Table 9 : Measured average voltages across phases

Based on these voltages, we will calculate the average power consumption for the systems investigated upon.

5.1.2 Currents of test setup

For the first three racks of equipment, we have taken the following measurements in terms of current used.

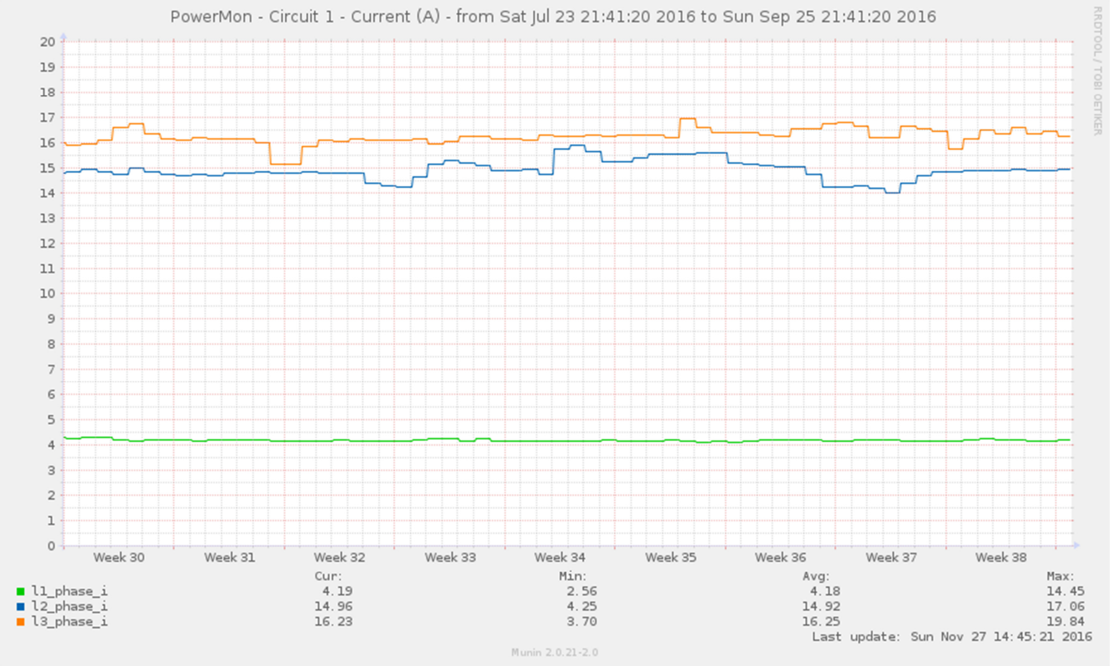

Figure 20 : Measured current for rack1, rack2 and rack3

While one can see actually a change in power usage, it should be noted that the power usage profile is rather constant. Slight variations on specific days could potentially be explained by the different test setups ran. It should be noted that tests included also power-off tests for short moments as well as tests running the equipment up at the same time. For this reasons, the minimum and maximum values can be small or large respectively – however as it can be seen from the graphics, the average current load is rather constant and typically within a range of +-10%.

In the following figure 21, the same graphs for rack 4, 5 and rack 6 are shown:

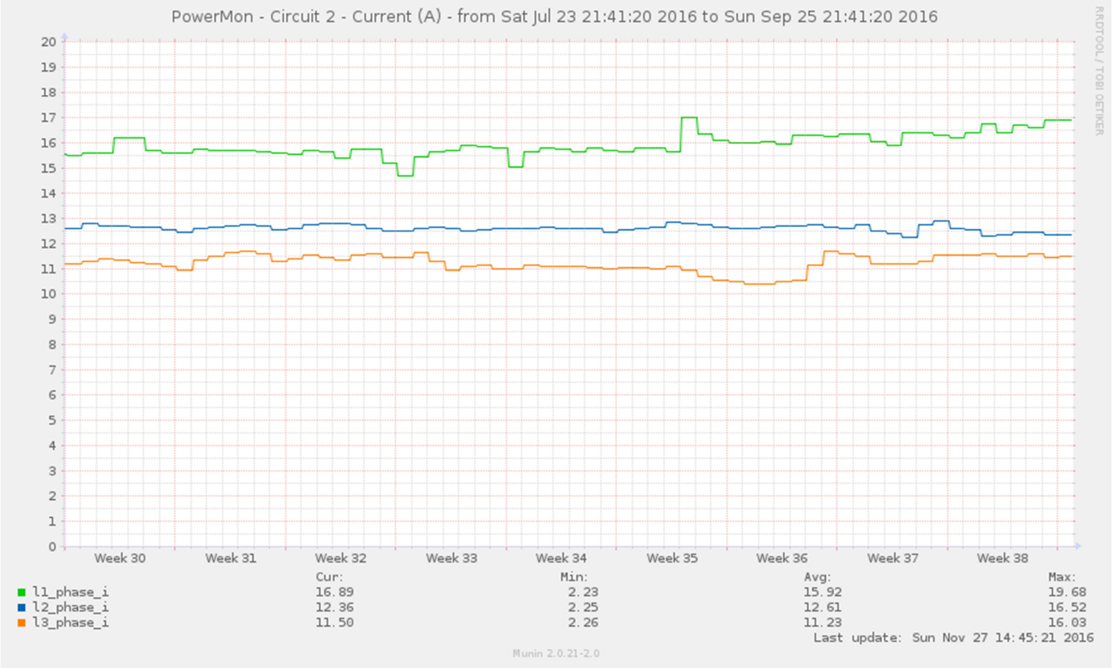

Figure 21: Measured current for rack4, rack5 and rack6

For reasons of completeness, also the power of the air conditions used in the lab setup has been measured. In the following diagram, the power consumption of the first air condition unit can be seen. This unit uses only a single phase, L3 – the other phases remain unused. It can be seen that the power draw is not as constant as with IT equipment – this can partially potentially be explained by outside weather conditions.

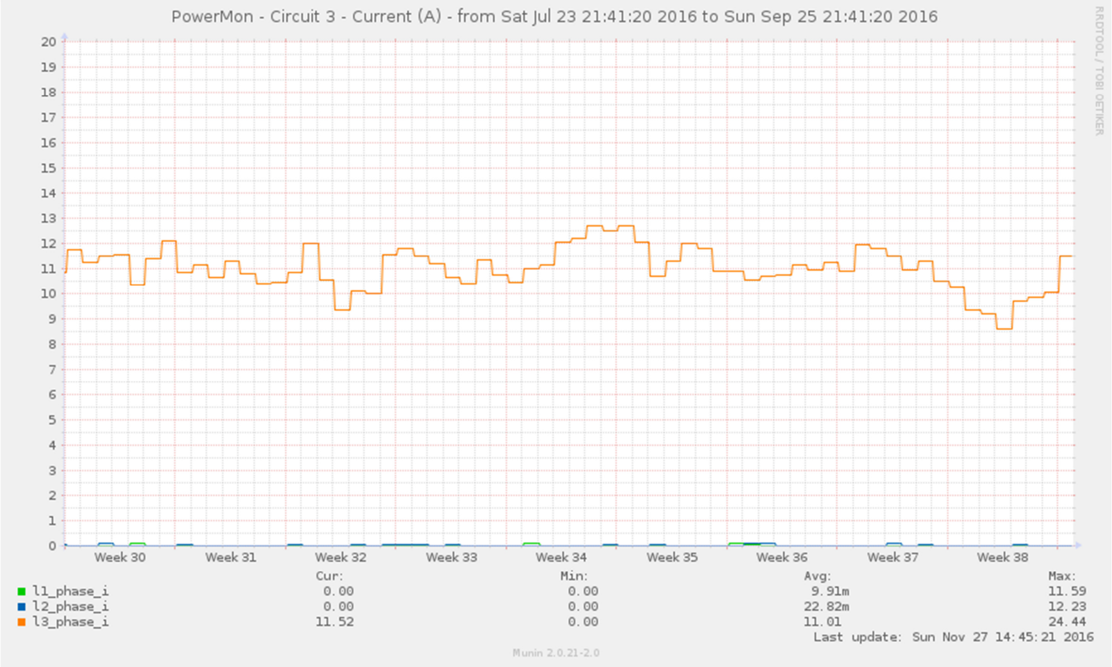

Figure 22 : Measured current for rack4, rack5 and rack6

Air condition 2:

Unfortunately, due a special de-icing function of this specific air-condition, there are significant short-term jumps found in the measurement results below – therefore, the graphical representation of the measurement setup is not ideal – the displayed average values however have been manually verified at different sample times and are representing the actual consumption. Also with this air-condition, we see significant changes in power draw – potentially due to external factors.

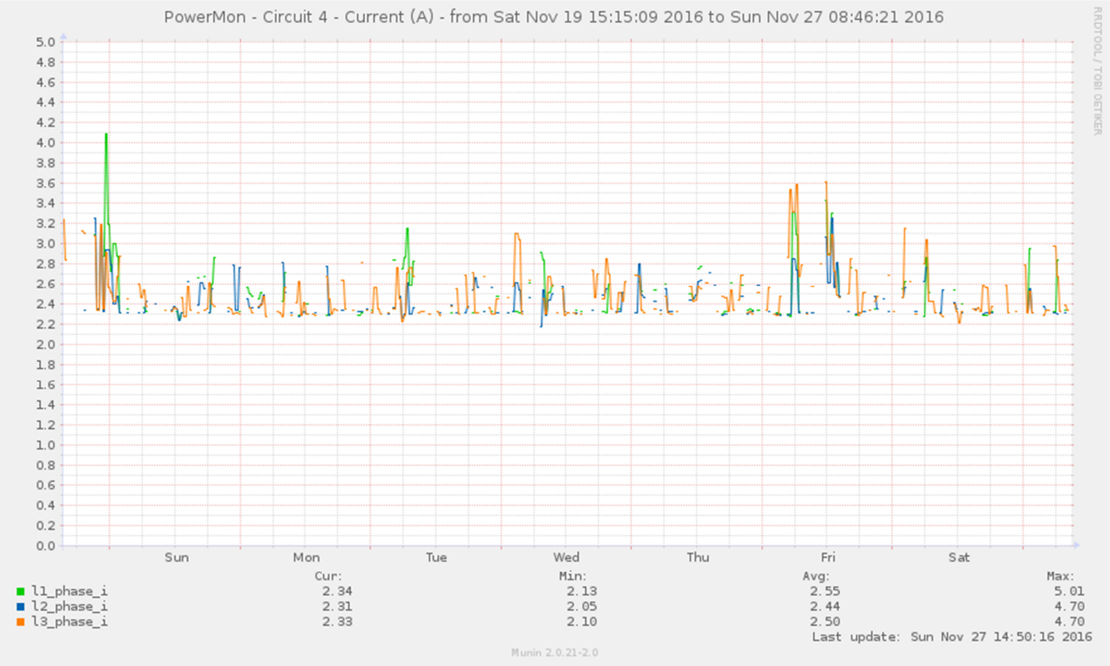

Figure 23 : Measured current for air-condition 2*[30]

In the following, the author will calculate the overall power consumption for each rack and then break down the consumption to the single server.

