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Data Center Energy Retrofits

Mikko Pervilä

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University of Helsinki
Finland

Supervisor
Jussi Kangasharju, University of Helsinki, Finland

Pre-examiners
S. Keshav, University of Waterloo, Canada
Prashant Shenoy, University of Massachusetts, USA

Opponent
Jon Crowcroft, University of Cambridge, UK

Custos
Jussi Kangasharju, University of Helsinki, Finland

Contact information

Department of Computer Science
P.O. Box 68 (Gustaf Hällströmin katu 2b)
FI-00014 University of Helsinki
Finland

Email address: info@cs.helsinki.fi
URL: http://www.cs.helsinki.fi/
Telephone: +358 9 1911, telefax: +358 9 191 51120

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Mikko Pervilä

Department of Computer Science
P.O. Box 68, FI-00014 University of Helsinki, Finland
pervila@cs.helsinki.fi
http://www.cs.helsinki.fi/u/pervila/

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Abstract

Within the field of computer science, data centers (DCs) are a major consumer of energy. A large part of that energy is used for cooling down the exhaust heat of the servers contained in the DCs. This thesis describes both the aggregate numbers of DCs and key flagship installations in detail. We then introduce the concept of *Data Center Energy Retrofits*, a set of low cost, easy to install techniques that may be used by the majority of DCs for reducing their energy consumption.

The main contributions are a feasibility study of direct free air cooling, two techniques that explore air stream containment, a wired sensor network for temperature measurements, and a prototype greenhouse that harvests and reuses the exhaust heat of the servers for growing edible plants, including chili peppers. We also project the energy savings attainable by implementing the proposed techniques, and show that global savings are possible even when very conservative installation numbers and payback times are modelled.

Using the results obtained, we make a lower bound estimate that direct free air cooling could reduce global greenhouse gas (GHG) emissions by 9.4 $\mathrm{MtCO_2e}$ already by the year 2005 footprint of the DCs. Air stream containment could reduce the GHG emissions by a further 0.7 $\mathrm{MtCO_2e}$, and finally heat harvesting can turn the waste heat into additional profits. Much larger savings are already possible, since the DC footprint has increased considerably since 2005.

Computing Reviews (1998) Categories and Subject Descriptors:

B.8 Performance and Reliability
B.8.1 Reliability, Testing, and Fault-Tolerance

General Terms:

Ph.D. thesis, data centers, energy efficiency, sustainable computing, green ICT

Additional Key Words and Phrases:

free cooling, heat harvesting, air stream containment

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By its nature, data center operation is a combinatory field of very diverse areas of expertise. Thus, I have had the duty and pleasure of obtaining knowledge, materials, and skills from a great many individuals from different departments, institutions, and companies.

From the Department of Computer Science, University of Helsinki I would like to thank first and foremost the staff of the Computing facilities: Petri Kutvonen, Pekka Niklander, Ville Hautakangas, Onni Koskinen, Jani Jaakkola, and Pasi Vettenranta. Without the tenacity of our IT crowd I would have probably never been able to scavenge all the components required for the different experiments. Teija Kujala provided me with a splendid and quiet little corner to read in when I had to recognize that an open office space was very counterproductive for a solitary researcher. Mikko Rantanen provided his considerable technical skills derived from his many years in the industry. Jukka Suomela has repeatedly been very helpful in finding the correct tools for my trade. Julien Mineraud wrote the tssgpub package that generates the splash pages and publication lists in this thesis. I am also grateful for the patience and feedback from members of the Collaborative Networking group. Finally, Tiina Niklander was a great mentor during my early years at the department.

The Helsinki Institute for Information Technology (HIIT) was also instrumental in building our oddball prototypes: Pekka Tonteri, Markus Nuorento, and Sami Niemimäki were always there to give ideas and feedback when I ran into trouble. Especially Pekka Tonteri went far beyond the expected while supporting my endeavours. Without them, building our CAC setups would have reminded more of constructing a piece of Swedish furniture without schematics, tools, or the right amount of components.

The University's Technical services also deserve a great many thanks not only for their construction skills, but also for their understanding and tolerance of letting us build on the roof of the Exactum building. Nothing much would have ever been built without Timo Ojanen. Likewise, I'm extremely thankful for Pirjo Ranta, Markku Hyytiä, and especially Olli

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The neighbouring Department of Physics formed a beacon of knowledge whenever my research had to connect with the surrounding real world. Especially Pasi Aalto and Eki Siivola deserve my thanks. Sampo Smolander was a terrific go-to guy whenever I had no idea who to talk to. Tomas Lindén and Pekko Metsä from their IT Department delivered both much needed materials and contacts in the true spirit of interdepartmental cooperation.

The greenhouse would never have been possible without the support of the Fifth Dimension project and our cooperation partners: Marja Mesimäki, Gosia Gabrych, Leena Lindén, Kari Jokinen, Daniel Richterich, Sini Veuro, Ulf Hjelm, Taina Suonio, and Susanna Lehvävirta. Lassi Remes filled in many of the gaps in my knowledge of greenhouses, which is to say that the exceptionally good harvest we got was mostly thanks to him.

My gratitude also goes to members of the industry who lent us their knowledge and materials at crucial times of the project. From Rittal, Marko Ruokonen, Jari Peltonen, and Pasi Kinnunen. From Dell, Pekka Vienola. From Windside, Risto Joutsiniemi and Marja Vähäsarja. From Unicafe, Katja Knuutinen and Miika Siekkinen. From Halton, Risto Kosonen. From Helen, Juha Sipilä for providing us with industry contacts we would have not made otherwise. And from CSC, Joni Virtanen and Peter Jenkins for providing us with both hardware and information in great quantities.

Members of the Metropoli Bulletin Board System once set me on the path of system administration. Through our many online discussions, I learned the basics of critical thinking, logical argumentation, and the tenets of the hacker ideals. Teppo Oranne was the grand old man of the BBS, and I have tried to keep in mind his many personal histories from the ICT industry. Johan Ronkainen has repeatedly taught me that true professional skill comes not (only) from schools, but from personal dedication and time spent training.

For their thorough reading and timely comments, I thank my pre-examiners S. Keshav and Prashant Shenoy. Similarly, Samu Varjonen and Mikko Pitkänen did a thorough job of reading the thesis, and provided plenty of suggestions and requests for clarifications. Jussi Kangasharju has remained an excellent supervisor throughout the research that has lead to this thesis. I could not have wished for more freedom from my boss and professor.

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In Helsinki, November 4th, 2013

Mikko Pervilä

Contents

List of Reprinted Publications

In each of the five publications contained in the thesis, I have emphasized the low cost and easy installation of the proposed improvements. In all cases, we have built real prototypes and verified them to work consistently and continuously. My personal contributions in each of the publications are as follows.

Free Cooling

Research Paper I: Mikko Pervilä, Jussi Kangasharju, "Running Servers around Zero Degrees," In ACM *SIGCOMM Computer Communication Review*, Volume 41, Issue 1. ACM, 2011, pp. 96-101, DOI http://dx.doi.org/10.1145/1925861.1925877.

> *Contribution:* I did the major parts of the work alone. Prof. Kangasharju supervised my work and did minor editing of the text. Figure 2 in was also done by him. I had some help in the physical construction phases as indicated by the acknowledgment section. Otherwise, the installation, design of the experiments, analysis of the results, the text, and figures were done by me.

Air Stream Containment

Research Paper II: Mikko Pervilä, Jussi Kangasharju, "Cold Air Containment," In *Proc. 2nd ACM SIGCOMM workshop on Green networking (GreenNet 2011).* ACM, 2011, pp. 7–12, DOI http://dx.doi.org/10.1145/2018536.2018539.

> *Contribution:* I did the major parts of the work alone. Mikko Rantanen designed and implemented the power measurement solution described in Sect. 3.1 of the publication. Prof. Kangasharju supervised my work and did minor editing of the text. Figure 2 was done according to my specifications by Janne Ahvo and used with permission. I had some help in the physical construction phases as indicated by the acknowledgment section. Otherwise, the design of the experiments, hardware choices, analysis of the results, writing, and figures were done by me.

Research Paper III: Mikko Pervilä, Mikko Rantanen, Jussi Kangasharju, "Implementation and Evaluation of a Wired Data Center Sensor Network," In *Energy Efficient Data Centers*, LNCS Vol.7396, pp. 105–116, DOI http://dx.doi.org/10.1007/978-3-642-33645-4_10.

> *Contribution:* The design and installation of the wired sensor network was performed as joint work with Mikko Rantanen. Prof. Kangasharju did minor edits of the text. Otherwise, the concepts, design of the experiments, analysis of the results, writing, and figures were mine.

Research Paper IV: Mikko Pervilä, Jussi Kangasharju, "Underfloor Air Containment," In *Proc. 2nd IEEE Online Conference on Green Communications (GreenComm 2013).* IEEE, 2013.

> *Contribution:* I did the major parts of the work alone. Prof. Kangasharju supervised my work and did minor editing of the text. He also did a part of the analysis regarding the GHG emissions of the entire ICT field mentioned in paragraph 1 of the introduction. I had some help in the physical construction phases as indicated by the acknowledgment section. Otherwise, the concepts, hardware choices, design of the experiments, analysis of the results, writing, and figures were done by me.

Harvesting Heat

Research Paper V: Mikko Pervilä, Lassi Remes, Jussi Kangasharju, "Harvesting Heat in an Urban Greenhouse," In *Proceedings of the first workshop on Urban networking - UrbaNe '12.* ACM, 2012, pp. 7–12, DOI http://dx.doi.org/10.1145/2413236.2413239.

Contribution: Lassi Remes chose the initial set of the plants, planted them with his spouse, and later advised on the use of pesticides & fertilizers. He also judged which plants survived the winter (not included in this paper). A number of volunteer workers helped in watering the plants. Prof. Kangasharju did some minor edits of the final text. Timo Ojanen advised on the design of the greenhouse, and a paid worker did more than half of the construction. Otherwise, the idea, design of the experiments, analysis of the results, writing, figures, and further projections were done by me.

Chapter 1

Introduction

The quote below is from "The History of Early Computing at Princeton", *Turing Centennial Celebration*, by Jon R. Edwards [19]. It describes the power and cooling solution of the electronic computing machine in operation at the Institute for Advanced Study (IAS) in Princeton ca. year 1952. The project was supervised by John von Neumann.

> "To meet the power requirements of the computer and its associated equipment, a 200 ampere feed was installed from the main building load center to the machine location. A closed circuit air cooling system provided clean, low humidity cooling air to the machine. Air was blown through a floor duct into the base of the computer, rising through it, and exhausting through a ceiling duct, returning through an exhaust blower air filter and cooling coils to the floor duct again. Two remotely located 7 $\frac{1}{2}$ ton compressors provided a year-round cooling operation."

It is very fascinating to note that so little has changed in the field in over 60 years. While liquid cooling solutions [65] have become available for the most power-intensive applications, air cooling remains the relatively safer, easier to install, and cheaper at scale alternative. The rest of the description still matches the best practices today. In fact, as we will see in chapter 2, the situation in many data centers (DCs) can be worse than in 1952 at the IAS.

In 2010, when we began work on the Exactum data center that would form the basis of most of the publications included in this thesis, nobody had any idea how much energy our DC consumed. The reasons for this were twofold. First, the university department that was paying for the electricity bill was responsible for maintaining the whole building, but not any of the servers. Later on, it turned out that this situation, called *split incentives* due to the conflicting interests of the departments, was widespread even among the industry [23, 55, 102, 109]. Here, as well as at other installations, the function of the DC was considered so important that even a massive power draw was acceptable by comparison.

Second, metering the power draw of the DC turned out to be a troublesome task in the sense that no off-the-shelf machine readable solutions were available. Even after extensive talks with a number of different vendors, the alternatives were less than perfect. The most far-fetched solution proposed involved uploading our data to a smart metering district grid and then purchasing the power usage measurements as an online service from a third party. We ended up reading our meters with two laptops using RS-232 serial cables soldered directly to phototransistors, which were then attached to the LED pulses of the meters. The lesson learned was this: still in 2010 data center research was a field that lacked readily documented solutions for the most common problems.

Yet a number of very large data centers had already been in operation for more than ten years. Their inner workings were just not made publicly available. Edwards' history of the IAS documents another clue to the reasons behind this. Early on in its design process, a decision was made by von Neumann and Goldstein to keep as much as possible of the materials concerning the machine's installation and operation in the public domain. This was done in order to avoid the problems caused by a number of the earlier ENIAC's parts having been patented. By releasing reports into the public domain, the idea was to enable other universities and institutions to build their own computing machines and improve on the general design.

While most of the computing machinery in 1952 was installed in government institutions, the largest DCs today are operated by IT companies. As new improvements in DC operation can quickly give a significant edge on a company's competitors, most ideas tend to be only sketchily published. One reason why they are published at all is that since at least 1999 [23, 48], DCs have been increasingly scrutinized by the public for their energy consumption and efficiency. Publishing information about the so-called flagship facilities has enabled IT companies to "green-wash" their DC operation by implying that *all* of their facilites employ the best-in-show techniques.

A tip-of-the-iceberg analogue is not wildly inaccurate: the industry giants know a lot about the best practices available, but only a few select items pass the veil of non-disclosure agreements. This theme of secrecy and partial availability pervades most of the work contained in this thesis. Background research has included browsing white papers, popular articles, and other anecdotal evidence concerning the most advanced data centers in the world. Putting it bluntly, while DC research is a fascinating topic, it can be frustrating when any request for data is met with a committee meeting considering why *not* to publish. We have thus tried to independently verify and document the missing pieces of techniques like free cooling (Pub. I) and cold aisle containment (Pub. II). These experiments have required us to build our prototypes from scratch. By doing so we are now able to present low-cost, easily installable solutions with quick payback times for those DC operators without their own research and development divisions.

1.1 Background and Motivation

There are two main methods of justifying research into the energy efficiency of DCs, or most parts of the ICT field in general. The first is money, since all current forms of computing automation draw power, which incurs a cost in the form of the electricity bill. The second is sustainability, for as the amount of computers scales upwards, so does the global use of energy that can be attributed to computing. The research field has alternatively been called "Green ICT"[1], "Sustainable Computing", or variations thereof. Regardless of its name, this type of research studies the energy used by the edge of the network, its core, and all interconnects between the two.

The edge of the network includes all stationary and mobile clients used for computing-related purposes. It usually excludes "home entertainment", typically meaning TVs, video projectors, audio subsystems, and some forms of video gaming consoles. Especially the last category is becoming increasingly contested as all current gaming consoles are able to connect to online services. The devices at the edge of the network typically draw less power than the servers they connect to, but there are many more clients. Therefore, the total energy consumed by making, shipping, operating, and recycling the clients quickly rises at scale.

Clients connections occur through a very diverse set of last-mile connection uplinks, including all forms of digital subscriber line (DSL) connections, WLANs, and other mobile data transmission pathways. Whereas mobile clients must be extremely stringent in the energy used for transmissions, fixed endpoints do not. The access networks must be constantly available, their power usage is more or less constant regardless of the amount of clients online. It is this always-on manner of operation which has led to a number of studies into minimizing the amount of concurrent links between two

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[1] As American dollars are colloquially known for their green coloring, there is a fitting double entendre in this title.

nodes in the network. Unfortunately, eliminating the built-in redundancy also endangers the fault tolerance of the networks, as both link failures and client usage patterns are difficult to predict.

Once the clients have navigated the interconnect network, they can request services from servers said to be located at the network core. In fact, there are many networks and many cores, but the terminology applies neatly whenever many servers are colocated. When multiple servers are piled up next to each other, new problems start to surface. These include the effects of failure rates showing up as almost daily individual hardware faults, but also problems with congestion, competing data transmission characteristics, and unlikely events affecting large sets of servers at once [6, 15].

Perhaps the easiest problem to understand is the combined power draw at the network core. As a single server should, optimally, handle as many clients as possible, the servers draw more power than the individual clients. All of the power draws transform into heat, which quickly accumulates near the servers. Hence, not only must the heat be eliminated, but the cooling apparatus for doing so consumes more power, which in turn turns to more heat. The combined power usage quickly dwarfs both individual clients and the access network's power usage, but perhaps not their combined efforts as the number of clients adds up.

Due to the fact that so much of the ICT field remains wrapped in non-disclosure agreements and prohibitions to publish, it is difficult to generalize which of the three parts of the network draws the most power. That is not to say that there would not have been very broadly circulated numbers about the global energy use and greenhouse gas (GHG) emissions caused of the ICT industry. It is just very difficult to find scientific, accurate, reproducible, and open sources for data.

1.1.1 Global Figures

The most quoted figure comes from the Gartner, a company that specializes in industry analytics. In 2007, they published a report [27] that estimated the global CO_2 emissions caused by the ICT industry as 2% of the global total. The report also mentioned that "[the] figure [was] equivalent to aviation", and that despite the positive effects from the use of ICT, this amount was unsustainable. When in 2008 the SMART 2020 report [109], produced by the Global e-Sustainability Initiative (GeSI), verified Gartner's analysis, the 2% figure became more or less an accepted fact. It is common in the motivation of conferences, workshops, and introductions to academic articles. Our publications are not exceptions to this.

Regardless of their circulation, both the Gartner and SMART 2020 reports are, by design, popular articles. Unfortunately this means that their scientific credibility is somewhat questionable with regards to reproducibility. In Gartner's case, the report is assembled by analysts who remain unknown, and no assumptions, calculations, or data is presented to reinforce the 2% figure. While the lack of these details would bar scientific publication, in Gartner's case they are company secrets, for the analysts make a profit of selling their reports. The SMART 2020 report is certainly more open in its approach, but many of their sources remain anonymous and thus, unverifiable.

These issues are perhaps inherent to the nature of market analysis, as many of the industry sources would not want to disclose the full set of data for open academic studies. Therefore, to motivate the scope of the problem, one can either disregard the popular figures completely, or accept their faults and choose to believe in their *relative* values. Barring further evidence, this thesis takes the latter standpoint. This may lead to three kinds of problems. The first is that the global figures are correct by accident, even though their calculations are unverifiable and, perhaps, erroneous. Second, the figures may underestimate the problem, and the GHG emissions caused by ICT are larger than 2%. In both of these cases, research into energy efficiency is justified. Third, it may happen that the figures overestimate, and the problem is much smaller. But even in this case the proposed solutions will reduce energy consumption, and will subsequently have an impact on the cost of DC operation.

Government agencies have also adapted to citing market analysis figures [5, 10, 23]. Their reports typically focus on single country and are published at intervals of three years or more. In a very rapidly changing field, the publication interval makes the accuracy of these reports problematic. One regularly cited source for further analysis is J. Koomey. In particular, his book, "Cold Cash, Cool Climate" [54] contains a comprehensive survey of scientific articles that motivate research into the sustainability of the ICT field. In the interest of maintaining a neutral tone, this thesis will focus on the energy savings only as efficiency improvements, and not consider the larger ecological situation. Despite this, it must be mentioned that both evidence for and belief in the climate change has added up at an extraordinary pace since work on Pub. I started.

While surveying research about the climate change, it is easy to fall into thinking that even in global energy usage, we should find and optimize the common case first. This implies that there would be a field or mode of operation which produces the highest number of emissions by a clear margin to the rest. Logic follows that we should concentrate our efforts into finding this culprit and then optimize it for the maximum reductions with the minimum effort.

Unfortunately, the available sources seem to contradict this line of thinking. Based on the available data, Koomey has projected the total power used by DCs as only 1.0% of the world electricity consumption in 2005 [51]. Likewise, the U.S. Environmental Protection Agency (EPA) estimated DC energy consumption in the U.S. as 1.5% in 2006 [23]. The growth rate for the period 2000–2005 was 16.7%, but for the period 2005-2010 only 12% [51] per year. The projections were updated in 2011 to reflect the most recent data. The global consumption of DCs was estimated as between 1.1% and 1.5% in 2010 [52], while the U.S. consumption had risen to between 1.7% and 2.2%. A reduction in the growth rate was attributed to the economic downturn[2] in 2008, leading to smaller numbers and fraction of installed low-end or *volume* servers.

The growth rates are especially important for two reasons. The first reason is that the DC field is not growing uncontrollably, which is the sensationalist approach taken by some early articles [48]. The second reason is that the growth rates project whether the global energy usage of the ICT equipment eventually reduces the combined usage of other fields ICT can be used to optimize. Namely, the key finding of both Gartner and the SMART 2020 report [27, 109] was that even though the combined energy used by all fields of ICT was comparable to a well-known culprit, the global aviation industry, the net effect of increased ICT was beneficial to the global situation. SMART 2020 further expanded that the use of ICT helps optimize and reduce the power draws of other consumers of energy, e.g., industrial processes, logistics, and maintenance. Such fields include transport and buildings [49], which are always mentioned in broad generalizations about which kinds of energy usage should be optimized first.

1.1.2 Claims and Research Scope

I have come to the conclusion that we should treat the power consumption of *all* parts of ICT systems as another attribute that must be optimized for efficiency, similar to the space and time complexities computer scientists are already familiar with. In particular, this means that there are enough researchers to set to work on different parts of the problems, both in parallel and overlapping. The demonstrated efficiency improvements can then be used to drive decisions on which techniques to implement first. A similar idea has been put forth by Koomey [54], although with the key difference that

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[2] However, Uptime Institute's survey [102] from 2012 presents response data which somewhat contradicts the downturn's effect.

he advocates results through entrepreneurship. Conversely, the techniques outlined in this thesis are in the public domain[3].

The major claim of my thesis is that using the *data center energy retrofits* presented in publications I–V, the majority of DC operators can significantly reduce their energy consumption. While the solutions are probably known for the operators of the largest DCs, the majority of the energy is consumed by a larger number of smaller facilities. If the retrofits are adopted often enough by the smaller facilities, this will have global repercussions. The retrofit materials are intentionally chosen with low capital expenses in mind, so that their payback times remain easy to justify for operators with strict budget limitations.

The scope of this thesis is the core of the network. In the publications that follow we are looking at a subset of the energy usage of DCs, the amount used by their cooling subsystems, and not their internal network topologies or computing distribution algorithms. Due to the secrecy and questionable sources of data available, I do not claim that the cooling system is always the most power-hungry subsystem of a DC, but similarly to DCs and the ICT field in general, cooling is a significant part of the problem. Neither do I claim that DC operation is the major consumer of power, or that it produces the most GHG emissions of the ICT field. I do however claim that the effects of DC power usage are visible on a global scale, and that alone warrants research into this topic. As cooling is a significant part of the problem, at least one thesis should try to solve it.

Finally, the chosen retrofits are *non-invasive*, meaning that no changes are necessary to the internal workload of the DC. This means that my research is complimentary to other approaches which seek to minimize the amount of (unrenewable) energy consumed by the servers. To name a few, these approaches include conserving energy by putting sets of servers [98] or entire DCs to sleep when the user request rate slows down [61], optimal virtual machine placement and consolidation [59], and geographical load balancing based to the availability of renewable energy sources [17, 60].

1.2 Contribution of this Thesis

In each of the five publications contained in the thesis, I have emphasized the low cost and easy installation of the proposed improvements. In all cases, we have built real prototypes and verified them to work consistently and continuously. The individual major contributions of the publications

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[3] Although both hot and cold aisle containment may have been patented in some countries, this does not prevent DC operators from installing containment setups themselves.

are as follows.

In publication I, “Running Servers around Zero Degrees”, I demonstrate that free air cooling is a feasible technique that can function around the year in Helsinki, with the implication that is also feasible in locations further up north. This discovery is very major for DCs, as it means that given a suitable installation location, the power wasted by cooling a DC can be eliminated for most parts of the year. My experiment also shows that condensation is not a problem for air-cooled server hardware, as it remains above the ambient temperature during normal operation.

In publication II, “Cold Air Containment” I verify the performance of a reasonably well known cooling optimization called cold aisle containment (CAC). In our operational DC I demonstrate an efficiency improvement of 20% , meaning that that many more servers could be installed in the DC with CAC. Furthermore, in publication IV, “Underfloor Air Containment”, I improve the efficiency an additional 9%. Both techniques can be used either independently or together. Publication II also presents our prototype implementation of the micro DCs presented by Church et al. [16] that we have named the *Helsinki Chamber* (HC).

