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Pervasive Computing & COMmunications

for sustainable Development

Vitalii Poliakov

Green ICT metrics and Biomimicry

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Supervisor(s) : prof. Eric Rondeau (University of Lorraine)

Examiners: *Eric Rondeau, prof.* (University of Lorraine)
Jari Porras, prof. (Lappeenranta University of Technology)
Karl Andersson, assoc. prof. (Luleå University of Technology)

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ABSTRACT

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Context: Sustainability issue of ICT have gathered attention in recent years, and researchers are working on this problem. Sustainability incorporates numerous interconnected aspects as well as methods to achieve it in ICT, so it is quite complicated to have a general view on a problem without a proper framework. However, a general methodology for such a research is missing. In this thesis work it is proposed to use Biomimicry approach as a framework for sustainability research and development, as it introduces systematics and also forces to account sustainable aspects. Additionally, an interesting problem of green network measurements for enhancing sustainability in ICT will be researched using mentioned approach. **Goal:** to investigate Biomimicry as a systemic approach for developing sustainable systems, as well as to apply it in green network measurements study. **Method:** comparative study is performed for examining Biomimicry approach, as well as a use case of green network measurements research is presented. **Results:** green network measurement can potentially improve sustainability, but only to a limited extent as it cannot incorporate all the aspects; within Biomimicry approach, two methodologies exist. **Conclusions:** Biomimicry is a good framework for developing sustainable systems, nevertheless, another methodology has to be introduced within it; new methodology has to incorporate advantages of two existing ones.

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Oddly, producing this thesis report was the hardest task for me among all of the activities in PERCCOM. The research is quite new, so many tries and fails were done before the present goal was defined.

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I was not alone here, in Nancy, during this last semester; Mohaimen, Alifia, Ramya, Chandra and Iqbal were supporting each other on our way to finishing the report, as well as organizing amusement on day-offs.

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Нельзя обойти вниманием мою прекрасную семью – мои бабушка, мама, папа, а также брат с сестрой, которые поддерживали меня на протяжении всего времени.

Нужно также поблагодарить мою любимую Карину за ту поразительную энергию, которой она меня наделяет и благодаря которой я смог в конце концов закончить этот текст.

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Vitalii Poliakov, July 2015

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List of abbreviations

CPU	Central processing unit
CUE	Carbon usage effectiveness
DC	Data center
DCeP	Data center energy productivity
DCiE	Data center infrastructure efficiency
DCP	Data center productivity
EDE	Electronics disposal efficiency
EPA	Environmental protection agency
ERE	Energy reuse effectiveness
ERF	Energy reuse factor
FTS/FTW	Follow the sun / follow the wind
GEC	Green energy coefficient
GHG	Greenhouse gas
ICT	Information and communications technology
IEEE	Institute of Electrical and Electronics Engineers
IS	Information system
IT	Information technology
KPI	Key performance indicator
LCA	Life cycle assessment
PERCCOM	Pervasive computing and communications for sustainable development
PUE	Power usage effectiveness
QoS	Quality of service
RoHS	Restriction of Hazardous Substances
SDN	Software-defined network
TCO	(swedish) Tjänstemännens Centralorganisation
VM	Virtual machine
WEEE	Waste Electrical and Electronic Equipment
WUE	Water usage effectiveness

Section 1 Introduction

1.1 Origins of sustainable ICT

The issues of sustainability and ecological impact in enterprises have been omitted in studies for decades since industrial revolution in Great Britain in XVIII century. Time passing, air and land pollution started to be quite vivid. Large cities suffered from a number of new atmospheric phenomena (for example, fogs and acid rains), additionally, quite a number of important resources has been confirmed to be in scarce. Due to problems mentioned, industries and independent organizations started to work on decreasing the environmental impact of production facilities.

In the field of information technologies, which are commonly abbreviated as IT, first serious and practical actions on improving the sustainability have started in early 1990's. Mostly, vendors and researchers were working on energy efficiency in microelectronics. It is quite clear that the primary reason for that were attempts to decrease power dissipation and consumption of microprocessors and other parts with parallel increasing the transistor number (which was still behaving according to the Moore's law (Bondyopadhyay 1998, 78-81). Indeed, lower power consumption was in a way a response to the sustainability issue, but mostly this effect was visible by the consumers – battery times of their laptops and heat at their laps.

In microelectronics, not all the advancement in power consumption enhancing is taking place in the hardware field. Software is also important, as it is actually controlling everything, and this aspect should also be taken into account. For instance, just recently the patch has been proposed to the linux kernel (Anonymous 2015b), which is fixing sleep state management for Serial ATA, and this fix introduces around 40% power consumption savings for Intel Hasswell and Broadwell series CPUs.

Later, attempts were taken for decreasing energy consumption in IT pieces (such as displays, printers, and so on). In this way, Energy Star initiative started in 1992 (Anonymous) and was the first one in that field. The interesting thing about it was its devotion to decreasing the greenhouse gases, which is step ahead from purely consumer-driven efficiency improving. Of course, consumers were mostly aware by quite visible energy usage reductions, which, according to (Tugend 2008), can take "... 20 to 30 percent less energy than required by federal standards".

Reports from Environmental Protection Agency (for instance, of 2013 (Anonymous 2013b)) indicate, that cumulative greenhouse gases (GHG) reductions due to solely Energy Star initiative from its beginning are equal to 2197.6 million metric tons of carbon dioxide equivalent (MMtCO2eq). Such savings are quite significant; the same source provides dynamics of GHG emissions by years indicating that in 2013 alone the figure was above 290 MMtCO2eq. For comparison, statistics tell that United Kingdom's total GHG emission in the same 2013 year were equal to 568.3 MMtCO2eq. As the reader can see, the total worldwide GHG emissions reduction induced by the Energy Star constitute more than a half of the same figure for an average highly-developed country.

However, the numbers provided by Energy Star seem not to be very trustful. In 2014, Environmental Protection Agency (EPA) have published a report (Adams, Besch-Turner, and Caroll 2008; Anonymous 2010) which tells that not all the sources used by Energy Star to determine GHG emission reductions are reliable, and their model for that needs validation as well. Note, that the official web-site of Energy Star has a repository of annual reports, and the last report is devoted to 2013 – which might not be clearly related to the EPA report, indeed.

Apart from the Energy Star initiative for IT pieces, the TCO certification initiative also exist. The difference between those two, however, is quite serious, and TCO tries to address much more aspects of green IT and sustainability in this field.

The actions mentioned were only dealing with energy consumption in microelectronics and standalone IT equipment. While this field, of course, required much of attention, no significant studies or researches were commenced in the field of ICT. From one point of view, the reason was quite clear – energy, consumed by the communication lines seems insignificant, and the consumption of the routing and switching hardware is mostly driven by the studies in microelectronics. This approach has some underpinning – during the semester 1 of PERCCOM it was identified on one of the courses that, for instance, single 100BASE-T Ethernet port consumes not more than0.1 W, while one Cisco 3560v2 24-port Ethernet switch without any incident connection takes35 W. According to these numbers, it is clear that the first attention needs to be directed to the hardware.

This way of thinking was nearly-acceptable in past times, when network scales were smaller. But today, broadband Internet connection is widely available in developed countries, and is starting its invasion into less developed countries. According to (Kemp 2015), the number of current Internet users in the world are estimated at more than 3 billion. Meanwhile, the growth of Internet users regardless the connection type are described by the following picture:

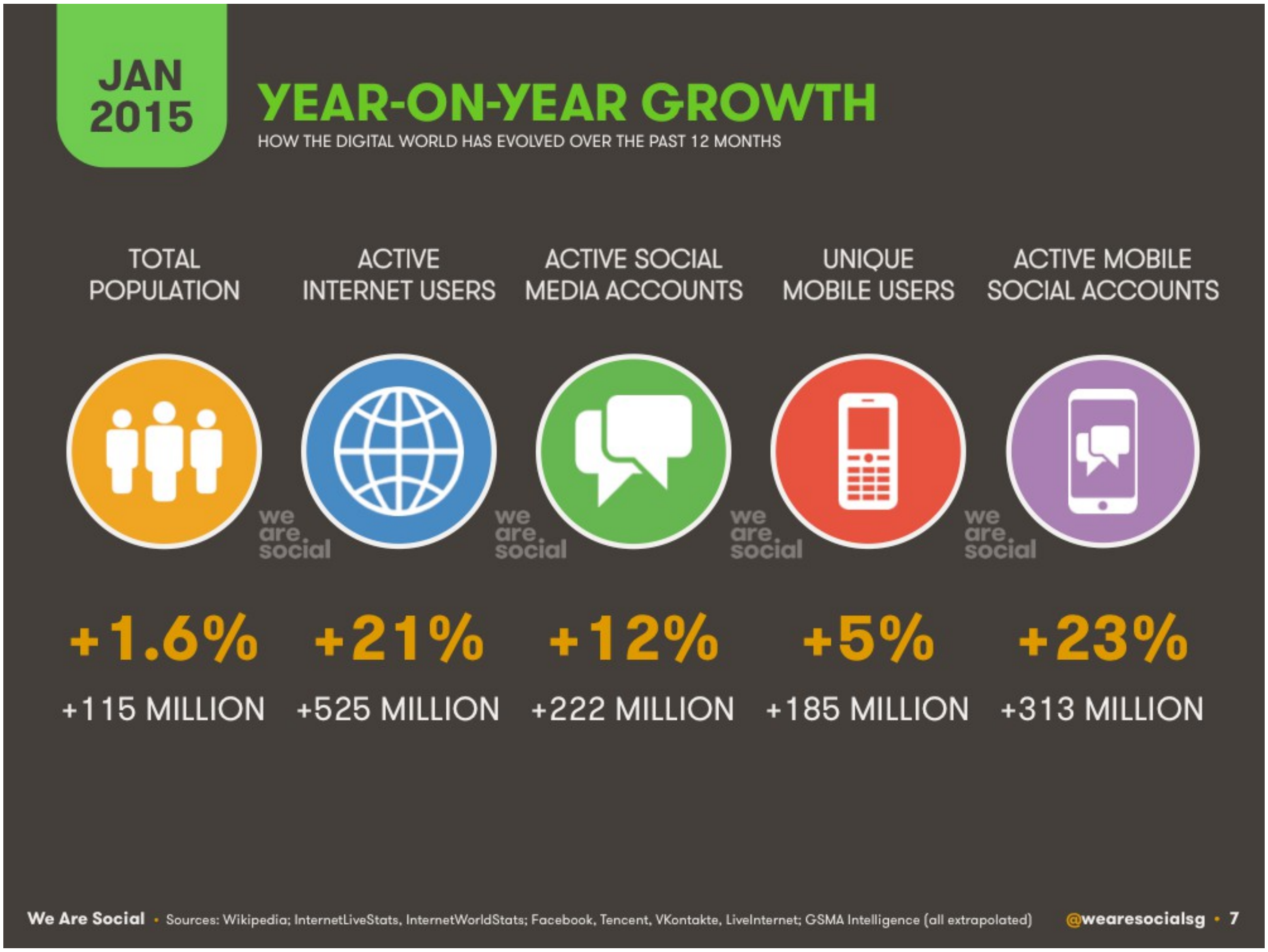

Figure 1 Dynamics of number of Internet users and other related figures in 2014-2015, credit to We Are Social.