The power consumption can be calculated here simply by creating the product of voltage and current. This is due to the fact that all equipment has a power factor correction embedded and therefore, no reactive power exists – all active power (W) is apparent power (VA). This has been verified by measuring the cos φ via the multimeter which has been confirmed to be 1.

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[30] Graphic presentation not ideal, see text

Circuit	**Phase**	**Avg. Voltage**	**Avg. Current**	**Avg. Power**	**Count [pcs]**	**Type of Systems[31]**	**Load per System [W]**
1	1	234,38	24,18	979,71	5x SRV	E5-2650v2	195,94
1	2	230,57	14,92	3440,01	14x SRV	x5160	245,72
1	3	230,89	16,25	3751,96	16x SRV	x5160	234,50
2	1	234,38	15,92	3731,33	16x SRV	x5160	233,20
2	2	230,57	12,61	2907,49	6xSRV[32] 4xSTOR[33]	x5670	235,72* 491,15
2	3	230,89	11,23	2592,89	11x SRV	x5670	235,72
3	1	234,38	n/a	n/a	n/a	n/a	n/a*
3	2	230,57	n/a	n/a	n/a	n/a	n/a
3	3	230,89	11,01	2542,09	1 pcs	Air-condition	Total Power 2542,09 W
4	1+ 2+ 3	234,38	2,55	969,00	1pcs	Air-condition 3~	Total Power 2846,2 W
4		230,57	2,44	927,20			
4		230,89	2,50	950,00			

Table 10 : Measurement results summary

As one can see within the table above, the actual power consumption of the servers of the same kind is quite similar. Actually, between the different equipment generations and purchase dates, there is only a small difference in overall consumption. The biggest notable difference exists to the newest machine type which is approximately 18,8% more energy efficient. As overall average weighted value for the power consumption the author will make use of the value 238W per average 2 CPU server of an older generation type machine.

---

[31] x[nnnn] -. nnnn indicates type of processor

[32] SRV = Server

[33] STOR = Storage System

5.1.3 Comparison between theoretical calculation and actual measurement results in terms of CPU performance

While previously presented theory was developed from a lot of data, it is still required to test the developed theory in this specific scenario, based on the found coefficient of 0.4401939.

By making use of the purchase date and herewith correlating the oldest system's CPU performance, a comparison between theoretical results and the actual development of CPUs can be created.

In order to achieve this, the oldest CPU has been set as reference point and is then compared to newer ones.

The result of this correlation can be found in the following table along with the deviation of reality from the theoretical result.

CPU No.	CPU	Time of purchase	Time-Delta to CPU1 in Years	Measured CPU performance	Increase in Performance (Absolute)	Expected increase in performance (Absolute)	Deviation in %
1	x5160	Q2/2009	0	1981	0		
2	x5670	Q3/2012	3,25	8126	4,102	4,181	**-1,9%**
3	E5-2650v2	Q3/2013	4,25	13089	6,607	6,494	**+1,7%**

Table 11 : Deviation of measured results from theoretical expectations

As it can be seen from these results, there is definitely a clear connection between theoretical increase and practically measured results.

Clearly, as there are many different CPUs on the market at the same time, the comparison can only be applied to the same category of CPUs (e.g. higher-end type in this case).

5.1.4 PUE calculation, Lab Setup:

Just as side note, not of larger relevance, from our data, the power usage efficiency of our lab setup can be calculated

Consumer	Total Power
IT Equipment	17403,39W
Air-condition	5388,29W

Table 12 : Total lab power consumption

It should be noted that this calculation is here just for completeness reasons – it is by no means representative as the reseached lab setup power for lights, building etc. is not included in the calculation – still,

according to the author's previous findings on PUE factors, one can see that the lab setup is rather efficient:

$$\frac{Total\ Facility\ Power}{IT\ Equipment\ Power} = \frac{22791{,}68\ W}{17403{,}39\ W} = P_{ue} = 1{,}31$$

Equation 17 : Power Usage Effectiveness

Clearly, this number is here only for illustrative purposes, limitations of PUE measurement criteria as previously described prevail.

5.2 Implications resulting from a frozen state vs. technological advancement

5.2.1 Frozen state

During a long-term satellite mission, usually up to now, upgrades are only undertaken if absolutely not avoidable – missions are typically operated, using a frozen state both with regards to hardware as well as software configurations. While this approach can be understood from an operational safety point of view, it brings along also several significant disadvantages. Vendors often end their standard support for the used equipment during the nominal mission lifetime which then can trigger the requirement for very expensive additional extended support contracts. In addition, it is not possible then to take advantage of the technological advancement with regards to both IT efficiency but also space requirements.

5.2.2 Technological advancement during the mission duration

In contrast to the previously described "frozen state" approach, it is also possible to build a technological infrastructure around the strategy to advance or upgrade technology during the running mission.

While the use of energy in comparison to the computational requirements is exponentially decreasing over time, the efficiency is increasing exponentially. This then in return results in much fewer physical machines being required in order to achieve the same computational results. In order to save costs with regards to IT data centers, it is very clear that a physical space reduction will result in the end in much less physical space required and thereby result in much lower facility costs. Especially with regards to data centers used for shared space craft operations or where additional spacecraft or missions are added, this can avoid the construction of entire new facilities.

Frozen configuration	System advancement approach
Highest operational safety and full testing took place on original hardware (+)	Measures required to ensure system is maintaining required operational safety (-)
Support issues with regards to both hardware and software due to lifecycle contradiction. Failure rate per equipment increasing (-)	Hardware always within the vendor supported window, only minor support issues only with regards to operating system software support (+)
Size and power requirements constantly frozen to a high state during mission start: Constant high space and power requirements (-)	Size and power requirements taking advantage of exponential technological development: Size and space requirement decreasing during runtime of mission (+)

Table 13 : Advantages (+) and disadvantages (-) resulting from different approaches

Based on the results outlined in the previous table, it becomes evident that in a scenario with fixed requirements with regards to the operational functionality, such one can take significant advantages from technological advancement. The same goals can later on be achieved due to significantly increasing chip complexity, with much less resources in terms of energy as well as with much less cost with regards to memory.

5.3 Technological development during a 15 year mission lifetime cycle and conclusions

The table below shows, based on the formulas in chapter 4, the actual technical advancement during different periods including the growth factor k or degradation factor b, where applicable. Table 14 is based on the calculation output described by the elaborated formulas in section 4.6.5.

It becomes evident that especially during long-term IT operations, hardware renewal and thereby cost optimizations are having a very significant impact.

The factors given in the table are relative multipliers; chip complexity and FLOPS/kWh are increasing over time, while memory cost per MB is dropping (thereby causing a fractional multiplier).

	t = 0	t = 3 years	t = 5 years	t = 10 years	t = 15 years
Chip complexity	1	2,83	5,66	32	181
FLOPS / kWh	1	3,75	9,03	82	737,24
Cost / MB	1	0,175	$\frac{1}{10}$	$\frac{1}{100}$	$\frac{1}{1000}$

Table 14 : Chip complexity, energy efficiency and memory cost development over different periods

Within an operational context, especially the power per computation in a three and within a five year period is of interest. As outlined in the second chapter, a period of three and five years can be supported by the largest server manufacturers by the means of service being offered per default with computing hardware or also by the means of standard contracts. Any support required outside of the scope of a period of five years would require specific negotiations and would lead to largely added cost.

For this reason, the author proposes to make use of the maximum default supportable period of five years to be used as baseline for any equipment replacement. The result here would be a 9:1 ratio in terms of energy consumption per calculation as well as a price drop to 1/10 in terms of memory pricing.

Clearly, existing machines and memories could not be re-used due to technical incompatibilities having arisen due to technological development in such a time frame – replacement cost impact will be outlined in a later chapter.

5.4 Tiering and data center costs

According to the existing research and literature, there are several models for determining data center construction costs. One example in this context here is the finding by research undertaken by the leading data center research authority, the Uptime Institute.

Their central finding in this context has been that data center construction costs can be estimated best by using a tier-based cost per power coefficient along with a size based cost factor (Turner, Seader, 2006).

A tier is to be seen as a level here and described by characteristics outlined in table 15, defining such different tiers.

According to the research results given in the referenced paper, different levels of tiering cause different costs per kW of payload power used.

In general, there are two definitions of tiering used in IT industry: One definition was created by the Telecommunications Industry Association as the standard ANSI/TIA-942 (TIA, 2006). The second definition was created by the Uptime Institute (UPTIME, 2012).

A summary of the definition by the uptime institute can be found in table 15.

In general, the definition by the Uptime Institute is more commonly used, better researched into and is more applicable in the context of the scenario researched into here.

Level of Tiering	Outline
Tier I	• Single, non-redundant IT equipment with both: Non-redundant power and network connectivity • No overcapacity in any components • Allowable downtime of up to 28,8 hours (or 99,671% availability) per year
Tier II	• Same as Tier I • In addition redundant capacity components • Allowable downtime of up to 22,7 hours (or 99,741% availability) per year
Tier III	• Same as Tier II • In addition, dual-powered equipment and redundant uplink • Allowable downtime of up to 1,58 hours (or 99,982% availability) per year
Tier IV	• Same as Tier III • In addition, all components are fully fault tolerant including uplinks, storage, chillers, cooling systems, servers • Dual power to every component • Allowable downtime of up to 0,44 hours (or 99,995% availability) per year

Table 15 : Definition of data center tiering according to the Uptime Institute (UPTIME,2012)

In the context of space operations, due to the requirements on availability found in the further research of this dissertation, it became clear that only the use of a Tier IV data center can be considered.

After clarifying the specific requirements with regards to the data center required availability, the cost finding by (Turner, Seader, 2006) can be consulted to estimate average data center costs for such an operational scenario. The summary of their research can be found below as a table which describes cost per kW of server used power (payload power) in a datacenters as well as cost per net square meter.

Tiering	Price per kW of payload equipment power
Tier I	10000 USD / kW
Tier II	11000 USD / kW
Tier III	20000 USD / kW
Tier IV	22000 USD / kW

Table 16 : Data center construction cost per kW of equipment power, based on the relevant tier (Turner, Seader, 2006)

In addition, the cost based on the electrical load, the cost of 2400 US$ per m^2 of floor space must be added.

In the relevant publication "Dollars per kW plus dollars per square foot […]"(Turner, Seader, 2006) it is outlined that there are more assumptions included in the model and that calculated numbers may only be accurate by ~+-30%. However, as we are only investigating into trends with multipliers in the range of 70000% as we have seen before, in the case of space operations over 15 years, a diversion by 30% can be neglected.

5.4.1 Application of results in the context of a real-existing scenario: Construction costs

In order to apply the found results in a real-existing scenario, three sample space missions have been chosen and both, power and space requirement parameters have been measured.

The mean average outcome of this measurement has led to the following requirements:

Requirement	Measured Data
Floor space	580 m²
Electrical Power	431 kW

Table 17 : Average measured floor space and power requirements for larger missions in spacecraft operations data centers

As outlined previously in the chapter "Power" for the average German data center, one could assume a load of 765 W / m² - in this case, a load of ~743W / m² was measured.

Using the previous findings of Turner / Seader, this leads to the following

Requirement	Cost according to model
Floor space	1,392 M USD
Electrical Power	9,482 M USD

Table 18 : Construction costs of data center in the context of the sample calculation

The estimated total construction cost of a data center of such a size is then in the range of 10,874 M USD.