Publication III, “Implementation and Evaluation of a Wired Data Center Sensor Network”, presents a very cheap, easy to install, and rugged *wired* DC temperature sensor network. The benefit of such a network is that it enables near real-time monitoring of a DC, allowing operators to discover hotspots and exhaust recirculation much faster than with computational fluid dynamics (CFD) modelling. The sensors can also verify a CFD model.

Last, in Pub. V, “Harvesting heat in an urban greenhouse”, I show that the exhaust heat of even our relatively minor HC prototype can be used effectively to warm a lightweight greenhouse constructed for this purpose. By using the waste heat of the servers, we were able to extend the growing period of many edible plants into the early spring and late autumn in Helsinki. This means instead of wasting the DC exhaust heat, dedicated installations to reuse it can be built both in urban and rural locations. I have documented the edible plant yields on the greenhouse website[4].

1.3 Contributions in the Publications

In publications I, II, and IV the major parts of the work were done by me. Mikko Rantanen designed and implemented the power measurement solution described in Sect. 3.1 of Pub. II. Prof. Kangasharju supervised my work and did minor edits of the texts. Figure 2 in Pub. I was also done

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[4] Available from http://wiki.helsinki.fi/display/Exactum5D

by him. In IV prof. Kangasharju did a part of the analysis regarding the GHG emissions of the entire ICT field mentioned in paragraph 1 of the introduction. Figure 2 of Pub. II was done according to my specifications by Janne Ahvo and used with permission. I had some help in the physical construction phases as indicated by the acknowledgment sections of each paper. Otherwise, the design of the experiments, hardware choices, analysis of the results, writing, and figures were done by me.

In publication III, the design and installation of the wired sensor network was performed as joint work with Mikko Rantanen. Prof. Kangasharju did minor edits of the text. The concepts, design of the experiments, analysis of the results, writing, and figures were done by me.

In publication V, Lassi Remes chose the initial set of the plants, planted them with his spouse, and later advised on the use of pesticides & fertilizers. He also judged which plants survived the winter (not included in this version). A number of volunteer workers[5] helped in watering the plants. Prof. Kangasharju did some minor edits of the final text. Timo Ojanen advised on the design of the greenhouse, and a paid worker did more than half of the construction. Otherwise, the idea, design of the experiments, analysis of the results, writing, figures, and further projections were done by me.

1.4 Structure of the Thesis

This thesis is structured as follows. In Ch. 2 we begin by briefly reviewing the general methods of building data centers. The following Sect. 2.1 defines the key metrics used in evaluation DC efficiency. Then the chapter presents a glimpse of the state of the art in the DC field by surveying some of the flagship facilities (Sect. 2.2) of different DC operators. Further on, the DCs are categorized (Sect. 2.3) according to their intended use and sizes in order to motivate why the majority of the DCs still tend to be operated in rather inefficient manners. Finally, the high-tech installations are compared (Sect. 2.4) with the grim reality of the majority of DCs: small- or medium-scale installations that would most benefit of the techniques presented in this thesis.

Chapter 3 presents the contribution of our work more thoroughly: a set of low-cost, easy-to-install retrofit techniques with very quick payback times for the capital expenses incurred. The techniques are divided into the themes of free air cooling (Sect. 3.1), air stream containment (Sect. 3.2), and heat harvesting (Sect. 3.3). Finally, Sect. 3.4 summarizes our temperature sensor

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[5] Ibid.

network and discusses alternative research approaches than constructing prototype implementations.

Chapter 4 concludes this thesis by first examining the relative costs of the retrofit techniques. It then discusses the relative merits and payback time scenarios in Sect. 4.1. Finally, Sect. 4.2 presents a few research digressions that we either chose not to follow or were unable to do so. These unfollowed paths might provide ideas for future work, for DC energy optimization remains both a hot and cool topic for further research.

Chapter 2

State of the Data Center Art

Data centers are deceptively simple installations when looking at the essentials of making one. For our purposes, a DC is defined as “any space whose main function is to house servers” [51]. First, as the amount of computer servers increases, they are stacked to save floor space. Then, the servers are installed into an external chassis called a rack. Racks permit DC operators to remove a server for maintenance from the middle of the stack without shutting down the other servers. The amount of servers in a rack depends on both the server type and the rack height. When the rack is full, a new one is brought in, and more servers can be installed into it.

Space permitting, multiple racks are installed side-by-side forming a row. As the servers’ air intakes are in their front, the idea is to keep each rack in the row facing the same direction. This limits the hot exhaust air from mixing with the cold intake air. Row length is dictated by floor space and ease of maintenance, as cable connections are normally in the servers’ rear sections. When a row is full, racks are installed in a new row. Now, a simple optimization is to position the new row face-to-face with the first one, so that their air intakes are opposite. This way, the new row’s air intakes can be provided fresh supply air, and not the exhaust of the first row. These two rows form an *aisle* between them, called the cold aisle [105] due to the influx of supply air. When the third row is added, it is positioned so that its exhausts are opposite to either the first or the second row’s exhausts. The newly formed exhaust aisle is then called a hot aisle.

In order to maintain a stable temperature in the DC, exhaust air must eventually be reconditioned. This task is handled by the cooling units, which draw in exhaust air, cool it down, and blow it back into the DC as supply air. Figure 2.1 shows one example of computer room air conditioning (CRAC) positioning, where the units are placed on the same floor as the server racks. Here, the CRACs supply cool air by blowing it under a raised

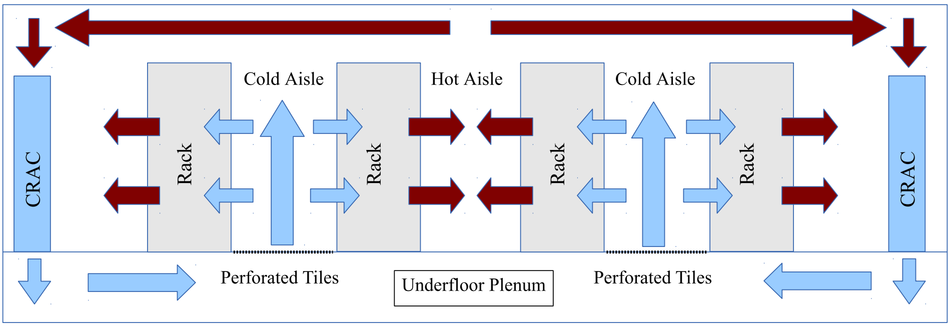

Figure 2.1: DC air flow diagram showing the positioning of the racks, CRAC units, underfloor supply plenum, perforated tiles, and the directions of the hot and cold air streams. Side view.

floor, maintaining an overpressure in the so-called underfloor plenum. The raised floor is built with removable tiles; in the cold aisle, the tiles are replaced with perforated ones so that supply air is pushed upwards towards the server intakes. But note that this example can not be generalized to all DCs. CRACs may alternatively be positioned in the DC ceiling, a second floor above the DC, or in-row with the racks themselves. These alternative placements have the benefit that they do not require a raised floor, which can be costly to install retroactively. The discussion on exactly which placement is the most effective has been going on since at least 1991 [82]. Though the solution depicted in Fig. 2.1 has so far remained conventional [5, 84, 92], at least some high-efficiency DCs use two-floor placements [42, 77].

At this point a distinction[1] should be made between air conditioning (CRAC) and air handling (CRAH) units. Formally, a CRAC uses an internal direct expansion (DX) compressor to produce the required cooling, while a CRAH employs an external source for cooling fluid. This implies that CRACs are more self-contained, and require only a supply of power to operate. Connecting the external cooling source for CRAHs is much more complex. This can consist of separate cooling fluid loops to one or more central cooling plants, and onwards to further heat rejection units located outside of the DC buildings. The reward for this added complexity is a higher energy efficiency, as a central cooling plant can be made more efficient than smaller distributed units. In common parlance the terms CRAC & CRAH have become quite mingled, with CRAC becoming more popular due to its resemblance to consumer-grade air conditioning (AC) units. Though

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[1] This distinction was originally lost in translation while writing Pub. II, as the Finnish word *vakioilmastointikone* can be taken to mean either type of cooling unit.

imprecise, we follow the general trend and use the term CRAC for all units. In almost all cases of Sect. 2.2, the facilities employ CRAH units, whereas the small-scale facilities described in Sect. 2.4 typically employ CRACs.

Precisely where and how the cooling is produced becomes quite important from the efficiency point of view. It is a key design decision when building DCs, difficult to modify afterwards, and can depend on the location of the DC. Similarly, how exhaust air is removed and recycled, and how air streams are separated are active research topics. We will return to these problems in Sect. 2.2, as we review some of the state of the art installations and what is known and unknown about them. In Ch. 3 we will describe the main contributions of this thesis: a set of low cost retrofit techniques that are very attractive to the larger part of DCs worldwide.

What falls outside of the scope of this thesis are the network [1, 50] and power topology designs of the DCs. Very briefly, network and power connections are installed per rack, meaning that each new rack has an associated starting cost. The costs and available network bandwidth limit the distribution of the servers in the racks. Therefore, it is beneficial for a DC operator to try to keep the racks full before starting a new rack. Likewise, sets of servers installed at approximately the same time can be positioned close to each other to enable high-bandwidth data interconnections or just to form logical maintenance units. Taken together, these two facts mean that, for example, all of the servers of a high-performance computing cluster are installed side-by-side. As higher performance has so far meant a higher power draw, these points with higher power intensities can form exhaust hotspots [5, 35, 97, 110]. The hotspots then dictate the requirements for the DC's cooling system. If servers are purchased iteratively, e.g., by following periodic budget constraints, this type of DC *evolution* yields a heterogeneous mix of server generations and power intensities throughout the DC.

Conversely, it is possible for a DC to remain somewhat homogeneous, if the servers are purchased approximately simultaneously, or if the DC operators assemble their server hardware themselves. This type of DC operation has been aptly named warehouse-scale computing by Barroso and Hölzle [6], although the idea of treating the DC as a computer was already mentioned by Patel et al. in 2001 [85]. The general idea is to redirect traffic between different DCs based on service availability, congestion, and client request patterns. Consequently, this mode of operation is possible only for those operators with multiple DCs at their disposal. Natural catastrophes and unlikely failure mechanisms can and do bring down entire DCs [15], making redundancy a requirement even at this level. But redundancy can become at odds with efficiency.

2.1 Efficiency Metrics

By far the best-known metric for general DC energy efficiency is the power usage efficiency (PUE) number defined by The Green Grid (TGG) non-profit consortium [4, 8]. PUE is calculated very elegantly as follows.

$$\mathrm{PUE} = \frac{\text{Total facility load}}{\text{IT equipment load}}$$

Total facility load is measured at the DC's power distribution grid connection, and then divided by the aggregate power draw of all of the computing servers. For long-term measurements, PUE can also be measured by the energy used [39]. Special care must be taken while counting only the hardware that belongs to the IT equipment load [8]. For example, power conversion losses caused by the servers' power supply units (PSUs) are part of the IT equipment load, whereas all other conversion losses related to cabling, voltage transformations, uninterruptible power source (UPS) battery conversions, etc., are not. Similarly, fans inside of the servers are counted as a part of the IT equipment load, whereas CRAC fans are not.

PUE has no upper bound, and in practice, the facility load should always be a little bit above the IT equipment load. A smaller PUE indicates a more effective facility. The minimum was later clarified to be 1.0, meaning that clever tricks like heat reuse can not turn the facility overhead into negative. For heat reuse there is a different metric, the energy reuse efficiency (ERE) [4, 87], though DCs employing reuse are still few.

PUE is ingenious in that it obfuscates both the size and capital expenses of the DC, and thus concentrates on the operational expenses alone. This allows both operators to maintain secrecy about their design choices, and making comparisons between vastly different types of DCs, though the latter has been discouraged [39]. Unfortunately, verifiable information on what represents good, average, or bad PUE numbers is somewhat lacking. Some IT companies like Google [34] and Facebook [64] do publish their own PUE numbers, but the calculations are not reviewed independently. According to their own info, Google's average PUE over their entire DC fleet is 1.1 as of Q2/2013, with some facilities below 1.06. By comparison, Facebook currently publishes the PUE readings from two of their sites, showcasing an annual PUE of 1.09 as of March 2013 for the Prineville site and 1.10 as of Q1/2013 for Forest City. The average for all DCs was 1.09 for 2012 [24].

Other sources for PUE data include The Uptime Institute's survey from March-April 2012 [102] and EPA's DC report from 2010 [104]. Uptime's survey includes over 1100 DC end users from all over the world, and they report an average PUE value between 1.8 and 1.89. Note that respondents were asked to select a category for the average PUE of their largest DC only, 75% ran more than one DC, and 29% responded that they do not collect PUE at all. EPA's report presents an average PUE of 1.91 from a study of 108 DCs[2]. EPA's DC operators have supplied their data voluntarily, which has lead to some suspicion that the results might overestimate those DCs with favorable PUEs to begin with [52]. While it is clear that the sample is not statistically representative for all DCs, it seems unlikely that the measured DCs were very optimized. EPA's presentation of the data demonstrates that neither the top 10 DCs operating in the coldest or warmest climates showed any variability in their monthly energy consumption.

A lack of variance by climate is indicative of closed-loop cooling system, as the main method of achieving a low PUE number is by different *economizer modes*, in which the cooling system uses less electricity but may consume other resources. The straightforward way to achieve this is to employ local reservoirs of cold air, water, or both [84]. These reservoirs are thus climate-dependent. Their availability is the reason why a DC's location becomes so important [30, 110], though a tradeoff exists between the coldest possible locations and the available network and power supply connections to them.

The use of tap water can achieve low-energy cooling even if no local sources are available. This has lead to some DCs becoming increasingly energy-efficient at the cost of wasting potable water. A separate metric, the water usage effectiveness (WUE) has been proposed by TGG [88], but WUE has not yet achieved similar success as PUE. The situation is improving, however, as 34% of Uptime's [102] responders are already collecting water usage data. Sharma et al. [99] noted that the matter of using water is even more complex, as water is also consumed indirectly by the power generation processes. Thus, local water used at the DC site may reduce the water consumed by the power utility. The problem with the efficiency metric proposed by Sharma et al. is that it requires calculating the water used indirectly in the generation of power. In some countries, like Finland, Norway, Sweden, Denmark, and Estonia, power is generated by a mixture of different generation facilities, and may be transmitted through the power utilities' interconnects over the country borders [22]. Fingrid, who operates the Finnish part of the grid, quotes transmission losses of 1.8% over a transfer volume of 64.2 TWh in 2012 [25]. This means that DCs connected to modern transmission grids are not bound to using only locally generated electricity, e.g., coal, but may purchase it over longer distances.

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[2] There is some confusion in the available sources regarding how many DCs EPA averaged over. Their model is composed of 61 DCs, but the histogram on slide 20 of [104] adds up to 108. This number is also mentioned on slide 18.

2.2 Flagship Facilities

Location has become a key driver for DC placement in multiple ways. DCs operating in the U.S., have been repeatedly criticized for their placement in rural regions that yield cheap floor space, but are also powered by traditional coal-based power plants [48, 106], or even their own diesel-powered generators [32]. Later, the trend has reversed so that DC placement has favored locations close to hydroelectric dams [30], keeping the logic that the DC is powered by the closest facility only. But when the electricity is generated by a mix of strategies following shifts in demand and supply, those generators that can ramp production up or down are typically coal- or gas-based installations. This means that green energy sources are always used to their full capacity, and without the DC there would simply be other consumers for the renewable energy.

Fortunately, the situation can be circumvented. If DC operators make commitments ensuring that *more* renewable energy sources get installed, the additional supply will follow the increased demand of DCs. This is the style of operation for Google, which has repeatedly purchased sources for renewable energy[3] to make up for the demand of its DC fleet. One such notable example is the case of Google's Hamina site, located on the southern coast of Finland. Here, the DC has committed to purchasing all the energy produced by a wind farm in Maevaara, northern Sweden [103], over a distance of ca. 680 km. The Hamina site is also notable for being the only one of Google's DCs to use sea water as its only cooling source [56, 69, 70]. Another notable Google DC is the one in Saint-Ghislain, Belgium, which reportedly began operation without chillers all-year [72]. The site has later added a water purification facility that collects water from the nearby Nimy Blaton canal, and purifies the water to make it usable for cooling purposes [70, 73]. Other Google water collection schemes involve reclaiming graywater from a municipality near their DC in Douglas County, Georgia, U.S. [13] and rainwater collection on an undisclosed site[4] in the U.S. [73].

Around year 2011, Facebook became the prime target for Greenpeace's campaign for DCs to "unfriend dirty coal" [106]. Facebook was quick to adapt, however, and has since increased its dependence on renewable energy sources [67]. As a follow-up, Facebook has become one of the most transparent companies when it comes to the energy-efficiency of its DCs. Not only does the company report near real-time PUEs [64], but also WUEs and total power draws for its DCs [24]. Facebook is also

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[3] http://www.google.com/green/energy/investments/

[4] Probably Berkeley County, South Carolina according to http://www.google.com/about/datacenters/inside/locations/berkeley-county/index.html.

one of the principal operators behind the Open Compute Project[5], which aims to publish new and more energy-efficient designs for DC operation. As a result, Facebook's Prineville (Oregon, U.S.) site's cooling design is exceptionally well documented by Hamilton [42]. Hamilton is also the vice president of the Amazon Web Services team, making Prineville perhaps the first publicly peer-reviewed DC in the world. The facility employs "air conditioner bypass via direct air with evaporative assist" by Niemann's classification [84], meaning that the DC draws in outside air and if necessary, conditions it with an evaporative system to a temperature suitable for cooling. This cooling technique is also known as adiabatic cooling. The exhaust air is drawn to a second floor above the racks, from where the air may be reused to warm supply air if the ambient temperature drops too low [42]. Despite its successful design, the exhaust loop did cause a sizeable number of problems when a malfunction in the circulation logic caused the exhaust to be entirely recirculated. As the humidity levels started increasing, condensation occurred inside the DC, killing a number of power supplies and other components [81]. These problems were fixed, however, and Facebook duplicated the Prineville design in its DC based in Luleå, northern Sweden.

The Luleå site is famous for being located in the intersection of multiple power supply lines originating from several hydroelectric dams in the vicinity. The overlapping supply feeds have enabled Facebook to avoid backup power up to 70% of their normal standards [75, 77]. This event signals a very important shift in the design logic of DCs, namely that of depending *more* on the state- or municipality-provided infrastructure instead of duplicating it for redundancy. A similar dependence has been seen earlier in the case of formerly Academica's, now TelecityGroup's DCs in Helsinki, Finland. Their facilities have been award-winning in their efficiency thanks to the contribution of the district cooling grid run by the capitol's energy utility, Helsingin Energia [100]. This district cooling grid was initially built around year 2000, and it complements the much wider district heating grid of the city constructed around 1953–1957. The cooling grid employs seawater as a natural cold reservoir which is used to cool down facilities connected to the district cooling grid. Examples include hospitals, but also office air conditioning systems. As the cool water gets heated up in the process, this energy may later be extracted by the utility and then used to warm the district heating grid.

Another marine source for cooling is the North Sea, or at least the winds cooled by it. HP's Wynyard DC site is located near Dublin, Ireland. Its original web site has disappeared from the company's servers, but the

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[5] http://www.opencompute.org/

contents are still available thanks to the Internet Archive [47]. Wynyard is notable for incorporating an early (2009) direct air economizer that draws in the naturally cold sea winds. The cooling setup is also remarkably similar to Facebook's Prineville, with the exception of using CAC (see Pub. II) instead of hot aisle containment (HAC) [42]. As a consequence, Wynyard claimed a PUE of 1.16 already in 2010 [93].

Microsoft also began operating a DC *almost* without chillers near Dublin in 2009 [68]. Originally, the facility operated with backup DX chillers for those periods each year the ambient temperature might exceed 35° C. This supply temperature is somewhat of a maximum for a large-scale DC, as several PC manufacturers cite it as the upper endpoint of the operating range [7, 35]. The original PUE was announced as 1.25 [71], but has later been improved by replacing the backup DX chillers with an adiabatic cooling system [78]. This and possibly other improvements have reduced the PUE to 1.17. Microsoft's Dublin DC seems to both supply intake and remove exhaust air through the roof of the facility.

Affectionately known as the "chicken coop DC" [74], Yahoo's Computing Coop (YCC) solution is different from earlier DC designs. In this case the entire building is left as open to the ambient temperature as possible, and hot air is gathered by a protrusion on the roof. The maximal use of outside air used is reported to result in only 212 hours per year when extra cooling is required. The YCC was originally completed in 2010. The same year, Microsoft announced a similar design nicknamed the "tractor shed" [75]. The concepts are similar, but the servers in the shed are further housed in Microsoft's IT Pre-Assembled Components (IT PACs), which are modular containers that include the necessary network interconnects, power supply and -backup units. Modular containers have slowly become more widespread [102], but Quincy is the largest DC using them that we know of.

Finally, it is interesting to note a few similarities between these DCs. Upon its announcement, Microsoft's Dublin site was reported as a replication of Google's Saint-Ghislain DC [68]. Yahoo's Lockport and Microsoft's Quincy certainly share similarities, although Microsoft's solution is further divided into the IT PAC modules. The air flow schematics of HP's Wynyard [93] and Facebook's Prineville [42] are remarkably alike, although with the difference of using CAC vs. HAC. It would be easy to attribute these similarities to individual workers switching camps, but they may also result from the convergence of the R&D processes. Whatever the cause, it is safe to say that the largest and most efficient DCs do resemble each other. But they do not resemble smaller DCs.

2.3 Different Types of Data Centers

In 2012, a popular article published in The New York Times concentrated on the sustainability of many DCs by drawing focus on their high energy requirements [31]. By itself, the story had novelty mainly for the general public, as the situation was already well known to both academics and the industry. Other factions, e.g., Greenpeace, were already known for having taken potshots toward individual DC operators like Facebook [67, 106]. In 1999, a somewhat sensationalist piece published by Forbes [48] had raised an early controversy [23] by suggesting that before 2010, half of all energy consumed in the U.S. would be consumed by DCs.

What was notable about the 2012 article was the author's long-term background research, including a sizeable number of interviews with DC operators and other experts. The diligent study allowed J. Glantz to paint a reasonably complete picture of the operation of different DCs. Despite its merits, many expert readers felt that the article had omitted a vital aspect of DCs: that there is not a single type of data center, but several [55, 90, 111]. The importance of the division forms around the fact that the different types of DCs are maintained very differently. Most notably, the very largest DCs, which consume the most energy, are typically operated much more meticulously than smaller facilities.

In his response to the New York Times' article, Koomey formalized this classification and coined the four subtypes of DCs [53]. This categorization is of particular importance as it reflects well with the earlier grouping of DCs into small, medium, and large-scale facilities used by the International Data Consortium (IDC) in 2007 [5, 10]. We will return to their relative sizes in the beginning of Sect. 2.4, but first describe the DC categories.

The first type of DC is the best known, for this type includes many of the so-called flagship installations operated by the IT industry giants, e.g., "Amazon, Google, Facebook, and Microsoft". Section 2.2 adds instances operated by Yahoo and HP into this category. These DCs are usually showcased by large ICT companies in order to prove their relative "greenness" and dedication to sustainable operation. And there is some truth in this, for the public cloud computing providers do excel in the energy efficiency of their facilities, since their business models depend on this. But note that this relationship is strictly one-way: not all of the DCs operated by a cloud providers are equally efficient. They also run much smaller facilities [35] that fit better into the other categories.

Second, the scientific computing centers are distinct for their user request patterns. While it can be argued that most of the cloud is dependent on the online services accessed by the clients at the network edge, scientific facilities often specialize in high-performance computing only. This means that their processing tasks may resemble much more the venerable batch-processing operating systems of yesterday. Hence, scientific facilities can show much more impressive utilization ratios. For example, National Energy Research Scientific Computing Center showcased an utilization ratio of 96.4% during July 2012 [31].