Figure 1 clearly tells that number of connected users grow, in the same time, number of mobile users is growing as well. The same forecasts are proposed by other sources, for instance, by (Dastbaz, Pattinson, and Akhgar 2015, 11-11-25). All this means that in the nearest future the traffic volumes and numbers of Internet-connected devices will grow significantly and thus there is a need to develop sustainable solutions for networking – both wired and wireless, within all the tiers. This is the time to discuss what do the sustainability and green IT mean.

While numerous ways to improve sustainability in ICT exist, as will be discussed later on, this thesis report elaborating on one particular method – network measurements. The concept of measuring network performance using a set of metrics (or Key Performance Indicators, KPIs) is a basic way to provide a Quality of Service (QoS) to a customer. Thinking about this concept, we might presume that it is possible to develop another kind of metrics which will measure green or sustainable aspects of the ICT operation. Then, if such metrics exist, it would be possible to include green considerations into QoS monitoring and so to provide a company or a customer a mechanism to control not only raw network performance but also the greenness or even sustainability of the network under his command.

The advantage of using network measurements for tracking green aspects of ICT is its instant nature. Metrics can show the measurement results real-time, thus giving an engineer an instant picture of a situation within the network or computing facility. Apart from this, it could be possible to define a set of recommendations for achieving exact values of metrics for a given network, thus giving an end-user an opportunity to control sustainability without knowing too much of technical details. These facts can definitely help to promote and deploy green metrics, thus increasing the positive effect of such an approach.

However, it is somewhat complicated to study green metrics without any supporting methodology. One of the reasons for that is overall complexity of green IT and sustainability terms, as the reader will have an opportunity to see. In order to address the problem of complexity, the Biomimicry approach will be utilized in this thesis, more precisely, the nature's laws, defined by Janine Benyus within it.

1.2 Research question

Generally, a successful and wide-spread technology has to be simple enough in usage so that non-technical users will also have a possibility to adopt it – and hence insure the wide adoption. This is exactly what is needed for any sustainable amendment to our current and future technologies, as the idea of sustainability will only work effectively in case everybody are pushing it. So, apart from designing a sustainable technology as it is, it is needed to take into account its simplicity – where applicable, of course.

For instance, let us consider the above mentioned case with the network measurement discussed in this thesis. Ideally, the end user of a system implementing this idea will only need to see if the green requirements are being met. This is simple and accessible to the user, and it's not necessary for him to know the underlying mechanism which is evaluating the green conditions. Together with the traditional technical requirements, we can illustrate the system development process using the V-model.

The V-model is defined in a very fuzzy way, and is frequently interpreted in quite different ways. Most generally, V-model can be seen as a sequence of operations for a system development. Its objective is directed to simplify and to provide an understandable view of the latter. It is much more convenient to perceive the V-model according to the figure 2, which is sourced from the work of Prosnik 2010, which is released by the Defense Acquisition University (DAU).

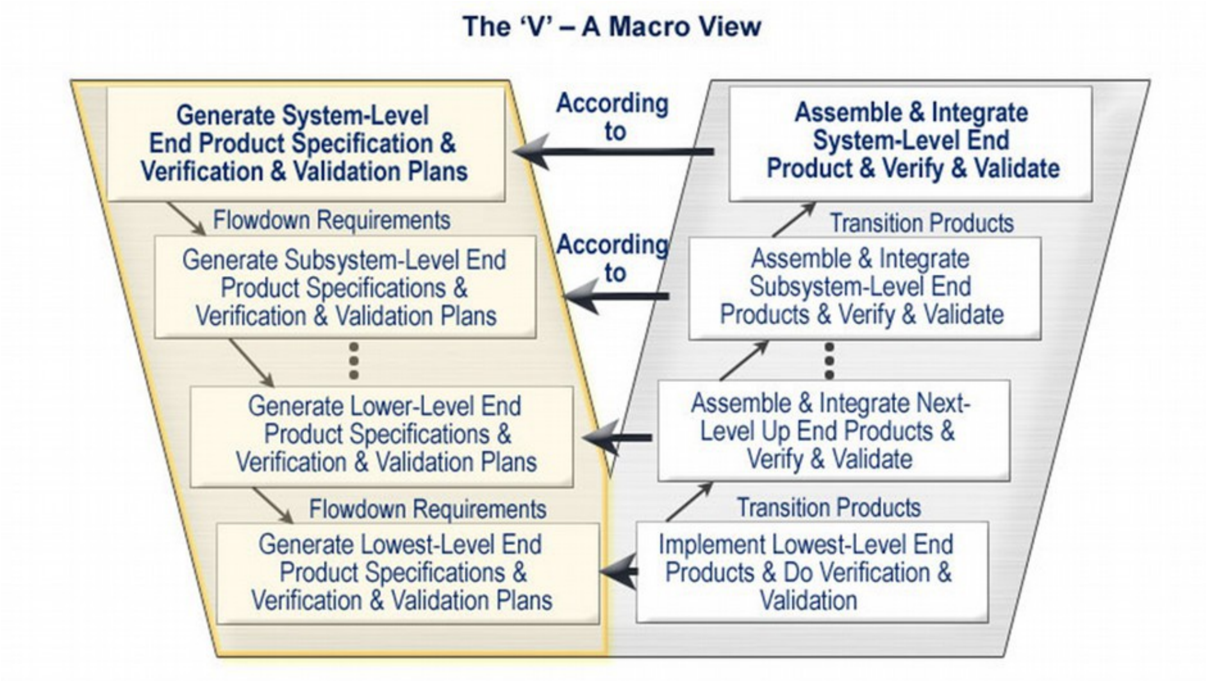

Figure 2 General V-model view

In the top-down approach, the designer is moving from the top of the left “wing” of V, through its bottom, to the top of right “wing”. While the left one is devoted to developing requirements for a system, the right one is following the requirement validation, level by level.

For our case of a sustainable system development, the important thing to note is the two sets of requirements – one set is defined by the user requirements, and another one is from the planet, or ecology. Both sets are traced and validated separately. Figure 3 depicts such a case in terms of a V-model.

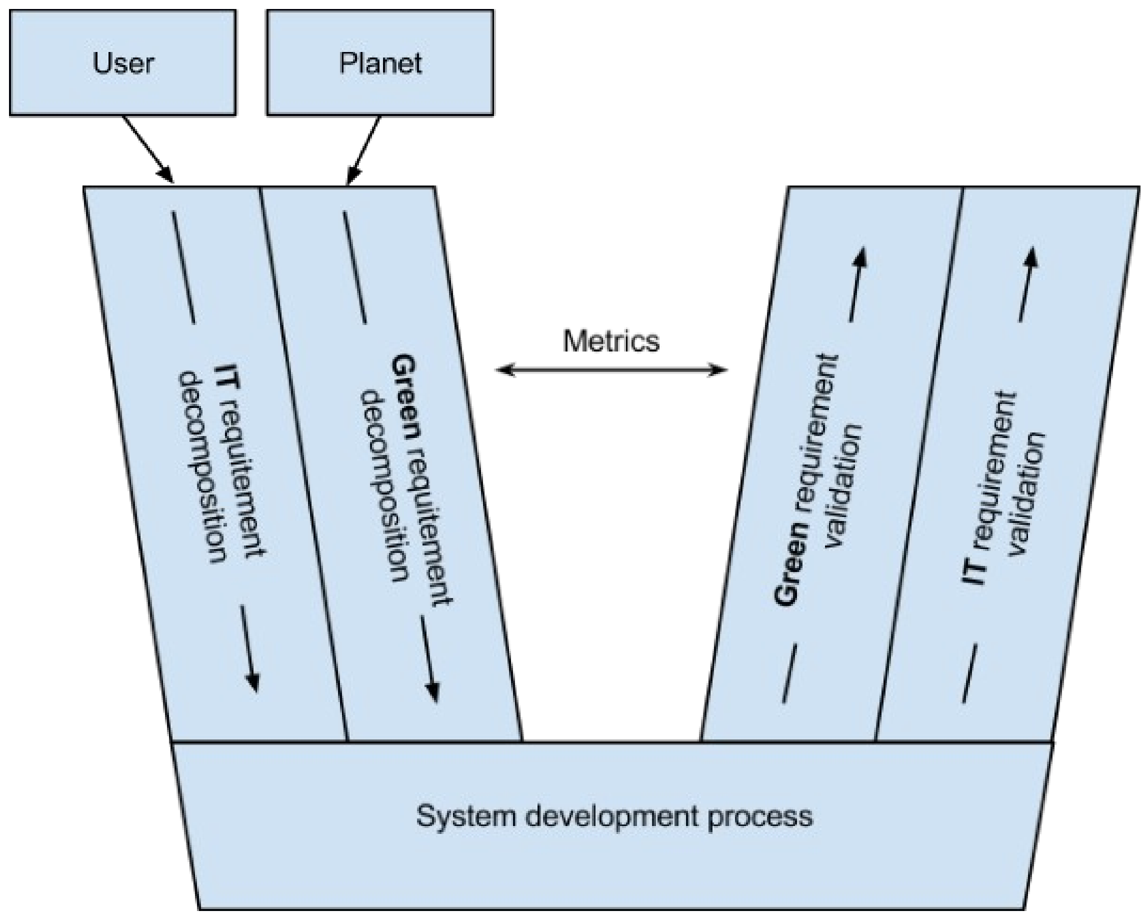

Figure 3 Design process of a sustainable IT system

As can be seen from the figure 3 technical requirements cannot be handled and validated together with green ones due to their different nature. Besides, it is quite clear that efforts to respect green requirements might be in a contradiction with respecting IT requirements. Indeed, there is a relation between them and it can be determined, for instance, experimentally – as hardware setups and other conditions vary greatly from one system deployment to another) Therefore, it is needed to satisfy both aspects very carefully and a balance between them has to be maintained.

The validation itself is quite a considerable problem to solve. While the end user is only validating the performance in subjective terms (for example, voice quality in telephone applications – a typical QoE metric), the requirements for a system has to be based on an objective and measurable units (in mentioned voice telephony case this can be formalized in jitter, rate and delay units – usual QoS metrics). In the same manner, the green requirements can be validated – the only issue is that at the current moment green metrics domain is developing in quite a slow pace.

Basing on the text above, we can emphasize three tasks in order for the sustainable part to integrate into the system: (a) define complete set of sustainable requirements; (b) define metrics which will quantitatively represent those simple sustainable requirements; (c) determine how to validate the requirements, as well as the acceptable ranges of all the requirements, and hence the metrics. This work is only discussing tasks (a) and (b), and task (c) needs special and often personalized attention.

Here is exactly the moment, where a methodology for studying the metrics can become useful. Sustainability is a multi-fold problem, and it is not always clear for an arbitrary end-user. This is the objective of task (a) from the previous paragraph – to present it in a simple yet complete and systematic way. Biomimicry is expected to introduce these into researching sustainable system development and the green metrics, as well as to relate them to nature's laws – which might be helpful to achieve sustainability in ICT.

Therefore, the general objective of this work is to investigate the systematic approach for validating sustainable requirements, as well as to provide an overview of the green metrics which may be applied to formalize those.

The present thesis is structured in the following way:

Section 1 have already introduced the need in enhancing sustainability in ICT, as well as objectives for this work;

Section 2 is discussing the green IT concept and present knowledge regarding green KPIs in ICT;

Section 3 explains in detail about biomimicry approach and the methodologies behind it;

Section 4 presents relation of current green KPIs to the biomimicry methodologies;

Section 5 concludes the work.