Clearly these costs are initial data center construction costs which cannot be gained back directly due to the fact that once the data center is constructed, the money has been spent. An indirect way however to gain further cost savings will be shown in chapter 5.8, here the author will discuss how many m²t or square meter multiplied by time will can be saved. Issue is however that these savings will only be useful if at the time of freeing space such space is needed. Savings on floor space therefore can be achieved by avoiding constructing additional data center space.

5.5 Assumptions and preconditions around the infrastructure in order to enable transferability of machines

Right now, indicators are showing, following an intelligent migration approach and herewith the technological developments on the market, could generate cost savings.

Unfortunately, due to the fact that hardware changes over time, the financial benefits come at a cost:

- Issue: Due to the changes required at each migration in terms of hardware infrastructure, a way of abstraction between hardware and software to be ran needs to be found.

Typically, the software of a space mission ground segment remains fairly static with regards. Exceptions are software patches to fix anomalies as well as patches to close significant security issues. While patches to fix anomalies are quite common, patches installed in order to enhance security are less frequent. Typically spacecraft operations take place in an isolated environment with a very limited number of externally facing interfaces. While there are limited possibilities to save cost on static software, there is unfortunately a new issue coming up here: As hardware changes over time, compatibility between the original software and the new hardware needs to be maintained.

In order to resolve this issue, introducing virtualization technology along with an abstraction enabling middleware to support application deployment is suggested.

The following figure provides an overview of the suggested approach to hardware virtualization following standard models of virtualization.

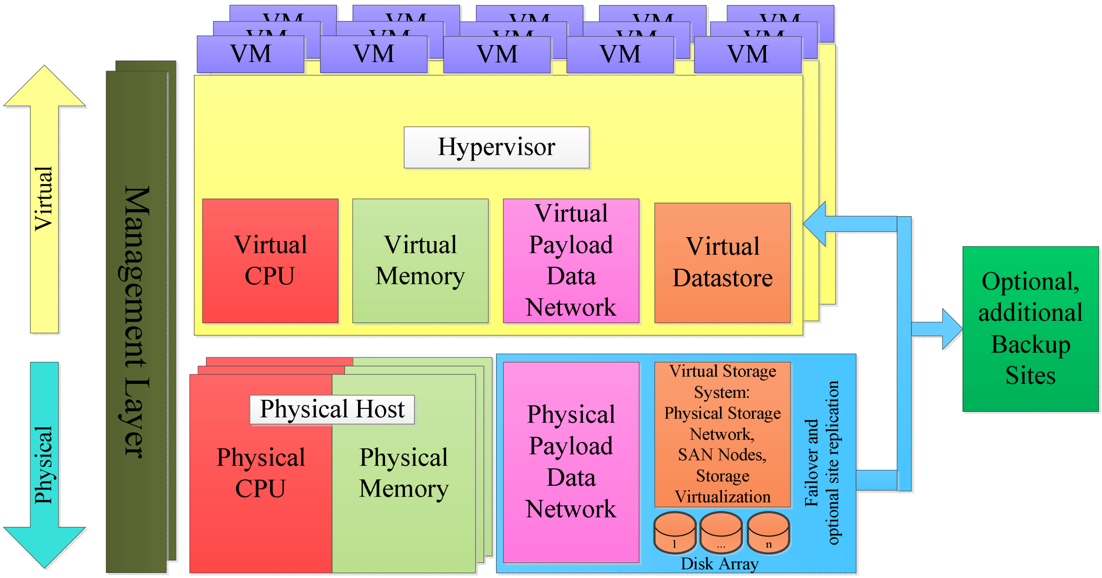

Figure 24 : Hardware Virtualization (Source: Gotter/Pfau, 2014)

At the bottom level of this architecture is a set of physical hosts, each of which has its own hardware resources such as CPUs and memory. Physical payload networks allow for communication between the physical hosts. In addition, physical disk arrays and a physical storage network provide the hardware resource for a virtual storage system.

Each physical host runs a software module called the hypervisor that maps physical hardware onto virtual hardware. This virtual hardware is used by virtual machines (VM) that run on these hosts. Each virtual machine is the host of a guest operating system and the software for the mission control system. Physical payload networks are mapped onto virtual networks and provisioned to the virtual machines. Likewise, the virtual storage system is provided as a virtual data store to the virtual machines.

Optionally, the virtual storage system can be mirrored by another backup system and data can be synchronized to the storage system of the backup system automatically.

A (possibly redundant) management layer supports the configuration, maintenance, and monitoring of the whole system.

In order to understand the approach in detail, it is required to take a closer look at te core software part called the hypervisor. The main tasks of the hypervisor are CPU scheduling and memory partitioning. In addition, the hypervisor manages the shared usage of the additional underlying hardware resources such as network cards. The hypervisor also controls the execution of virtual machines above and interfaces with the relevant management processes, e.g. in order to establish high availability functionalities.

A hypervisor alone is not sufficient to create a fully featured mission control system infrastructure. Management functionality plays quite an important role because it is crucial to the usability of the system.

There are several different types of hypervisors. In general, we have to differentiate between bare-metal hypervisors and hypervisors deployed on top of existing operating systems, adding a guest operating system in parallel to the main operating system that runs the hypervisor. While systems deployed in parallel to the main operating system play an important role when it comes to desktop and development environment virtualization, the author’s main choice and recommendation for mission critical systems is to make use of a bare-metal hypervisor.

The reason is that bare-metal hypervisors are independent of side-effects introduced by an intermediary operating system. After reviewing the solutions available on the market, it has been concluded that in terms of bare-metal hypervisors, there is only a small choice available. Potential products of choice include:

- Microsoft Hyper-V standalone Server
- VMware ESXi
- and Oracle VM Server / XEN

While the development of Microsoft's Hyper-V was mainly focused on their software product lines and only supports certain editions of Linux, the best support given by the Oracle VM Server seems to be for Solaris and Linux with

Windows being supported via Xen PV drivers. By trying out different solutions in practice over several weeks in terms of compatibility, in this scenario, it has been found that the best solution for the specific application case is VMware ESXi. This is because VMware has the broadest and most generic OS support among all solutions available. Among the described solutions, VMware is also the only provider independent of an in-house operating system product.

The following figure outlines the suggested approach which allows decoupling application software from server hardware.

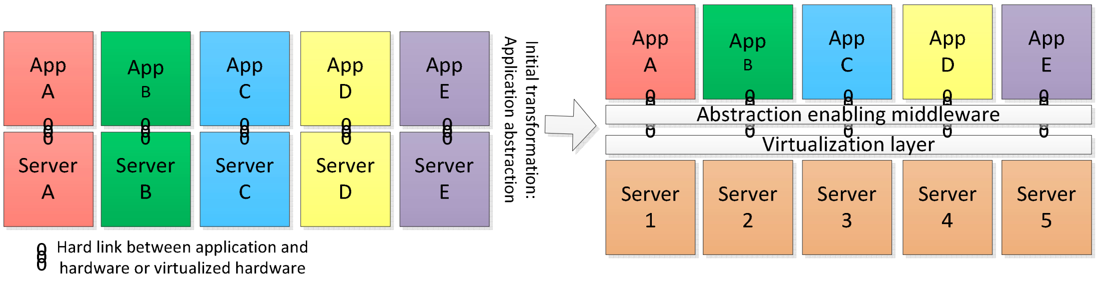

Figure 25 : Introduction of an abstraction enabling middleware and virtualization layer

5.6 *Reliability*

In the context of the overall thoughts to reduce the number of computers computer, one very important factor must not be left without research: An analysis on reliability is required.

In order to ensure practical usability and acceptance of the proposed changes, the author will in the following compare the availability of the typical “Do nothing and freeze approach” and the proposed “leverage technical advancement” scenario. As a reliability analysis of the overall spacecraft control ground segment result in too large complexity, focus of the reliability analysis will be on the most critical key component: The spacecraft control system. As outlined in the previous chapters before, one typically central and key number is the mean time between failure (MTBF).

5.6.1 Mean Time Between Failure

In case the finding in relation to this research question would indicate a negative impact on availability, the use of the approach would likely be dropped in practice as any kind of decrease of availability and could likely be considered not to outweigh the costs savings.

In order to determine the system availability of both approaches, an availability analysis on a small portion of a generalized, simplified model of a spacecraft ground segment mission control system, is undertaken. In order for such one to be meaningful, one first needs to understand the core functions of such one.

In the following graphic, a few central components of a spacecraft ground segment mission control system are described in an abstract way. As outlined in the previous chapters, one can expect a total number of approximately 600 servers to be operating within the data center of a larger scale mission or mission family, subject a non-migrated original setup. Servers in the following graphic are described only at a high level - several servers are grouped together in terms of the illustration.

Here, the elements presented in figure 26 will be described:

Spacecraft operators are operating the spacecraft control system via a set of **operator thin-clients** at different work positions. Typically, one work position consists of three screens. Per thin-client, depending on the hardware type, one to three screens can be connected. Depending on the mission size, the number of thin-clients can range from fifteen to seventy devices, driving up to seventy screens.

Within a normal setup, the thin-clients are connected to **thin-client servers** acting as connection brokers in order to establish a session to the system used via a network (Fogg, Keppenne, 2012).

The reason behind for choosing such a setup is a decoupling of the actual application from the access system, thereby allowing to flexibly replace the client device quickly e.g. in the case of a hardware failure.

The actual mission control system application then runs typically across **multiple mission control system servers**. Data created by and required for the mission control system is stored in **redundant databases**, containing also **parameter and file archives**.

Now, the Spacecraft Ground Segment Mission control system needs to be connected to the actual spacecraft. This is taking place via **ground station interface servers**, communicating with the mission control system servers in order to receive telemetry from the satellite(s) and send telecommands to the satellite(s).

Typically, these ground station interface servers are then connected further to a ground station network control system and **ground station communications network** which routes the relevant traffic to the required ground stations which then uplink the data to the spacecraft and downlink received data from the spacecraft.

In order to demonstrate the principle behind the proposed system changes without making the investigation utterly complicated, the analysis will be limited to a selected smaller part of the system described, outlined by the red box in the following figure.