Colocation (colo) facilities are run by vendors who, like the cloud providers, specialize in running DCs. The difference is that the colo operators expertise cover only the placement, construction, operation, and maintenance of the DC infrastructure. The specific IT hardware installed can be provided or recommended by the colo contract, sometimes called a "hosting" contract, or left entirely as the customer's choice, indicating a "housing" version. Colocation can be very good for online services that further depend on other services, e.g., online trading [33]. This results in companies paying quite high premiums for some colo facilities depending on their physical location and network connection characteristics. Beyond cultivating these types of relationships, what falls outside of the colo operators' domain are the applications that run inside the DC. This means that the average server utilizations can be much lower than in the case of the public cloud's, and on par with the last category of DCs.

The last category was tentatively named the "in-house" DCs by Koomey. This title reflects upon the primary mode of operation for the companies housing these DCs, which tends to be other than computing. In-house DCs are usually office or technical spaces converted for DC use, and contain servers which have been stepwise acquired as needed by other company processes. It is this category which tends to contain the smallest facilities, involve the most wasteful practices, and be the largest of the four by numbers.

2.4 Server Closets

During the 2011 European Data Centre Summit hosted by Google, the keynote speech by U. Hölzle [46] contained a very concrete message for the researchers and engineers present: concentrate on improving the non-enterprise DC facilities. By drawing upon the data published in 2006 by the IDC [5], and further analyzed by the National Resources Defense Council (NRDC) [10][6], Hölzle presented an easily digestible infographic that divided the installed server base at the network core into categories based on the

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[6] Citation refers to the 2012 version of the report, earlier versions contained the same division of DCs.

	# servers	PUE	avg # servers	total energy
Server closet	1,657,947	1	1	11%
Server room	1,942,214	1.9	2	24%
Localized DC	1,674,648	1.9	26	21%
Mid-Tier DC	1,511,999	1.9	161	19%
Enterprise-class DC	3,074,424	1.2	491	24%
Total	9,863,237			100%

Table 2.1: Power consumed by the combined servers of different categories of DCs. Calculated as number of servers × watts per server × PUE. Percentages shown are fractions of the sum of power consumed by all DCs. Numbers from IDC's 2006 report [5].

sizes of the DC facilities. Hölzle's simplified version showed the installed servers to be split up into 41% "closet & small", 31% "localized & medium", and 28% "enterprise" DCs [10, 46]. The actual data from IDC is somewhat more granular[7], further dividing the smallest category into 17% of size "server closet" and 20% "server room", and the middle category into 17% "localized" and 15% "mid-tier". Last, "enterprise-class" makes up for the remaining 31%. The size limits defined for the categories are, in increasing order, less than 200 ft^2 (<19 m^2), less than 500 ft^2 (<47 m^2), less than 1,000 ft^2 (<93 m^2), less than 5,000 ft^2 (<465 m^2), and over 5,000 ft^2 [5, 10].

The vast majority of the DCs belong to the two smallest categories. According to IDC [5], a full 51% of all DCs belong to the smallest category of server closets, with an additional 45.5% in the next-smallest category of server rooms. Taken together, these two categories numbered about 2.2 million in 2005, compared with the just under 80,000 of all other DCs. What's worse, between 2005-2009 the two smallest categories were projected to increase with compound annual growth rates (CAGR) of 4% and 3.3%, respectively, compared with the CAGRs of 0.0%, 1.0%, and 2.8% of the larger categories (ordered by DC size).

While the IDC report could not tell much about the amounts of power the different DCs were using, by looking at the PUEs of the enterprise-class DCs presented in Sect. 2.2 and the average PUEs described by the surveys discussed in Sect. 2.1, we can make some conservative estimates. It seems that by now, the ICT industry giants all know how to build a DC with a PUE of 1.2 or less, so we will use that as an estimate for the enterprise-class DCs. Currently documented average PUEs are close to 1.9, and were reported for

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[7] There is a discrepancy between the percentages reported by NRDC [10] and the absolute numbers from IDC [5]. Our percentages are calculated from IDC's numbers.

the largest DC of operators with at least (75%) one facility [102]. Thus, we will use this number for the localized and mid-tier categories. Next, IDC's DC taxonomy [5] describes the smallest category of server closets as usually not containing cooling or backup power systems. Hence, we use a PUE of 1.0 for these DCs, as the requirements for power conversion and lighting are negligible when, on average, only a single server is installed. Finally, it is very difficult to estimate a PUE for the next-smallest category of server rooms. IDC does mention that these rooms have "upgraded air conditioning, UPS equipment, and some security". Without further evidence, we have duplicated a PUE of 1.9 for this category as well.

Table 2.1 plots the relative amounts of energy used by the different DC categories based on the assumptions given above. By adjusting for the power consumed by the whole DC based on the estimated PUE metrics of the different categories, we can see that the smallest two categories draw a little over a third of the combined power consumed by all DCs. The next two categories account for an additional 40%, with the largest, enterprise-class DCs being responsible for the last 24%. Thus, while the largest DCs should manifest the newest and most energy-efficient, techniques, 76% of the power is drawn elsewhere. There are at least two alternatives that may be attempted to reduce the aggregate power draw of the combined non-enterprise DCs.

The first is to implement techniques that can be incorporated cost-effectively and quickly by the operators of the non-enterprise DCs. In the next chapter, we will introduce the main contribution of the thesis, techniques which fit this description of *data center energy retrofits*. Sadly, not all techniques can be applied in all cases. IDC's report also outlines the average number of servers in each category, and while the two smallest categories dominate the number of DCs, they may contain as few as one or two servers per DC on average. This makes it plausible that some of our techniques are most useful for the middle categories. However, while these are averages, individual installations do vary. In Sect. 4.1 we will revisit the applicability of our techniques per DC category.

The second alternative involves migrating all services to larger and more efficient DCs, and then shutting down the smaller installations. The second alternative has so far proven difficult, as not only the operating costs involved, but also laws and regulations have hindered some DC operators from shifting their confidential data across country borders to the cloud [5, 26]. And this may have been a good thing.

Chapter 3

Energy Retrofits

The history of computation suggests that there have been several back-and-forth movements of where the larger part of data processing is performed. The earliest change occurred when most users stopped working on university-scale computing machinery and turned instead to personal computers. These distribution shifts manifest as differing distances a user request has to travel before its response is formed. For example, current mobile clients can offload tasks to networked servers in order to save local battery lifetimes. Thus, we are still experiencing a shift towards the core of the network. As mentioned in Sect. 2.3, there have been attempts to criticize this shift by questioning the energy demands of the DCs [48, 106]. So far, the attempts have not thwarted the growth of the industry. This situation might now be changing, since the new issue brought to public consciousness concerns the *trust* users put into the DC operators, and whether that trust has been misplaced.

Edward Snowden is the whistleblower who quickly rose to public prominence during June 2013 [28, 38]. In his iconic, closely-cropped video interviews, Snowden explained his background as an employee of a company subcontracted by the National Security Agency (NSA). It had been part of Snowden's job as an analyst to mine the databases the NSA had at its disposal for signs of international terrorism. Snowden explained that the job included not only the capability, but a routine to tap into several DC operators' databases, including "Google, Facebook, Apple, Microsoft".

Later articles have verified Snowden's story and expanded on the abilities of the so called XKeyscore interface, one of the tools NSA has at its disposal [37]. At the time of writing, the jury is still literally out to decide whether NSA will keep its monitoring privileges [101]. Regardless of the verdict, considerable damage has already been done to the DC operators who were forced to participate in the program by a combination of U.S. laws and gag orders [26]. The latter have been especially harmful, for they still prevent DC operators from revealing the true extent of the monitoring [18]. While earlier articles have presented facts about the energy efficiency, or lack thereof, of the DC industry, the new situation is different for it plays on the users' *fears* of the unknown due to the gag orders.

It is an open question whether the aftermath will trigger IT operators to re-embrace their server closets. Very generally, there are two options for the future[1]. First, if the public outbreak tones down, and the migration of the closets to the high-efficiency cloud and colo DCs continues unabated, this chapter's techniques will remain usable for the immediate future. As the payback times are in all cases very short, even a delay of a few years will yield savings. And since national and regional data storage laws have thus far prevented the migration altogether in some cases [5, 26], some server closets might remain in operation for the foreseeable future. The second alternative is much worse for the energy efficiency. If the users decide that the cloud may no longer be trusted, a distribution shift back towards the network edge might occur. In this case the efficiencies of the server closets will grow more important. We will need not only cooling solutions, but a wide range of energy improvements that can be adapted all the way down to the very smallest DCs.

We are not the only ones who have recognized the problem of optimizing the non-enterprise DCs. In the 2011 European DC Summit mentioned in Sect. 2.4, Google introduced their own small-scale optimization study. The video feature, web site, and accompanying white paper outlined the steps Google had taken along with the PUE improvements achieved [35]. While looking at the presentation I confess to having felt a certain degree of accomplishment, for Pub. II had already been submitted, and the air stream containment we had built differed from Google's solution mainly by the materials used. While our solutions were not yet polished to the same presentational levels, the core ideas were similar. Neither we nor Google stopped there, however. The three best practices introduced by their study involved a 85 kW DC that was stepwise improved from a PUE of 2.4 to a much more impressive 1.5. The same changes were later reproduced in four other DCs. The best practices were as follows:

1. Measure performance
2. Optimize air flow
3. Turn up the thermostat

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[1] There is a third option as well. The occurrence of a so called *disruptive event* could cause the public to hasten the migration to the public cloud, despite the continuing surveillance of the government agencies.

There are quite direct connections between these best practices and four of our publications, although the order in which we experimented was somewhat different than Google's. Publication I was done first, and it involved turning the thermostat up, or in our case, down. It will be presented in Sect. 3.1. Publications II and IV detail our implementation of CAC and its extension, underfloor air containment (UAC). These solutions are detailed in Sect. 3.2. Next, Pub. V presented in Sect. 3.3 falls outside the best practices of Google, and paves the way for future work, in which we hope to see DCs that direct their waste heat for useful purposes. Finally, while Pub. III is directly related with the category of measuring performance, it has significant differences to Google's approach of using CFD. Because of this, we describe the wired sensor network in Sect. 3.4, which covers the different strengths and weaknesses of building actual prototypes vs. CFD-based modelling studies.

3.1 Free Cooling

As outlined in Sect. 2.1, one of the straight-forward methods of improving PUE is to employ a cooling system that has an economizer mode. Another option is to increase the supply temperature of the CRACs, which reduces the power used for cooling, but also warms the air which reaches the server intakes. The limits set on how high the intake temperature may reach have traditionally been made by two authorities: the server manufacturers' warranties and the American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.'s (ASHRAE) recommendations. The problem with both sources is their bias in reporting operating temperatures lower than necessary for the server equipment [80]. In the case of the server manufacturers, this mode of operation is known as sandbagging [7], and it is done in order to insure that the equipment reliability is not compromised. The members of ASHRAE are vendors of cooling equipment, and it would be quite disastrous for some of their business if it was discovered that a properly located DC requires no cooling whatsoever.

Such a discovery was anticipated by McKeown already in 1986 [63] and finally presented by both Intel [2] and Microsoft [7] in 2008. Both companies published proof-of-concept (POC) reports of installations where servers had been air cooled using direct outside air. Intel's experiment involved running 896 blade servers for ten months divided into two (2 × 448) compartments, one with a DX cooling system using an air economizer and the other with a conventional CRAC. No humidity control was involved in either compartment. The failure rates showed a small increase from 2.45%

in the DX to 4.46% in the economizer compartment [2]. While seemingly a significant elevation, no rigorous statistical analysis was presented, so the elevation could also have been caused by random variation. In the case of Microsoft, there are much fewer details available [7]. The servers subjected to the test amounted to five HP DL385 units running for 7–8 months with zero failures. More interestingly, Microsoft ran the servers in a tent and subjected them much more thoroughly to the mercy of the ambient climate.

While we were oblivious[2] of Microsoft's publication, Intel's caught our interest. In Pub. I we describe our own experiment, in which we installed 18(+1) servers pairwise indoors and in a tent erected on the roof of the CS Dept. building. The servers in both groups ran for a period of eight months, although Pub. I only contains details for the first three months of operation[3]. Our main research question was the feasibility of extending direct free air cooling into the colder climate of Helsinki, Finland, and in the case of a negative answer, what kind of new common-mode failures (CMFs) [3] would appear in the very low local winter temperatures.

When Pub. I was finished the answer to the feasibility question was considered positive, for even at the end of the experiment and eight months of operation, we had found no CMFs related to the temperature or humidity ranges. Since then, we have encountered a CMF related to one fan type, and this failure mode is still under study [89]. The results of our research are important for air economizers seem to be abundant in enterprise-class DCs. Whereas larger DCs can condition the outside air using water and adiabatic systems, depending on the location, water supply might be scarce. For smaller DCs the use of direct outside air would result in the lowest capital expenses for the cooling solution. In addition, our research complements other independent studies regarding the temperature operating ranges of computer equipment, and how varying the temperatures affects failure rates [20, 21, 91, 95, 96]. The newer analyses seem to question the previous "industry folklore" that a lower operating temperature yields less failures. Many of the studies would have remained impossible without data derived from warehouse-scale computing architectures. The results are key in understanding whether the energy savings of an elevated supply temperature are offset by an increase, if any, in equipment replacement costs.

There may also exist upper bounds for the ambient temperatures at which commercial, off-the-shelf (COTS) hardware should be run [62, 79, 86]. Due to the economies of scale involved, it is financially prudent for DC operators to

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[2] We were unaware of Microsoft's experiment in our review of related work for at the time, it was promoted by Microsoft with much less enthusiasm than Intel and their POC.

[3] Two of the servers have been reused in later experiments, and have thus far remained outdoors and online for over *three years* of operation. We are planning a follow-up article.

purchase large quantities of so-called volume servers from the manufacturers. This implies that the DC operators do not build their own servers, which is the approach of at least some cloud operators, e.g., Google and Facebook. COTS servers contain firmware controllers that set the operating speeds of internal fans according to the ambient temperatures [79]. In addition but to a smaller extent, leakage currents in components, including CPUs, are aggravated by increases in the ambient temperature [86]. A steadily increasing supply temperature may thus yield savings at the CRAC, but aggregate losses at the IT hardware level. As mentioned in the beginning of Sect. 2, a heterogeneous mix of servers can cause hotspots where the local temperature is elevated due to eddies in the air flow [79]. Therefore, optimizing the cooling in a DC involves not only tuning the supply air temperatures, but also directing the air flow.

3.2 Air Stream Containment

There are some reasons why direct outside air cooling might not be feasible for all DCs despite a pre-selected and compatible climate. Mainly, particles in the air [2, 7, 36, 63, 94] from either pollution or plant-based pollen might be carried all the way into the server intakes, and eventually cause fan failures [89]. Other reasons include external limitations on the DC location caused by laws and regulations [5, 26], or the network latency requirements of hosted web services [33]. In-house DCs may also be located so that no pathway exists for delivering outside air to the DC.

Even if the cooling is derived from direct outside air or an air economizer, problems in the DC's *internal* air flow may cause inefficiencies that result in temperature hotspots. Consider the example CRAC positioning of Fig. 2.1 where supply air is diverted through perforated tiles upwards into the cold aisle, and conversely the exhaust air is pushed into hot aisles by server fans. Already in 1991, Nakao et al. [82] identified the effects of exhaust air short-circuiting, i.e., mixing of the hot and cold air streams. This phenomenon results in wasted cooling capacity either through unnecessary warming of the intake air or cooling leakages in the hot aisles. The mixing may occur either around the edges of the rack rows, or directly through them if there are gaps without servers in the racks. An underpressure in the cold aisle side caused by an insufficient ratio of CRAC supply to server intake air [29, 97], may draw the exhaust around the racks, or in some observable cases, even through servers with less powerful fans (see Pub. III). Similarly, if the CRAC units' return-side fans are not operating at sufficient levels, an exhaust side overpressure may push the exhaust back into the cold aisle.

In Pub. II we examine a by now very well-known technique used to mitigate air stream mixing, cold aisle containment (CAC). With CAC, the cold aisles are contained with side walls and roofs which separate the supply and exhaust air flows. CAC was identified as a key optimization technique by Google in 2011 [35], and it has been documented in at least one white paper by HP in 2009 [45]. Niemann mentioned home-brew CAC setups already in 2008 [83]. In contrast to earlier works, ours is the first scientific study that operates on a live DC. HP studied CAC through emulating servers with load banks [45] while we used a real, heterogeneous and production-use 80 kW DC. We were able to perfectly replicate HP's 20% increase in blower air flow, which means that a DC using CAC may install 20% more servers while maintaining the same cooling solution. More importantly, if CAC is installed to begin with, the DC may reduce the CRACs' capital expenses. The key drawback of our study was that we were unable to measure PUE changes due to the fact that our DC is connected to two different chilling plants, with the second also used for other purposes. Despite this, the 20% reduction in supply air is expected to yield larger savings in a holistic analysis, for the inefficiencies of the cooling system mean that for a DC without CAC and a constant IT equipment load, the Total facility load will be higher (see Sect. 2.1).

In Pub. IV we revalidate our initial, homebrew DC CAC solution built with duct tape and plastic sheets using a much more high quality, but still DIY installation. The effects of the new CAC version remained identical within our measurement errors, meaning that even a quick and dirty CAC just works[4]. In the same publication, we extend CAC to the underfloor plenum (see Fig. 2.1) and thus direct the volume of supply air to more closely reach the server intakes. Our reason for working with the plenum was to study the effects of leakage air flows caused by gaps in the raised floor tiles [43] and underfloor blockages [44, 108], which are difficult to study with CFD [9]. The construction materials are, again, as cheap as possible. With an initial cost of just tens of euros, and an installation time of just one hour for a 74 m^2 DC, we were able to measure an additional 9% improvement in the air speeds inside of the CAC. The new solution was titled underfloor air containment (UAC). As CAC and UAC are directly compatible in all DCs with an underfloor plenum, these techniques complement not only each other, but also the free air cooling solution. For even if the cooling is achieved for free, air blowers must still be used not only to direct cold supply, but also for gathering warm exhaust air.

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[4] Our YouTube presentation achieved over 40,000 views, raising the public awareness towards this technique: http://www.youtube.com/watch?v=m8NcIN4rNqU

3.3 Harvesting Heat

Publication II also introduced the Helsinki Chamber (HC), our prototype chassis for direct outside air cooling. The concept of the HC closely resembles ideas presented earlier by Church et al. [16] and Brenner et al. [11, 12]. Church et al. presented the unconventional idea of splitting a larger DC into multiple micro DCs that would be located sparsely to avoid thermal hotspots. Brenner et al. start from a different angle by placing their servers near a large greenhouse, which is then heated by the exhaust air. Both lines of research involve distributing the computation near the clients at the network edge. Our HC is the extension of our earlier tent-based setup (Pub. I), but with dual chambers for the cold and warm air streams. The HC has a PUE of exactly 1.0. By combining the micro DCs with the CAC technique, we have successfully operated servers for three years in the HC.

Our own greenhouse project started off from the endeavour to find some use for a DC's waste heat. For this, we needed a realistic target to heat up. Initial plans included building a sauna, but these were scrapped due to the fact that we did not have engineering proficiency with the required heat pumps. In the end we opted for a direct heat reuse target, and built a lightweight greenhouse in connection to the HC. The main differences to Brenner et al. [12] are our edible crops and that the DC came first, not the heating target. Publication V describes our first eight months of operation and the edible plants we cultivated. At the time of writing, we are well into the second growing season and batch of plants. A number of volunteers have taken over and tend the plants, which nowadays consist of chilies only.

For many reasons, growing chilies with the exhaust heat of servers has been met with a spectacularly good media reception, and our project has been mentioned in numerous blog posts, the social media, and the largest local newspapers[5]. This was not entirely unexpected, as the experiment was designed with also the PR value in mind. We did this in order to raise the public awareness about the waste heat produced by many DCs, since currently most heat is just dumped into bodies of air, water, or both [41].

Some exceptions exist, though. One of the DCs presented in Sect 2.2, the one by Academica / TeleCityGroup [100], already falls into this category, and it would be beneficial for the energy efficiency of the larger community if this trend would continue [14, 58, 66, 76]. A simple use case is to heat the office space connected to a large-scale DC, but as Pub. V demonstrates, many more opportunities could be custom-built in both urban and rural areas at very competitive capital expenses.

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[5] We maintain a partial list at https://wiki.helsinki.fi/display/Exactum5D/Citations

3.4 Models vs. Measurements

The reasons why we have eschewed the use of CFD modelling in favor of building actual prototypes and measuring them are twofold, namely the costs and time involved. The fact remains that both may very well combine in the case of non-enterprise DC operators. An increasing amount of CFD tools are available through open source toolkits, but learning how to use the toolkits still takes time. Without prior knowledge of the complexities involved, the learning curves can be especially steep. Van Gilder noted on the computational complexity that still remains in CFD models [107], and also remarked that server air flows differ per unit based on their configuration. Seymour et al. explained the issues of modelling racks by showing how they can not be modelled as homogeneous units, and that server installation order affects the air flow [97]. Germagian has shown the effects of under- and oversupply of cold air [29]. These factors mitigate the attractiveness of CFD for server closet operators, who will either have to learn the tools themselves or employ CFD analysts to do the job for them. These consulting services can easily result in quite hefty price tags. Google's POP presentation revealed[6] one such price range as "$5,000–$10,000" for their 85 kW DC [35].

Publication III presents a cheap, lightweight, and easy-to-install wired sensor network that contrasts with other, wireless solutions [57]. Wired sensors can be used to cover some of the CFD use cases, though certainly not all of them. While CFD is the better solution for planning a DC from scratch, the use of sensors and lightweight prototypes can be a more agile tool if the set of possibilities is constrained to begin with. This is a recurring situation in the case of smaller DCs, as there may simply be no more space to expand or shift racks around. The extremely cheap sensors we advocate can also be used to monitor a DC in near real-time. In Pub. III we describe three scenarios which would have remained difficult to analyze using modelling only. Finally, our sensors can be used to verify a CFD.

It is up to the specifics of the individual DCs whether our sensor solution fits the bill, but Pub. III makes a back-of-the-envelope comparison with the price range given above by Google. Using the mid-point of the price range, we project that our sensor network could be used to instrument a DC with a floor size of over 2,500 m^2. Even assuming a much higher sensor density per m^2, similar capital expenses would cover a DC of 471 m^2. Incidentally, as the size limit for the enterprise DCs was defined as 465 m^2 by IDC [5], we consider the wired sensor solution to be both a quick to install and very low-cost data center retrofit.

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[6] http://www.youtube.com/watch?v=APynRrGuZJA around 11:17 / 27:52

Chapter 4

Conclusion

We are now ready to quantify the capital expenses of our energy retrofits and make some projections on the operational expenses that can be saved by the use of the retrofits detailed in this thesis. We have not included any rates for the hours of workmanship in the capital expenses, though the individual publications do contain the installation times required. The rationale is that the hourly rates vary too much regionally and per employing institution. For all other expenses, we have been as precise as possible in our bookkeeping. Unfortunately, our university has licensed a rather cumbersome enterprise resource planning software, which did manage to obfuscate some of the resource costs. We provide estimates for the missing figures whenever we know that something has been lost; however, the possibility exists that one or two receipts have remained undetected.

In the case of our free cooling experiments, our costs included purchasing the tent, the first generation temperature data loggers, and developing the HC prototype. The development was done iteratively, as some equipment was purchased and later retired. In perfect hindsight we would have managed to avoid some of the costs involved. In building the HC, we received some materials *gratis* from our university's Technical Department. These materials include water-proofed plywood and some metal sheets for the reflective covers. It is very unlikely that the costs exceeded 100 €, given a reasonable initial order quantity. Likewise, we gratefully received some exhaust grilles to be used as the HC back covers from Halton, Inc. While these grilles are somewhat specialized pieces of building construction materials, there is no reason why their purpose could not be duplicated in less developed regions of the world. Combined with the recorded costs of 1,060.36 €, our best estimate is that a HC can be duplicated at a cost of 1,300 € or less. In all honesty, even a minimally serialized manufacturing process would probably reduce the price to below 500 €. To give these costs a comparison point, a 42U server rack costs roughly between 450–1000 €, meaning that a free cooled micro DC could be purchased and operated at roughly twice the cost of a normal rack.