Section 2 Green IT

2.1 Green IT concept

The term “sustainable development” has emerged before appearing in ICT domain. It was first used by Brundtland commission in 1987 as a “development that meets the needs of the present without compromising the ability of future generations to meet their own needs”, as stated in their report (Brundtland 1987). Since then, the term “sustainability” has found its place in the dictionary with such a meaning and was applied in different fields of production and economics. Another good representation of sustainability can initially be found in (Anonymous1992), which treats sustainability as an issue, consisting of three basic pillars: environment, ethics and economics. This interpretation was positively accepted by researchers, and today it is commonly called as Sustainability Triangle.

It took, however, quite some time for the ICT domain to accommodate sustainability. One of its first appearance took place in 2005 in the paper (Matsumoto, Tamura, and Fujimoto 2005, 492-498), done by Japanese researchers. In this paper they are not utilizing the term to full extent, mostly by evaluating and predicting CO2 emissions caused by ICT. Nevertheless, the article is predictably warning about the emissions being increased and calling for an action.

The first serious work discussing the sustainability in ICT to its full extent has been done by Steve Elliot in 2007 in his paper “Environmentally sustainable ICT: a critical topic for IS research?” (Elliot 2007, 114). It is quite clear from the title that he is evaluating the need to investigate such a phenomena. S. Elliot tests the definition and scope of the problem in order to determine, should the sustainable ICT be studied. The results tell that the topic is acceptable for research, and the author concludes that “...the paper finds support for each of the initial research questions and concludes that the environmental sustainability of ICT should be seen as a sustainable topic in the mainstream of IS research”.

In fact, seems that this moment of time is the emerging of green IT. The author of above mentioned paper is promoting the concept, and it seems that researchers have accepted it. As you can see, the time span from starting the Energy Star initiative (which, if you recall, is the beginning of energy-awareness in large IT pieces) and the former paper is 15 years. Clearly, the need to investigate more into sustainable ICT have been preparing to be studies for all this time, and if S. Elliot would not report his article, somebody else would.

After 2007, we can finally see more and more papers related to sustainable IT and green computing. As for the former, the first appearance of the term and its definition has took place in article “Harnessing Green IT: Principles and Practices” in 2008 (Murugesan 2008, 24-33). Citing from the paper, the green computing is defined as “the study and practice of designing, manufacturing, using, and disposing of computers, servers, and associated subsystems — such as monitors, printers, storage devices, and networking and communications systems — efficiently and effectively with minimal or no impact on the environment”. As you can see, the definition is not only taking into account energy-related issues as Energy Star, but rather exploiting all the stages of IT/ICT equipment life cycle. This is closely related to the sustainable development. Such a definition is fully compatible with the former, but it also breaks down sustainability into more details, which are specific to ICT and which make sense in this domain. This definition is extremely good and effective, and experience in PERCCOM has shown me that the current green IT research is completely based on it.

There are four parts of an IT piece life cycle, as listed in the definition: designing, manufacturing, using and disposing. Generally, these phases can be broken down to a more fine-detailed representation, but the phases listed are introducing the impact into the environment and are enough to be taken into account. The goal of green IT is to promote sustainable thinking into all the phases – starting with designing and finishing with disposal. Different organizations are working on different phases in this concern, and different measures are introduced in order to enhance the resource efficiency.

Designing the IT appliance in order to make it compatible with the green IT concept is closely related to the term “eco-design”, which, according to Wikipedia, is “an approach to design of a product with special consideration for the environmental impacts of the product during its whole lifecycle” (Anonymous2015a). At a first glance, such a definition is overlapping the definition of green IT mentioned above, however, the reader should not be confused with that and remember that the design is the crucial moment for the whole life cycle of an appliance. This is the stage where the most important work is done, and this phase solely defines how should the product be manufactured and how should it be disposed after. And, of course, this stage is the most difficult, especially for considering the green IT. The challenge of designers which are developing a “green” product is incorporating the following: (a) a need to utilize wisely the most up-to-date technologies to ensure that the product can be manufactured with minimum environmental impact and using as few non-renewable resources as possible; (b) designing the product in such a way that the disposal will take minimum efforts, introduce minimum environmental impact and ensure to recycle maximum non-renewable materials from the piece. Such a challenge is extremely complex, and several methods on dealing with it are introduced up-to-date. The approaches are somewhat different, and the reader can consult the article (Knight and

Jenkins 2009, 549-558), which is published in 2009. However, its worth highlighting the Life Cycle Assessment (LCA) method, which seems to be the dominating one according to the experience experience at PERCCOM. Additionally, professional sources (for instance, (Schatsky 2011)) suggest that LCA is finding more and more adoption in industry and business, quoting from the article: “By one measure, the number of scientific publications dealing with LCA has more than doubled in the last two years. LCA tool vendors and consultants are reporting growth of 30–40% annually. … Large companies like Unilever have embraced it in support of a public commitment to understand the environmental impacts of all of their products”. LCA is closely related and is a key principle of green IT, as it is one of the crucial tools helping to make a green product. However, such a process might be very complicated (and so it is in most cases, as reported in (Knight and Jenkins 2009, 549-558), especially in the domain of electronics – as such appliance is, obviously, very complex). That is why the topic of LCA is quite “hot” nowadays, and you can find quite some papers trying to formalize and facilitate this complicated procedure, for instance, (Hauschild et al. 2013, 683-697). As for the general overview of LCA, reader is suggested to read about its history in (Klöpffer 1997, 223-228), and then read about current methodology at profile web-sites, such as https://www.sftool.gov/ and http://www.epa.gov/ .

In fact, there exist an additional field, which the design is responsible for. It is the duration of usage phase. As the reader will see in the next paragraph, the manufacturing of an ICT appliance is very impactive to the environment both in terms of basic resources – electricity and water – and in terms of specific resource usage. Actually, for networking equipment manufacturing is almost solely defining the environmental impact, which is demonstrated further. Thus, it is beneficial to design the product in such a way that the user would use it as long as the technological progress allows, ideally – even more. In case of obeying such a principle, the share of manufacturing impact would be less significant comparing to the usage phase, plus, the production rate would slow down hence reducing the manufacturing pollution. However, even if this idea sounds very simple, in practice its adoption is very complicated and depends on economical and ethical factors. For example, if talking about smartphones, there is such kind of people who want to have the most modern model (which are usually updated once in 9-12 months), and one is ready to pay for the new headset even if his current headset is perfectly functional. Such a situation leads to significant shortening of usage phase; it is known that high-end smartphones to be comfortably functional during at least 3 years after their introduction – which is three times more then the usage phase described in hypothetical case above. Statistics prove the existence of such an issue: according to Greenpeace (GREENPEACE) "...the average lifespan of computers in developed countries has dropped from six years in 1997 to just two years in 2005; mobile phones have a lifecycle of less than two years in developed countries; 183 million computers were sold worldwide in 2004; 674 million mobile phones were sold worldwide in 2004 – 30 percent more than in 2003".

Manufacturing the product, compatible with green IT paradigm is related to usage efficiency of basic resources (such as water and electricity), as well as efficient utilization of contained resources – those, of which the product is built. It is very important to consider this phase and to put efforts to decrease its impact. On of the very good review papers on LCA in ICT, published in 2014 by Arushanyan and others (Arushanyan, Ekener-Petersen, and Finnveden 2014, 211-234) give a great overview regarding current evaluations of manufacturing phase impact and its comparison to other phases. Authors of mentioned paper discuss several existing LCA studies in ICT domain, and it turns out that the opinions are very different whether the manufacturing phase is the most impactive or not. However, there is a common pattern – as suggested by the paper, those studies which are counting displays into the LCA tend to state that usage phase is as impactive as manufacturing. On the contrary, studies which are not counting displays (which is very suitable case for networking equipment), argue that manufacturing phase makes much more environmental impact comparing to other phases. Regardless the methodology, the manufacturing is introducing a very considerable share of direct environmental influence, and that is why it is also important to advance in in efficiency in this phase. Mostly, making manufacturing more efficient is done as a part of production specifications, where internal production engineers improve the processes. Such activities are not usually publicly exposed and are a subject to confidentiality. Nevertheless, this gap in publicly available knowledge is identified and researchers are filling it. For example, the paper (Dornfeld 2014, 63-66) gives a brief overview of existing innovative techniques to make manufacturing more sustainable.

The usage phase is considering how much resources are going to be utilized for keeping the appliance operating. Considering the ICT domain, this usually touches upon energy consumption – as this it the only direct resource required for ICT operation. This leads to the issue of reducing the usage phase impact being two-fold. At first, the most effective research is done on microelectronics level, as discussed earlier – the more efficiency is introduced into underlying hardware, the less energy is used. Though in past years semiconductor industry was rushing to conquer performance milestones, often on the expense of energy consumption, today's semiconductor technologies are developed enough to handle modern applications, so industries start to decrease the power package of the products retaining the same performance. This is working fine and the reader can now observe that electronics around us is becoming smaller, cooler, more energy-autonomous (where applicable).

Nevertheless, another approach exists for decreasing usage phase influence – and it is related to constraining the usage itself. This is the field, where one of the contributions of the present Master thesis lies. The easiest example is about light bulbs, or tap water – governing bodies are heavily promoting people to use these resources as efficiently as possible, not leaving the lights on when leaving the room or turning off the water while brushing the teeth. This method is working fine for tap water, but it may not be as useful for ICT appliance which is built to be utilized 24 over 7. In such case, researchers are working on much more sophisticated technologies. For example, one of the “hot” topics in today's research is sleeping mode on Ethernet switches. The most probably successful and commonly-adopted technique is developed at IEEE within 802.3 development program, and is called Energy Efficient Ethernet (IEEE 802.3az), which is nicely described in (Christensen et al. 2010, 50-56). Studies presented in this paper suggest that the savings with 802.3az may approach 82% comparing to the raw Ethernet, thus (quoting) “... result in large energy and economic savings likely exceeding $400 million per year in the US alone. Those savings can be maximized using packet coalescing if a careful analysis of the trade-offs between energy consumption and network performance is considered”. Another study, done by IEEE in 2011 (Reviriego et al. 2011, 578-580), acknowledge initial results, only pointing out that the overhead of such technology may be very pronounced in case of very low link loads, and, in general, its effectiveness is depending on the traffic pattern.

Of course, usage phase is not only about energy consumption, it may also include GHG emissions – which is directly related to energy consumption. Also, other more specific influences might be considered – for instance, radio pollution or acoustic noise, but this is somewhat out of direct resource consumption (though compatible with the green IT definition – “... with minimal or no impact on the environment” (Murugesan 2008, 24-33).)

Finally, the last phase of an IT/ICT equipment life cycle is considering disposal and end-of-life treatment. The main issue, associated with that is the fact that IT appliance is very complex, contains large amounts of rare chemical elements and sometimes even dangerous substances (however, this issue has been partially taken under control by RoHS). Complexity of the equipment makes recycling (or at least resources extraction) very difficult, and so it turned out that large amounts of ICT equipment were being re-sold to third countries and then deposited at land fills. From one point of view, such an approach is beneficial. Think about it: re-selling the appliance is extending its usage phase (which is very good); absence of recycling might be also a good thing from some point of view, because the equipment is very complex and so it is not guaranteed that the benefit from recycling will be greater than resources expenditure for the process.