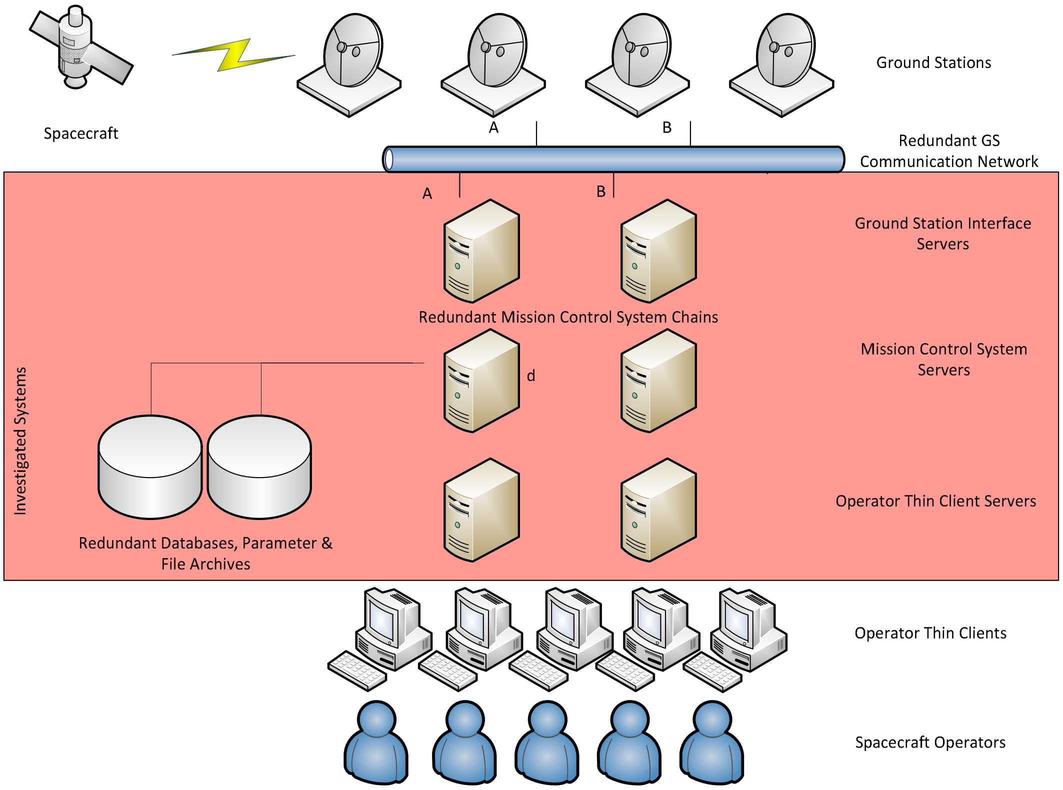

Figure 26 : Simplified spacecraft ground segment mission control system

As it can be seen, a dual redundancy in terms of IT systems is for seen. In terms of spacecraft operations terms, such a redundant setup of computing infrastructure is called a “chain”. In figure 26, one can see the existence of two “chains”. Each of these chains consists of several servers making use of computers connected in terms of availability calculations serially. Overall, the availability is then increased by parallel redundancy of these systems.

The aim is to reduce the number of components minimally possible. Should the outcome of the research be such that the author’s suggested approach is not able to meet the required availability level, one may consider to recalculate the availability in a less extreme scenario, recognizing however the found limitations of the approach. If the author’s approach however also meets the requirements on the proposed 9:1 scenario, then no limitations would need to be considered.

In the following, the author will undertake the actual MTBF calculation for the example described by figure 26. As one outlining precondition to our analysis, he assumes to undertake no changes on the software other than adding the abstraction enabling middleware together with the virtualization layer or hypervisor outlined in Figure 17. Through testing and practical results, it has been shown that actually adding a hypervisor does not decrease system reliability but through the additional monitoring functionality can actually be increased. Virtualization and hypervisors are currently very mature and are used world-wide in mission critical applications, therefore, the actual investigation is focusing on the system side.

In the following, the author breaks down the systems described in figure 26 into individual systems which consist each of pieces of equipment with individual MTBF figures and MTTR specifications.

The information on the actual MTBF of each equipment has been taken from manufacturers calculations undertaken for the specific equipment – in addition this data has been sanity checked with real-world operational data.

In order to calculate the actual overall availability however, as described in the previous chapter, a figure for MTTR is required. In this context of operational spacecraft infrastructure, typically there is a set of cold standby spares held on site for each system type. The availability of such spares actually allows ensuring a low MTTR of two hours on all systems used.

As the thin client system used which requires two components to be available for availability, this specific system is in particular driving availability to a lower level.

5.6.2 MTBF in a non-migrated without any enhancement steps as baseline

In order to calculate MTBF for any scenario, a MTBF diagram needs to be concluded in order to describe MTBF dependencies and to assist with building the calculation of the overall MTBF.

For a non-migrated scenario, such a diagram has been developed and can be found below.

This chapter describes the current state without any enhancement steps being taken and numbers presented here are only meant to be an inventory in order to use this as baseline.

From the diagram, it becomes clearly visible, that there are two sides to be involved here into MTBF calculations which are:

- Networks
- Systems

As both of these component groups are fundamentally different in terms of MTBF numbers and due to sharing the network infrastructure between all involved systems, is simplifies the analysis significantly.

On the left side of the diagram, network components used are described (e.g. switches). Out of a total of five networks, only two instances are shown in order to make the diagram more readable – the other three networks are identical in terms of MTBF.

Overall, in order to generate availability, all five networks need to be available. As a failure of a single piece of equipment would lead to unavailability, for each network component a redundant equivalent exists which takes over automatically should the primary equipment fail.

On the systems side, on the right side of the diagram, only one chain is shown. It becomes clear from the previous formula and theoretical background that such a setup is not really ideal, unless equipment would have an indefinite MTBF. For this reason, there is a second set of redundant systems used in order to increase reliability again. In the following, the MTBF for a single chain will be calculated first. Then, in order to undertake the relevant final redundancy calculation combining thesystems MTBF with the networks MTBF will follow; For this reason, MTBF calculation will be two-staged.

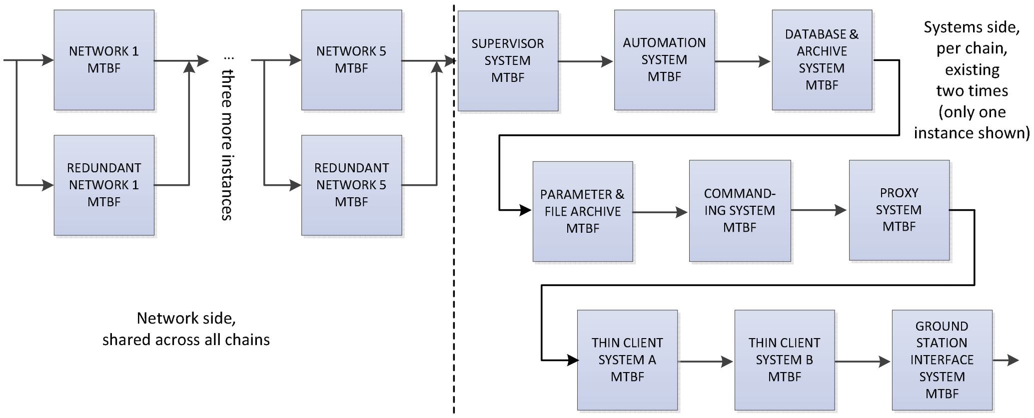

Figure 27 : Spacecraft ground segment mission control system reliability diagram as a non-migrated scenario

5.6.3 Network MTBF in a non-migrated scenario

It has to be noted that other than the pure system MTBF, one has to take also network switches into account in terms of MTBF calculations. Here in a traditional setup there are typically minimum 5 different network switches used – for reasons of requiring many connection ports which a single component cannot deliver as well as for reasons of requiring different networks to be physically separated.

Unfortunately, this requirement is also driving complexity in terms of the hardware side, but also in terms of causing the MTBF to be higher as all networks are required for the Spacecraft Ground Segment Mission Control System Element to be available.

The first calculation is undertaken in table 19, for the network scenario of five networks based on equal switches, each with redundancy. For reaching availability, at least one switch of each network must be available.

By making use of the MTBF Numbers in combination with the figure above on the arrangement of the individual components, it is possible to actually calculate the availability per each group of components in order to then undertake further calculations based on the serial connection of the networks in terms of reliability. As described previously in the theoretical chapters, serial connections decrease reliability. For this reason, already a redundancy is built in each group of components.

Component	Component count	Number of components required for availability	MTBF [h]	MTTR [h]	Availability (per component)
Network					
Redundant Network 1	2	1	384211	2	0,999994795
Redundant Network 2	2	1	384211	2	0,999994795
Redundant Network 3	2	1	384211	2	0,999994795
Redundant Network 4	2	1	384211	2	0,999994795
Redundant Network 5	2	1	384211	2	0,999994795

Table 19 : Network components used in a non-migrated scenario

By making use of the relevant applicable formulas, we get to the results outlined in the following table 20.

It also becomes clearly visible, that network components are not a large issue with regards to MTBF in terms of them not contributing largely to unreliability or decreased system availability.

Component	Total MTBF per group of components[h]	Availability (total per group of components)	Availability total in %	Downtime per year in seconds (per group of components)
Networks				
Redundant NW 1	73809046263	0,9999999999729030	99,99999999729030	0,000854531
Redundant NW 2	73809046263	0,9999999999729030	99,99999999729030	0,000854531
Redundant NW 3	73809046263	0,9999999999729030	99,99999999729030	0,000854531
Redundant NW 4	73809046263	0,9999999999729030	99,99999999729030	0,000854531
Redundant NW 5	73809046263	0,9999999999729030	99,99999999729030	0,000854531

Table 20 : Availability and downtime of network components used in a non-migrated scenario

By now serializing the individual groups of network components, we can then calculate the overall MTBF figures for the shared network used in a non-migrated scenario.

Overall MTBF (h) for Network	Average MTTR [h]	Overall total availability	Overall total availability for Network in %	Total downtime per year in seconds for network
14761809253	2	0,99999999986452	99,99999998645	0,004272647

Table 21 : Total availability and downtime for network in a non-migrated scenario

As it can be seen from the numbers in table 21, it becomes clear that network components do not contribute largely towards issues of unavailability. The overall downtime to be expected in terms of being caused by the network is around 4ms.

5.6.4 Systems MTBF in a non-migrated scenario

With regards to systems, we start once again from the previously described diagram at the systems side and from this actually then derive the relevant calculation in terms of calculating the reliability data for a single chain.

It should be noted that actually, all components within a chain are serially connected. While potentially it is possible to operate a satellite in emergency mode while not all systems are available, such operations will likely be unpredictable would be considered abnormal and therefore are considered also as a failure state or downtime.

Quite a few MTBF numbers used for the calculations are identical – this is due to the reason that actually the same base hardware systems are used. Typically, once items have been proven as to be reliable, within space operations, such items will then be re-used if the target purpose allows such.

Component	Component count	Number of components required for availability	MTBF [h] per unit	MTTR [h]	MTBF [h] total per system
TM/TC interface handling systems					
Ground Station Interface System	1	1	124392	2	124392
Mission control system servers					
Commanding system	1	1	124392	2	124392
Parameter Archive and File Archive system	1	1	118000	2	118000
Proxy system	1	1	124392	2	124392
Database and Archive system	1	1	118000	2	118000
Automation system	1	1	124392	2	124392
Supervisor system	1	1	124392	2	124392
User interface layer					
Thin client system	2	2	92000	1	46000

Table 22 : Central components used in a non-migrated scenario

Based on the MTBF and MTTR figures described in table 22, the availability can be calculated using the formulas described in the relevant chapter. The results of this availability calculation are shown in the following table. It should be noted that availability of 99,998% may seem high, however in terms of actual downtime, this still results in around 11 minutes of downtime which is not acceptable for example in life critical systems.