For the CAC and UAC experiments, the costs are a little more interesting. As mentioned in Pub. II the first version of the CAC, built with the lowest material costs, amounted to a total of 120.65 €. This setup consisted of the two separate aisle halves as discussed in the publication. In the second version, we replaced the plastic sheets with sturdier and more fireproof plastic walls for a one-time cost of 252.75 €, still keeping the same roof structure. This brings us to a total of 373.40 € for a solution that lasted almost two years in continuous use, as mentioned in Pub. IV. Eventually, while doing the UAC experiments, we did rebuild a third version of the CAC from scratch. By installing lightweight aluminium frames and polycarbonate plastic panelling, we ramped up the costs to a total of 2,338.25 €. As mentioned in the publication, there were no measureable differences in the air flows of the second and third generations. In addition, the differences between the first and second versions were caused by the original separation of the CAC. If we had avoided this mistake to begin with, we could have built a much cheaper, but not as durable CAC. Duct tape only lasts for so long in a well-ventilated space.

The greenhouse costs were the most difficult to quantify. By summing up all our existing receipts we have incurred a total of 631.53 € in material costs, but there is some uncertainty in this number. First, we scavenged some of the materials for free, including the cargo pallets the greenhouse is built on. These were seen as logistical waste and had become somewhat of a storage problem on the campus. Second, the 2×4” timber used for the greenhouse frame never appeared in our Dept.’s invoices, and was probably joined with some larger purchase done by the Technical Department. This is also true for the first generation of polycarbonate plastics, and also for some miscellaneous nuts and bolts. In total, it is very unlikely that these material costs exceeded 500 €, bringing us to a maximum estimate of 1200 € for the greenhouse.

Finally, the costs of the sensor network were the easiest calculate, as they are already well documented in Pub. III. For just under 160 €, we instrumented our 74 m^2, 80–115 kW DC. The price per sensor is dominated by the relatively high cost of the USB host adapter, but this is to be expected in the target domain, which consists mostly of smaller or equal-sized DCs. While the sensors are usable for DCs of all sizes, they do not directly result in energy savings, and are excluded from the following payback time analyses.

Split incentives, risk aversion, and the negligible cost of power in com-

	%	$MtCO_2e$
DC footprint in 2005	100%	93
non-enterprise DCs (76%)	76%	70
cooling subsystems (17% of 76%)	17%	12
chilling (79% of cooling)	13%	9.4
free cooling	13%	9.4
air handling (21% of cooling)	3.6%	2.6
CAC (20% of air handling)	0.73%	0.5
UAC (9% of air handling)	0.33%	0.2
CAC+UAC	1.1%	0.7

Table 4.1: GHG emissions produced by the non-enterprise DCs in 2005 and savings achievable by different energy retrofits. Based on the GHG emissions by the SMART 2020 report [109].

parison with the benefits are some of the impeding factors for DC energy retrofits [23]. As mentioned early on in Ch. 1, departmentally conflicting split incentives can work against DC energy optimization attempts. In our case, the invoicing practices have sometimes worked in our benefit. Risk aversion has been the tried-and-true mode of operation for many IT admins, but offloading the research prototypes to be done by researchers has allowed us to sidestep this issue. Whether the short-term operational expenses can now outweigh our capital expenses remains to be seen in the next section.

4.1 Discussion

By combining the data presented in Table 2.1 with the global GHG emissions estimated by the SMART 2020 report [109], we can now estimate the savings achievable by the energy retrofits presented in the previous chapter. Table 4.1 presents one estimate on how many million tonnes of CO_2 equivalent ($MtCO_2e$) the main techniques of free cooling, CAC, and UAC can save. As the installed server base data is from 2005 [5], we use the SMART 2020 report's DC GHG emissions for that year. This is done by projecting the 2002 figure, 75 $MtCO_2e$, forwards in time using the 7% CAGR presented in the report. This leads to a projection of 93 $MtCO_2e$ for all DCs in 2005. From the total emissions we exclude the 24% consumed by the enterprise-class DC, with the assumption that they already contain comparable efficiency improvements. Next, we calculate the GHG emissions caused by the DC cooling subsystems, which amount to 17% of the total or 12 $MtCO_2e$. Following Barroso and Hölzle [6], we divide this figure into 79%

(9.4 $MtCO_2e$) for the chillers and 21% (2.6 $MtCO_2e$) for the air handling units (CRACs or CRAHs, see Sect. 2). All of the GHG emissions related to chilling could potentially be eliminated if an air economizer mode could be employed in all DCs for all parts of the year. Conversely, the 21% caused by the air handling units, i.e., fans, could not be eliminated fully. These emissions could, however, be further reduced by the use of the CAC, UAC, or both techniques.

These results are certainly not exact, although they may be illustrative for our purposes. Free cooling is not an alternative in all parts of the world, nor even in all buildings located in suitable climates. Likewise, most DCs are simply too small (see Sect. 2.4) to employ CAC, or will contain no underfloor plenum for UAC . Due to these flaws, the $MtCO_2e$ calculations represent a best case scenario. On the other hand, it should be noted that the amount of emissions has risen yearly since 2005, and as mentioned in Sect. 2.4, the fraction of non-enterprise DCs was projected to rise faster than its counterpart. However, the calculations give us insight into the relative merits of the techniques. For example, free cooling could yield almost two orders of magnitude more GHG reductions than UAC and CAC combined. CAC alone could yield savings in the order of 0.7 $MtCO_2e$ yearly by the 2005 emissions. To put this number into some perspective, I calculated[1] my personal carbon footprint as roughly 10 tons of CO_2e for the past year. This number seems to match other available estimates for the Finnish average [40]. Now, if only one DC in ten thousand implements CAC, my own emissions are offset for five years[2].

Somewhat more precise calculations can be performed regarding the operational costs. Koomey has estimated the average power drawn per server in 2005 as 222 watts [51]. Using this average number we can calculate the energy consumed annually by the DC categories. Further on, by combining the fractions from Table 4.1 we can then deduce the reductions in energy consumed per size category. For the server closets, nothing much can be done. Since these spaces contain only a single server on average, there is certainly no advantage of applying CAC or UAC. While the 222 W drawn might ultimately be cooled by an office A/C unit, it is also possible that the load results in heating savings in more frigid climates and/or parts of the year. Likewise, server rooms are not much better. For only two servers per DC on average, the initial costs of building a HC and moving the servers outside are still not justified.

The results get somewhat better while examining the localized DCs and

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[1] Using http://www.carbonfootprint.com/calculator.aspx

[2] Which is, incidentally, the time it has taken to complete this Ph.D. thesis.

	%	Localized DC	Mid-Tier DC
# of DCs		64,264	9,386
# of servers		1,674,648	1,511,999
E / a (in GWh)		6,188	5,587
chilling	13.36	827	746
air handling		225	204
free cooling		827	746
CAC	0.73	45	41
UAC	0.33	20	18
CAC+UAC	1.06	65	59

Table 4.2: Energy savings achievable by the different retrofits grouped per DC size category. Based on the GHG emissions by the SMART 2020 report [109], IDC installed server bases from 2005 [5], and Koomey's estimates on average power draws per server in 2005 [51].

mid-tier DCs. Table 4.2 presents the results for these two categories. The annual energy consumed by all DCs in these categories were approximately 6,188 GWh and 5,587 GWh, respectively. These numbers may then be split into 827 GWh and 746 GWh used for chilling, and 225 GWh and 204 GWh used for air handling purposes.

Suppose now that all the servers could be shifted into HCs, reducing the energy required for chilling to zero. The combined savings would amount to 1573 GWh, but a large number of additional HCs would have to be built. The average numbers of servers in these categories are 26 and 161 according to Table 2.1. We assume that in both categories the average height of servers is 1.5U rack height, meaning that for each HC, the number of servers to be installed is 26 from the localized category and 28 from the mid-tier category. At an estimated cost of 500 € per HC, the costs would then amount to $(1674648/26 + 1511999/28) * 500 = 59205000$ or just over 59 million euro. Fortunately for the payback time analysis, the costs per GWh are also considerable. At a global average cost of \$0.09 per kWh [112], the payback time would be only 0.56 years, or roughly seven months.

For the CAC and UAC techniques the payback times are somewhat longer. IDC's report [5] lists the total number of DCs in the localized and mid-tier categories as 73,650. As discussed earlier, the cost of our second CAC version was 373.40 € for a 74 m^2 DC, or roughly 5 € per m^2. As we do not know the exact or even average sizes for the localized and mid-tier DCs, installation costs are estimated based on the upper bounds for these categories. The given maximum floor sizes of 93 m^2 and 465 m^2 yield the costs of 469 € and 2346 €, respectively. As the UAC costs are minuscule by comparison, we can assume that the plastics required for the UAC are included in the surplus hardware contained in the CAC purchases. Thus, CAC and UAC could be installed simultaneously if there is an underfloor plenum to work with. It is not unfair to assume that for localized DCs with 26 servers on average, a plenum probably does not exist, but for the mid-tier DCs containing 161 servers on average, the plenum might as well exist. Thus, we will count CAC savings for both DC sizes, but UAC only for the latter, yielding a combined savings of $45 + 41 + 18 = 104$ GWh per year. The installation costs are calculated as $64264 * 469 + 9386 * 2346 = 52180339$ or just over 52 million euro. The payback time is in the order of 7.5 years, which seems steep at first. However, note that there are four things that reduce this estimate. First, the floor sizes are definitely overestimations. Second, while the energy intensities of the servers have definitely been rising, the floor sizes have not. Third, amortization costs for the cooling systems are usually counted in periods of 10–15 years, making even this worst case payback time worth the capital expenses. Fourth, as we have shown in Pub. II, in some cases CAC is able to optimize the air handling to a degree that fewer CRAC units are needed to operate the same amount of servers in the DC. In our case, installing CAC enabled us to run the Exactum DC with four CRAC units instead of five. Even a single unit saved will immediately cover the major part of the installation costs for CAC.

4.2 Future Work

Therefore, I believe that the energy retrofit techniques explained in this thesis are a good fit for a large number of non-enterprise DCs. Which retrofit to implement remains to be decided by each operator, however. For the enterprise DCs, there might still exist a few operators who have not installed air containment, or that have not considered air economizers. I hope that this thesis provides incentives to finally take heed and make energy efficiency a short-term goal, if only for the short payback times involved.

There is always more work to be done, and one more [todo] to be squashed. Some of the paths we did not take involve a study regarding the optimal placement of DCs. By using integer linear programming (ILP) techniques and loss functions for the transmission of heat, cooling, and power, we hoped to solve a set of equations that would indicate whether rural or urban DCs make more sense for the society at large. This research is currently delayed because we have been unable to properly quantify the loss functions of the electricity and district cooling grids. In the same vein we also tried to make an in-depth study of the DCs connected to the Helsinki district heating & cooling grid. Perhaps due to the limitations of confidentiality involved, or just stressed by company-wide financial events, the operators of the relevant DCs never replied to our initial queries.

Fortunately, the general public opinions are changing. A recent YouTube video shot by Pekka Tonteri of HIIT shows, with certain joviality, myself brushing away the snow from our servers in the HC. All of the servers shown in that video survived the test and were, in fact, cleaner after the snow had melted. The video was duly noted on the popular social media site reddit[3] [sic] and translated by volunteers. Perhaps due to its short running length, only 17 seconds, the video became viral and reached 100,000 views in a very short period of time. If a picture is worth a thousand words, that video runs for almost five hundred thousand words, exceeding the length of this thesis and all the works contained in it. It is my sincere hope that either the video, the thesis, or preferrably both reach the operators, so that more DCs will finally install energy retrofits.

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Research Theme A: Free Cooling

Research Paper I

Mikko Pervilä, Jussi Kangasharju

Running Servers around Zero Degrees

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Contribution: I did the major parts of the work alone. Prof. Kangasharju supervised my work and did minor editing of the text. Figure 2 in was also done by him. I had some help in the physical construction phases as indicated by the acknowledgment section. Otherwise, the installation, design of the experiments, analysis of the results, the text, and figures were done by me.

Running Servers around Zero Degrees

Mikko Pervilä
Department of Computer Science
P.O. box 68 (Gustaf Hällströmin katu 2b)
FI-00014 University of Helsinki, Finland
pervila@cs.helsinki.fi

Jussi Kangasharju
Helsinki Institute for Information Technology
Department of Computer Science
P.O. box 68 (Gustaf Hällströmin katu 2b)
FI-00014 University of Helsinki, Finland
jakangas@cs.helsinki.fi

ABSTRACT

Data centers are a major consumer of electricity and a significant fraction of their energy use is devoted to cooling the data center. Recent prototype deployments have investigated the possibility of using outside air for cooling and have shown large potential savings in energy consumption. In this paper, we push this idea to the extreme, by running servers outside in Finnish winter. Our results show that commercial, off-the-shelf computer equipment can tolerate extreme conditions such as outside air temperatures below $-20°$ C and still function correctly over extended periods of time. Our experiment improves upon the other recent results by confirming their findings and extending them to cover a wider range of intake air temperatures and humidity. This paper presents our experimentation methodology and setup, and our main findings and observations.

Categories and Subject Descriptors

B.8.1 [**Performance and Reliability**]: Reliability, Testing, and Fault-Tolerance

General Terms

Experimentation, Reliability

Keywords

Sustainable computing, cooling, empirical system reliability

1. INTRODUCTION

According to an analysis published by HP in February 2009 [3], data centers would be the sixth-largest consumer of electricity if they were classified as a separate industry. By this analysis, research concentrating on reducing data center power consumption should show major benefits from both the green computing and financial viewpoints. In difference to home equipment, whose heat emissions are beneficial to indoor heating in cold environments, the heat generated by data centers can be collected only in the most recently designed architectures. As collecting the heat seems difficult, we turn our focus into preventing it.

Using outside air to cool the data center can yield energy savings from 40% to 67%, according to HP and Intel [1] respectively. We have begun a small scale experiment to verify the claims of Intel and HP, and also to extend their results to our environment.

Using the naturally cold winter in Finland, we seek to understand in how extreme conditions COTS and server equipment can be operated. During the winter of 2009-2010, outside temperatures of $-22°$ C were measured by the Finnish Meteorological Institute. While these measurements were taken in Southern Finland, much more extreme conditions occur in the Northern parts.

If we can bring the server equipment to tolerate North European conditions, we have shown that Intel's results from New Mexico and HP's from North East England can be extended to most parts of the globe. In addition to extending the area of feasibility, we are also interested in the effects of allowing the intake air a much wider range of variation. If the equipment can tolerate both long- and short-term fluctuations, we could eschew any conditioning of the intake air, including temperature and humidity stabilization.

This paper is structured as follows. In Section 2 we review related work. Section 3 presents our research questions and methodology. In Section 4 we present our main results and findings from our experiment. Section 5 discusses the implications of our results in relation to existing work and presents directions for future work. Finally, Section 6 concludes the paper.

2. RELATED WORK

As far as we have been able to ascertain, the closest works stem from industry white papers explaining the current state of the art of data center cooling. HP has analyzed the magnitude of the industry and reveal some details of their Wynyard data center [3]. A good entry point into current data center cooling solutions is provided by the summary article from Intel's Digital Enterprise Group [5]. It is further supplemented by the proof-of-concept air economizer cited [1] above. Interestingly, Intel's previous report [2] has argued convincingly against air economizers.

In addition to white papers, a more distant relative lies in the field of computer overclocking. A number of competitions have focused on driving COTS motherboards and CPUs well below their normal operational parameters by

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This is a minor revision of the work published in *Green Networking'10*, http://doi.acm.org/10.1145/1851290.1851293.

employing extreme cooling solutions ranging from liquid nitrogen to geothermal cooling [6].

Our work differs from the white papers in the direct use of intake air with very dynamic temperatures and humidities. Most of the cited cooling solutions assume stable or near-stable input temperatures by conditioning the cooling medium with an intermediary step. Intel's air economizer article is the closest related work. We seek to extend their previous results by letting the intake air conditions vary in a significantly wider range.

3. FEASIBILITY, RESEARCH QUESTIONS, AND METHODOLOGY

First, the major research question of this work remains whether unconditioned outside air is a feasible cooling solution. If Intel's proof of concept can be extended to our Northern climate, this would indicate that newly built or *Greenfield* data centers can do without air conditioning units.

Second, the equipment failure rate affects both financial and green endeavors. Financial endeavors are by definition mainly interested about the price. If the outside air technique is feasible but causes a higher equipment failure rate than by using familiar air conditioning, the projected costs must be carefully considered. If the failure rate rises only a little or not at all, replacement costs must be balanced with the purchase and energy costs of air conditioning. For green endeavors, this equation becomes trickier, as the comparison would need to factor in the amount of resources consumed by the manufacture and logistics of new components.

Third, a minor research question concerns which components will fail first. In what is called *industry tribal knowledge*, subjective viewpoints about the humidity or cold breaking component X run rampant. If the extreme temperature and humidity shifts indeed cause certain components to regularly fail, we should be able to detect this as a common-cause failure on multiple hosts nearly simultaneously.

Finally, we deliberately included some hosts from a series of workstations that we already knew to be unreliable. Their problems have to do with the hardware temperatures elevating due to bad air flow circulation. We were interested to see in how far the cooler outside conditions would alleviate the known problems, if at all.

The test setup was taken in two consecutive phases. To begin with, a prototype test was undertaken to ascertain that a real measurement was worth the trouble. After the prototype test completed successfully, a normal phase of testing was setup and started. Both phases are described in the following sections.

3.1 Prototype and Normal Phases

For the weekend from Friday, Feb. 12th to Mon 15th, we ran a generic PC sandwiched between two hard plastic boxes. The boxes did not really impede air flow or contain any heat, but served to protect against snow reaching the computer internals and melting into water. During the test, we monitored both hard drive S.M.A.R.T. readings and the internal temperature sensors through Linux' lm-sensors package. The local meteorological measurement unit located in the building next to ours recorded temperatures as low as $-10.2°$ C for the weekend, with an average of $-9.2°$ C.

The prototype survived the test, remaining operational for the whole weekend. Readings recorded by lm-sensors showed that the CPU had been operating in temperatures as low as $-4°$ C. While this result is surprising, similar readings have been noted by the overclocking communities.

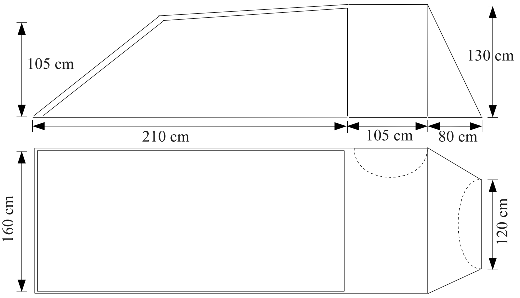

Figure 1: Schematic for tent shielding the computer hardware from rain and snow.

We were forced to stop the prototype test the following week due to external constraints: the two plastic boxes that we had borrowed for this test had to be returned. Nevertheless, we deemed the test a success and scheduled a more extended test to begin the following Friday (Feb. 19th).

Operating on a shoestring budget, we asked for permission from the department's IT staff to reuse old workstations destined for recycling. Due to local tax regulations, hardware removed from usage can not be given out to employees or donated. As things were, most of the PCs were still fully operational. In addition, we procured some workstations which were considered unreliable, mentioned above, and also a batch of seven rack-mountable servers. The computer equipment is more thoroughly described in Section 3.4.

The main problem to overcome was how to shield the computers from water or, in our case, snow. Many solutions were considered, but in the end we opted for a lightweight tent aimed for three-person camping trips.

3.2 The Tent

In order to maximize air flow, the ideal protective construction would be something resembling an outside storage shed with only minimal cover, e.g., of the kind that hardware stores use for construction materials. Due to time, location, and resource constraints, we were forced to compromise with the protective solution.

We located the tent on the roof terrace of the Department of Computer Science. The location is very good, since a power outlet designed for outdoors use is positioned just next to the site, and access to the roof terrace is monitored by video surveillance.

A diagram of the tent is presented in Fig. 1. When erected, the tent consists of a roughly tube-shaped, double-layered structure of polyester fabric. Soon after installing the equipment, we were forced to make repeated modifications to the structure, as the tent proved surprisingly good at retaining heat. Later changes include removing the inner layer.

There are four main factors affecting the inside temperature of the tent. These are, in order of importance, the

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An hourly webcam image of the terrace (with the tent) is available at http://www.cs.helsinki.fi/Exactum-kamera/

outside air temperature, sunlight and wind speeds, power draw of equipment, and which tent flaps are open.

We tried to reduce direct sunlight hitting the tent fabric by installing a partial, reflective foil cover of the same material used in first-aid rescue sheets. The purpose of these sheets is to keep incapacitated patients warm in cold environments. For our purposes, the reflective cover measurably decreases the internal temperatures, as we later show in Section 4.1.

Wind speed remains somewhat of a problem. As the tent is designed to actually block out the wind chill effect, we have tried to modify the structure by cutting open the internal fabric and removing the protective tarpaulin from the bottom. As our terrace is elevated higher than the roof, some cool air is able to circulate through the floor and into the tent. This way, the electronic equipment is still protected by the outer fabric, but the heat dissipation factor is as high as possible.

The last modification to normal operation was to let the outer front door remain in a half-open position. This seems to improve air flow from the back and through the bottom of the tent on days with even a moderate amount of wind.

3.3 Measurements Taken

Following data center best practices, our analysis concentrates mainly on the temperatures and relative humidities (RHs) surrounding the electronic equipment. These measurements are separated into data gathered from inside and outside of the tent.

For outside data gathering, we were fortunate enough to receive access to the Department of Physics' weather station located just outside our building. The station is known as SMEAR III and is co-operated with the Finnish Meteorological Institute, who provide data gathering services for nearly all interested parties.

Inside the tent, we used a Lascar EL-USB-2-LCD data logger as the sensor device. Measurement error for the unit is ±0.5° C, ±3.0% RH typically and ±2°, ±6.0% RH maximum. Data loggers of this type are used by companies transporting edibles, for example. The advantage of the data logger is that it is machine readable, although only by manually inserting the device into an USB port. Due to this, we have been forced to remove a number of outliers in the measurements caused by removing the data logger and carrying it indoors. These outliers have been removed from the graphs.

Finally, in order to gauge the amount of heat generated by the hardware we used a Technoline Cost Control unit. It has recently been tested [4] by local colleagues and found to perform very admirably given its price. The unit was used to measure normal and maximum power draw of the server hardware. The total load of the tent remained below 1100 W during normal operation, including the mechanical fan installed later.

3.4 Hardware

In total, we operate 19 computers in three form factors. The first set is from a small vendor ("A") using COTS hardware to build "cloned" desktop machines. These machines are built in medium tower cases and contain two hard drives formed into a Linux multiple devices software mirror. The second is a large vendor ("B") producing mass-manufactured small form factor PCs as workstations. Only a single hard drive can fit in the case due to the form factor. The third is a large vendor ("C") offering rack mounted heavy duty servers in the 2U form factor. There are five hard drives in each, two of which compose a hardware mirror, and the remaining three a stripe set with parity.

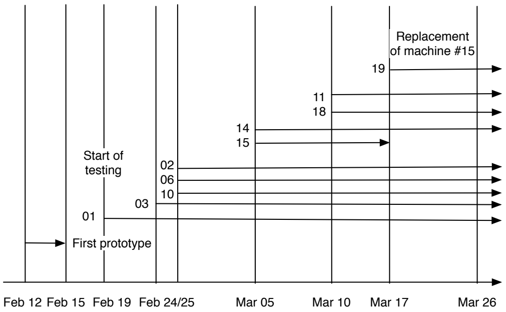

Figure 2: Dates of when servers were installed.

In order to distinguish faults caused by our chosen conditions, a control group was installed into the department's basement. Computers are thus installed pairwise so that identical units are placed into the control group in the basement and the test group in the tent on the terrace. The department's basement doubles as a protection shelter for staff, thus, the control group operates in a sparsely furnished environment with stable, office-type air conditioning. The operating conditions are therefore well within specifications.

For our tests we installed ten hosts from vendor A, four from B, and four from C, yielding a symmetric nine hosts in the basement and nine in the tent. A timeline of when servers were added is depicted in Fig. 2. The numbering refers to the the servers on the terrace. (The 19th server was used to replace one server that partially failed during the test; see Section 4.2.)