Nevertheless, recycling is considered to be very important. According to UNEP, United Nations Environment Programme, "Electronic waste (e-waste) – from computers, televisions, telephones, cell phones, electronic toys, and other sources – is posing a new management challenge to Asia and the Pacific. E-waste is currently one of the fastest growing segments of solid waste" (UNEP (United Nations Environment Programme) 2005, 17-18). Thus, initiatives for its promotion are emerging. In Europe, initiative called Waste Electrical and Electronic Equipment (WEEE) came to a legislative power in 2003 for this purpose. Several studies were conducted in order to identify whether WEEE is beneficial; the most solid and up-to-date one is done by researchers of Swiss Federal Laboratories for Materials Science and Technology in 2011. In their paper (Wäger, Hischier, and Eugster 2011, 1746-1756) they provide an overview of existing evaluations, as well as conduct their own one basing on Swiss e-waste flow data. The conclusion of the research is that the recycling e-waste is definitely beneficial, quoting: "The outcome of this study confirms … and shows that a collection and recovery system for WEEE, as it is established in Switzerland, has clear environmental advantages compared to a baseline scenario assuming incineration and/or landfilling of this type of waste” (Wäger, Hischier, and Eugster 2011, 1746-1756). Hence, we can conclude that the recycling is beneficial and should be adopted.

As the reader is able to see throughout these paragraphs, quite a number of different approaches are proposed up to the moment in order to achieve compatibility with green IT concept in the field of ICT. Though much more techniques are still pending to be researched well, and one of them will be paid a special attention in this thesis.

2.2 Green IT and measurements

2.2.1 Introduction

As the reader could see, the most effective work has been and should be done for enhancing design, manufacturing and disposal phases. These tasks are lying somewhat outside of a ICT engineer's responsibilities. However, network engineer on place can tweak and tune the network for its usage phase, and, possibly, influencing other phases as well.

As already discussed, the usage phase is characterized almost exclusively by energy it consumes. Hence most enhancements within its boundaries will be touching upon the ways to decrease non-renewable energy consumption of the network whilst maximizing its performance, both the actual networking and computing infrastructures. With improving energy consumption, this solution is decreasing GHG emitted due to energy generation as well.

Several approaches for decreasing energy consumption are being researched and implemented today. One way has been already exemplified earlier in this thesis – IEEE

802.3az, described Energy Efficient Ethernet. However, this example is quite narrow, because not all the networks are built over Ethernet, thus another ideas have come up in recent years. Also, one could imagine that it might be possible to design a routing algorithm which is taking into account different energy-related concerns of nodes inside the network. In fact, such an approach is now being researched, for instance, in paper (Bianzino et al. 2010, 1422-1427). Another opportunity is to build redundant computing infrastructures ensuring almost 100% green power supply. Next, the reader could also imagine an optimization of a cooling system at a computing facility, which is forced to switch off due to artificially decreased job quotas for computing – as a measure to decrease operating temperature. Numerous possibilities, however, non of them are trivial or lying on the surface.

The common pillar unifying the ways on improving ICT systems sustainability from network engineer's point of view is network measurements. Truly, any green routing requires nodes to measure at least energy and populate it through routing protocols; sophisticated algorithms for balancing computing facilities are also relying on more complex parameters, which are however also based on energy consumption. This means that the research of such kind is touching upon network metrics, and these metrics might be thought out as green Quality of Service metrics.

Hence, it is important to analyze and develop network and computing performance metrics for their relation to sustainability. This is complicated, especially when it is about anything more sophisticated than pure energy consumption. But the biomimicry might be a good framework for this purpose; this concept will not help to develop new metrics directly, but will definitely help to determine what to develop and how will the new metrics exactly enhance sustainability of an ICT system.

Though green metrics concept is fairly new, quite a number of KPIs can already be found in existing literature. Some papers are utilizing them in order to achieve more specific goal, while another papers and reports have introduced metrics as the main goal. So, it is important to research the current literature on the presence of green metrics and analyze them within our approach. It is quite likely that such metrics are complete, and so there is no or a little need to develop new ones.

2.2.2 State-of-the-art for green Key Performance Indicators

One of the main contributor to the issue of defining the metrics for sustainable ICT is the Green Grid – a non-profit consortium of industry representatives, policy makers and other concerned bodies. This organization is working on improving the resource efficiency in large computing facilities, such as data centers – and this efforts are directly compatible with the green IT concept. The following literature review will start with their contributions.

The rest of the review will be exposing the academic research, which is not too much active. Nevertheless, there exist some valuable papers making a good input to the problem solving, and they will be discussed here.

1. PUE and DCiE

The most basic and widely-used parameter touching upon energy efficiency in computer systems is Power Usage Effectiveness, PUE, developed by The Green Grid in 2007. It is introduced first in (Anonymous2007) and then refined in (Belady et al. 2007). The mathematical representation of PUE is:

$$PUE = \frac{Total\ Facility\ Power}{IT\ Equipment\ Power} \quad (1)$$

It is important to define what is included in the term “IT Equipment” and what is not. According to the (Anonymous2007), the IT equipment includes “...compute, storage, and network equipment, along with supplemental equipment such as KVM switches, monitors, and workstations/laptops used to monitor or otherwise control the datacenter.”

PUE has quite a number of issues, which are making this metric to be incorrect and near-useless, as for some of the engineers (Clark 2013). Also, t here is a well-known example of a data center having a PUE equal to exactly 1.0 (Razey 2014). However, it turned out that calculation in this case was performed taking into account renewable sources and by tuning the formula, which is not very strict for PUE (Judge 2014). Another issue of it is not taking into account any kind of reusing the energy inside the facility. This problem, however, have been solved with introducing ERE metric, which is discussed later.

In spite of all the issues and inconsistencies mentioned above, the interesting thing about PUE is that this is the only, in fact, sustainability metric which is widely deployed and heavily used. As you will see later, The Green Grid have developed quite a number of other metrics, but non of them are usually listed among data centers' general specifications – except PUE.

Additionally, the papers mentioned are proposing a quantity, reciprocal to PUE – DCE (Anonymous2007) or DCiE (Belady et al. 2007). The difference between two latter metrics is in the designation – according to the sources, “Datacenter Efficiency” (DCE) is confusing, so they replaced it with “Datacenter infrastructure Efficiency” (DCiE). It is calculated as:

$$DCiE = \frac{1}{PUE} = \frac{IT\ Equipment\ Power}{Total\ Facility\ Power} \times 100\% \quad (2)$$

PUE and DCiE demonstrate the same parameter from two slightly different points of view – either the facility energy demand compared to the IT equipment energy demand or to show the fraction of the total facility power consumption, which is devoted to the IT equipment.

2. CUE

Another metric introduced by The Green Grid is called CUE – carbon usage effectiveness (Belady et al. 2010). It belongs to the xUE family of parameters, helping to assess energy efficiency of a computing facility. In particular, such a metric shows how much greenhouse gas is emitted by the whole facility per one kWh consumed by the IT equipment.

Alike to PUE, it is developed only to estimate efficiency during the operation phase. The basic equation to calculate CUE is:

$$CUE = \frac{Total\ CO\ emissions\ caused\ by\ the\ Total\ Data\ Center\ Energy}{IT\ Equipment\ Energy} \quad (3)$$

Important to note that CUE is a source-based metric. According to the original paper, the total CO_2 emissions have to be calculated basing on the carbon emissions on the source – for example, an energy producing company. The IT Equipment Energy is calculated taking into account the same limitations as for PUE. In contrary to PUE, which is dimensionless, CUE has a measurement unit – kilograms of carbon dioxide equivalent per kilowatt-hour.

It is quite clear from the formula that CUE is very closely related to PUE. The numerators in formulas for both metrics are mentioning the Total Facility Energy, and the difference is that PUE is taking exactly energy, but CUE is taking carbon emissions induced by the production of this energy. This means that enhancing PUE we can improve CUE as well – and this point is confirmed in (Belady et al. 2010).

Due to the relation of CUE to PUE, the former is also inheriting latter's gaps and inconsistencies.

3. WUE

Next member of xUE group is taking account the water. It is called Water Usage Effectiveness (WUE), and it was introduced in (Patterson et al. 2011). WUE is quite similar to CUE, describing the amount of water utilized by the datacenter per one kWh consumed by the IT equipment. It also carries out the same function as CUE. However, the particularity of WUE is that the authors recommend to distinguish it as site-based and source-based. It is also stated in the original paper that both sub-types of WUE are important and have to be monitored in together – however, by different parties (datacenter for site-based and energy distributor for source-based).

WUE and WUEsource are calculated as:

$$WUE = \frac{Annual\ Site\ Water\ Usage}{IT\ Equipment\ Energy} \tag{4}$$

$$WUE_{source} = \frac{Annual\ Source\ Energy\ Water\ Usage + Annual\ Site\ Water\ Usage}{IT\ Equipment\ Energy} \quad (5)$$

IT Equipment Energy is calculated in the same way as for PUE. Calculation of the annual water usage of both types should take into account all the water used in the datacenter operation, including humidification, water used for energy production, and any other usage scenario. This particularity makes WUE differ from CUE, as the former metric does not only include energy-related components.

There are, indeed, gaps in WUE which are making it less usable. First of all, it tells nothing about the components of water consumption, so it is not possible to see the actual water usage scheme at a data center for an external observer. This may, potentially, lead to the same kind of cheating as in (Judge 2014).

4. ERE and ERF

Energy Reuse Effectiveness (ERE) was introduced by (Patterson et al. 2010) and it is addressing one issue of PUE – accounting reused energy (in any form). The reused energy in datacenters, most commonly, can be exemplified by heat which is driven from the racks to warm up the living areas nearby. As far as such a phenomena is not described in the PUE specification, different engineers were interpreting influence of reused energy in different ways, thus introducing ambiguity in the final results and even making possible to achieve PUE’s of less than 1.0 – which is not possible by the definition (Anonymous 2007).

ERE is an attempt to eliminate such an ambiguity. It is calculated as:

$$ERE = \frac{Total\,Energy - Reused\,Energy}{IT\,Energy} \tag{6}$$

As it is possible to see from the formula, the minimum possible ERE value equals zero (assuming the Reused Energy is coming exclusively from the Total Energy with possible conversions). Note, that Reused Energy is specified as energy, not leaving the site premises.

It is feasible to establish a connection between PUE and ERE, as they are quite close in their mathematical definitions. The original white paper proposes another quantity which is designed to relate PUE and ERE. It is called Energy Reuse Factor (ERF) and is mentioned in (Patterson et al. 2010). ERF is defined as:

$$ERF = \frac{Reused\,Energy}{Total\,Energy} \tag{7}$$

In words, ERF represents the fraction of the total energy (consumed by the site) which is reused. Hence, it is possible to define the relation between PUE and ERE as

$$ERE = (1 - ERF) \times PUE \tag{8}$$

In spite of the fact that ERE seems to be more precise and developed metric than PUE, it is important to outline that they are demonstrating energy efficiency from slightly different points of view. It is possible to make a datacenter with PUE close to it’s theoretical minimum, but it does not necessarily imply that the fraction of energy reused is high hence ERE is minimal; in the same way, datacenter can be designed to reuse a large fraction of consumed energy, but PUE might be very large as well at the same time. In other words, these two metrics are related but depend on another parameter – ERF, so it is convenient to consider both PUE and ERE for efficiency assessment. This has been also confirmed in the original paper.

5. DCP family

Data Center Productivity (DCP) metric family is introduced in 2008 within White Paper 13 of Green Grid (Anderson and Cader 2008) alongside with the first example of it – Data Center Energy Productivity (DCeP). The whole metric family is devoted to quantifying the performance of a computing facility with respect to a unit of some resource. In particular, DCeP demonstrates the ration of useful work to the total energy, consumed by the facility to produce this work:

$$DCeP = \frac{Useful\ Work\ Produced}{Total\ Data\ Center\ Energy\ Consumed\ Producing\ this\ Work} \tag{9}$$

In this formula, it important to identify what does the “Useful Work Produced” mean. Its definition is quite complicated and takes into account different aspects of tasks; readers are offered to consult the source on that matter. The result of calculation is commonly measured in Normalized Tasks per kWh.