Component	Availability (individual)	Availability (total per group of components)	Availability total in %	Downtime per year in minutes (per group of components)
TM/TC interface handling systems				
Ground station interface system	0,999983922	0,999983922	99,99839221	8,4506
Mission control system servers				
Commanding system	0,999983922	0,999983922	99,99839221	8,4506
Parameter Archive and File Archive system	0,999983051	0,999983051	99,99830511	8,9083
Proxy system	0,999983922	0,999983922	99,99839221	8,4506
Database and Archive system	0,999983051	0,999983051	99,99830511	8,9083
Automation system	0,999983922	0,999983922	99,99839221	8,4506
Supervisor system	0,999983922	0,999983922	99,99839221	8,4506
User interface layer				
Thin client system	0,999978261	0,999956523	99,99565232	22,851

Table 23 : Availability and downtime of central components used in a non-migrated scenario

Using the results from the previous calculations, one can then calculate the overall systems availability per chain. The results of these calculations can be found in the following table.

Here, we see that actually one chain could be down on a time of average 96 minutes per year. As previously outlined, dual redundancy is used in order to lower this downtime to a more acceptable level.

Overall MTBF (h) per chain	Average MTTR [h]	Overall total availability per chain	Overall total availability per chain in %	Total downtime per year in minutes per chain
12676,88	2	0,999851019	99,98510195	78,304

Table 24 : Availability and downtime per chain in a non-migrated scenario

Following the previously outlined approach on availability of n identical systems in parallel with n being defined as two, we get to the following results in terms of availability.

Identical chains in parallel [n]	Chains required for operation [n]	MTBF over two chains [h]	Availability	Downtime per year in seconds
2	1	40175790,32	*0,999999950219*	1,56990

Table 25 : Total availability and downtime for systems in a non-migrated scenario

As one can see from this result, the actual downtime to be expected here is in the range of around one point six seconds per year.

Adding the network components now into this calculation, creates as final result the overall MTBF and availability of the sample simplified Spacecraft Ground Segment Mission Control System.

Network MTBF [h]	Systems MTBF [h]	Average MTTR [h]	Overall MBTF [h]	Overall total availability in %	Total downtime per year in seconds
14761809253	**40175790,32**	**2**	**40066744,53**	**99,999995008**	**1,57417**

Table 26 : Availability and downtime in a non-migrated scenario

In the further progress, it will reviewed, which effect the proposed changes will have in terms of reliability towards our original scenario.

5.6.5 Network Virtualization

Before going ahead and calculating the MTBF in a migrated scenario, it has to be noted that not only systems may be virtualized, but also network resources are affected; The network setup is significantly simplified.

In a traditional setup, there are typically minimum 5 different network switches used – for reasons of requiring many connection ports which a single component cannot deliver as well as for reasons of requiring different networks to be physically separated.

Unfortunately, this requirement is also driving complexity in terms of the hardware side. As one can see from the previous example, in terms of MTBF, the impact is minimal even all five different networks need to be available in order for the Spacecraft Ground Segment Mission Control System Element to be available.

Due to the fact that it is now possible to make use of virtualized networking within the virtualized system, significantly reducing external connectivity and in addition also making use of VLAN features, also the MTBF diagram is simplified.

The following figure describes the simplified setup more closely.

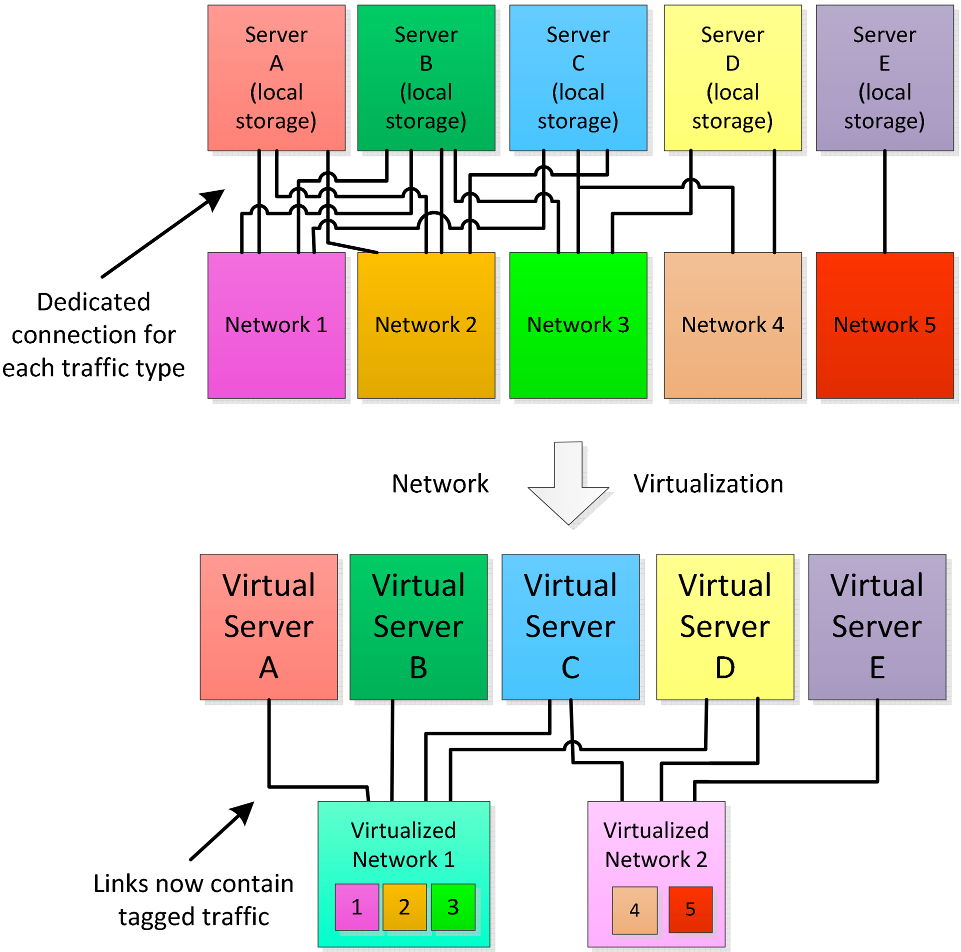

Figure 28 : Sample network virtualization on a spacecraft ground segment mission control system

One can only make use of network virtualization as this is a feature enabled by the virtualization layer, enabling virtual connectivity to be undertaken within the migrated system. Compared to the traditional setup, only two networks are required due to the use of VLAN tagging. VLAN tagging is a technology which enables network traffic to be distinguished based on a tag which is attached to every packet on a network level.

For security reasons, in the investigated on setup, two separate networks are maintained in order to ensure physical data separation.

Even the impact is small, it has to be noted that the due to simplification, network MTBF is expected to be increased simply by the reduction of the number of components required functioning in order to generate availability.

As typically, network components deployed in the past 5+ years are compatible to the IEEE 802.1Q standard (IEEE, 2012), actually not even a hardware change is required in terms of network switches. In fact, there are not even any load concerns as the setup we are proposing is reducing the external load on the network by keeping most of the required inter-system traffic within the virtualized system; only external traffic is required to pass via network infrastructure.

5.6.6 Overall MTBF in a migrated scenario

In the following, the author will develop actually a migrated scenario for the systems described previously, being standard components of a spacecraft ground segment control system.

On the network side, as previously described, VLAN tagging has been applied and has led to a setup with only two network segments, consisting each of a primary and a redundant system. While the impact on overall availability in terms of MTBF is not high, the impact on network MTBF is still significant.

On the systems side, we are now making use of a system consisting of a primary and secondary virtualization server along with a virtualized storage system. It should be noted that such a storage system is typically shared across multiple systems.

In the following, the same calculations are undertaken again, based on a simplified system, resulting from our proposed consolidation ratio per migration steps.

The following picture actually describes the entire remaining infrastructure in comparison to the previous diagram which had only one chain shown on the systems side. Actually, here it can be seen that the exactly proposed 9:1 ratio has been made use of in terms of systems consolidation ratio. Unfortunately however, in terms of storage, an external storage system has been added in terms of pragmatically keeping the system setup simple and adding even further features. Having system external storage allows to actually have even further flexibilities in terms of software, allowing for example also to access data of relevant systems while they are unavailable. The type of storage used here is a so called non-exclusive SAN storage which can be shared across further infrastructure. While it becomes clear that this slightly brings down the consolidation ratio of 9:1 on the power side, it should also be clear that this type of storage is strictly speaking not needed for the operation, but adding features in the context of a migration vs. absolutely maximizing saving is something which has to be upon when a migration step is undertaken.

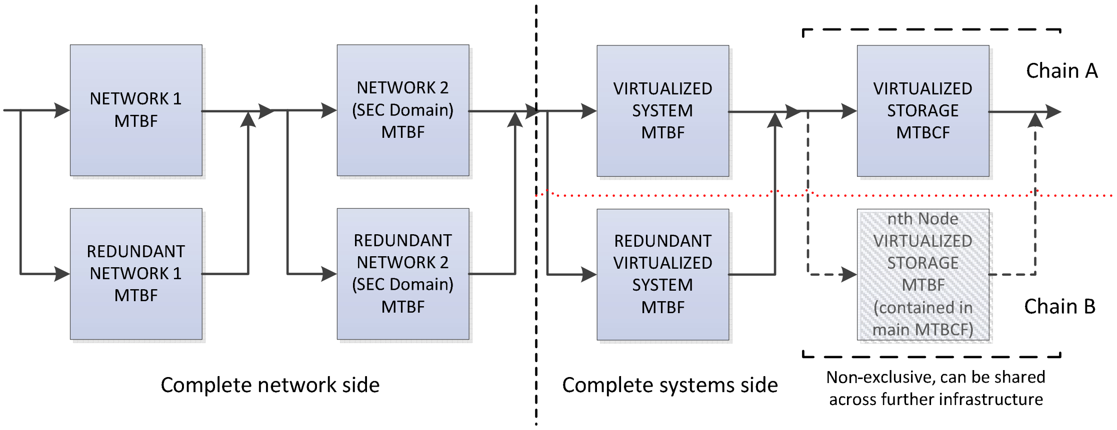

Figure 29 : Spacecraft ground segment mission control system reliability diagram as a migrated scenario

The following tables outline the network availability and MTBF in the simplified setup.

Component	Component count	Number of components required for availability	MTBF [h]	MTTR [h]	Availability (per component)
Network					
Redundant Network 1	2	1	384211	2	0,999994795
Redundant Network 2	2	1	384211	2	0,999994795

Table 27 : Network components used in a migrated scenario

Based on the two redundant components, the following can be calculated.

Component	Total MTBF per group of components[h]	Availability (total per group of components)	Availability total in %	Downtime per year in seconds (per group of components)
Networks				
Redundant NW 1	73809046263	0,9999999999729030	99,99999999729030	0,000854531
Redundant NW 2	73809046263	0,9999999999729030	99,99999999729030	0,000854531

Table 28 : Availability and downtime of network components used in a migrated scenario

By combining the relevant results of the individual redundant networks, we can calculate the overall availability and downtime as shown in the following table.

Overall MTBF (h) for Network	Average MTTR [h]	Overall total availability	Overall total availability on network in %	Total downtime per year in seconds for network [s]
36904523131	2	0,99999999994581	99.999999994581	0,001709058

Table 29 : Total availability and downtime for network in a migrated scenario

With regards to systems, calculations are going to make use of the following data.