3.5 Load

All servers execute a synthetic workload, which consists of packing a Linux kernel source directory with the standard tar and bzip2 archive programs. After packing, each compressed tarball is verified by calculating its md5sum hash function and comparing the result with an initial value calculated before installation. If the results differ, the packed tarball is stored. If not, the tarball is overwritten in the next cycle.

Each host executes its synthetic load every 20 minutes. In order to avoid synchronization, some fuzz is added to the starting phase: each host sleeps for 0 to 119 seconds before commencing the archival process.

At the time of writing, we have collected results from a total of 119516 executed runs from the 19 hosts executing the synthetic load. Of these results, six have been found faulty and examined more thoroughly in Section 4.2.2.

Some load is additionally generated by the monitoring host, which recovers all calculated md5sums and data gathered from the local sensors every 20 minutes. The transfer is done using public-key authentication through an OpenSSH tunnel, and new files are transferred by the rsync program.

4. CURRENT KNOWLEDGE

At the time of writing, the first server installed has been operating for three months with only very minor glitches, which are described in Section 4.2. The last of the hosts was installed March 13th, meaning two and a half months of operation at the time of writing. Of the eighteen hosts installed initially, one has encountered two transient system failures, and after having been taken indoors, has remained in stable operation. A failure rate of 5.6% may seem harsh initially, but Intel has reported a comparable rate of 4.46% during their experiment [1].

Despite the relatively small number of transient system failures we have learned a number of lessons. In the following section, we take a look into the development of temperatures and relative humidities inside the tent and review the faults encountered more thoroughly.

4.1 Temperature and Humidity

Figure 3 shows the evolution of the temperatures both inside and outside the tent during the experiment. The outside temperature is from the SMEAR III station and the inside temperature is from the Lascar data logger. The figure also shows a few key events, marked R, I, B, and F, which are explained below. Because the Lascar data logger arrived late, tent-internal temperature and humidity data from the early parts of the experiment are missing.

Figure 3 shows a number of changes in the tent's internal temperature. Major operations undertaken to limit the heat retained by the tent fabric have been marked with letters beneath the figure. In order of appearance, the coding is R for installation of the reflective foil cover, I for removal of the inner tent, B for partial removal of the bottom tarpaulin, and F for installation of a common tabletop motorized fan.

What is clearly visible towards the end of the graph is the week-long heat period encountered in Helsinki during the third week of May. Outside temperatures rose quickly to relatively high temperatures of $20 - -25°$ C, causing a subsequent elevation to $25 - -30°$ C in the tent's internal temperature. After that one week of unusually warm weather, Helsinki has now normalized to much more usual temperature levels.

Relative humidities are shown in 4. Because RH values are defined by their ambient temperatures, the figure is somewhat difficult to analyze. What is visible, however, is that the tent has been able to retain more stable relative humidities than outside air, although sharp temperature drops are still visible. As we increase air flow to lower the inside temperatures, the humidity also begins to vary more intensely.

4.2 Faults Encountered

During the full test run thus far, we have encountered four cases of system failures and six cases of miscalculated synthetic loads. Two of the system failures can be written off as being caused by hardware faults present even before the test. The other two are more difficult to explain. We will describe the system failures first, and then move on to the synthetic loads.

4.2.1 System Failures

The first problem was discovered in the host that has been in continuous operation for the longest span of time. This host has encountered outside temperatures of $-22°$ C. After the initial period in the most extreme cold, the host's lm-sensors started to malfunction. Before the failure, the motherboard's sensor chip had reported CPU temperatures of below $-4°$ C, followed by clearly erroneous readings of $-111°$ C . After detecting the anomaly, we tried to redetect the sensor chip with hopes of resetting its internal readings. Instead, the opposite resulted, and the sensor chip ceased to be detected at all. After a week, we risked a warm system reboot, which caused the sensor chip to work again. It is difficult to say if the sensor hardware or its accompanying kernel modules were the root of the fault. However, no further problems have been detected on this host.

Host #15 from vendor B encountered a system failure on Saturday, March 7th at 04:40 (a.m.). The host in question was running in the tent. After an inspection and reset on the following Monday, no cause for the failure could be determined. The failure was initially marked as transient and the host resumed normal operations in the tent.

Unfortunately, the same host encountered another failure on Wednesday, March 17th at 12:20 (p.m.). The host was reset in outside conditions but could not resume normal operations. It was again taken inside for an inspection. A standard Memtest86+ run caused another system failure within a few hours. After this, the host was left to operate in an indoors environment. No further failures have been detected on the host. Note that this host was from the series we already knew to have frequent defects. We must thus concur that during this test, the system series known to be defective operated no better in outside conditions. None of the hosts in the control group have failed yet, and neither has the new host that replaced host#15 in the tent.

Finally, the two problems that we can explain relate to the network infrastructure. In order to share the network connectivity we employed two 8-port network switches known to contain cosmetic errors, i.e., an annoying whining sound during normal operation. Both of the switches encountered a failure after a week or so of tent operation. After some testing, the remaining switch that had never been used for this test manifested an identical failure state. We can therefore conclude that the problem is inherent in these individual switches and existed even before we began our test.

4.2.2 Wrong hashes

Our synthetic load has encountered problems in 6 out of a total of 119516 test runs. The ratio of tent/basement errors is a follows: two hosts placed outside reported one wrong md5sum hash each, and one host placed inside reported four wrong hashes. Of the problematic archive files, we were able to recover the two most recent ones.

While inspecting the tarballs with the bzip2recover utility, it became clear that only a single one of the 396 bzip2 compression blocks had been corrupted. No errors have been reported by the file system or the kernel, and the hard drives have passed their S.M.A.R.T. long test runs. The current conjecture of a failure cause is therefore a memory error. All three hosts that have reported faulty hashes contain memory chips without error-correcting parities.

By calculating the size of the source directory to be compressed, the average block size of the compressed tarball, and the amount of cycles we have estimated the amount of memory pages read and written to lie in the ballpark of 14 billion. If the estimate is correct, and the six faulty archives are caused by a single memory page fault each, the failure ratio is around one in 2,5 billion.

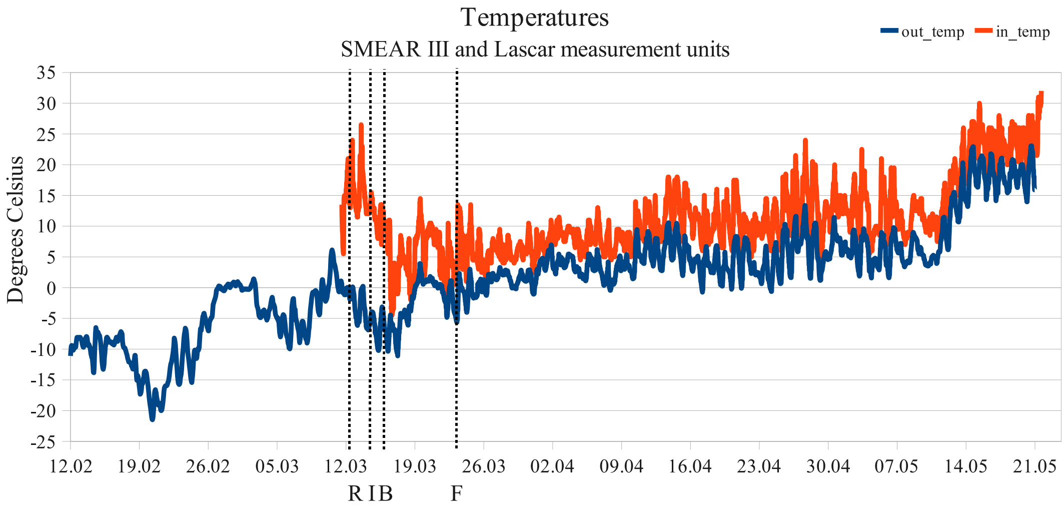

Figure 3: Temperatures outside and inside the tent.

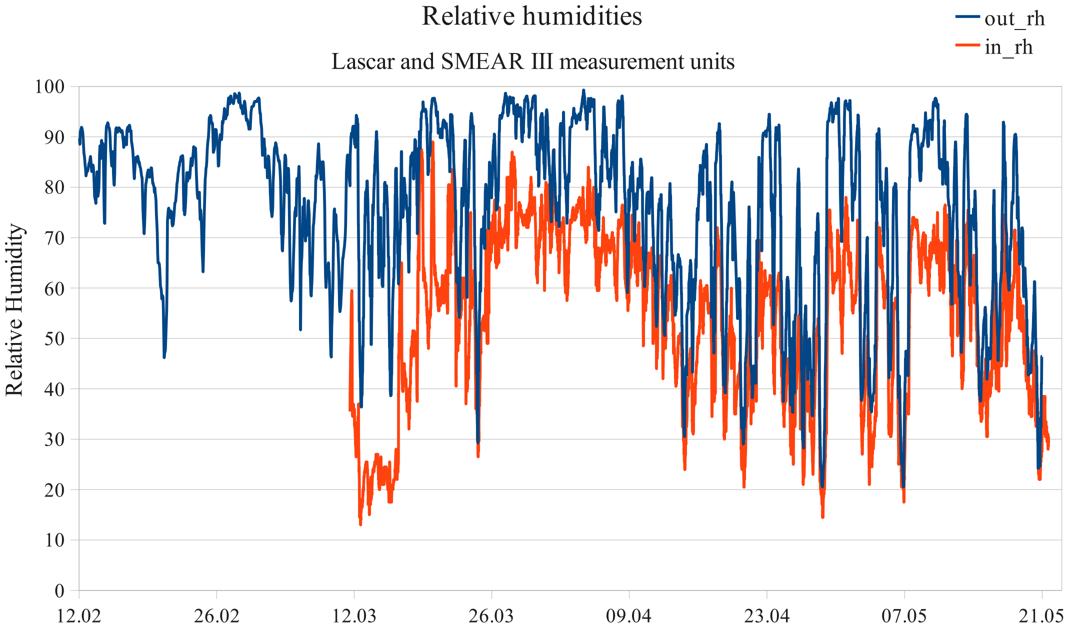

Figure 4: Relative humidities inside and outside the tent. Missing inside measurements are due to the Lascar data logger's delayed arrival.

5. DISCUSSION

Alongside with our measurements, the CS Department is building a new computing cluster. Upon completion, the cluster is estimated to become the third fastest supercomputer in Finland. Our server room is being retrofitted with added cooling capacity to accommodate the new equipment.

Calculating the amount of power consumed by the new devices, we know that the cluster can operate at a peak load of 75 kW. In order to cool this load, we have installed three new computer room air conditioning (CRAC) units, drawing a total of 6.9 kW of power. The unit that provides cool water to cool the CRACs operates in a designated heating, venting, and air conditioning (HVAC) area. That unit's power draw is specified as 44.7 kW. Last, the final piece of the setup is the liquid cooling unit positioned on the department's roof, which has a specified power draw of 3.8 kW. If we could just sum those figures up, the new cluster's power usage effectiveness (PUE) rating would be a rather efficient 1.74. Unfortunately, such is not the case, as our existing CRACs take care of some of the thermal load. This means that for PUE, the situation is worse, and more energy is wasted.

At the beginning of our test nobody really knew if the idea was entirely plausible, and if so, how long would the servers run. Now we know that at least a couple of months is a realistic guess, and that sub-zero temperatures or relative humidities above 80% or 90% are not a certified cause for server failures.

With these percentages, a central question concerns whether water can condense in the hardware, potentially short circuiting the electrical components. Our current knowledge is that water has few possibilities to condense in the equipment, as this would require the outside air to suddenly become warmer than the computer cases. As the cases are heated by their internal power draw and their inside air circulates due to the system fans, this phenomena is not as likely as some initial ideas suggested.

The air cooling tests described herein will continue to provide new data and knowledge about malfunctions encountered and shifts in the operating conditions. So far, neither the extreme colds of our winter or the rapidly changing conditions of spring have not been terminal for the hardware. As higher and higher summer temperatures are becoming common, we will see how temperature peaks affect our control group. It is certainly still possible that within the next months of operation, some components may start to regularly fail.

6. CONCLUSION

In this article, we have shown that current computer equipment is able to withstand very wide-ranging temperatures and humidities for extended periods of time. Further experimentation is necessary to find the limits of feasibility for this type of operation. Our future research will extend the initial results herein with more data over longer periods of time, over varying meteorological conditions, and more diverse hardware.

Through our current results, we have been able to independently verify the previous findings of computer manufacturers. These results promise very significant potential reductions in data center energy use, through the use of outside air for their cooling. As our department is also soon running very power-hungry hardware, we are dedicated into finding new and more efficient cooling solutions.

7. ACKNOWLEDGEMENTS

For their assistance at the setup phases of this project, we would like to thank Pekka Niklander and Pekka Tonteri from the IT staffs of the CS Department and HIIT respectively. Pasi Aalto of the SMEAR III project was invaluable in providing us with meteorological data. Finally, Ilona Riipinen and Sampo Smolander from the Physics Department clarified many concepts related to humidity and condensation.

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Research Paper II

Mikko Pervilä, Jussi Kangasharju

Cold Air Containment

In *Proc. 2nd ACM SIGCOMM workshop on Green networking (GreenNet 2011)*. ACM, 2011, pp. 7–12, DOI http://dx.doi.org/10.1145/2018536.2018539.

Contribution: I did the major parts of the work alone. Mikko Rantanen designed and implemented the power measurement solution described in Sect. 3.1 of the publication. Prof. Kangasharju supervised my work and did minor editing of the text. Figure 2 was done according to my specifications by Janne Ahvo and used with permission. I had some help in the physical construction phases as indicated by the acknowledgment section. Otherwise, the design of the experiments, hardware choices, analysis of the results, writing, and figures were done by me.

Cold Air Containment

Mikko Pervilä
Department of Computer Science
University of Helsinki
pervila@cs.helsinki.fi

Jussi Kangasharju
Helsinki Institute for Information Technology
University of Helsinki
jakangas@cs.helsinki.fi

ABSTRACT

This article describes two benchmark studies involving the cooling technique known as cold aisle containment (CAC). One test case studies a 26U server rack operating on unconditioned outside air only in a carefully controlled setup. The other examines a server room with a power draw of over 80 kW during normal operation. In both cases we measure how incorporating CAC changes the air flow, electricity consumption, operating temperatures, and cooling requirements. Our results show how the air flow separation affects the temperatures in the server room and verify that using CAC can reduce CRAC power by roughly a fifth.

Categories and Subject Descriptors

B.8 [**Hardware**]: Performance and Reliability; B.8.1 [**Performance and Reliability**]: Reliability, Testing, and Fault-Tolerance

General Terms

Experimentation, Reliability

Keywords

Sustainable computing, cooling, empirical system reliability

1. INTRODUCTION

For the past 20 years, the standard method of building data centers (DC:s) is the so called hot aisle / cold aisle layout. Server racks are placed in rows so that their front panels face the same direction, and a gap, called an *aisle*, is left between the rows. If the DC does not use in-row air conditioning units, the floor is raised so that an air pathway forms underneath it. The aisle between the front panels uses perforated floor tiles. Computer-room air conditioning (CRAC) units pump cold air into the raised floor space, so that the air exits upwards through the perforated tiles and into the front panels of the server racks. The aisles with perforated tiles are called cold aisles.

Exhaust air is vented through the rear panels of the racks. The rear panels oppose the next row's rear panels, again with an aisle between them. The tiles between the rear panel rows are not perforated. The hot air rises naturally upwards towards a clear pathway between the tops of the racks and the ceiling. Thus, the exhaust aisle is called the hot aisle. CRACs use powerful fans to draw in the exhaust air and cool it into new supply air, which is pumped back under the floor.

Figure 1(a) shows the motion of air under these ideal conditions. In real data centers, multiple factors render the air circulation cycle sub-optimal. The major issues are obstructions in air flows, unmatched supply and intake air flows, cold air leakages, localized hotspots, and hot air recirculation.

Much of the work concerning the effects of air flows on data center cooling needs and electricity consumption has been done through emulation [5, 7], not real equipment [1]. In this paper, we push the envelope further by experimenting with cold air containment using real servers in both a controlled setup as well as an operating data center.

1.1 Related work

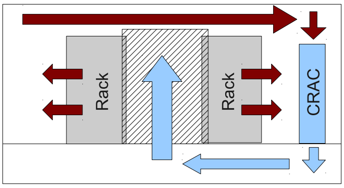
Data centers are under constant scrutiny to improve cooling efficiency as the amount of power used by the ICT industry increases. The big players in the field are hardware and software manufacturers that employ the largest data centers. Not all of their solutions are known [4], since cooling improvements yield direct reductions of the power requirements of a data center. These reductions translate directly as economic gains and thus become competitive advantages.

As early as 1991, Nakao et al. [7] considered the effects of hot air circulation caused by exhaust air short circuiting back as supply air. Recently, white papers describing new ideas surface at an increasing pace. Space constraints force us to we prune this section to those articles that are most relevant to air stream containment, with a strong emphasis on measured experiments.

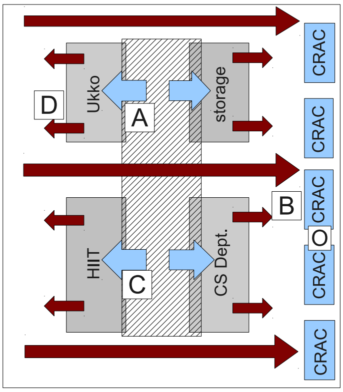
Intel's white paper by Atwood and Miner [2] is attributed as the pioneer work in using natural air for data center cooling. Their technique was later verified by Microsoft's [3] tent experiment, while we extended the technique's feasibility into a much harsher climate [9].

Natural air cooling can be impossible to retrofit to an existing DC, either due to the ambient climate or building limitations. A complementary solution is aisle containment. Hilss and Iyer [5] describe HP's results with CAC. They performed an emulation-based study using ten racks equipped with 2.4 kW load banks. Using CAC yielded a maximum

GreenNet'11, August 19, 2011, Toronto, Ontario, Canada.



(a) Side view of air flow with CAC



(b) Top view of air flow with CAC

Figure 1: Separation of cold and hot air streams

CRAC efficiency improvement of 41% when the racks were loaded with an average of 9 kW. Adams [1] measured the effects of the complementary technique, Hot Aisle Containment (HAC). The study omits a comparison to the situation before HAC was installed.

Patterson [8] analyzed the tradeoff between centralized cooling through CRAC:s vs distributed cooling with server fans. Both are modelled diligently, with the conclusion that turning up the supply temperature can result in negative savings as server fans will need to ramp up their rotations per minute. Thus, cooler supply air could reduce the total power draw of the servers.

In this paper, we verify the results of Hilss and Iyer [5] in a real data center environment. We extend the work of Adams [1] by measuring the opposite CAC technique and also include data before and after our changes. Section 2 describes our initial prototype with some preliminary results. In Section 3 we study the development of a real-world, small scale DC with a power draw of 80 kW during baseline operation and over 110 kW during high-performance cluster computations. Section 4 concludes with lessons learned while building a home-brew CAC setup, and what changes can be expected by those willing to duplicate our methods.

2. COLD AISLE CONTAINMENT

Both aisle containment techniques are simple in their key idea: either the hot or the cold aisle is covered at the top and edges of the aisles. This forces the hot and cold air streams to separate. The shaded areas in Figures 1(a) and 1(b) show how CAC limits the flow of the cold air stream so that it must pass through the equipment racks.

In both cases the aisles must be refurbished so that leakages are minimized. Reasonably airtight doors are required at the edges to allow for operator access, and cable ducts must be isolated to prevent leakages. Different vendors' solutions range from purchasing entirely new racks to installing plastic curtains constraining the air flows. Obviously, replacing the racks is a very time-consuming and delicate operation, which makes retrofit-capable solutions more desireable.

Our solution consists of see-through plastic blankets, a handful of PVC tubes, and plenty of duct tape. We decided to verify whether a solution constructed as cheaply as possible would yield benefits for energy consumption, cooling requirements, or operating temperatures of an existing set of servers. The major difference to [5] is that we use real servers: the combined effect of hundreds of temperature-driven fans might yield additional benefits when supplied with colder air.

Our key research questions were as follows. If one or more of the answers proved positive, other DC:s in the small to medium range could improve their existing installations' energy efficiency with a shoe-string budget.

1. Can CAC reduce the cooling load of the CRAC:s?
2. Will CAC yield a more uniform supply air temperature?
3. Will the servers use less energy in total when given more uniform supply air?
4. Does CAC reduce the electricity consumption of our DC?

The experiments take a black-box approach at the rack level. We measure the supply and exhaust air temperatures as well as the aggregate energy consumption of the data center, including CRAC:s but exluding the chiller plants and cooling towers. These exclusions are caused by practical limitations at our installation. Finally, we do not monitor internal server temperatures, but assume that they are linear to inlet temperatures. Despite these limitations, we show that CAC is an efficient technique and can be retrofitted with very low additional costs to existing DC installations.

2.1 Prototype Helsinki Chamber

As a first step, we constructed a small, controllable prototype setup to verify how CAC would help in stabilizing inlet air temperatures. This prototype was designed to employ both CAC and unconditioned natural air cooling.

Continuing on our previous, experimentation-based studies on air-based free cooling [9], we now operate 14 rack servers in a modified enclosure on the roof terrace of the Department of Computer Science. Two of our servers were used in our previous experiment as well; they have been cooled with unconditioned outside air for 14 months at the time of writing.

Our custom-built enclosure contains a 26U 19" Rittal rack. We have named this type of enclosure a *Helsinki Chamber* (HC), following the style of previously existing Kyoto Wheels [6]. Figure 2 shows the schematics of our own construction. A full evaluation of the merits and flaws will follow in a later work, when we have gathered data for the summer months as well.[1]

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[1] A view of the setup is available from http://www.cs.helsinki.fi/Exactum-kamera/.

We designed the HC not only to employ CAC during the warmer months of the year, but to intentionally recirculate exhaust heat during winter. However, due to an unexpected very sharp temperature drop in February 2011, we have now employed CAC with supply air as low as -23°C. Our prototype uses duct tape to isolate all leakages, but a temperature-driven vent would be straight-forward to add. The ideal solution would be that the servers themselves would recirculate the warm exhaust air when the inlet temperature drops too low.

2.1.1 Construction and instrumentation

The 26U of servers running in the HC have a combined power draw of over 3.4 kW. A full 42U rack would imply a power draw of 5.5 kW. The servers draw in supply air from the lower front of the HC, through two standard, Euro-type pallets elevating the HC about 30 cm from the roof of the building. After periods of heavy snowfall, some manual labour is required to ensure that the intake vents do not entirely block.[2]

The HC is instrumented with four Lascar EL-2-USB-LCD data loggers[3] that record temperatures, relative humidities, and dew points. The sensors are marked in Figure 2 as $A - D$. Sensor A is positioned at the highest rack server and B is positioned at the intake of the HC. The difference $A - B$ shows how much supply air is warmed by exhaust air recirculation combined with heat radiated by the servers. Sensor D is positioned at the bottom of the exhaust section, while C is positioned at the top of the exhaust. The difference $D - C$ shows the buildup of exhaust heat. Finally, the pairwise differences $A - C$ and $B - D$ show how much exhaust heat the servers are venting.

2.1.2 Restricted air flow

We isolated the perforated holes of the 19" rack using duct tape on February 10th, 2011. Before this, we had allowed hot air to recirculate and mix with the supply air. Because of the sharp temperature drop just after Feb. 10th, intake air temperatures dropped below -20°C. In order to verify how much the isolation affected inlet and exhaust temperatures, we did a pairwise search for matching ambient temperatures from Feb. 1st to March 1st, 2011. As the HC air intake is indirect, we considered the wind factor effect to be negligible. A visual inspection of the graphs showed no evidence of skew due to sunlight.

Due to space concerns, we have omitted the graphs from this article. They all follow the same pattern: there is a sharp increase in sensors A, C, and D before CAC installation caused by the increased computational load on the servers. After the change, readings from sensor A drop by a regular -10°C, whereas readings from sensor D increase by 10°C. In other words, exhaust recirculation is now blocked and the temperature difference $A - B$ lowers from around 20°C to 8.5°C on average. The remainder was caused by exhaust recirculation through the servers, and eliminated later.