6. GEC

Green Energy Coefficient (GEC) is, perhaps, the simplest metric, produced by The Green Grid so far. It is both simple in its definition and its details. It was introduced as an appendix to the paper (Anonymous2012).

In words, the GEC exposes the percentage of the energy which is generated from green sources. According to the paper, the only difficulty of this definition is the fact that different states may have different definitions of “green sources”. In order to overcome this issue, authors of (Anonymous2012) have decided to explicitly define this term as “...any energy for which the data center owns the legal right to the environmental attributes of green/renewable generation”. They also stress that legal right are recognized as so called Green Energy Certificates or similar products. Additionally, authors suggest the companies to include such certificates or equivalent in case they using GEC in their reports.

The formula of GEC is the following:

$$GEC = \frac{\text{Green energy used by the data center}}{\text{Total Data Center Source Energy}} \qquad (10)$$

The quantities have already been explained.

7. EDE

The following metric is proposed by The Green Grid in (Brown 2012) is associated with ICT equipment disposal. It is called Electronics Disposal Efficiency (EDE). It seems that EDE is the only (or one of the very few) metric for electronic waste disposal available. It is not considering the usage phase of an appliance but the disposal phase.

The formula for its calculation is:

$$EDE = \frac{Weight_{responsibly\ disposed}}{TotalWeight_{disposed}} \tag{11}$$

According to the paper, “responsible disposal” is an important term, which means disposing through recycling centers, certified for disposing electrical waste.

One thing should be taken into account when considering EDE as a metric: it is hardly monitorable, thus having some kind of a contradiction to its application in this thesis. EDE is not changing dynamically; rather, it is manually calculated once in some period. Nevertheless, this metric can be a part of a KPI monitoring process in a way of a permanent characteristic of a computing facility, which might be taken into account by potential green routing protocols.

8. *"Powering a data center network via renewable energy: A green testbed”*

The article (Nguyen et al. 2013, 40-49) explains a working example of natural-sources powered cloud infrastructure. The infrastructure is hypervised and based on SDN elements, which assures the controlling is centralized and all the measurements inside the network are done across the entire infrastructure. The paper gives exact techniques on how to implement energy measurements and power source hot-swap, etc.

The idea is to power the datacenter network from several independent sun or wind energy sources; these separate facilities are referred as “nodes” and are built of power generation equipment itself, controlling network with a server, a power distribution unit and a feedback connection to the public power grid. The node carries out measurements of environmental parameters and provides information for the datacenter network controller for making decisions on managing the network power supply. The controller can automatically migrate and consolidate VMs across datacenters in order to achieve required computing performance and maximum green energy share for powering the infrastructure.

Two interesting quantities are introduced in this paper:

$$P_v = \left(\frac{\alpha \times M_V}{M_H} + \frac{\beta \times U_V}{U_H} + \frac{\gamma \times O_V}{O_H} \right) \tag{12}$$

$$P_m = \mu \times \left(\sum_{1}^{L} \frac{M_V}{B_S} \times \frac{P_S}{2} \right) \tag{13}$$

Equation (12) represents the power consumption of a VM, and, according to the source, the following quantities are used for the calculation: Mv, Uv, Ov – accordingly RAM volume, number of CPUs and I/O capacity of a given VM; Mh, Uh, Oh – accordingly RAM, number of CPUs and I/O capacity of the hardware server which hosts the given VM; PH – maximum power consumption for the hardware server; α, β, γ – memory, CPU and I/O constants which have to be automatically quantified beforehand, as described in (Kansal et al. 2010, 39-50).

Equation (13) is calculating the energy used to perform the migration of a VM. Here μ represents the constant counting the energy requirement for redundancy and cooling; L is the number of switching devices between the source and the destination; M_v is the size of a VM in computer memory units; B_s is a bandwidth between two single switches on the way; P_s is the power of a switching device. This formula is quite interesting, it makes possible such an assessment for any kind of data. However, its calculation can become quite complicated whenever the route includes external network segments, as the exact switch parameters are not available anymore.

These values are being constantly monitored, and depending on them the controller may make a decision to relocate the VMs in order to utilize more green energy than available at the given moment and under given configuration.

9. *"Distributed computing for carbon footprint reduction by exploiting low-footprint energy availability"*

Paper (Van Heddeghem et al. 2012, 405-414) is proposing the FTS/FTW (follow the sun/wind) mechanism for job processing at the datacenters. The idea is that given some DC infrastructure (DC can be of any scale, down to a single server), which is distributed across the world and have an access to low-footprint energy (solar/wind), we can assume that some of the DCs can have more sun or wind or other renewable resource while the rest is getting scarce for them at a single period of time. This means that we can migrate the jobs from one DCs to others in order to benefit from the renewable energy (note a number of restrictive assumptions in the paper). This is quite a similar idea as described in the previous article, but in this case authors devote the whole research to the concept and proposing more comprehensive mathematical model for describe the best ways on how to achieve highest energy savings in such an architecture.

The model for carbon footprint calculation lies within the scope of this thesis. This model quantifies the GHG emissions in case of deployed FTW/FTS architecture on the sites. Hence, let us consider it:

$$F = \frac{F}{E_u} = m f I_H + n I_L \sum_{k=n}^{m} \left[\binom{m}{k} p^k (1-p)^{m-k} \right] + \\ + \sum_{k=0}^{n-1} \left[\binom{m}{k} p^k (1-p)^{m-k} \left((n-k) I_H + k I_L \right) \right] \quad (14)$$

The equation for it is comprised of several summands representing different aspects considered for calculation. First summand accounts manufacturing footprint of all the datacenters in the network; the second – the usage footprint of datacenters in case enough or more of them are powered from green energy sources at the given moment of time; the third summand describes usage footprint in a case opposite to the previous condition. Note, that the data transportation footprint is not included into the model because, according to the article, such emissions take a small share of the entire emissions thus can be neglected. The measurement unit is GHG grams in CO_2 equivalent per 1 kWh. Detailed quantities description can be found in the source article.

Several missing points exist. First, the approach does not consider the share of the total processing power, required for the jobs, to the full available processing power; for simplicity, authors assume that the jobs are always loading the facilities to a full extent. Second, the VM transportation over network footprint is neglected. Again, this is done for simplifying the calculations.

Also, it is notable that the model does not really represent a metric, also, it is based upon a narrow and quite unreal theoretical use case. However, the model can provide the basis for development of other models for more realistic cases.

10. "Peam: Predictive energy-aware management for storage systems"

Article (Jiang et al. 2013, 105-114) is discussing the efficiency of data transmission over the network. The main idea is that it is possible to send data "as is", or archive it before sending (putting, e.g., several files into one tarball without compression), or archiving it and compressing. Authors provide experimental findings showing that different data characteristics (such as number of files, type of files, etc) make one method more efficient than others. In this way, transmitting a very large amount of files is less energy consuming if the files are archived before; in contrast, if the number of files is fairly low, the archiving becomes unnecessary and induces more energy consumption.

As the result of the paper, they propose an intellectual model which is deployed at the servers and decides whether to prepare the data for transmission or not. The part of the model interesting for us is the power consumption calculation, presented on the next formula:

$$P_C = P_i + \sum \left(U_{component} \cdot \left(P^{max}_{component} - P^{idle}_{component}\right)\right) \quad (15)$$

Here Pi – the power of a component in an idle state; $U_{component}$ is a utilization of the component; $Pmax_{component}$ and $Pidle_{component}$ are the powers of the component under the maximum load and in idle state, respectively.

As can be seen from the formula, the relation between power consumption and utilization of the component is assumed to be directly and linearly proportional (Based on (Xu and Fortes 2011, 225-234), "*Based on the results … a commonly used linear power model* $P = p_1 + p_2 \cdot \mathrm{CPU\%}$ *(P denotes the power consumption and CPU% is the percentage of CPU utilization) is used to estimate the power consumption of physical servers*").

In fact, the power consumption part of the model is not very well explained in the paper. It is still not clear what do they refer as a "component" and what is not, thus we cannot conclude on how to implement such a measurement on a real system.

11. "Monitoring and assessing energy consumption and CO2 emissions in cloud-based systems"

Authors of (Cappiello et al. 2013, 127-132) are discussing federated clouds and the Key Performance Indicators which are useful for monitoring them. The paper provides quite a comprehensive set of KPIs. From one point of view, they are directly based on widely-used ones (e.g. PUE and GEC), but from the other side – give a new look on the issue of determining the energy efficiency of data centers.

The main assumption of this paper is introduced in their federated cloud model. This model contains three layers: application, virtualization and infrastructural. By this, authors separate different KPIs by their layers of influence. The infrastructural layer metrics listed are common: CPU utilization, energy consumption, CO_2 emissions, PUE, et cetera. Hence, they will be omitted here.

Coming to the virtualization and application layers, the KPIs proposed include some of the trivial ones, equivalent to infrastructural layer metrics, as well as a special ones which are worth considering.

For virtualization layer:

$$VM-PUE_{ik} = \frac{P_{ik}}{\sum_{j} P_{ijk}} \tag{16}$$

Formula (16) describes PUE of the VM. Here P_{ik} – power consumed by the k-th VM used by the i-th application; possibly, other tasks are taking place on the same VM as well; P_{ijk} – power, consumed by the exact application tasks.

$$VM-EP_{ik} = \frac{NTrans_{ik\Delta t}}{P_{ik} \cdot \Delta t} \tag{17}$$

Equation (7) represents VM energy productivity – equivalent to DCeP of the DC (ratio of the work output of the data center and the total energy of the data center), but for the VM. $N_{transikdt}$ – number of completed executions of tasks, deployed on the VM_{ik} within time interval dt.

$$\text{VM-GE}_{ik} = GEC \times \left(P_{ik} \cdot \Delta t\right) \tag{18}$$

GEC of the VM – how much is the share of green energy used to power the VM_{ik}.

Application layer can be described in a similar way but the calculation for such metrics has to consider application-specific parameters.

$$A-PUE_i = \frac{\sum_k P_{ik}}{\sum_{jk} P_{ijk}} \tag{19}$$

The application energy efficiency, represented by equation (19), is defined as the ratio of power consumptions of all the VMs which have the i-th application deployed on them to the power consumptions of the exact tasks, performed within the i-th application deployed over k VMs.

$$A-EP_i = \frac{NTrans_{i\Delta t}}{\sum_k \left(P_{ik} \cdot \Delta t\right)} \tag{20}$$

Formula (20) is showing the energy productivity of an application. It is calculated as the number of executions of the entire application over the time t to the total energy consumed by all the VMs which are having this application deployed over the time t.

$$\text{A-GE}_i = \sum_k \text{VM-GE}_{ik} \tag{21}$$

Equation (21) is describing an application green efficiency, calculated as the sum of GEs for all the VMs having the application deployed. Be careful, expression inside the sum is not a difference of two terms, but rather a single term which is described in formula (18).

12. *“Designing green network architectures using the ten commandments for a mature ecosystem”*

There exists a paper researching networking domain using the biomimicry approach, (Drouant et al. 2014, 38-46). In this paper authors explain the concept of the ten commandments (also used in this thesis), as well as provide examples and use cases of enhancements and KPIs regarding them. It is very useful to cite the metrics, proposed there. A good thing is that metrics proposed are already analyzed regarding the biomimicry approach, so no additional analysis is required.