Component	Component count	Number of components required for availability	MTBF [h] / MTBCF [h]	MTTR [h]
Virtualized System MTBF				
Virtual System	2	1	147926 [MTBF]	2
Virtual Storage System	1	1	133003430 [MTBCF]	2

Table 30 : Central components used in a migrated scenario

Within the migrated setup a separate virtualized data storage system is used. Within this system, MTBF has no direct relevance as due to the design of the storage system, failures are to be expected and handled accordingly:

As the virtual storage system is based on self-contained triple redundancy cluster, only the mean time between critical failures (MTBCF) is specified. Within such a storage system, regular data storage device (e.g. disk failure) is to be expected. As however, disks reside again within redundant disk sets (e.g. RAID6+ TP), disk replacement can take place while full system availability is guaranteed. In such a case, the MTTR is not relevant as the defect does not require the system to be down in order to be repaired.

Component	Availability (individual)	Availability (total per group of components)	Availability total in %	Downtime per year in seconds (per group of components)
Virtualized System				
Virtual System	0,9999864799	0,999999999634404	99,9999999634404	0,011529421
Virtual Storage System	MTBCF justification	0,999999984962794	99,9999984962794	0,474213326

Table 31 : Availability and downtime of central components used in a migrated scenario

By combining both components, one can calculate the overall MTBF for the migrated systems.

Total MTBF for systems [h]	Availability	Downtime per year in seconds
129846506,4	*0,9999999845972*	0,485742751

Table 32 : Total availability and downtime for systems in a migrated scenario

As one can see from this result, the actual downtime to be expected here is in the range of around zero point five seconds per year.

Adding the network components now into this calculation, we get to the following results as final result for the sample simplified Spacecraft Ground Segment Mission Control System in a migrated scenario.

Network MTBF [h]	Systems MTBF [h]	Average MTTR [h]	Overall MBTF [h]	Overall total availability in %	Total downtime per year in seconds
36904523131	**129846506**	**2**	**129391250**	**99,9999984543**	**0,4874518**

Table 33 : Availability and downtime in a migrated scenario

By putting the results found here in relation to the previous installation, the author can herewith confirm that his proposed setup meets the desired goal not to offer worse hardware reliability than the original scenario.

Scenario	Systems MTBF [h]	Overall total availability in %	Total downtime per year in seconds	Reliability in %
Non-migrated	**40175790**	**99,999995008**	**1,57417**	**100%**
Migrated	**129846506**	**99,9999984543**	**0,4874518**	**323%**
Delta	**89670716**		**1,0867**	**223%**

Table 34 : Overall availability and downtime comparison between both scenarios

Hereby, an answer to the research question three: “Is the availability of the systems negatively impacted by following the proposed “intelligent migration” approach? “ has been found.

As shown through the relevant calculations above, a possible increase of reliability through migrating the system to a more modern, virtualized platform of around 223% or a decrease of downtime per year by one second can be achieved.

As it has been shown, migrations can not only help to decrease cost, system size and hardware complexity, but can also help towards improving overall availability and increasing MTBF.

5.7 Application of results in the context of a real-world scenario: Power costs and space requirements during a runtime of 20 years

As a scenario of 20 years is investigated into, in order to calculate the power costs and space to be potentially to be saved, it is assumed that a migration step takes place every 5 years – a timeframe which usually can still be supported by using standard industry support contracts.

By applying of the previous research results, we can see the following scenarios to take place then.

Requirement	Migration step	Time in years	Measurement	m^2t [in months]	GWh
Do nothing and freeze approach					
Floor space	0	0-20	580 m^2	139200	-
Electrical power	0	0-20	431 kW	-	75,5112
Totals				139200	75,5112
Intelligent migration					
Floor space	0	0-5	580 m^2	34800	-
Electrical power	0	0-5	431 kW	-	18,8778
Floor space	1	5-10	102 m^2	6120	-
Electrical power	1	5-10	47,73 kW	-	2,0905
Floor space	2	10-15	18 m^2	1080	-
Electrical power	2	10-15	5,2868 kW	-	0,2316
Floor space	3	15-20	3,18 m^2	190,8	-
Electrical power	3	15-20	0,58547 kW	-	0,02564
Totals				42190,8	21,2256

Table 35 : Steps of requirement changes during the runtime

As savings in terms of electricity, one can see a total savings potential of ~54 GWh. In order to determine the potential electricity based cost savings, the author is basing the electricity cost forecast on the statistical forecast undertaken by the EU until 2050 (EU, 2013) with the granularity of five years. As base, price, the results of a study undertaken by the Fraunhofer ISI about electricity costs of energy intensive industries (ISI, 2015) has been used. As base price, in July 2015, 12,2 €/cents per kWh were used.

The following table 36 outlines the potential electricity, cost and carbon dioxide savings potential within a time frame of 20 years. Carbon dioxide savings are based on the assumption of a CO_2 generation of 0,55 kg / kWh as outlined by the German Federal Office for Environmental Protection.

Year	Migration step	Cost €/cents / kWh	Forecast (EU, 2013)	Electricity amount in GWh	Cost
2015-2020	0	12,2	100%	18,8778	2.303.092 €
2020-2025	0	13,054	107%	18,8778	2.464.308 €
2025-2030	0	12,688	104%	18,8778	2.395.215 €
2030-2035	0	11,712	96%	18,8778	2.210.968 €
Total electricity amount based on GWh (freeze)				75,5112	
Total Electricity cost: Freeze Scenario					9.373.583 €
Total Carbon Dioxide Emissions in t					41531
2015-2020	0	12,2	100%	18,8778	2.303.092 €
2020-2025	1	13,054	107%	2,090574	272.904 €
2025-2030	2	12,688	104%	0,231561	29.380 €
2030-2035	3	11,712	96%	0,025643	3.003 €
Total electricity amount based on GWh (migrate)				21,22558	
Total electricity cost: Migration Scenario					2.608.379 €
Total carbon dioxide Emissions in t					11674
Total Electricity savings potential					6.765.204 €
in % of cost					72,17
Total Carbon Dioxide savings potential in t					29857
in %					71,89

Table 36 : Calculation of electrical requirements, price development and total costs over a period of 20 years

Environmental aspect: In terms of other then purely financial aspects, the potential CO_2 savings correspond to 169456887 km driven by a car creating 176 g CO_2 per km or to one year of usage of 16946 cars, driving 10000 km each.

Based on these findings, it is now possible to answer research question four: **RQ4: How much energy and CO_2 emission caused by energy usage can be saved and when following an upgrade interval of e.g. 5 years during a mission lifetime of 20 years?**

According to the sample calculations undertaken, one can save up to 71,89% of the primary energy and thereby also the relevant equivalent of CO_2 emissions.

5.8 Building usage vs. write-off time

In typical operational scenarios, the requirement for equipment to be installed can increase through several factors. Such factors can be for example the increase in terms of numbers of to-be-supported missions, additional spacecraft, the requirement of a larger data archiving facility, a larger data analysis center or other factors.

In general, it the requirement for more data center space is existing in most spacecraft operations control centers in Europe. For example the European Space Agency in Darmstadt (Germany) has increased their data center floor space significantly in the past years. EUMETSAT in Darmstadt as well as the Galileo Control Center in Oberpfaffenhofen (also Germany) have constructed entirely new data center buildings, in order to be able to install all required equipment.

Coming back to the author’s previous spacecraft operations example, and the further assumption of a complete usage of the freed-up space being possible after each migration step (or in fact, avoiding the construction of new facilities due to re-use of existing space), one can determine the actual cost-savings based on freed space.

According to the German tax situation, data center buildings are usually written off within a time period of 25 years; 4% of the building costs are depreciated per year.

Based on this definition, per square-meter, a total usage timeframe of 300 months is reached.

Based on these developments, and assuming the immediate re-use of existing to-be-freed facilities, the author now undertakes the relevant cost saving calculation. By using the model outlined by Turner / Seader, one is reaching a base-cost of 8 USD per m^2 per month of usage. In addition as outlined by this specific model, also the electrical load must be considered. In the author’s application scenario, as outlined earlier, an average electrical load of ~ 743 W / m^2 is being made use of.

As a result from this power usage, it is required to add toto the simple floor space cost, a cost of 16348 USD / m^2 over a duration of 25 years, resulting in 54,49 USD / month in addition.

With this specific power density, the result is a total cost of 62,49 USD per m^2 per month which can be re-gained.

As previously found, a scenario making use of the “Do nothing and freeze approach”, the total is reaching 139200 m^2 months.

m^{2}t	Cost m^{2}t (load factor 743W/m^2)	Total USD
Do nothing and freeze approach		
139200	62,49 USD	8699200
Intelligent migration		
42190,8	62,49 USD	2636683
Delta		
97009,2	62,49 USD	6062105
In percent		
Total savings potential with regards to floor space		69,7%

Table 37 : Calculation of cost savings with regards to freed-up floor space

As it can be seen from the calculation above, also with regards to the building write-off time, very significant savings can be generated by following an intelligent migration approach.

As a rough estimate from our previous calculation of the data center costruction cost to be estimated in the range of 10,874 M€, one could conclude to be able to save 7,58 M€ - however, this can never be applicable unless the freed space is required for re-use at exactly the time of a proposed migration.

In the relevant publication “Dollars per kW plus dollars per square foot […]” (Turner, Seader, 2006) it is outlined that there are more assumptions included in the model and that calculated numbers may only be accurate by ~+-30%. However, as we are only investigating into one factor – the factor building cost / floor space cost and savings from electricity savings are in addition to the floor space savings, such is considered to be accurate enough in the overall picture.

Savings in terms of floor-space are an additional gain on top of the gained electricity savings.

5.9 Replacement cost vs. cost savings

As described in Chapter 6.3, after 5 years, approximately only 11% of the original equipment is required in order to deliver the same performance figures as per the initial purchase.

By using the previous example again, one can with little additional input data undertake the following estimations:

As having found previously in, the total power consumption is 431 kW. Not all of this energy is available however to the equipment. In fact, unless newly built, most space operations data centers investigated have shown a PUE of approximately 2.0 which is only slightly better than European average of 2.5 (ResearchTrust, 2012).

Based on this information, approximately 215.5 kW of electrical power are available to equipment. As further input, in a sample space operations lab setup, approximately 78% of the electrical load has been generated through servers, while the rest of the consumption was created by network equipment as well as disk arrays.

Following this logic, approximately 168 kW are generated directly by servers.

As average load, in the lab setup, we have measured 238 W of power usage at an average 50% CPU usage per representative server used here (Idle: 143W, max: 332W).

Based on these figures, one would expect to find around 705 servers with each two CPUs to be operational at the same time. Unfortunately, reality is a little more complicated here: Overall, there are 804 servers deployed in the operational scenario.

This is due to the fact that there are not always two-CPU machines deployed, but also single CPU machines. In this context, the relevant power figures are a little different: At 50% CPU load, according to individual measurements comparable to the lab setup such machines consume 145 W (Idle: 99W, max: 191W).

Out of these 804 servers, 552 servers were two-CPU machines and 252 servers were one-CPU machines.

Overall however, the single CPU machine count has a minor effect; the total repurchase or upgrade cost in case of a 1:1 re-deployment would be slightly increased.

This is simply due to the fact that the same CPU count to be reached with single-CPU machines requires more base chassis which increases the price significantly.