The experiment on our prototype HC gave confidence that cold air containment was a feasible technique for stabilizing the inlet temperatures of a 26U rack.

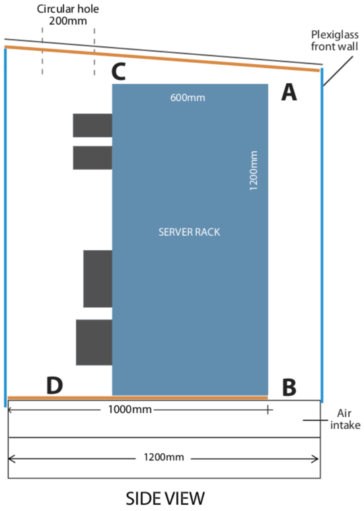

Figure 2: Helsinki Chamber schematics, side view, and the locations of the data loggers $A - D$

3. EXACTUM DATA CENTER

As the follow-up, we moved from cold air to cold aisle containment in the server room of our CS department building (named "Exactum"). The server room is a small-scale data center housing the combined IT equipment of the Department of Computer Science and the Helsinki Institute for Information Technology (HIIT).

The DC has undergone a very natural evolution from using mid-tower PC:s to extensive virtualization and state-of-the art blade enclosures. Due to its history, our set of hardware is extremely heterogeneous. The latest addition to the palette is the Ukko High-Performance Computing Cluster, which consists of 240 blade computers and a total of 1920 physical cores. Ukko by itself is specified for a maximum active power draw of 74 kW.

For the CAC experiment, we chose a before and after type measurement. Both are further subdivided into an idle phase, where the Ukko cluster idles with almost no load, and an active phase, where Ukko is given a computationally intensive task that raises its active power draw from under 34 kW to a steady 68 kW.

3.1 Different power lines

For energy measurements we used Hager EC-370 power consumption meters[4] read through their LED light outputs. We soldered two BPW85A phototransistors to the DTR-DTS and RTS-CTS signal pairs of a RS-232 cable, and then used the RXTX Java library to read the RS-232 signals. Each LED signal was translated into fractional kWh:s and then recorded into a RRDtool database.

The power consumption meters were connected before UPS devices and power distribution units (PDU:s) in order to capture the actual power usage of the DC. The measure-

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[2] This turned out to be much less work than we expected. The first author spent a total of 3 * 30 minutes shoveling snow during last winter.

[3] See http://www.lascarelectronics.com/ for full details.

[4] See http://www.hager.com/ for full details.

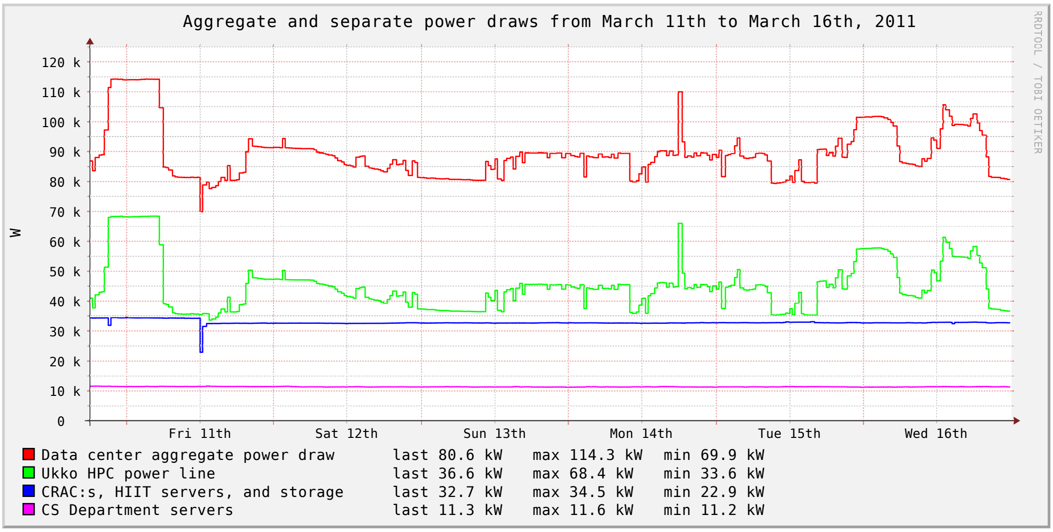

Figure 3: Aggregate and separate power draws of the Exactum data center

ments contain the CRAC units but exclude chiller plants and cooling towers.

Due to historical reasons, Exactum's DC electricity is supplied by three different power supply lines. This was very beneficial for our experiment, as it allowed us to separate the loads of the infrastructure services (two line) from the power-intensive loads of the Ukko cluster (one line). Most importantly, we discovered that the infrastructure services had very stable power draws during our experiments, whereas the total power consumption of the DC was dominated by Ukko's computational load. This allowed us to measure both a baseline and a pathological power draw of the DC by controlling only the CPU loads of Ukko.

Figure 3 depicts the power draw of the three power supply lines and their sum as the aggregate power draw of the entire DC. Our infrastructure services are divided into two categories: CS Department servers and the rest, i.e., CRAC:s, HIIT servers, and storage units. As can be seen from the figure, the infrastructure power draws vary within a few hundred watts normally. The sharp drop visible during Friday, March 11th was caused by human error, as the power meter's phototransistor got accidentally dislodged from the LED.

The EC-370 meters were able to measure both active and reactive power readings. We monitored the power factors before and after CAC installation, both during peak and normal computational loads. Probably due to the UPS devices, the power factors of the power lines connected to the infrastructure servers remained stable at 0.99 and 0.89. For Ukko, there was a small change from 0.96 to 0.97 during periods of heavy computation. During these periods, the DC's combined power draw remained steady at 114 kW.

3.2 Temperature changes

Even without the peak 114 kW loads, our CRAC:s had started to struggle. As the DC's physical size is only just over 70 m^2, we were operating at idle and peak power densities of over 1.1 and almost 1.6 kW/m^2. An earlier inlet monitoring system reported a steady increase of about 4°C within the last year. According to our vendor, the cooling system had reached its maximum capacity and could not be further optimized.

We instrumented the data center using five Lascar EL-2-USB-LCD data loggers. As we were mainly interested in the mixing of cold and hot air streams, not all of the inlet temperatures of the servers, the low number of measurement points was deemed sufficient.

Figure 1(b) shows our rack configuration and data logger placement. The first aisle consists of four racks for the Ukko cluster and three racks for storage devices. The second aisle consists of four racks for the CS Dept.'s systems, and four racks for HIIT's systems.

Data loggers were placed as follows. Sensor B was placed under the raised floor in front of the middle CRAC. Sensors A and C were placed near the tops of HIIT's and Ukko's racks. The differences $C - B$ and $A - B$ indicate supply air temperature elevation from the CRAC:s to the server inlets nearest to the rack tops. Sensor D was positioned near the middle of the Ukko's exhaust panels. The difference $A - D$ shows the maximum temperature elevation for inlet to exhaust air, as Ukko was known to be the most power-intensive of the servers. Finally, sensor O was positioned at the return intake of the middle CRAC, and $O - B$ shows the temperature delta at the CRAC.

3.3 Cooling fluid loops

Exactum's DC was retrofitted with additional cooling in early 2010 when Ukko was installed. Previously, the DC ran on two CRAC:s supplied by the neighboring building's chiller plant. With the increase in heat load, a new, dedicated chiller plant and four new CRAC:s were installed to Exactum. The previous two CRAC:s were left running, bringing the total to two old and three new units in the data center, plus one new unit in the adjacent room housing the UPS devices.

Both chiller plants are connected to their own cooling towers via secondary, closed loops. Both towers use free cooling whenever outside temperatures are below 3°C. Using free cooling simplifies the analysis, for we can study the baseline effects of CAC without considering the average times and amount of power direct expansion systems spend running.

Sadly, the chiller plants proved impossible to instrument conclusively. We were forced to compromise due to the lack of line valves in the pathways of the cooling fluids. The only possibility was to measure the intake of primary cooling fluid (water) for the older CRAC:s at two different valves, and the return flow of cooling liquid (35% ethylene alcohol) from the tower to the newer chiller plant at Exactum.

Exactum's secondary cooling liquid loop did not reveal much data. The temperatures followed ambient temperatures closely, which is not surprising considering the effectiveness of free cooling during the winter in Finland. The older chiller plant's primary cooling loop proved more interesting, since it shows the chiller plant reacting to Ukko's computational load. Before CAC, the chiller plant would periodically drop down the cooling fluid temperature by about 2°C. After CAC, these drops are no longer required, meaning that less work is required of the chiller plant, and thus, less energy is used in general.

3.4 Structural changes

We used duct tape and plastic cut-outs to isolate openings between our racks and the servers. Gaps between the side walls and openings underneath the racks were covered in a similar manner. All cracks in the raised floor were carefully covered. The front panels of the Ukko cluster and storage units were sufficiently isolated, requiring no further work.

On top of the racks we installed PVC tubes to support the roof of the CAC aisle. We covered the PVC tubes and the edges of the cold aisles using two long sheets of see-through plastic. Our original plan was to build a continuous cover for both aisles, but in practice it was easier to build two aisles with their own doorways. In hindsight, this was a mistake, for the CAC aisles pressurized unequally. We have later reconstructed the two into a single, continuous aisle.

After the covers had been secured, both aisles were pressurized by the supply air supplied from the CRAC:s. An unforeseen benefit of using the plastic covers is that they flex along with the air pressure. The DC operators can easily verify that each aisle is provided with enough supply air: if the demand exceeds the supply, the covers are sucked inwards by the negative pressure. In the opposite case, the covers blow outwards. We try to avoid this for maximum efficiency and also due to structural reasons, since there are limits to how much tension the duct tape can withold.

The CAC installation took less than three hours for three persons.[5] The material costs amount to 29.50 € for the plastic covers, 37.14 € for the PVC tubes, and 54.01 € for the duct tape, for a total of 120.65 €.

3.5 Results

In order to compare temperature changes we selected two time frames consisting of 16 hours each. The time frame before CAC runs from March 4th, 12:00 to March 5th, 03:56. The first 7.5 hours consist of normal operating load, whereas for the following 8.5 hours the Ukko cluster calculates near full capacity. The time frame after CAC runs from March 10th, 20:00 to March 11th, 12:00. Ukko runs near full capacity for the first 9 hours, after which the DC resumes normal operation.

Figure 4(a) shows the supply temperature measured by sensor B. All CRAC:s had already been set to operate at full cooling capacity, and their fans set to maximum power. The supply temperature was just above 15°C. Figure 4(c) shows that when this supply air reached the highest server inlets, the temperature had already risen to above 19°C. This elevation was caused by exhaust recirculation. When Ukko operated near full capacity, the elevation kept on rising above 21°C.

Figures 4(b) and 4(d) show the changes after CAC installation. We were able to return the three newer CRAC:s back to temperature-driven fan speeds and set new supply temperatures to 25°C. The older CRAC models were left to operate at the same setting as before the change. Mixing the different CRAC supply air streams caused both Ukko's and HIIT's (not shown) inlet temperatures to stabilize near 18°C, about 1°C less than previously. Further, running Ukko near full capacity no longer had visible effects on its inlet temperatures as exhaust recirculation was eliminated. This was also verified by plotting the inlet temperature differences $A - C$ (not shown).

Return temperatures rose only about 2°C. The elevation was reduced by the fact that we removed all perforated tiles from the hot aisles. They had been installed in order to mitigate exhaust hotspots near heavily loaded servers.

After the changes, the CRAC:s kept operating at very minimal capacities. We continued to experiment and were later able to **turn one newer CRAC off completely** while still maintaining the same inlet temperatures as before CAC installation. The other CRAC:s did not have to compensate: the end result was a 2 kW reduction in total DC energy consumption. The drop is just barely visible in Fig. 3, above the label “Fri 11th”. As can be expected, the drop is minimal when compared to the aggregate power draw of the DC. The real benefits can be reaped by avoiding the purchase of an additional CRAC unit.

Finally, both our IT staffs have reported that the DC working conditions *feel* better, perhaps due to the exhaust heat being removed more effectively. As our operators are by necessity quite conservative, this reaction to the change seemed surprisingly positive.

4. CONCLUSION AND FUTURE WORK

Depending on how the individual CRAC:s consume power, our low-cost CAC has reduced our cooling requirements by roughly one fifth. This directly verifies Hilss and Iyer's [5] findings and answers our first research question positively. It also means that we can now install more servers and thus increase our thermal load further.

Inlet air temperatures for our computing cluster are no longer affected by exhaust recirculation which means a more uniform operating temperature. This answers our second research question positively. Since our cooling equipment no longer operates over its capacity, Ukko can be fully loaded for longer periods of time.

We have noticed no changes in the server fans as their power draw remained the same. It is not surprising, as

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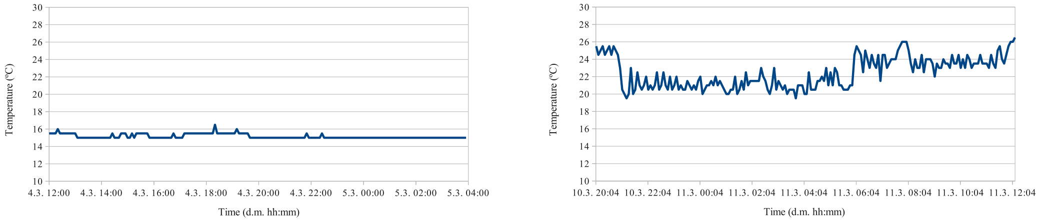
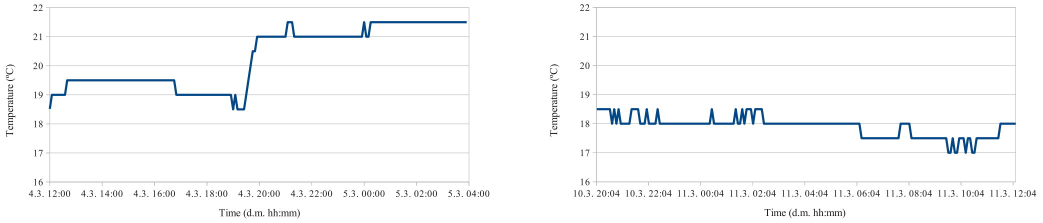
[5] A video of the finished installation is available from http://www.youtube.com/watch?v=jZIuJIVYsDs



(a) Supply temperatures before CAC

(b) Supply temperatures after CAC



(c) Ukko's inlet temperatures before CAC

(d) Ukko's inlet temperatures after CAC

Figure 4: Temperature changes before and after CAC installation

the inlet temperatures did not reach above 22°C even before CAC. Thus, our third research answer is a tentative no. Additional experimentation is necessary to measure how steadily raising the supply temperature will affect the aggregate power draw of the DC.

As for the fourth research question, CAC has been able to reduce our DC's total power consumption, although with only 2 kW as the computational loads remain unchanged. At the time of writing it seems entirely plausible that we might be able to reduce a second CRAC with further changes, e.g., better supply air pressure stabilization, CRAC management based on CPU loads, and better under-floor air flow management.

5. ACKNOWLEDGMENTS

The authors would like to specially thank Ville Hautakangas and Onni Koskinen from the CS department's IT staff for their assistance while planning and implementing the actual CAC construction. Also from the IT staff, Pekka Niklander was invaluable while planning the power measurements. Olli Moisio from the technical department helped us with the cooling fluid flow and power measuruments. Last but not least, Mikko Rantanen designed and implemented the phototransistor connection to the power measurement units.

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Research Theme B: Air Stream Containment

Research Paper III

Mikko Pervilä, Mikko Rantanen, Jussi Kangasharju

Implementation and Evaluation of a Wired Data Center Sensor Network

In *Energy Efficient Data Centers*, LNCS Vol.7396, pp. 105–116, DOI http://dx.doi.org/10.1007/978-3-642-33645-4_10.

Contribution: The design and installation of the wired sensor network was performed as joint work with Mikko Rantanen. Prof. Kangasharju did minor edits of the text. Otherwise, the concepts, design of the experiments, analysis of the results, writing, and figures were mine.

Implementation and Evaluation of a Wired Data Center Sensor Network

Mikko Pervilä[1], Mikko Rantanen[1], and Jussi Kangasharju[2]

[1] University of Helsinki, Department of Computer Science
PL 68, 00014 Helsingin yliopisto, Finland
`pervila@cs.helsinki.fi`
`mcrantan@cs.helsinki.fi`
[2] Helsinki Institute for Information Technology
Department of Computer Science
PL 68, 00014 Helsingin yliopisto, Finland
`jakangas@cs.helsinki.fi`

Abstract. As an alternative to often costly computational fluid dynamics (CFD) modelling of a data center (DC), we describe an ultra-low cost solution based on a wired sensor network. We describe the sensor hardware, packaging and cabling in detail, as well as the software components. Our prototype has been in production use for twelve months at the time of writing. This article presents detected air flow patterns that would have been difficult to discover using modelling alone, but easy to find with the measurement-based approach. We evaluate the benefits and drawbacks of our solution when compared with CFD models and existing alternatives. Key features of our approach are its accuracy, ease of deployment, and low purchase, construction, and operating costs.

1 Introduction

The benefit of building a CFD model is that proposed air flow modifications can be evaluated without the need of real changes in a DC. Yet CFD models are known to be both extremely computationally intensive and sensitive to any unanticipated air flow changes. The complexity required to calculate the complete air flow model is typically mitigated by simplifying the model, i.e., making generalizations about the conditions in the DC. The derived model is representative for a fixed point in time, but air flow changes can be caused by many day-to-day events in a DC, including hardware failures.

We argue that even though CFD can be useful in finding some problematic areas for air flow, without additional verification there can be no certainty that the CFD model remains precise for the whole DC. On the other hand, validating the entire CFD model for a large DC can be a serious burden. It is also difficult to describe the full complexity of a real DC in a model. Overlooked details can produce surprising defects in the resulting model, causing it to differ from the measured reality. The problem is the inherent requirement of true initial knowledge in a simulation-type study. For example, the effects of changes in the perforated floor tile configuration [13] and obstructions in the underfloor plenum [3] are well known.

In CFD modelling, groups of servers are typically modelled as *blocks* with a homogeneous air flow. However, as new server designs are constantly produced, even units from a single vendor can have extremely varying airflow characteristics [12]. Devices like switches and routers can also eschew the front-to-back cooling pattern [10] completely. Server air flow is not proportional to the amount of power drawn by a server, is difficult to estimate based on reported fan speeds only, and can change considerably by reordering the same servers in the rack [10].

Even though CFD modelling might work well for newly built, homogeneous environments, it can fail in colocation-based data centers. In these DCs, the heterogeneity of the customer base leads to an equally diverse set of installed hardware. A similar type of evolution can be observed in warehouse-scale computing environments [8], after a subset of the initial equipment has been obsoleted or replaced due to failures.

In DCs reaching the warehouse-scale, failures become the norm, not an exception [1]. Even though air flow dynamics may change only a little when a single server is taken offline for repairs, failing power-distribution units (PDUs) or computer-room air conditioning (CRACs) units will have much more far-reaching consequences. During the past twelve months of operating our measurement system in our department's DC (see Sect. 3), we have encountered both a massive power supply failure and a CRAC failure. Knowing exactly where hot spots did and did not start to develop allowed our system administrators to avoid shutting down our computing equipment. Yet the time to react precluded a CFD-based approach, for the temperatures were rising by the hour.

The combined weight of these issues points to the fact that instead of CFD, measurement-based approaches have been revisited successfully in the past few years [2, 4–7, 11]. The contribution of this article is the complete description of an ultra-low cost *wired* sensor network which can be implemented in small- to medium-sized DCs within the order of days. As the sensors can be replaced with any equivalent devices, all the software components are open sourced, and the rest of the hardware is COTS equipment, the proposed solution is immediately available for all DC operators. Almost no skills in electronics are required, including soldering, and existing ethernet cabling may be reused. The sensor network can also be used to verify CFD models or act as a baseline for comparisons against more advanced, possibly wireless research experiments.

We present our implementation in Sect. 2. Section 3 presents some new discoveries, while Sect. 4 discusses the merits and flaws of our measurement-based solution. Section 5 concludes this article.

2 Design Decisions

By surveying the field of existing approaches it becomes clear that there are a number of vendors willing to sell or lease their measurement solutions, including advanced software applications designed for easy temperature visualization. On the other hand, a respected estimate [14] divides up to 72% of all DCs into the small- or closet-sized and medium categories. It follows that these smaller DCs have smaller operating budgets, meaning that outsourced solutions can be prohibitively expensive.

Even though it is easy to agree that operating any DC in a manner which is "green" or "sustainable" is a desirable objective, the driving force behind business decisions still remains the purchase costs vs. benefits. Thus, our primary objectives have been to build a sensor network that is both cheap and very easy to install, yet so reliable it requires almost no manual upkeep. We will examine the latter two requirements first, then present our solution and calculate the actual costs for our implementation.

2.1 Wired Versus Wireless

To our knowledge, the largest published number of operational temperature sensors is by HP [6, 4]. According to them, a 70,000 ft^2 (ca. 6,503 m^2) DC which employs 7,500 sensors has been operational since 2007 in Bangalore, India. This number translates to ca. 1.15 sensors/m^2, which we have considered a reasonable requirement. Unfortunately, nearly all of the other implementation details remain unknown. It is unlikely, however, that each sensor was cabled separately.

A number of previous solutions have concentrated on wireless or hybrid approaches in communicating with the temperature sensors. Microsoft Research's Genomotes [5] are implemented with a wireless master node which then daisy-chains up to seven slave nodes through the venerable RS-232 interface. The entire chain uses a single USB port for a power supply, although the master node also contains a rechargeable battery as a backup. Following Microsoft, chaining multiple sensors into a bus seemed reasonable.

Microsoft's justification for their hybrid approach is the ease of cabling since only the slave nodes need to be physically connected. The master nodes can reside at the top of the server racks and communicate wirelessly. They key problem of reliable wireless data collection is solved by Microsoft's RACNet solution. While we agree with their analysis of the overabundance of cabling already present in any modern DC, we differ in the conclusion. Since there is already so much cabling present, we consider that modest additions can still be tolerated. Thus, our solutions either adds its own or reuses existing, but unused cabling.

2.2 The Source of Power

Even if all of the data transfer can be performed wirelessly, present wireless technologies still require a separate power source for the sensors. On the other hand, replacing batteries can quickly become a tedious task for the DC operators. Thus, it would be prudent if a single wire can provide both a data signal and a power source. Fortunately, such products have been designed by multiple vendors, e.g., the Inter-Integrated Circuit ($\mathrm{I}^2\mathrm{C}$) by Philips and the 1-Wire by Maxim, formerly known as Dallas Semiconductors.

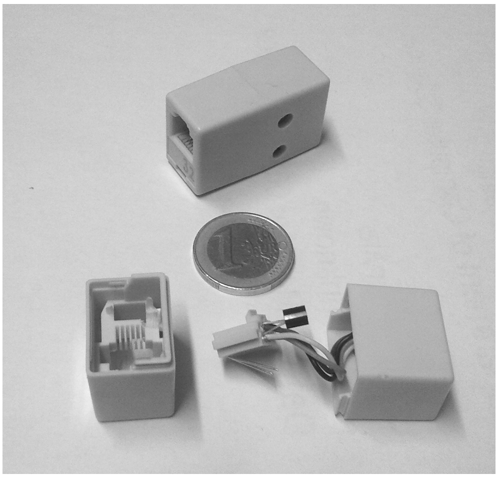

Fig. 1. DS18B20 sensor packaged in a RJ11 female-female adapter

The idea in both product families is simple. By using from two to four conductors cabled together, a single cable can provide a network of devices both power and signals for a data channel. Such setups are particularly suitable for DC environments [7], because an unshielded twisted-pair cable will contain four pairs equalling eight conductors. Moreover, the sensors use very robust signalling techniques allowing reported cable lengths of up to 200 m. In our case, we chose to use the existing ethernet cable rails, but connect our sensors using a separate two-pair RJ11 cable in order to simplify our cabling design. All of our sensors connect to a single bus presently.