Here only the formulas and a short comment will be listed for each metric, as the full explanation is quite large to quote. The reader is strongly encouraged to consult the paper to have a better view on this problem.

So, the original paper proposes four metrics related to some sustainability aspects: KPIs on recyclability, on energy consumption, on pollution and on relevance to user needs. Here they are.

KPI on recyclability:

$$\Gamma = \frac{\sum^{i \in \overline{X_r}} \rho_i}{|\overline{X_r}|} \tag{22}$$

here $\overline{X_r}$ is a set of equipment “... which will never be repackaged”, according to the authors, and ρ_i is recyclability rate of an equipment.

KPI on energy consumption:

$$E = E_m + \int_{t=0}^{end\ of\ lifecycle} P_u(t)\,dt + E_d \qquad (23)$$

here E_m is a manufacturing energy overhead, E_d is disposal energy overhead, and the middle term represents the energy consumption of an appliance during its usage phase.

KPI on pollution:

$$\Phi = \sum_{s=m,u,d} \frac{\alpha}{\tau} \times E_s \qquad (24)$$

Here m, u, d correspond to manufacturing, usage and disposal; α is a CO_2 conversion factor for a given energy source; τ is an energy transportation losses factor.

KPI on relevance to user needs:

In fact, this metric is not quantifiable at this moment; the authors are proposing to use a radar diagram to track different aspects of a user needs relevance, so it is not exactly monitorable therefore will not be considered here.

Now, when all the found metrics are explained, it is useful to put all of them into a brief table. Table 1 beneath will be showing which part of sustainability issue (energy consumption, disposal, etc) is addressed by the KPI, as well as their boundaries (theoretical, thus not taking into account common limitations) and measurement units.

Table 1 Brief characteristics of the KPIs being analyzed in the thesis work

	Sustainability aspect	Boundaries (theoretical)	Measurement units
PUE (1)	Energy usage effectiveness	[1; ∞]	[–]
DCiE (2)	Energy usage effectiveness	[0; 100]	[%]
CUE (3)	GHG pollution	[0; ∞]	[kg $_{CO2eq}$ / kW]
WUE (4)	Water usage	[0; ∞]	[kg / kW]
WUEsrc (5)	Water usage	[0; ∞]	[kg / kW]
ERE (6)	Energy usage effectiveness	[0; ∞]	[–]
ERF (7)	Energy usage effectiveness	[0; 1]	[–]
DCeP (9)	Energy usage effectiveness	[0; ∞]	[Norm. Tasks / kW]
GEC (10)	Pollution; natural resource usage	[0; 1]	[–]
EDE (11)	Disposal	[0; 1]	[–]
P_u (12)	Energy usage effectiveness	[0; ∞]	[W]
P_m (13)	Energy usage effectiveness	[0; ∞]	[W]
F (14)	GHG pollution	[0; ∞]	[g $_{CO2eq}$ / kW]
P_c (15)	Energy usage effectiveness	[0; ∞]	[W]
VM-PUE$_{ik}$ (16)	Energy usage effectiveness	[1; ∞]	[–]
VM-EP$_{ik}$ (17)	Energy usage effectiveness	[0; ∞]	[Norm. Tasks / kW]
VM-GE$_{ik}$ (18)	Pollution; natural resource usage	[0; 1]	[–]

Table 1 Brief characteristics of the KPIs being analyzed in the thesis work

	Sustainability aspect	Boundaries (theoretical)	Measurement units
A-PUE_i (19)	Energy usage effectiveness	[1; ∞]	[–]
A-EP_i (20)	Energy usage effectiveness	[0; ∞]	[Norm. Tasks / kW]
A-GE_i (21)	Pollution; natural resource usage	[0; 1]	[–]
Γ (22)	Disposal	[0; 1]	[–]
E (23)	Energy usage effectiveness	[0; ∞]	[W]
Φ (24)	GHG Pollution	[0; ∞]	[g_{CO2eq}]

Section 3 Biomimicry

3.1 Introduction

There are numerous possibilities for implementing green approach in ICT, as the reader could see in the previous paragraph. Some of them are attracting attention for research, while another are still waiting to be considered. One of the methods from the latter group is Biomimicry.

The approach itself is quite old. People were observing the behavior and structure in nature throughout years, and were wise enough to apply them in order to build mechanisms. Very few examples of such are: aircrafts, which are completely based on birds' wing structures and aerodynamics; hook-and-loop fasteners, which are inspired by bur from plants like yellow avens; jet force, used in aircraft and rocket engines; imaging sensors and lenses, which are based on a human eye structure. Not all the design choices were copied from nature intentionally, but some definitely were.

Biomimicry concept as it is known now started in 1997 with the book of Janine Benyus called “Biomimicry: Innovation Inspired by Nature”. In that book, the author presents how did she discover the concept, the fascination about it, and the ways to introduce biomimicry into our life, indeed. Janine Benyus is describing how interested were the researchers taking part in discussions on that topic, yet nobody had have started any real research or promotion of biomemetics in their fields (this is for 1997, of course). The reader is proposed to have this book as a complementary reading in order to understand the idea behind the thesis more clearly.

The outcome of biomimicry is to make systems sustainable. One of the concepts, used in the book – mature ecosystem – will be discussed later on, but what is important now is that such ecosystem is sustainable; members of it are achieving their needs without sacrificing other's needs. Author is stressing that becoming a mature ecosystem is an objective to fulfill – and that is why it is interesting to apply biomimicry into our life. Possibly, if we adopt rules under which mature ecosystems live, our own ecosystem will also become mature and hence sustainable.

In order to promote this, Janine Benyus, together with her colleagues, has founded a Biomimicry institute, which is a non-profit organization. Alongside with asknature.org website, these resources are helping people to learn the concept of biomemetics and get inspired by it. There exists, however, a for-profit organization called Biomimicry Group, also founded by Benyus and provides consulting and research in this field. Trainings and workshops are available as well.

Despite that only these organizations are continuously working on promoting Biomimicry, the concept is gaining quite some attention. Some industries were using and benefiting from following the nature before the term “Biomimicry” even existed in current meaning; some other started to pursue this way of thinking after the mentioned book went out and the discussions started. For this moment, businesses are also trying to adopt biomimicry. It is reported by Fermanian Business & Economic Institute (Anonymous 2013a) (Bagley 2014) that the US patent and research amounts related to bioinspiration have increased by 5.5 times since 2000. This progress is very promising, and the facts mentioned are suggesting that the idea of adopting natural technologies into innovation process will become much more common.

In order to conduct a biomimicry-related research for this thesis work, a methodology is required. Within biomimicry, two of them can be found. They are called “Ten commandments of a mature ecosystem” and “Design lens”.

3.2 Ten commandments of a mature ecosystem

The ten commandments concept has been introduced in the already mentioned book by Janine Benyus, more precisely in (Benyus 1997, 248).In order to explain this idea, it is important to define three stages of inhabitant development level:

- Type I systems, referred as "weed" in the book – systems, which have an ultimate objective to increase in population as fast as it is possible. Members of such ecosystems are rushing to develop regardless the environment health; they are not taking into account shortage of resources and environmental balance. Species of this kind exhaust the environment and, when the resources become scarce, move on to the next place – which is suitable for living. Additionally, they have loose relationship with environment and relatively simple life cycle.
- Type II systems – systems, members of which have decreased reproduction demands, development pace and resource usage. The balance of environment, however, is not taken into account, nevertheless, such systems evolve through time and, luckily, can transform to the Type III systems.
- Type III systems, referred as "woods" in the source – such ones, which are characterized to be inverse to Type I systems. Unlike the latter, "woods" are increasing population slowly, with much more complex life cycle stages. The development of such species is designed in such a way that the environment remains in balance with them; environment integrates these systems and benefits from them. Such systems take resources in no larger amounts then they can give back to the environment in other form.

Basing on this classification, the author together with colleagues has been identifying th e common laws, which Type III ecosystems obey – in order to apply them in our society. The rules have been defined, and the book refers to then as the ten commandments. They are:

1. use waste as a resource,
2. diversify and cooperate to fully use the habitat,
3. gather and use energy efficiently,
4. optimize rather than maximize,
5. use materials sparingly,
6. don’t foul their nests,
7. don’t draw down resources,
8. remain in balance with the biosphere,
9. run on information, and
10. shop locally.

According to the book, species, which are living in balance with the environment, are using these commandments in order to do so. Thus, it would be useful for humanity to adopt the commandments; this may help to reduce environmental footprint of our specie and, in future, to become an integral part of environment.

In order to be successful, such a transition has to be done in each and every domain and scope of our life – ICT as well. As such, the presented ten commandments introduce not only a good objective to achieve in our development, but also an efficient framework to analyze existing and design future ICT systems.

A very good overview of such an approach is presented in (Drouant et al. 2014, 38-46), where the authors explain possible examples of application of the ten commandments to the infocommunication systems.

3.3 Modern biomimicry approach – Design Lens

The reader can see that some of the ten commandments are not applicable to the ICT monitoring. For instance, how can the “Remain in balance with the biosphere” or “Shop locally” commandments implemented in an infocommunication system for monitoring purposes? They might have use considering the ICT in general – (Drouant et al. 2014, 38-46) suggest that the “Remain in balance...” commandment can be applied as a sensor system which is responsible for monitoring the environment; “Shop locally” is understood by the authors of mentioned paper as a need to deploy local Content Delivery Networks in order to minimize data transportation energy consumptions; and so on. Nevertheless, applying the ten commandments in a raw form to the specific problem of this thesis is quite complicated and fuzzy. This might also be fair for other narrow industries and problems within them.

In order to facilitate application biomimicry principles in special fields, the Biomimicry Group has introduced a so-called Biomimicry Design Lens (Anonymous 2014), which is continuously being refined to accommodate present needs. This is a set of diagrams, containing foundations of a biomimicry design approach. One of the diagrams, called “Life's principles”, is clearly an evolution of the ten commandments, so it will be useful for the purpose of this thesis. Here is the diagram itself, shown in Figure 4:

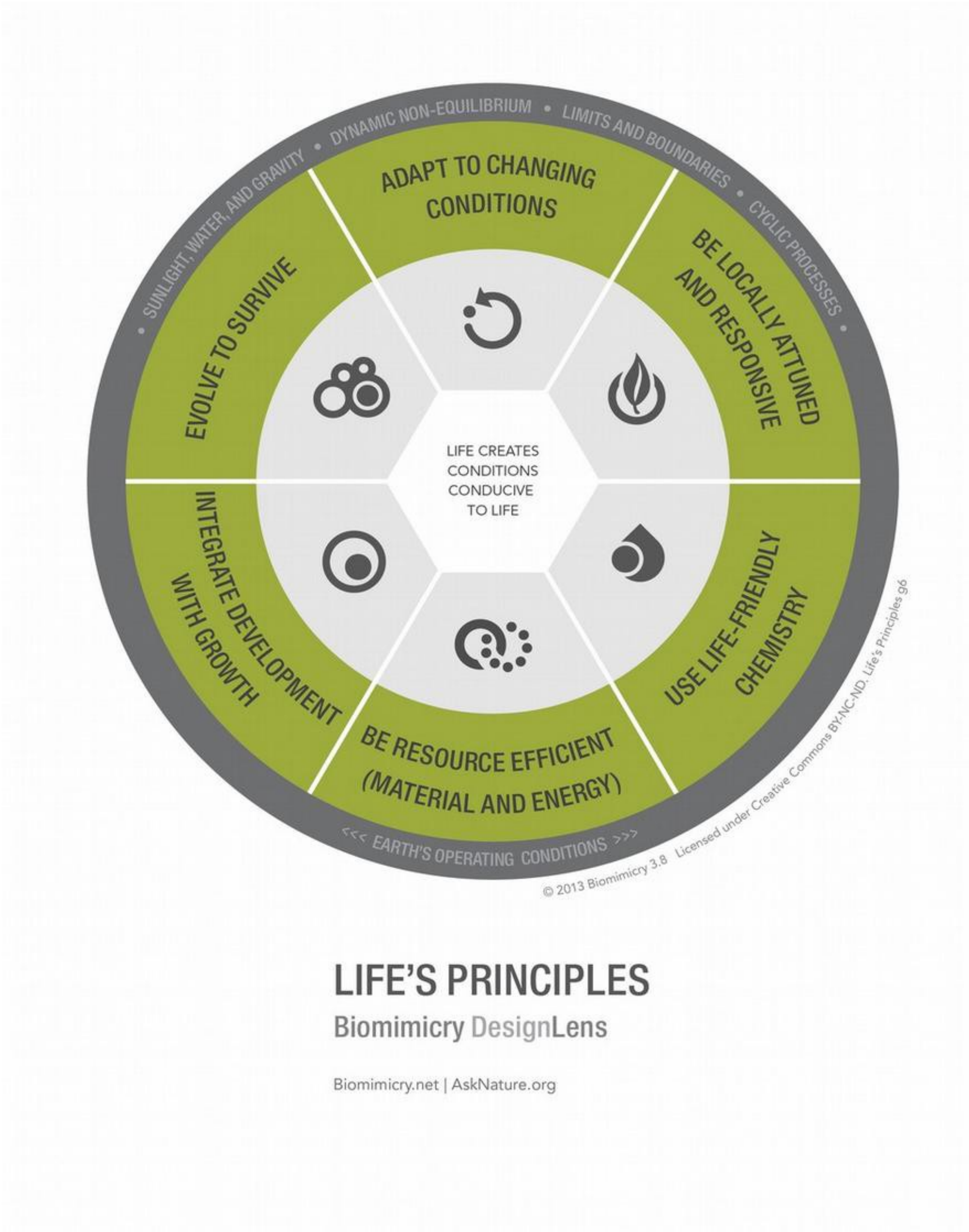

Figure 4 Life's Principles of a biomimicry Design Lens

Correlation between the ten commandments and the Design Lens is complicated. Though their objective is the same – to provide a set of recommendations for developing sustainable products or services – the rule classification is different. Let us discuss what elements the Design Lens is comprised of and how can we apply them in ICT monitoring:

Adapt to changing conditions – this aspect touches upon making systems more robust and resilient. Resiliency, basically, can be achieved by decentralization and redundancy. This is, of course, a task for both design and monitoring: whilst ICT systems designers are fulfilling these conditions in paper, monitoring is devoted to make the concept real and working. The topic of resiliency is quite popular nowadays in research.

Be locally attuned and responsive – this is mainly about establishing cyclic processes, local relationships and prioritizing usage of the local resources. This applies for ICT in general and to ICT monitoring to a certain extent; for instance, cyclic processes are supposed to be a job for a designer (who ensures an appropriate end-of-life treatment), however, the aspect of local resource prioritizing may be considered as a job for monitoring. The reader should remember one of the papers from previous chapter, which is describing FTW/FTS approach – and this is exactly the case for this part of the Design Lens.

Use life-friendly chemistry – such an aspect is, clearly, connected to the resources the products are comprised of, in our case – for ICT appliance. Such appliance contains a large amount of rare materials (which are not quite recoverable in the process of recycling) and in the past it even contained dangerous materials (which are now prohibited to use by RoHS and TCO, discussed earlier). Unfortunately, this issue cannot be solved with monitoring; the only way to improve the situation is to research and develop new recyclable, environment-safe, more common (in a perfect case, renewable) materials (for instance, like in (Chen et al. 2007, 228-232)).

Be resource efficient – the objective of this aspect should be very clear from its title, again. The only detail which is important is that, according to the authors, it includes not only efficiency in resources and energy, but in recycling as well. Nevertheless, monitoring may only solve the issue of resource efficiency; even more, this is the domain, where metering can be applied to the full extent, as demonstrated in the previous chapter. Additionally, authors list here multi-functional design and low-energy processes, which are applied in ICT (as, for instance, server virtualization and energy improvements in microelectronics).

Integrate development and growth – for this one, authors are suggesting several details, and two of them are applicable to the ICT in general. First, systems should combine modular components. Such an idea is already heavily utilized by ICT manufacturers for building appliance – almost entire range of products is built from quite a limited set of chipsets, wireless modules, ports and so on. Indeed, the nomenclature of these standard modules is limited but large, but the progress is clear. Note, that this recommendation is also fulfilled in the software, which is often object-oriented thus containing reusable parts. Secondly, according to the authors, systems should self-organize – and this is right a topic for wireless sensor networks, where independent nodes have to automatically build up a robust network. Indeed, such a paradigm might be used in conventional networks (though the number of nodes is much smaller in this case). In order for the self-organization to be possible, any key parameters have to be monitored.

Evolve to survive – this aspect is dealing with foreseeing unexpected conditions while designing systems, as well as implementing design according to the best practices, which have to be developed enough. These problems are not likely to have any direct relation to ICT monitoring.

As the reader can see, some aspects seem to be missing in the Design Lens compared to the ten commandments. This can be easily demonstrated on a comparative table, listed here as Table 1. In this table, Design Lens aspects represented by columns are to relate to appropriate commandments out of ten once. The relations are two-way. In the table, aspects or commandments not having an appropriate pair are highlighted in red. Take a note that commandment “Don't foul their nests” can be related to aspect “Be locally attuned and responsive” with some degree of a doubt, as the aspects themselves are not clearly explained by the authors; such a relation will be accepted in this thesis work.

Table 2 Relation of the Design Lens aspects to the ten commandments

	Adapt to changing conditions	Be locally attuned and responsive	Use life-friendly chemistry	Be resource efficient	Integrate development with growth	Evolve to survive
use waste as a resource				+		
diversify and cooperate to fully use the habitat	+	+				
gather and use energy efficiently				+		
optimize rather than maximize						
use materials sparingly				+		
don’t foul their nests		?				
don’t draw down resources				+		
remain in balance with the biosphere	+					
run on information		+				
shop locally		+				

Concluding the explanation of the biomimicry approaches, it should be noted that the ten commandments and the Design Lens turned out to be not exactly equivalent – some aspects are missing between them. Still, it is not clear enough which one of them is more useful due to this issue, so both will be applied to the KPIs analysis in the next chapter.

Section 4 Relation between green KPIs and biomimicry

4.1 Relation to the ten commandments

Let the relation be explained one by one.

1. PUE, DCiE

Relation of PUE and DCiE to the ten commandments is identified by their purpose. As far as they touch upon the issues of better energy utilization in datacenters, these two metrics can definitely be classified as belonging to the commandment “Gather and use energy efficiently”. In this way, the PUE or DCiE values relate to the commandments in the following form:

$$\left(\frac{1}{PUE} = DCiE\right) \propto \textit{Gather and use energy efficiently} \tag{25}$$

2. CUE

It is possible to state that CUE is addressing commandment “Don’t foul their nests” as it is dealing with non-desired subsidiary product of energy production. Their mathematical relation is therefore described as:

$$\frac{1}{CUE} \propto Don't\ foul\ their\ nests \tag{26}$$

3. WUE

In spite of the fact that WUE is close to the CUE, it’s relation to the commandments is slightly different. WUE is definitely addressing commandment “Use materials sparingly”, as it is dealing with usage effectiveness of basic resources, which do not include energy. WUE_{source} is compatible with this commandment as well. Additionally, WUE_{source} is working within boundaries of commandment “Gather and use energy efficiently”, as it is directly taking into account water consumption for energy production. Their relation to the commandment is:

$$\left(WUE = WUE_{source}\right) \propto Don't\ foul\ their\ nests \quad (27)$$

4. ERE, ERF

As for classifying ERE and ERF by the commandments, their targets differ a little. ERE is addressing the issue of both energy usage and reusage. It is still connected to PUE thus showing how efficiently the given datacenter is using the energy for its primary task – computing; at the same time, it accounts energy reused in any form. Hence, we can classify it as belonging to “Use waste as a resource” and “Gather and use energy efficiently”. Meanwhile, the ERF does not have any relation to PUE and it is only showing the reused energy fraction. In this way, ERF only implements the “Use waste as a resource” commandment. Their relation is:

$$\frac{1}{ERE} \propto Gather\ and\ use\ energy\ efficiently \quad (28)$$

$$\frac{1}{ERE} \propto \textit{Use waste as a resource} \qquad (29)$$

$$ERF \propto \textit{Use waste as a resource} \qquad (30)$$

5. DCeP

Though DCeP is not very similar to other energy-concerned metrics, it is still showing how efficient is the datacenter per unit of energy consumed. Clearly, this is describing how effectively the energy is used for a job, in this case – for performing computations of any kind. Hence, the suitable commandment here is “G ather and use energy efficiently”. The relation of DCeP to the commandment is:

$$DCeP \propto \textit{Gather and use energy efficiently} \qquad (31)$$

6. GEC

Green Energy Coefficient is most probably connected with commandment “Don’t foul their nests”. The percentage of green energy to the entire energy produced is, clearly, defining the degree of GHG emissions (as well as many other subsidiary effects) required to run the datacenter. Hence, GEC is relating to the commandment as:

$$GEC \propto \textit{Don't foul their nests} \qquad (32)$$

7. EDE

It's relation to the commandments is clear enough – the metric is dealing to issues of useful materials recycling and environmental contamination in the process of disposing the hardware and after it. Hence, we can consider EDE as implementing commandments "Use waste as a resource" and "Don't foul their nests". The metric is proportional to its commandments in the following way:

$$EDE \propto Use\ waste\ as\ a\ resource \quad (33)$$

$$EDE \propto Don't\ foul\ their\ nests \quad (34)$$

8. "Powering a data center network via renewable energy: A green testbed"

The metrics (12) and (13), proposed in this paper, are helping to assess the energy consumption of different procedures of a computing facility. Hence, it is feasible to classify those metrics as compliant with commandment "Gather and use energy efficiently". As such, the relations are:

$$\frac{1}{P_v} \propto Gather\ and\ use\ energy\ efficiently \quad (35)$$

$$\frac{1}{P_m} \propto Gather\ and\ use\ energy\ efficiently \quad (36)$$

It should be noted and interpreted carefully that, in fact, P_v is not exactly implementing the commandment listed – it says "...efficiently", but the metric does not take into account any kind of performance. Therefore, it might be possible to decrease the power P_v on dramatic expense of performance, which will not be compliant with the commandment anymore.

Besides, the paper is using the metrics in order to implement Follow The Wind/Follow The Sun approach, thus it is also good to relate them to commandment “Diversify and cooperate to fully use of the habitat”. However, the latter relation is not direct, and such cases will be discussed later on.

9. “Distributed computing for carbon footprint reduction by exploiting low-footprint energy availability”

The model (14) described in that paper is dealing with accounting carbon footprint of various processes of a datacenter. Thus, this case is also compatible with commandment “Don't foul their nests”:

$$\frac{1}{F} \propto Don't\ foul\ their\ nests \tag{37}$$

And, equivalently to previous paper, the focus is held on Follow The Wind/Follow The Sun approach, so “Diversify and cooperate to fully use of the habitat” commandment is applicable here but not directly.