In our scenario, this is however even an advantage which can be used to create even greater cost savings: As it is being proposed to upgrade to a scenario which is has efficiency optimized, one can always use the maximum CPU density in each server.

In the scenario investigated into, the initial average purchase cost of each dual CPU server was 4738 EUR and 3835 EUR per single CPU server.

Amount	Cost per Server	Total per Position
552 pcs Dual-CPU server	4738 EUR	2.615.376 EUR
252 pcs Single-CPU server	3835 EUR	966.420 EUR
Initial hardware purchase cost (ex. labor, installation)		3.581.796 EUR

Table 38 : Initial purchase cost

Based on the previous findings on power efficiency increase, in the first migration step in an optimized scenario with only two CPU machines replacing the single CPU machines by making use of a virtual platform, the following projected costs could be seen to occur.

With regards to server re-purchase pricing, the same price as the initial procurement price plus predicted inflation is used Own research covering the past 10 years shows, server purchase prices to be approximately the same if comparing current state-of-the-art machines to prices of past state-of-the-art machines.

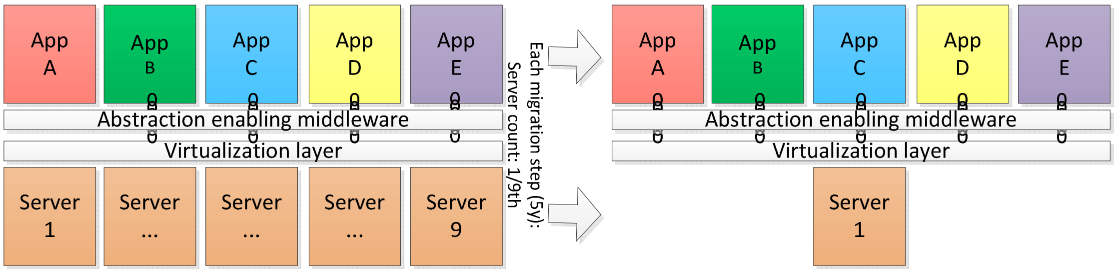

Figure 30 : Visualization of migration step 1

Based on the previous findings, the following table contains the expected hardware re-purchase cost for migration step 1.

Amount	Cost per Server	Total per Position
78 pcs Dual-CPU server	4738 EUR	369.564 EUR
Hardware re-purchase cost (ex. labor, installation)		369.564 EUR

Table 39 : Migration step 1 hardware purchase cost

While real-world costs for replacement and migration are not only including pure hardware costs, one can assume these to be the biggest contributor to costs, based to the preconditions on enablement of transferability outlined. The author estimates the upgrade, integration and migration costs to be maximum 50% in addition to the to-be-replaced hardware costs, once the proposed combined intelligent migration approach is followed. This is mainly due to almost no software changes required as running software is abstracted from the hardware already.

Due to the author’s suggested approach introducing a hypervisor at this point, one would also need to consider the cost for this additional hypervisor licensing at this point.

While quite a few the basic hypervisors like KVM, XEN or pure ESXi are cost free, if additional functionality like an enterprise class management layer would be desired, such one would only be available at additional cost. Typical cost for such functionality is in the range of (2017) of ~1800 EUR per Dual-CPU server. Clearly, such additional functionality is as additional feature not really part of the author’s comparison exercise and therefore excluded from cost estimation.

Based on this assumption, replacement costs are estimated to reach a total of ~ 552 k€ or a total of approximately 15,4% of the cost is to be generated by a migration in comparison to the original cost.

Hypothesis 2: By re-investing a significantly smaller, to be found percentage, in comparison to original IT budget, after a typical duration of an IT industry equipment lifecycle (e.g. 5 years), IT infrastructure with the same or better performance and with a significantly higher energy efficiency can be purchased.

Herewith, hypothesis two can be confirmed to be met at below 20% of the original purchase cost.

5.10 Main finding

In the model example of a data center with operational time of twenty years, simply via the generated power savings, a cost saving of 2,2 M€ is generated over a period of five years within years five to ten.

The following table illustrates the base data gathered from the previous calculation model:

Year	No migration [k€]	One migration [k€]	Two migrations [k€]
2015	461	461	461
2016	921	921	921
2017	1382	1382	1382
2018	1842	1842	1842
2019	2303	2303	2303
2020	2796	2796	2796
5Y Δ	N/A	N/A	N/A
2021	3289	2851	2851
2022	3782	2905	2905
2023	4275	2960	2960
2024	4767	3014	3014
2025	5246	3067	3067
10Y Δ	N/A	**2179**	N/A
2026	5725	3120	3073
2027	6205	3173	3079
2028	6684	3226	3085
2029	7163	3280	3091
2030	7605	3328	3096
15Y Δ	N/A	**4277**	**4509**
2031	8047	3377	3097
2032	8489	3426	3097
2033	8931	3475	3098
2034	9374	3524	3099
2035	9816	3573	3099
20Y Δ	N/A	**6243**	**6717**

Table 40 : Accumulated electricity cost in the view of different scenarios

As one can see from this calculation, the required reinvestment cost is only a quarter of the gained savings – break even is reached rather quickly, leaving ~€ 1.65 M available as pure savings on electricity.

Even if no further migration steps would be undertaken, on electricity alone, during the entire runtime, a total saving of approximately € 5.8 M is projected to occur.

Based on this research outcome, research question number two can be answered:

RQ2: Does it pay off, within the context of some typical missions and with respect to previously defined criteria, to actually undertake the effort in order to migrate IT infrastructure in comparison to the "freeze and do nothing" approach?

From the author's perspective and by financial means, it absolutely pays off to undertake the effort to migrate the IT infrastructure.

Figure 31 illustrates the accumulated electricity cost based on three scenarios:

No migration undertaken ("Frozen state"), one migration taking place after 5 years and two migrations taking place (each after 5 years).

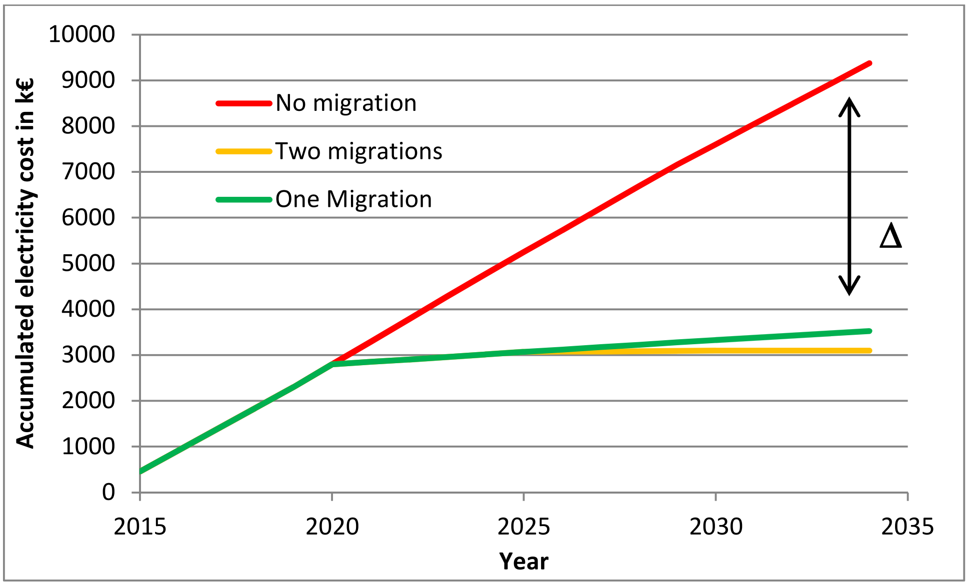

Figure 31 : Accumulated electricity cost in three scenarios:

No migration, one migration after 5 years, two migrations each after 5 years

From the diagram, also the first research question can be answered:

RQ1: What does the exponential development in IT resources mean economically for long-term IT operations with fixed requirements?

As it can be seen from the diagram, it becomes evident that the first migration has the biggest cost savings impact. While there is a further savings potential of approximately further 500k€ implied by a second migration, biggest cost accumulation is avoided by undertaking the first migration step. This outcome is simply based on the fact of a continuous fixed power consumption being linear function while actually the technological development on CPUs in terms of power consumption per calculation creates an logarithmic decline in power requirement.

Whether a second migration step actually makes sense should be decided closer to the point of migration and up to a decision based on a financial background but also up to another detailed reliability and risk assessment.

When in addition also considering the investment cost required as a purchase undertaken from 2020 to 2021 and 2025 to 2026 respectively, the following figure 32 outlines the results.

As it can be seen from the following figure, only in the year of re-purchase, the overall result is minimally negative (~114k€). Immediately in the following year, the overall balance is reached again and the actual savings start to outweigh the investment costs.

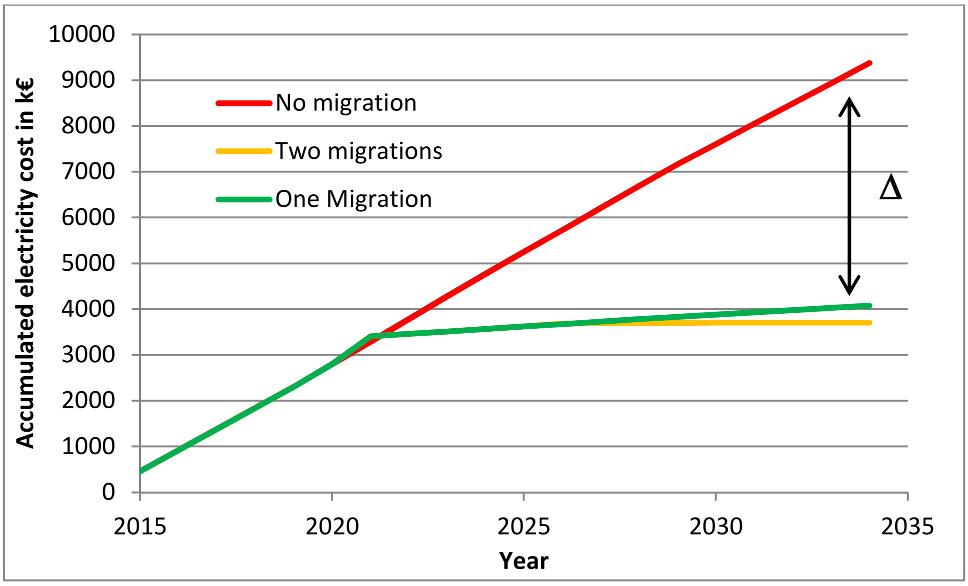

Figure 32 : Net cost savings, accumulated electricity cost in three scenarios plus investment cost:

No migration, one migration after 5 years, two migrations each after 5 years

As a summary of the previous findings, also Hypothesis one can now be verified.

Hypothesis 1: It is possible in a long-term operational IT scenario, to lower IT costs in a self-paying way without decreasing reliability.

As previously described, this hypothesis is two-fold: Cost savings shall be self-paying during the duration of the reviewed scenario, so there is actually a return on investment of the steps undertaken within reasonable time. As one can see from the figure 32 the delta between the accumulated costs in a frozen scenario and in a scenario where migrations are undertaken provides a return on investment within approximately 14 months.