2.3 Connecting the Sensors

We chose the 1-Wire products due to our previous experience with them, an open source API, and good support from the Linux community. Auxiliary evidence [4, 11] suggests that HP did employ sensors from the same manufacturer [7] in their DCs around 2006. Our design is based on the Maxim DS18B20, which is roughly a pin-sized[3] sensor with three conductor legs. It's accuracy is $\pm 0.5\,^{\circ}\mathrm{C}$ when operating in the range of $-10\,^{\circ}\mathrm{C}$ to $+85\,^{\circ}\mathrm{C}$. This sensor has remained in production for a number of years, and is widely used by a large base of electronic hobbyists and professionals alike.

In order to connect the DS18B20 to the RJ11 cable, we needed to package each sensor for easy connectivity and eventual replacement when the sensor

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[3] `http://www.maxim-ic.com/datasheet/index.mvp/id/2812`

would fail. Due to the cabling, the choice was easy, and we chose the RJ11 female-female adapter jack used for cable extensions. To improve air flow, we used a drill press to perforate the casing with four 4 mm holes. The jack itself can be easily pried open into two halves, and with a little bit of gentle bending, the DS18B20 can be seated inside the plastic casing. Excluding the drill press, a single sensor can be built in three minutes or less with only minor practice. The end result is portrayed in Fig. 1 along a 1 € coin for size comparison.

The RJ11 jacks and cable form a sensor bus using 6-position, 4-conductor RJ11 connectors, and the bus itself terminates via a 6-position, 6-conductor RJ12 connector to a DS9490R adapter. The DS9490R is read through a host computer's USB port. Our current installation uses 15 sensors and over 75 m of cable. The limiting factor was that we simply did not need any more sensors. The sensor positioning is further explained in Sect. 3.

2.4 Results and Cost

Each DS9490R is read by the DigiTemp[4] Linux program, which scans for all sensors on the bus and then retrieves their temperature readouts. We wrote a very simple wrapper script to pipeline the data to the well-known RRDtool[5] utility. RRDtool is designed to redraw time series graphs in multiple formats and time resolutions (see Sect. 3). We poll all of our sensors every 60 seconds and archive copies of the DigiTemp outputs in addition to the RRDtool databases. RRDtool then graphs its data every five minutes and the graphs are copied to a publicly accessible directory[6].

We have published a full step-by-step instruction manual which includes detailed connection diagrams, photographs of each relevant step, and a video of the assembly process[7]. The total costs for our current solution amount to just under 160 € for the whole 15 sensor network, or more precisely, 10.51 € per sensor including taxes. These prices could be reduced by ordering the sensors directly from Maxim. While we paid 3.50 € per sensor, the quoted price is about $1.84 per sensor for orders of over 1,000 units. Also, for our modestly sized network, the USB host adapter price is almost half of the total.

3 Data and Knowledge

Our main DC has a floor space of just over 70 m^2 (ca. 750 ft^2). Despite the compact size, the DC draws over 115 kW of power during computationally heavy experiments. Cooling is handled by five CRAC units for the IT load plus one for the battery backup (not shown). The CRAC units are cooled by two separate chilling plants. Cool air from the CRAC units flows to an underfloor plenum and then through perforated tiles into the server inlets. All of the servers are placed

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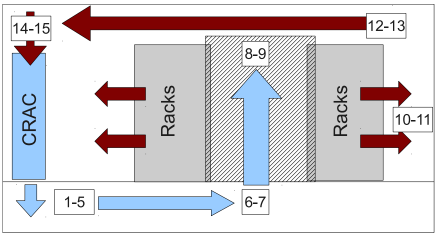
[4] `http://www.digitemp.com/` by Brian C. Lane

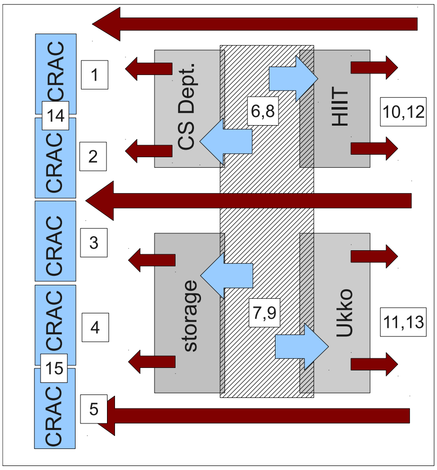
[5] `http://oss.oetiker.ch/rrdtool/` by Tobias Oetiker

[6] `http://www.cs.helsinki.fi/group/greenict/`

[7] `http://blogs.helsinki.fi/pervila/?p=116`



(a) Sensor placement, side view



(b) Sensor placement, top view

Fig. 2. Sensor placement in the data center, side and top views

into two rows with their fronts opposing each other, forming a cold aisle. The ends and roof of the aisle are sealed to prevent air recirculation, forming a cold aisle containment (CAC) setup. The CAC is reasonably airtight. The CRACs form a third row on the west side of the cold aisle. For further details, see [9].

Figure 2 shows how we placed our 15 sensors. For each of the five CRAC units, we placed one sensor near their supply air vents in the underfloor plenum. Sensors 6–7 were placed just under the perforated floor tiles at 1/5 and 4/5 of the cold aisle length. Sensors 8–9 were placed at the corresponding lengths near the roof of the CAC section. Four sensors were placed at the same lengths on the exhaust or hot aisle side, near the opposite wall of the DC as seen from the CRACs. Sensors 10–11 were placed at 1 m height and 12–13 at 3 m height. Finally, sensors 14–15 were placed over the return vents of the CRAC units.

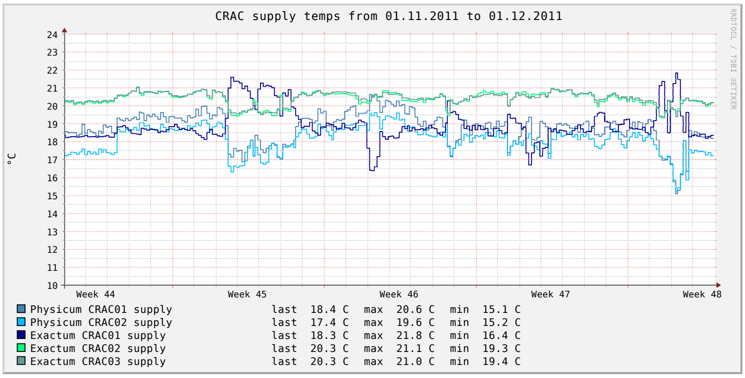


Fig. 3. CRAC supply temperatures from November 2011

The placement logic is that we wish to measure the full cycle of the air flow from the CRAC units to the underfloor plenum, then upwards into the CAC section, out from the far side of the racks, over the top of the racks, and back into the CRAC units. First, analyzing the graphs allows us to see whether the CRACs are supplying the DC with enough cooling. Second, we can detect increments in the supply air temperature from the CRAC units to the server inlets, caused by exhaust air recirculation. Third, temperature imbalances caused by different air flow requirements are visible by comparing sensor readouts from the lengthwise pairs. Finally, the exhaust measurements allow us to measure the heat removed by the CRACs, showing if heat is supplied or removed from the DC by other means.

3.1 Machines in Disagreement

Due to historical reasons, the five separate CRAC units are driven separately and not through a centralized system. In Fig. 3 we show the CRAC supply temperatures during November 2011. The two elder units, designated Physicum CRAC01 and CRAC02 in Fig. 3, make their cooling decisions based on a sensor located within the cold aisle. The three other units measure the ambient temperature locally and adjust their cooling power individually based on their measurements. Finally, the unit designated Exactum CRAC03 has been turned off. Thanks to the CAC, we have been able to save over a fifth of the required CRAC power [9].

The fluctuation of supply air temperature is not caused by the differing views of the CRACs alone. Figure 4 and Fig. 5 reveal differences in the return air temperatures, meaning that exhaust heat is divided unevenly across the row of four operating CRAC units. This is caused by the power supply cabling installed above the racks. The cables and connectors would be difficult to model using

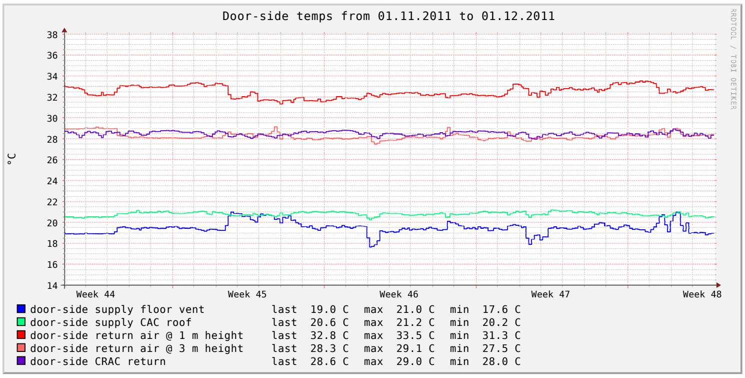


Fig. 4. Door-side temperatures from November 2011

CFD, but show to be quite effective in restricting air flow. We will discuss other findings from Figures 4 and 5 in more detail below.

The end result is that without a centralized management system, the four operational CRACs are continuously readjusting their blower speeds and supply air temperatures. Although all of the units have been manually tuned for a target supply temperature of 22° C, the max and min columns of Fig. 3 show that each unit fluctuates with varying variances. This effect has been previously reported by [2], and their centralized management system was able to save up to 58% of the CRAC operating power by minimizing the fluctuation.

3.2 Cold Aisle Imbalances

Figure 4 shows the top half of the DC shown in Fig. 2(b), designated as the *door-side*, following our IT administrators' naming convention. This half contains the even-numbered sensors 6–14. The other half is depicted in Fig. 5 and is designated the *rear-side*. It contains the odd-numbered sensors 7–15. In the figures, the lowest line shows the supply air temperature at the floor of the cold aisle and the second lowest line is the roof of the cold aisle. The top three lines (not clearly visible as three lines in Fig. 5) show the return air temperatures behind the racks (at heights of 1 and 3 m) and the CRAC return air temperature.

As the CRACs fluctuate, the two halves of the cold aisle receive different amounts of air flow and at different supply temperatures. The rear-side is supplied more by Physicum CRACs and consequently follows the target temperature of 22° C more precisely due to the better CRAC sensor placement. However, these CRACs end up performing the major part of the cooling, for warmer door-side supply air reaches the sensor, meddling with the CRACs decision logic.

Since our CAC is custom-built by ourselves, we have tried to ensure that it is relatively airtight near the key areas and blocks off exhaust air recirculation.

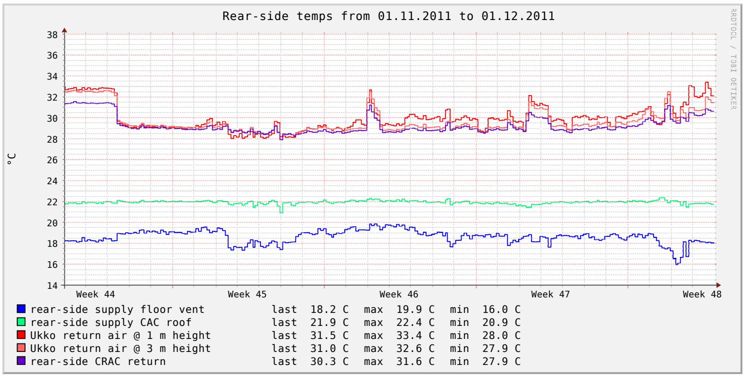


Fig. 5. Rear-side temperatures from November 2011

Thus, Fig. 5 presents a very interesting question about the rise of the supply air temperature from the bottom of the cold aisle to its roof. During normal operations, the delta is around 3° C, which can not be explained by heat conducted or radiated from within the cold aisle.

We have eliminated the possibility of a sensor failure and also verified that none of the installed servers or network devices are exhausting heat into the inlet side. Neither can the delta be satisfactorily explained by warmer supply air flowing from the other half of the cold aisle, as that half's supply temperature maximum just barely reaches this half's minimum. Thus, hot air seams to leak into the CAC from *somewhere else* than from within, the edges, or roof of the cold aisle.

After these options have been exhausted, not many possibilities remain. Our current hypothesis is that either a cold aisle underpressure or hot aisle overpressure is caused by the blade servers installed near the sensor. Either effect is then sufficient to push or draw exhaust air through or around the blade servers and into the cold aisle. We have been able to partially verify this hypothesis using a specially constructed server enclosure. By limiting either the inlet or the exhaust air flow, the inlet air temperatures do rise above the ambient temperature. In the enclosure, this heat must be derived from the exhaust air, since no other sources are nearby.

3.3 Not a Closed System

Although it is standard practice to model a DC as a closed system, this assumption does not seem to hold quite true in practice, although the difference is more difficult to detect. We have long suspected that the building where the DC is housed either contributes or burdens the cooling loads. According to a recent discussion with a local vendor of gas-based extinguishing systems for DCs, a similar effect has been found in many other environments. Minute changes to the building plans done at the construction site can cause drafts in a DC environment, potentially mitigating the effectiveness of a gas-based extinguisher. Thus, the only possibility for the vendors is to test the correct functionality of the extinguishers in practice.

Figure 4 shows that measured at the 1 m height, the exhaust air stays reasonably constant around 32° C, while Fig. 5 displays a much lower exhaust temperature around 29° C. The spikes in this graph are caused by computing tasks being executed at the blade servers. In both figures, the 1 m temperatures remain consistently above both the 3 m height and the CRAC return temperatures.

Therefore, some of the exhaust heat seems to be lost on its way back to the CRACs. It is credible that the servers near the CRACs are simply exhausting colder air, which draws down the temperatures measured at the CRAC returns. But this seems less credible on the other edge of the room, as sensors 11 and 13 measure a homogeneous installation of blade servers. Thus, it seems that Fig. 5 displays some of the heat being drawn by the building walls.

4 Discussion

In the previous section, we have demonstrated some events caught by our sensor network -based approach which would have been difficult to model without comparable initial knowledge about the DC installation. Our aim is not to prove CFD unfeasible, just to show that in some situations, the measurement-based approach can be a better starting point. The information gained from the measurement could then be used to build a much better model. In the case of small- to medium-sized DCs, the wired sensor network alone may suffice to discover the worst hotspots and subsequently optimize the cooling air flow.

4.1 Cost Evaluation

Perhaps the main merit of our implementation is its very affordable price. It is difficult to find comparable prices for a CFD-based approach. A single data point was presented during Google's European Data Summit 2011. During a retrofit of a network equipment DC the cost of "a couple of iterations" of CFD modelling was estimated as "USD$5K–$10K" (Joe Kava during his presentation[8]). As the actual load of the DC was around 85 kW and the maximum load around 250 kW, this gives us a possibility for a comparison.

Assuming the midpoint of the price range, the exchange rate of 0.761 € per dollar, and our actual price of 10.51 € per sensor we could purchase 914 sensors plus the required cables and accessories for connectivity. If our implementation generalizes to larger data centers, our density of 0.21 sensors/m^2 means that we can instrument a DC with a size of over 2,535 m^2. Even following HP's much higher sensor density of 1.15 sensors/m^2 (see Sect. 2.1), the sensors could cover

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[8] `http://www.youtube.com/watch?v=APynRrGuZJA` around 11:17 / 27:52

a DC of 471 m^2. As our price per sensor does not include workmanship costs, this comparison is not entirely fair. On the other hand, the quoted price range of \$5,000–\$10,000 very likely does not include software licenses.

4.2 Functionality and Reliability

The visualization software is definitely the weak point of the wired sensor-based approach. It is not difficult to discover that as a visualization engine RRDtool is quite old-fashioned in its syntax and hence, can be quite difficult to configure successfully. We are trying to mitigate these problems by releasing a set of helper scripts which make the initial steps much easier. In order to make the temperature information visually connect to the DC installation, some third party software is required to link the graphs near their correct locations on a map of the DC. One alternative for this is to use the NagVis[9] toolkit for the well-known Nagios[10] infrastructure monitoring daemon. As Nagios is very common in DC environments, this match seems natural and the solution straight-forward.

Compared with a wireless solution like Microsoft's Genomotes (see Sect. 2.1) the difference is that we have not fully solved the infrastructure problem. Each wired sensor bus must connect to a host computer, which must be able to run the DigiTemp application for sensor readouts. In addition, our solution does not come with a built-in battery backup. While these are true disadvantages to our approach, we feel that the prodigious cable lengths permitted by the sensor network mitigate the flaws at least somewhat. For a small- to medium-scale DC, not many sensor buses are really required. Similary, as the sensors themselves are extremely Spartan in their energy consumption, a single backup battery could provide enough power for the operation of both the sensors plus their host laptop.

5 Conclusion

In this article, we have provided the implementation details for a wired sensor network suitable for use in many small- and medium-scale data centers. As the proposed sensor network is both very inexpensive and fast to install, it can replace CFD-modelling in some DC installations, and thus work as a shortcut for system operators wishing to learn more about their DC's energy efficiency. In other installations, the sensor network could be used to gain initial insight before a full CFD modelling takes place, and verify the CFD model iteratively as it is being built. Finally, the proposed wired sensor network can be used as a baseline for comparing more advanced, possibly wireless sensor networks.

Through our own DC installation, we have evaluated some air flow conditions which would have been difficult to model without the measurement-based data. Our temperature graphs are available for interested parties, and we have also published a step-by-step guide describing in detail how to implement a similar sensor network.

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[9] `http://www.nagvis.org/screenshots`

[10] `http://www.nagios.org/`

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Research Theme B: Air Stream Containment

Research Paper IV

Mikko Pervilä, Jussi Kangasharju

Underfloor Air Containment

In *Proc. 2nd IEEE Online Conference on Green Communications (GreenComm 2013).* IEEE, 2013.

Contribution: I did the major parts of the work alone. Prof. Kangasharju supervised my work and did minor editing of the text. He also did a part of the analysis regarding the GHG emissions of the entire ICT field mentioned in paragraph 1 of the introduction. I had some help in the physical construction phases as indicated by the acknowledgment section. Otherwise, the concepts, hardware choices, design of the experiments, analysis of the results, writing, and figures were done by me.

Underfloor Air Containment

Mikko Pervilä and Jussi Kangasharju
Department of Computer Science
University of Helsinki
PL 68, FI-00014 Helsingin yliopisto
Email: {pervila,jakangas}@cs.helsinki.fi

***Abstract*—This paper presents Underfloor Air Containment (UAC), a straightforward extension to Cold Aisle Containment (CAC). Both techniques aim to eliminate air stream mixing and thus reduce the volume of supply air needed for cooling. In UAC the underfloor air supply plenum of a data center is mechanically restricted to the floor sections containing the perforated tiles. We have implemented UAC in our department's 110 kW, 74 m^2 data center. Through experimental evaluation and per-tile air velocity measurements, we show that UAC improves the air velocities passing through the perforated tiles in the CAC by 9%. Our solution is light-weight, very low cost, and rapidly installable in other data centers.**

I. INTRODUCTION

In 2007 a popular analysis by Gartner [1] estimated that the combined greenhouse gas (GHG) emissions caused by all fields of ICT amounted to 2% of the man-made total. Combining that data with the SMART 2020 report [2] we can see that the GHG emissions from ICT are growing much faster than the overall GHG emissions. This strongly implies that the share of ICT today is considerably larger than the often-quoted 2% and probably nearer to 3%. There has been no indication that the growth rate would have yet substantially diminished.

Thus, urgent action is required to cut down emissions from all fields of ICT. If we are to avoid a climate catastrophe, directly applicable techniques must be adapted both at the edges of the network and its core. As small changes repeated often enough can yield large savings globally, it is less important to concentrate only on the largest consumers. Even smaller reductions should be installed if their capital costs are relatively small or insignificant compared with the savings.

When 41% of data centers (DCs) are formed by small-scale installations [3] and they are often operated by companies whose expertise is not in DC operation [4], it is hardly surprising that these DCs can become very inefficient through gradual evolution. In order to reduce the energy requirements of these DCs, we need techniques that can be applied retroactively. And to remain attractive for the DC maintainers, these techniques must have small capital expenses, short installation times, and require little expert knowledge to install. Our previous work fits neatly into this category of *data center energy retrofits*.

Most DCs employ computer room air conditioning (CRAC) units that supply cold air for the servers. The air can be supplied either directly or through a raised floor called an underfloor plenum. Regardless of the method, without air stream separation server exhaust air can easily mix with the supply air flow, mitigating its cooling effectiveness. Earlier, we have verified the effectiveness of an air stream separation technique called cold aisle containment (CAC) [5], [6]. We have shown that an effective CAC setup can be built using very low cost plastics, in a short time span, and using very limited knowledge. This makes our solutions applicable to a wide range of existing data centers.

This article presents a complimentary technique that further optimizes the cooling air flow for DCs using an underfloor supply plenum. The idea is rather straightforward: we extend the air stream containment into the plenum under the server racks. By doing so we effectively diminish the volume of space where cooling is supplied by the CRAC units. This in turn leads to less turbulence caused by underfloor blockages, smaller leakage of air through gaps in the raised floor structure, and a larger air flow rate where cooling is needed.

A. Related Work

The key issues of using an underfloor plenum are air flow blockages and leakages [7]–[10]. Blockages are relatively well understood and often caused by power and network cabling, floor support structures, extinguishing systems, and other accumulated materials in the plenum. Air flow leackages are often caused by cable cutouts inadequately sealed by grommets, but also by other gaps in the the raised floor.

Despite the well known issues regarding the plenum, relatively few solutions to improve the air flow through the raised floor have appeared. Zhou et al. [11] recently proposed adaptive vent tiles (AVT), which are a motorized version of the standard perforated types. Using AVTs and an elegant optimization algorithm, they were able to reduce the cooling power usage by 10–14 kW in a DC employing a 300 kW IT load. At least one company specializing in DC environments offers products designed for plenum air flow control [12]. Unfortunately, they do not provide any public data about the efficiency gains of using their product. Finally, VanGilder and Schmidt [8] evaluated raised floor air uniformity, but exluded underfloor blockages from their CFD simulations.

To our knowledge, this article is the first academic study on the benefits of using UAC in a DC. We present two main experiments involving the combination of UAC and the low-tech CAC [5] we built earlier, and then UAC combined with a much more expensive, improved CAC we have only recently completed. An in-depth examination of perforated floor tile air velocities shows that the aggregate improvement of UAC is about 9% over the whole CAC.

This paper is structured as follows. Section II describes our data center and the UAC setup that we evaluate. Section III presents our measurements and results. In Section IV we discuss the limitations and wider applicability of our UAC solution. Finally, Section V concludes the paper.

II. DATA CENTER LAYOUT

Our experimental DC is named the Exactum DC after the building housing it. For brevity, we reiterate only the key attributes here. For further details, see our previous studies [5], [6]. A floor plan of the DC is shown in Fig. 1. The raised floor is constructed using $60 * 60$ cm tiles, some of which are perforated to allow for air flow. The width of the DC is 11 tiles and the length 19 tiles, yielding a floor area of just over 74 m^2, excluding some unusable space wasted by the architecture.

The floor is raised by approximately 60 cm and consists of three types of tiles and their accompanying support structures, as pictured in Fig. 2. The tiles are raised from the actual floor below using support pedestals, which are adjustable to ensure a completely level floor plan. Pedestals are distributed so that they support the tiles from their corners, meaning that most pedestals support four tiles each. Pedestals closer to the walls of the room may support either one or two tiles, also by their corners.

Most of the tiles in the DC are solid and demonstrated by the white color in Fig. 1. In addition, there are two types of perforated tiles which differ in their air flow rate due to the fraction of perforated to solid area. Perforated tiles with a smaller flow rate are depicted by a light gray color and designated the identifiers $1, 7, 9, 19, 21, 23$. The larger flow rate tiles are marked by a dark gray color and designated $2, 4, 5, 6, 8, 17, 20, 22, 24, 25$. Note that #25 is located outside of the CAC. This perforated tile was installed by our administrators in order to make sure that the network devices located in the rack next to it would receive adequate air flow. These devices incorporate reverse air flow, meaning that they draw their supply air from the back of the rack.