10. “Peam: Predictive energy-aware management for storage systems”

This paper presents a model for predicting energy consumption of a data transmission procedure, and our interest is on the formula (15) for computation energy consumption, as described. Therefore, the commandment compatible with it is a “Gather and use energy efficiently”, clearly.

$$\frac{1}{P_c} \propto \textit{Gather and use energy efficiently} \qquad (38)$$

As with KPI (12), this one does not elaborate on efficiency, so its relation to the commandment listed is somewhat arguable.

Again, the paper actually presents a more global objective, and this objective implements another commandment – “Optimize rather then maximize”, because such parameters as transmission time and compression overhead for computing are sometimes inversely proportional.

11. “Monitoring and assessing energy consumption and CO2 emissions in cloud-based systems”

Two groups of metrics are highlighted from this paper: for virtualization layer and for application layer. Metrics from these layers are correspondingly equivalent, thus will be considered here once.

First, the VM- and A- PUE (16), (19) (either VM-layer or application layer) is conveying the approach of original PUE thus also conveying the same commandments implementation – “Gather and use energy efficiently”.

N ext, VM- and application-layer Energy Productivity (17), (20) are equivalent to DCeP in their objective, thus are compatible with commandment “Gather and use energy efficiently”.

Finally, Green Efficiency for both layers (18), (21) are very similar by design to the GEC, hence implementing the “Don’t foul their nests” commandment.

Their mathematical relation can be written as follows (remember, KPIs here are listed once per type):

$$\frac{1}{*\text{-}PUE} \propto \textit{Gather and use energy efficiently} \tag{39}$$

$$*\text{-}EP \propto \textit{Gather and use energy efficiently} \tag{40}$$

$$*\text{-}GE \propto \textit{Don't foul their nests} \tag{41}$$

12. “Designing green network architectures using the ten commandments for a mature ecosystem”

The paper already contains good analysis of the KPIs introduced regarding the ten commandments, so the results of it will be listed here. The KPI on recyclability – equation (22) – is elaborating on commandment “Use waste as a resource”; KPI on energy consumption – equation (23) – is implementing commandments “Gather and use energy efficiently” and “Don’t draw down resources”; KPI on pollution – equation (24) – implements commandment “Don’t foul their nests”. In more detail, the relation can be written as follows:

$$\Gamma \propto \textit{Use waste as a resource} \tag{42}$$

$$\frac{1}{E} \propto \textit{Gather and use energy efficiently} \tag{43}$$

$$\frac{1}{E} \propto \textit{Don't draw down resources} \tag{44}$$

$$\frac{1}{\Phi} \propto \textit{Don't foul their nests} \tag{45}$$

It is useful to represent all this analysis in a table, where the relation is more informative; for this purpose, Table 2 will be used. Note, that commandments not represented by any KPI are highlighted in red.

Table 3 Relation of the KPIs found to the ten commandments of a mature ecosystem

	use waste as a resource	diversify and cooperate to fully use of the habitat	gather and use energy efficiently	optimize rather then maximize	use materials sparingly	don't foul their nests	don't draw down resources	remain in balance with the biosphere	run on information	shop locally
PUE (1)			+							
DCiE (2)			+							
CUE (3)						+				
WUE (4)					+					
WUE src (5)					+					

Table 3 Relation of the KPIs found to the ten commandments of a mature ecosystem

	use waste as a resource	diversify and cooperate to fully use of the habitat	gather and use energy efficiently	optimize rather then maximize	use materials sparingly	don’t foul their nests	don’t draw down resources	remain in balance with the biosphere	run on information	shop locally
ERE (6)	+		+							
ERF (7)	+									
DCeP (9)			+							
GEC (10)						+				
EDE (11)	+					+				
Pu (12)			+							
Pm (13)			+							
F (14)						+				
Pc (15)			+							
VM-PUEik (16)			+							
VM-EPik (17)			+							
VM-GEik (18)						+				
A-PUEi (19)			+							

Table 3 Relation of the KPIs found to the ten commandments of a mature ecosystem

	use waste as a resource	diversify and cooperate to fully use of the habitat	gather and use energy efficiently	optimize rather then maximize	use materials sparingly	don’t foul their nests	don’t draw down resources	remain in balance with the biosphere	run on information	shop locally
A-EPi (20)			+							
A-GEi (21)						+				
Γ (22)	+									
E (23)			+				+			
Φ (24)						+				

4.2 Sustainable KPIs and the Design Lens

Analysis of the KPIs, used in this thesis, regarding their sustainability potential have been already investigated in previous sections. Since then, it seems to make sense to contract the explanation of the relation between KPIs and the Design Lens into a table with commentaries.

Table 4 Relation of the KPIs found to the Design Lens aspects

	Adapt to changing conditions	Be locally attuned and responsive	Use life-friendly chemistry	Be resource efficient	Integrate development with growth	Evolve to survive	Commentary
PUE (1)				+			PUE demonstrates that computing facility is spending as much energy on computing as possible, so this is about resource efficiency.
DCiE (2)				+			DCiE is based on PUE, so the same classification applies.
CUE (3)		+					This metric is about carbon emissions, so implies responsibility to the environment.
WUE (4)		+		+			WUE touches upon water usage at a computing facility, thus can be classified to the resource efficiency aspect.
WUE src (5)				+			The same, as in case of WUE.

Table 4 Relation of the KPIs found to the Design Lens aspects

	Adapt to changing conditions	Be locally attuned and responsive	Use life-friendly chemistry	Be resource efficient	Integrate development with growth	Evolve to survive	Commentary
ERE (6)				+			ERE is about reusing the dissipated or emitted energy, which was first consumed by computing facilities. Though this metric was implementing two different commandments out of the ten, in Design Lens single aspect completely describes it alone.
ERF (7)				+			ERF is also about reusing the energy, so it is classified in the same way as ERE. However, the reader can notice that green aspects somewhat differ between ERE and ERF, which is reflexed by the ten commandments, but not by the Design Lens.
DCeP (9)				+			DCeP is demonstrating how much performance is produced over a kW of energy used, so it is definitely about resource usage efficiency.

Table 4 Relation of the KPIs found to the Design Lens aspects

	Adapt to changing conditions	Be locally attuned and responsive	Use life-friendly chemistry	Be resource efficient	Integrate development with growth	Evolve to survive	Commentary
GEC (10)		+					This metric concerns the amount (more precisely, a share) of an energy used which is produced from renewable resources. It is indirectly connected to carbon emissions (plus possibly other emissions) and, hence implements environmental responsibility aspect.
EDE (11)		+		+			Disposal is considering two issues: materials recycling and decreasing landfilling. Thus, EDE can be classified to two aspects of the Design Lens.
Pu (12)				+			From now on, metrics are considering energy, except metrics (18) and (21). Hence, the rest can be classified to the resource efficiency aspect.
Pm (13)				+			See explanation for (12)
F (14)				+			See explanation for (12)
Pc (15)				+			See explanation for (12)

Table 4 Relation of the KPIs found to the Design Lens aspects

	Adapt to changing conditions	Be locally attuned and responsive	Use life-friendly chemistry	Be resource efficient	Integrate development with growth	Evolve to survive	Commentary
VM-PUEik (16)				+			See explanation for (12)
VM-EPik (17)				+			See explanation for (12)
VM-GEik (18)		+					This metric is representing energy share, produced from renewable resources (equivalent to GEC from The Green Grid). Hence, VM-GEik is implementing the aspect about local responsibility
A-PUEi (19)				+			See explanation for (12)
A-EPi (20)				+			See explanation for (12)
A-GEi (21)		+					See explanation for (18)

Table 4 Relation of the KPIs found to the Design Lens aspects

	Adapt to changing conditions	Be locally attuned and responsive	Use life-friendly chemistry	Be resource efficient	Integrate development with growth	Evolve to survive	Commentary
Γ (22)				+			Recyclability metric, according to the authors of this one, elaborates on waste disposal. Hence, it implements aspect for resource efficiency.
Ε (23)				+			Authors have proposed relation to two commandments, but Design Lens brings them together to an aspect about resource efficiency – which is fair.
Φ (24)		+					Pollution metric is about responsibility for environment, so, clearly, this KPI belongs to local responsibility aspect.

As the reader can see, the metrics presented are covering only a small fraction of the whole Design Lens concept. Taking into account the outcome of the aspects in Design Lens, this situation is quite fair; however, previous section contains examples of potential metrics which implement the remaining aspects (for instance, regarding resilience and “Adapt to changing conditions”). Such metrics are not commonly considered as green, but nevertheless they are sustainable, so they have to be also considered when using the biomimicry approach.

Section 5 Conclusion

Computer networks volumes has been growing very fast since their invention. As the reader could see, there is no expectation for this domain to slow down. Nevertheless, the efforts to decrease environmental influence of ICT, which grows together with the domain itself, were mainly revolving around making separate network elements to consume less energy. This approach is indeed producing noticeable results, but clearly there are other ways to be investigated to achieve greenness of an ICT domain.

Using the QoS concept and network monitoring techniques to enhance its greenness is a little step on the way of making the networking domain sustainable. Yes, it is not a big leap; papers, presented as the base for this thesis suggest that methods introduced provide great results, however, reader might remember that the general objective for humanity and for all the domains of our life is to become sustainable – and sustainability does not only consider environmental issue. Moreover, environmental issue itself does not only consider resource usage and pollution.

The reader can observe the tables which are relating the ten commandments and the Design Lens to the KPIs presented. One thing which is common for both is that most of the aspects or commandments are not implemented by KPIs in any of the ways. Of course, the general findings (which are based on the KPIs) proposed by the papers might implement some of the missing aspects, but this does not change the situation. It seems that network monitoring cannot solve the sustainability issue in ICT alone, so other methods are required.

Nevertheless, one of the assumptions has been confirmed. The assumption that the biomimicry might be a good framework to assess sustainability of an ICT system seems to be true. It brings systematics into research and represents a good methodology for integrating various aspects o f complex systems such as ICT. Besides, biomimicry is based on the ideas of green and sustainable development, so it is particularly useful for applications such as in this Master thesis work.

But, this is not equally true for two different methods presented. For instance, the idea of the ten commandments is covering different aspects of sustainability in a more fine grain. Using ten commandments as a framework is definitely helping to classify and track different efforts devoted to enhance small parts of a sustainability issue. Yet many of this “grains” are not quite applicable to ICT which casts a little doubt on its use in this exact domain.

As for the Design Lens, on the other hand, which is intended to be the official biomimicry methodology – it did not work very good in the research due to another reason. Yes, it does make more sense to be utilized in systems such as ICT, but the diagram itself contains just several aspects each one with very broad sense. The issue here is that careful explanations regarding Design Lens are only available from commercial courses, so hardly available for the community. Due to this, usage of such methodology for tracking sustainability research is also a little complicated.

Concluding on the methodologies, Design Lens seems to be more appropriate for classifying metrics and other efforts in ICT in general and network measurements in particular. Its aspects are covering sustainability in much more formalized way, so it's application is more convenient and useful. Yet, Design Lens requires more details to be defined – either by community or by the authors. Regardless of the quality of current frameworks, the general idea is definitely interesting for validating the Planet-imposed requirements in a sustainable system. Even at this point of sustainable frameworks development, they already cover most of sustainability issues in a nice way, thus providing a good tool to develop and validate green requirements.

All in all, now we can observe a large interest to the sustainability in many areas, including ICT. It may not be clear yet how to achieve this goal, but hopefully the interest will continue to grow and we might have a chance to observe a great development and fascinating breakthroughs, making ICT more sustainable, and our society – more responsible.

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