With regards to reliability, conclusions have been drawn in chapter 5.6.6, it has been demonstrated that reliability can actually be increased to 223% by proposed changes.

Through these findings, hypothesis one can also be confirmed.

6 DISCUSSION

In long-term space missions or other complex, mission critical IT undertakings, lasting 10+ years, there is a clear disproportion between the mission requirements and the technological development on the IT market.

Clearly, while this dissertation focuses on spacecraft operations scenarios, one can transfer the findings to other areas of applicability. Precondition for transferring the demonstrated approach one to one is the reviewed IT undertaking to be complex (e.g. 100+ computers), as well as having the requirement of operating for a long time-frame of e.g 10+ years.

If another scenario than the mentioned one is reviewed and the undertaking reviewed is not complex (e.g. tens of computers, not hundreds) then still the same principles may be applied, but limitations of reducing the computer count may be hit earlier as no further reduction of computers could be possible due to having the need to keep redundancy concepts established.

In case availability is not critical, still the same principles apply, however reliability may not be of such a high concern.

While in the presented complex and mission critical spacecraft operations case, typically performance and platform requirements are more or less fixed ahead of a mission, IT computing performance advances exponentially during the anticipated operational lifetime.

During such a typically long timeframe of operational use, literature reviews show, that there is not only an exponential drop in price per computation, but it has been found, in addition to memory prices measured in cost per MB, computer hardware prices in terms of performance per cost are also dropping exponentially. Here, coefficients have been determined, allowing to predicting technological development for the future, based on long-term historical data; these coefficients can be used in order to predict the number of transistors per processor, calculations per power and price per unit of memory.

With regards to efficiency gains in terms energy required per calculation of actual computing equipment from the commercial market, during further research, the author was able to reproduce the theoretical findings and confirm such with a rather low margin of error.

While undertaking research, it became evident that data center efficiency is also playing a role in this context – and was looked into. Other than describing and suggesting improvements to applicable and most common methods for measuring data center efficiency, the author has undertaken an evaluation in terms of power usage efficiency of the lab setup which was used to practically confirm theoretical results. It however became clear that while data center efficiency is desired to be as high as possible; such one has clear limits which are easily out weighted by the development of power efficiency of processors themselves, especially during long timeframes envisaged.

For this reason, the most important factor having been found is to make use of efficiency gains of newer computer processor generations. Unfortunately, practically almost no missions make use of this potential during their lifetime. If long-term, complex IT undertakings like in our example space missions were able to follow these performance improvements of IT, significant savings with regards to power consumption would be possible.

While financial savings in terms of electricity may be the primary objective, automatically, a reduction of greenhouse gasses output based on the lowered energy consumptions is resulting. Through EPA provided data, it has been found that emissions created by the generation of electrical power are terms of greenhouse gasses in the range of 99% based on CO_2. For this reason, CO_2 needs to be considered as the most important environmental indicator and lowering of its emissions is a goal to be aimed for. Such reduced CO_2 emissions are definitely a gain for the protection of the environment.

In addition to these primary financial savings, also during the progress of a mission, significant savings with regards to data center space would be possible which could allow secondary financial savings. Such ones can be realized in particular at shared IT operations centres like for example shared spacecraft control centers. In such a scenario, through the when-available re-use of re-gained data center space, it might even be possible to avoid the construction of entire facilities, once steps like migrations to follow the progress of IT had been taken.

Due to not knowing how much demand for data center space exists at the time of freeing space (e.g. other undertakings like for example other space missions), only numbers in terms of m^2t are presented which lead to an order of magnitude to be in the range of $\sim$ 69% during the reviewed timeframe of the tax based write-off period of 25 years. Further research in this area could be undertaken, based on other specific examples of applicability.

In order to actually enable the possibility of such cost, floor space and CO_2 savings, based on our analysis of the factors involved, we are proposing an approach, allowing the use of advancements in IT technology during mission lifetime.

If the suggested approach is followed straight from the beginning of a space mission, complicated migration steps can not only be avoided, but cost savings are becoming embedded into IT infrastructure planning.

While the suggested approach implies changes towards an existing infrastructure, one further finding has been that it is important to evaluate changes with regards to their influence on availability of the system. In the specific case researched into, due to the criticality of the infrastructure analysed upon, no changes would be acceptable which would lower the availability.

With regards to the technical approach, the author is suggesting utilizing systems virtualization on all levels as the main driver.

By using virtualization along with a middle layer, one decouples the operational software from the underlying infrastructure, thereby facilitating migration strategies that keep infrastructure in line with general IT improvements.

As other result from the recommended virtualization exercise, one should also consider implementing network virtualization as such one can also significantly simplify the technical setup, thereby resulting again in cost savings.

On the financial side, are now able quantify the potential benefits of the technical improvements occurring during a typical mission lifetime.

By making use of the outcome of this initial research and applying it to a typical mission operations scenario, the author shows the potential cost savings in a real-existing configuration.

In order to apply these findings to a real-existing configuration, the author has researched on three larger programme size sample missions / groups of satellites with an operational duration of 15-20 years. His findings here have been that with only a single migration after 5 years of mission runtime, electricity costs can already be reduced by approximately 67%.

Even further, based on research undertaken, hypothesis can be confirmed to be true:

Hypothesis 1: It is possible in a long-term operational IT scenario, to lower IT costs in a self-paying way without decreasing reliability.

In order to create acceptance with decision makers, for a suggested solution to be successful, at least any proposed approach recommended would need to at minimum paying for itself (self-paying concept). Findings however, even when considering migration costs, provide more than enough evidence that in case of the scenario looked at is being long enough, costs cannot be only lowered in a self-paying way but can provide a quick return on investment. Break-even will be reached rather quickly and from this point in time onwards, significant real savings will be generated.

During further research, hypothesis could also be confirmed to be true:

Hypothesis 2: By re-investing a significantly smaller, to be found percentage, in comparison to original IT budget, after a typical duration of an IT industry equipment lifecycle (e.g. 5 years), IT infrastructure with the same or better performance and with a significantly higher energy efficiency can be purchased.

While it has been found that it is possible at a percentage of below 20% of the original purchase price to re-purchase and implement a replacement infrastructure after 5 years of use, it was also possible to demonstrate that at least the original performance at a much better computational efficiency in terms of units of energy per calculation can be reached this way. In the further it was as well demonstrated that relevant and required changes to IT systems are possible without actually compromising availability but merely also actually improving the mean time between failures.

During the progress of this thesis, several papers were presented at scientific space and other conferences. These were perceived to be very helpful, by different representatives of international space agencies, in finding a strategy towards the achievement of significant cost reduction in space operations.

Beyond the use within the space domain, the found principles can be applied to also a wider other range of applications which have similar scenarios. In future it is for example to be expected that wider scale of public life like for example aircraft control, traffic flow and monitoring systems, public water and power supply and others will make use of even more information systems which have to be operated long term and if concentrated in fewer places can also create a complex infrastructure. Re-applying the found approach to such scenarios can also help to reduce costs here significantly.

7 CONCLUSION

As it has been demonstrated, any approach operating computers beyond the time-frame of five years should be subject to an economical review. In any larger computing environments with an operating period beyond five years, there is a more than clear possibility for realizing cost savings created through the increase in computational efficiency through technological advancement by the means of planned system migrations. Such technological advancement can be used to leverage costs in multiple directions.

In the scenarios described, it was demonstrated that potential electricity savings can easily reach the range of millions of EUR based on the shown examples of larger space missions. In our sample, such savings amounted to 5,8 MEUR for one infrastructure migration and to 6,3 MEUR for two infrastructure migrations within the a time-frame of 20 years.

While the exact amount of savings depends on the specific scenario, overall computer count and also on the specific migration costs, clearly a high enough systems count larger than for example fifty systems and timeframe of seven or more years, savings become significant. In the researched scenario it has been shown that after five years, the same performance of computing equipment can be achieved with ~11% of the original equipment size and at also only around 15% of the original cost.

In addition to direct savings by more energy efficient machines, savings can also be realized by the avoidance for the need of cooling. Even in case IT infrastructure is state of the art and rather energy efficient with a power usage efficiency as low as ~ 1,3, as the used lab setup had, such a scenario still uses approximately 30% of the electricity required for cooling IT infrastructure.

Typically, while also not being common in practice, unless cogeneration concepts like combined heat and power systems or trigeneration concepts like combined cooling, heat and power systems are used, energy consumed by computers and air condition is released into the environment as thermal energy and is also economically lost; again a very strong indicator to lower power consumption of computing equipment.

Once the computer electricity usage is lowered, also air condition power consumption will lower proportionally – again an indicator how important it is to pay close attention to operating computer systems providing a high efficiency in terms of computations per unit of energy (e.g. floating point operations per watt of energy usage).

As it has been identified, in terms of environmental factors, CO_2 should be used as the most important environmental indicator. In addition to pure financial savings, also the CO_2 output generated through the power consumed by computing infrastructure can be drastically reduced – in the given example up to 72%.

Main cost savings resulting from technological advancement can be gained through savings on electricity and thereby on direct operating costs. Even though electricity may be the most directly noticeable factor, very high savings may be gained also be gained by the re-use of existing data center floor space which freed after each of the suggested migration steps. Even calculated within this thesis in terms of costs, calculating such savings into the final savings calculation was on purpose not undertaken due to the reason such cost savings can only be realized in case there is a requirement for additional space available – a fact which is up to the individual case and cannot be predicted. Nevertheless, potential for cost savings can also be large here in case – in the reviewed example, in an ideal case 7,58 MEUR, could be saved. Gained space savings can also in certain circumstances avoid the construction of entire new facilities.

If the described approach is chosen, in order to enable such savings, the required migration enabling measures should be planned in as early as possible as such advance planning significantly lowers effort for the required migration steps to be implemented.

While cost savings are the goal to be reached, there are a few side-conditions which can help to make migration steps planned as easy as possible and to increase user and decision maker acceptance:

One of these side conditions is to as far as possible decouple software and hardware in order to enable the portability of software from one platform to the other as well to enable the possibility of consolidation on more energy efficient platforms. Such decoupling can be achieved by using technologies such as virtualization or container technologies – ideally in order to maximize savings starting with initial planning in theory and in terms of practical procurement starting with the initial purchase.

Another side condition is to keep the availability and the mean time between failures of systems at least at the level of the initial, non-migrated design. As it has been demonstrated, to reach such at least equivalent availability and mean time between failures is an exercise of the right system design, a goal which can be reached by appropriately structuring a replacement design. In our example calculation, it was possible could demonstrate the possibility of increasing system reliability after a migration to 223% - a fact which by itself should be a reason to consider replacing technologically out dated equipment.

Overall, the author hopes to influence the mindset of decision makers on long-term operating IT infrastructure in a way to make them consider actual planned IT infrastructure replacement not as a to be ideally avoidable cost or inconvenient task to follow, but rather to see such as a possibility to both achieve economical savings but also as a step towards a more modern infrastructure eventually coming at no additional cost and also protecting the environment.

While this dissertation has mainly focused on energy as well as data center space savings as the largest cost contributor in this specific context, it is likely that also other costs arising it the context of long-term complex IT operations like for example labour or cost of hardware itself could be lowered. Details on such cost savings could be subject to further research in this area.

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9.1 End of Dissertation