A. Gaps in the Floor

In addition to the perforated tiles mentioned previously, air flows through the raised floor through gaps between the tiles and cable cutouts made intentionally. Gaps between the tiles occur when the tiles are handled due to maintenance. The tiles can now easily switch orientation, meaning that they no longer rest exactly as intended on the pedestals. This can even lead to visible gaps forming between the tiles. Also, as the tiles are worn down by use, smaller leakages occur near the edges where the tiles meet.

Cable cutouts are made in the floor near the rears of many racks to allow electrical or network cabling to be installed in the underfloor plenum. Cutouts should always be sealed with grommets. Grommets typically use either flaps or brush-like structures to reduce air flow around the cables. The quality and age of the grommets dictates how well they handle their intended purpose, but the overall result is that some air always leaks through.

B. Air Velocity Measurements

Since the Exactum DC is a live production environment for many research groups, its current layout has evolved somewhat piecemeal. This includes a cooperation effort of no less than four different university departments responsible for the servers, network, power cabling, and cooling respectively. Due to the weight of history, some installation details have become lost. Unfortunately, this includes the manufacturers and models of the perforated tiles, meaning that we do not currently know what the tiles' perforated areas are.

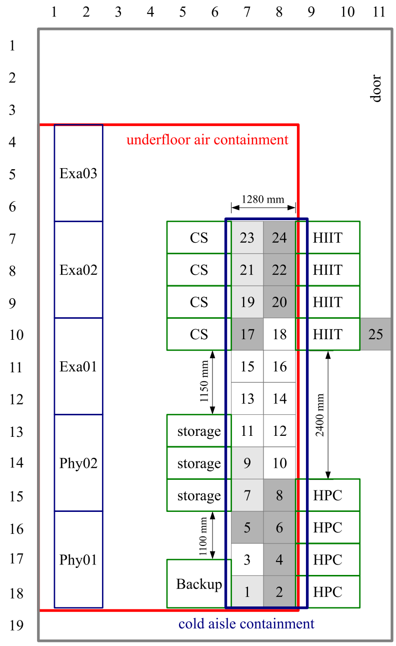

Fig. 1. Exactum DC layout and perforated tile numbering

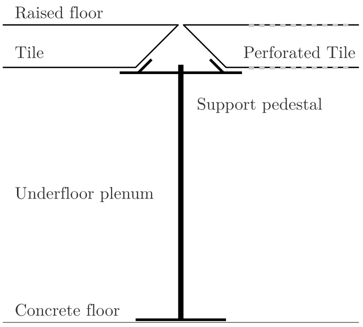

Fig. 2. Underfloor plenum, tiles and support structure

This implies a small problem to solve concerning measurement units. Air flow in DCs is usually measured in volumetric flow rates, meaning that the results are reported in ft^3/min, l/s, or m^3/s. Since the perforated areas are currently unknown, instead of using volumetric flow rates, we have chosen to report air velocities in m/s. While volumetric air flows are calculated assuming a uniform flow through a duct or a perforated tile, air velocities are spotwise measurements. Avoiding the assumption of uniform air flow proves useful in Sect. III-C, where we measure the tiles per quadrant and confirm that significant differences do occur per tile.

For our measurements, we used a TSI VelociCalc 5725 rotating vane anemometer. The meter is calibrated to an error rate of < 0.1 m/s, and it is able to record air velocity, volumetric flow rate, and temperature. Though the volumetric flow rate measurements as such are useless without the correct perforated areas of the tiles, this combination of data points means that we can later reconstruct the real volumetric flow rates per tile. Detailed specifications regarding the meter are available on the web site[1].

C. Underfloor Air Containment

The installation of the UAC itself was relatively simple. Our construction material was polyethylene sheets reinforced by nylon wire mesh. The mesh made the material not only heavier and more durable, but also simplified attaching the sheet to the support pedestals (see Fig. 2) using cable ties. The material costs for the installation amounted to 39.77 €.

In order to minimize leakages, we affixed the UAC curtain so that its top edge was wedged between the raised floor tiles. Conversely, the bottom edge was weighted down on the concrete floor using steel bars. As the plastic sheet was relatively heavyweight to begin with, installation was quite simple and completed in one hour by the first author working alone, i.e., one hour of work effort for one person.

The UAC curtain is depicted in Fig. 1 by the rectangle colored in red. The topmost edge runs between rows 3 and 4 from the CRAC side of the room to between columns 8 and 9. Then, the UAC extends rearwards towards the section between rows 18 and 19. From here, the UAC turns again towards the CRACs and continues to the wall just next to the CRAC designated "Phy01" [5].

The primary effect of the UAC is to reduce the volume of the underfloor plenum used for supplying cold air for the servers in the CAC. By installing UAC, we have reduced the cooled floor area by $(209 - 120)/209 \approx 42.6\%$. Note that while floor tile leakage may be roughly uniform throughout the raised floor, the cable grommets are not evenly distributed. Thus, our UAC can be expected to remove roughly half of the leakage due to the grommets, as the other half are still in the pathway of the supply air, i.e., in front of the CRACs.

We opted for a rectangular shape for the UAC for ease of construction and did not attempt to fully minimize the area to be cooled. An obvious optimization would be to have the top edge go diagonally from the CRAC "Exa03" towards tiles #23 and #24. However, we do not believe this to yield significant additional benefits and the ease of construction was a more important factor in our case.

D. Existing and New CAC

As outlined in our article [5], our CAC setup was installed using low-cost plastics. This means that the construction materials consisted mostly of transparent polyethylene plastic sheets and duct tape. The wall materials were later upgraded to polypropylene sheets for easier access through sliding doorways. This incurred some additional costs, for a total of 373.40 €. Some leakages have later on appeared near the roof of the CAC, caused by degrading duct tape.

Though the leakages could have easily been reinforced with more duct tape, we had other incentives to improve the outlook of the CAC. Thus, we set out to not only install UAC, but also improve the CAC with a much more advanced (and high-cost) setup. For further details regarding material and construction choices, please visit our web site[2]. We return to the costs of the improved CAC in Section IV and its effects in Section III-A. Without spoiling too much in advance, the improvements provided by the much improved materials where almost completely visual and not quantitative.

E. Measurement Methodology

In order to separate the effects of the two different changes, we set out to do our measurements in phases as follows.

1) 8 h period representing situation before any changes
2) 8 h period representing UAC + existing CAC
3) 8 h period representing UAC + improved CAC
4) 8 h period representing no UAC + improved CAC

In order to yield meaningful before/after type measurements we set all four operational[3] CRAC units to a fixed blower speed. This setting is temporary and the units will be returned to a variable speed after our measurements have been completed.

The rationale between the different measurements is as follows. First, the situation before any changes was undertaken to verify that the air velocity, and thus, flow rate, through either kind of tile was reasonably stable throughout the CAC. Any larger variations would have been indicative of dynamic turbulence effects in the underfloor plenum, or possibly malfunctioning blower units in the CRACs. In all measurements, the readings were extremely stable no matter how long the measurement intervals were.

Second, the measurement taken with UAC and our previous CAC indicates whether UAC could improve our less than ideal CAC setup. If the UAC could improve air flow in the CAC enough to eliminate exhaust recirculation caused by leakages, other DCs could avoid costly CAC improvements altogether.

Third, the measurements completed with the improved CAC represent the "ideal" situation attainable using a DIY installation. The fourth measurements were completed to attain the per tile and per quadrant readings, which we will discuss in the next section.

III. MEASUREMENT DATA

All measurements were done with the rotating vane resting on top of the measured tile, and each position was carefully marked for repeatability. The measurement interval was 60 s and each sample was taken over a 10 s average. We did experiment with other mesurement and sampling intervals, but the differences remained below the measurement error. Whenever not explicitly stated otherwise, we have reported the average results over all samples taken.

Initially, we verified the flow rates of only three tiles in the CAC. These tiles are numbered in Fig. 1 as tiles #6,

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[1] http://www.tsi.com/VELOCICALC-Rotating-Vane-Anemometer-5725/

[2] http://wiki.helsinki.fi/display/ExactumDC/Third+CAC

[3] Even though the DC has five units, one has been taken offline following the efficiency improvements caused by our CAC setup [5].

#20, and #25 respectively. Tiles #6 and #20 correspond to the CAC temperature measurement sensor positions further detailed earlier [6]. This allowed us to compare the effects of changing air velocities with our CAC temperatures.

We had only one anemometer at our disposal. The 8 h measurement periods were completed by interleaving 2 h measurements from tiles #6 and #20, swapping the vane position at each interval. Measurements at tile #25 were done after the 8 h periods and were considerably shorter, since we had already verified that the readings remained stable despite the measurement period.

A. Three Tiles Only

In phase 1 of our measurements, we recorded the air velocities with all CRACs set to fixed blower speeds, no UAC, and with the previous CAC still installed. Air velocity through tile #6 was 2.61 m/s (stdev 0.0164) while tile #20 showed 3.1 m/s (stdev 0.0149). Within our measurement error, tile #25 maintained the same flow at 2.99 m/s (stdev 0.0468).

Subsequently, we constructed the first version of the UAC and measured phase 2. The air velocity measured at tile #25 dropped to 1.88 m/s (stdev 0.0506) and conversely, tile #20 arose to 3.34 m/s (stdev 0.0204). We also verified that the temperature delta from the floor of the CAC to its roof measured at tile #6 was reduced from approx. 1.7°C to zero. This strongly suggested that more air was flowing into the CAC and, consequently, less outside of it. Hence, UAC seemed to be improving our previous CAC, which indicates that even the low-cost version remains sufficient for many DCs.

Despite the encouraging results, our first problem was the air velocity measured at tile #6, as it had now dropped to 2.19 m/s (stdev 0.0248) – a reduction of approx. 0.3 m/s. After repeating our measurements and improving the UAC with rubber (polyurethane) foam seals near the CRAC walls, we were able to further reduce the velocity at tile #25 to 1.47 m/s (stdev 0.0111). Yet, this did not improve air flow at tile #6. At this point, we constructed the improved version of the CAC and verified our measurements (not shown). There were no visible changes in either the air velocities or the temperature measurements.

B. Each Tile

After negotiations with multiple colleagues with extensive backgrounds in computational fluid dynamics (CFD) modelling, we set out to measure a much more holistic picture of the perforated tiles in the CAC. Using 30-minute intervals we recorded the air velocity at each of the 16 perforated tiles.

Table I records the latest measurements. First, note that the reduction of tile #25 is by design, since it is left on the other side of the UAC. Second, it seems that our initial selection of tiles was extremely lucky, since #6 was only the other of the two tiles in the CAC with reduced air velocities. If we had not chosen this measurement point, parts of the picture would have remained unseen to us.

By calculating the changes in air velocities at each tile, we can now estimate the aggregate change caused by UAC. For the comparison to be fair, we include tile #25 in the aggregate "before UAC", since the perforated tile was installed on purpose. In other words, we exclude it from being part of the unintentional leakage of the raised floor. Conversely, we disregard the negative change of tile #25 in the aggregate "after UAC". Whatever air flows through the tile now is part of the raised floor leakage, though we can not measure all of it.

TABLE I. AIR VELOCITIES IN M/S, MEASURED PER TILE

Tile #	Before UAC	After UAC	Change
1	1.19	1.4	0.21
2	2.49	2.58	0.09
4	2.24	2.12	-0.12
5	2.46	2.58	0.12
6	2.63	2.24	-0.39
7	1.54	1.59	0.05
8	2.39	3.4	1.01
9	1.47	1.62	0.15
17	3.47	3.9	0.43
19	1.46	1.64	0.18
20	2.9	3.45	0.55
21	1.55	1.72	0.17
22	2.72	3.09	0.37
23	1.59	1.74	0.15
24	3.35	3.73	0.38
25	3.3	1.38	-1.92
total	36.75	38.18	1.43

TABLE II. AIR VELOCITIES IN M/S, MEASURED PER TILE QUADRANT

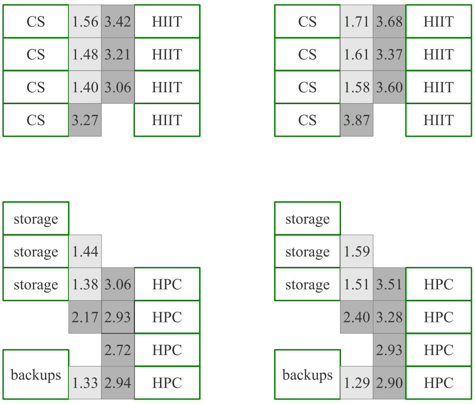
	Before UAC		After UAC		Change	
Tile #	avg	stdev	avg	stdev	avg	stdev
1	1.33	0.056	1.29	0.120	-0.0375	0.065
2	2.94	0.505	2.90	0.521	-0.0375	0.016
4	2.72	0.538	2.93	0.761	0.205	0.223
5	2.17	0.240	2.40	0.269	0.235	0.029
6	2.93	0.726	3.28	0.731	0.3525	0.005
7	1.38	0.234	1.51	0.206	0.1275	-0.028
8	3.06	0.332	3.51	0.284	0.455	-0.048
9	1.44	0.117	1.59	0.137	0.15	0.019
17	3.27	0.275	3.87	0.179	0.6	-0.096
19	1.40	0.062	1.58	0.087	0.18	0.025
20	3.06	0.258	3.60	0.206	0.535	-0.052
21	1.48	0.128	1.61	0.144	0.13	0.016
22	3.21	0.280	3.37	0.329	0.155	0.049
23	1.56	0.064	1.71	0.075	0.1475	0.012
24	3.42	0.172	3.68	0.178	0.26	0.006
25	3.25	0.165	1.38	0.346	-1.87	0.181
total	38.60	4.15	40.19	4.57	1.5875	0.421

Therefore, the effect of UAC can be calculated simply as $(1.43+1.92)/36.75 \approx 0.091$ or roughly 9%. In order to verify this number we then decided to increase our granularity, and measure each tile at four different positions.

C. Each Quadrant

Next, we verified our measuments by examining each tile more closely. We divided each tile clockwise into four quadrants so that using the orientation of Fig. 1, the top right quadrant of each tile is titled Q1, the bottom right Q2, and so on. The additional measurements revealed that the underfloor air flow was very nonuniform indeed.

We will discuss some of the more surprising readings and then present the average results both in Table II and Fig. 3.



Before UAC After UAC

Fig. 3. Per tile air velocities in m/s, calculated as averages of the per quadrant measurements

Most notably, the tiles which exhibit reductions in air velocity are no longer the same as in the per tile measurements. When the air velocities are calculated as the averages of the four per quadrant measurements, the negative changes are now found in tiles #1 and #2. Their negative changes are also much smaller.

In addition, there are quite significant differences per quadrant for some of the tiles. For example, in our readings taken without UAC, the largest intra-tile reduction occurred at tile #6. Its Q2 indicated an air velocity of 3.6 m/s while Q4 measured only 2.08 m/s. In other words, a reduction of almost 50% in less than 30 cm. With UAC, the situation changed somewhat, but large differences in the tile quadrants could still be seen. The largest change occurred at tile #4 when its Q1 showed 3.57 m/s and Q3 only 1.94 m/s. All in all, the sum of stdevs increased very slightly from 4.15 before UAC to 4.57 after UAC.

We can also calculate the aggregate changes between the different halves of the CAC, as represented by tiles 1–9 and 17–24. By doing this, we notice that UAC seems to benefit the door-side half of the CAC more, as its aggregate increases by 2 m/s, while the rear half's increases by only 1.45 m/s.

Despite these changes, the overall effects of installing UAC remained the same even when the air velocity measurements were completed per quadrant. Including #25 in the situation before UAC and omitting it from after UAC yields us a calculation of $(1.5875 + 1.87)/38.60 \approx 0.09$ or, again, very close to 9%.

D. Measurement Errors

For future studies, it is useful to provide some estimates for the measurement errors between the readings taken per quadrant and per tile. By calculating the average air velocity for each tile from the four per quadrant calculations and choosing this average as the tile's "true" reading, we get the differences to the per-tile measurements as presented in Table III.

TABLE III. MEASUREMENT DIFFERENCES IN M/S PER QUADRANT AND PER TILE

Tile #	**Before UAC error**	**After UAC error**
1	-0.1375	0.11
2	-0.45	-0.3225
4	-0.4825	-0.8075
5	0.2925	0.1775
6	-0.2975	-1.04
7	0.1625	0.085
8	-0.665	-0.11
9	0.035	0.035
17	0.2	0.03
19	0.065	0.065
20	-0.16	-0.145
21	0.07	0.11
22	-0.4925	-0.2775
23	0.0325	0.035
24	-0.0725	0.0475
25	0.0525	0.0025
total	-1.8475	-2.005

From these numbers we can notice that the measurements per tile seem to undercount the aggregate changes somewhat. The aggregate error is -1.8475 m/s without UAC and -2.005 m/s with UAC. Interestingly, the errors are very unbalanced when measured separately for the CAC halves. Without UAC, the aggregate error for the door-side half (tiles 1–9) of the CAC is -1.543 m/s, while the rear half's error is only -0.305 m/s. With UAC, the aggregate errors both rise and lower to -1.873 and -0.133 m/s respectively.

Although UAC works, it can not homogenize the air velocities, and thus not the air flow rates through the tiles. While the key result of a 9% gain was achieved through both the per tile and per quadrant measurements, the first-mentioned do hide some parts of the overall flow heterogeneity. This seems to be an effect of extremely complex air flow changes in the plenum under the perforated tile, making CFD modelling of the effects we have measured difficult indeed [8].

IV. DISCUSSION

First, the costs of our improved CAC operation were an order of magnitude higher, raising from the 373.40 € mentioned in Section II-D to 2,338.25 € for the new material costs. In addition, the installation took much longer. The previous CAC was installed in 6 man-hours, while the new installation took six and a half man-*days* to complete. While we completed the more professional CAC in order to verify the efficiency of the previous low cost solution [5], it is no surprise that our IT operators were much more pleased with the end result, despite the additional costs they paid. The goodwill generated is of importance while negotiating future experiments in our DC, although other operators can make do with the low-cost version just as well.

In theory, the main drawback of installing CAC or UAC is the reduction of supply air volume in the DC [13]. This means that in case of a power supply failure, there is a smaller reservoir of cold air in the DC. This flaw must carefully be balanced against the benefits of CAC. The main benefit is that CAC can much more easily be retrofit into an existing DC.

By comparison, a hot aisle containment (HAC) setup requires considerably more complete air ducts for the exhaust or return flow. As neither HAC or CAC can entirely avoid overheating scenarios, it is our recommendation that the shutdown temperatures of servers should not be disabled. Fortunately, in most commercial servers this remains impossible.

Another drawback is that UAC may not be applicable in all DC environments. If the CRAC units are distributed evenly along all of the walls of a DC, there may not exist suitable floor areas for installing UAC. This is an unavoidable problem of some DC environments. However, for global energy reductions to occur, it is enough that UAC is employed in those cases where it remains applicable.

Finally, UAC is not able to remove or even diminish turbulence caused by underfloor blockages. Despite this drawback, it presents a sizeable improvement in air velocity through the perforated tiles in the CAC. A 9% improvement in CRAC blower speed means that more servers can be installed in the DC. In addition, we have earlier shown that in the same conditions, CAC yielded an improvement of 20%. As both CAC and UAC can be installed very cheaply, their combined enhancement of almost 30% CRAC blower power makes the payback time very attractive[4]. CAC is by now a very much standard DC technique for improving air flow. It is our hope that UAC will also catch on.

V. CONCLUSION

In this paper we have presented our Underfloor Air Containment solution for optimizing air flow under a data center raised plenum. Our solution complements existing cold air containment techniques and allows for a more efficient control of the cooling supplied by CRACs. We have implemented UAC in our department's 110 kW, 74 m^2 data center and our extensive measurements show that UAC has improved the aggregate air velocity by 9% within the CAC. UAC is readily adoptable in other data centers with minimal installation cost and effort required. UAC also combines well with CAC.

In addition to the benefits of UAC, we have demonstrated how underfloor blockages can yield very nonuniform air velocities, and thus flow rates, through the perforated tiles in a CAC. While UAC is unable to homogenize the air flow, there are direct benefits of increasing the aggregate air flow in the CAC. Simultaneously, these effects imply that the measurements attained by prototype testing would have been extremely difficult to attain through computational fluid dynamics modelling only. Finally, installing UAC reduces the needs for high-quality cable cutouts or grommets. The savings attained through reduced energy and purchase costs yield an almost immediate payback time for the materials involved.

ACKNOWLEDGMENT

The authors would like to thank Timo Ojanen for repeatedly lending his construction skills throughout the deployments of our prototypes. Without Timo, not much would have been built. Markus Nuorento was of crucial help during the construction phases and provided not only manual labour, but critical improvements in the construction process. Mikko Rantanen helped out with sealing the UAC and also doing some of the wind speed measurements. Petri Kutvonen and Pekka Tonteri deserve special praise for their open-mindedness in allowing us to experiment with an operational DC. Finally, Sampo Smolander, Pekko Metsä, Tomas Lindén, and Taina Ruuskanen from the Department of Physics were especially helpful in verifying the measurement methodology.

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[4] In our case with Finnish electricity prices, the payback times of our combined installation is on the order of a few months. For higher prices, the times would be correspondingly shorter.

Research Paper V

Mikko Pervilä, Lassi Remes, Jussi Kangasharju

Harvesting Heat in an Urban Greenhouse

In *Proceedings of the first workshop on Urban networking - UrbaNe '12*. ACM, 2012, pp. 7–12, DOI http://dx.doi.org/10.1145/2413236.2413239.

Contribution: Lassi Remes chose the initial set of the plants, planted them with his spouse, and later advised on the use of pesticides & fertilizers. He also judged which plants survived the winter (not included in this paper). A number of volunteer workers helped in watering the plants. Prof. Kangasharju did some minor edits of the final text. Timo Ojanen advised on the design of the greenhouse, and a paid worker did more than half of the construction. Otherwise, the idea, design of the experiments, analysis of the results, writing, figures, and further projections were done by me.

Harvesting Heat in an Urban Greenhouse

Mikko Pervilä
Department of Computer Science
University of Helsinki
pervila@cs.helsinki.fi

Lassi Remes
Department of Agricultural Sciences
University of Helsinki
lassi.remes@helsinki.fi

Jussi Kangasharju
Helsinki Institute for Information Technology
University of Helsinki
jakangas@cs.helsinki.fi

ABSTRACT

This article describes the first eight months of operation of a prototype rooftop greenhouse located in Helsinki, Finland. The greenhouse is heated by exhaust heat harvested from a rack of computer servers, while the servers are cooled by unconditioned outside air only. We describe which plants have thrived in this kind of a synthetic environment. Plants in the greenhouse include multiple edible species, including seven types of chili peppers. Yields, in particular for chilies, have been excellent. Our chilis have been served in local university cafeterias in the city beginning from autumn 2012.

Categories and Subject Descriptors

B.8 [**Hardware**]: Performance and Reliability; B.8.1 [**Performance and Reliability**]: Reliability, Testing, and Fault-Tolerance

General Terms

Human Factors, Experimentation, Measurement, Reliability

Keywords

Sustainable computing, cooling, empirical system reliability, heat harvesting

1. INTRODUCTION

Throughout the history of computer science the distribution of network services has shifted from the core of the network to its edge and then back again. Currently, we might be approaching the apex of centralization, as the majority of our computation is performed in very large data centers (DCs) and content-delivery networks. This ephemeral mode of computation has been appropriately titled the cloud. If history is to repeat itself, the cloud will be superseded by a redistribution of the computation back towards the clients.

Such a shift could bring computation all the way back to the client computers. However, without major breakthroughs in battery lifetimes, this solution remains infeasible if the clients are to retain their mobility. An alternative approach is to position the computation near, but not on the clients themselves. This form of distribution of computational nodes might resemble so called micro data centers [1,2]. Since the nodes are smaller, we would thus require more of them.

Each node should be placed so that it satisfies the latency requirements for as many clients as possible. In an urban environment, placing the computation efficiently can be costly in terms of space. Our prototype solves this problem by using previously unused rooftop area. While every office in our building is internally billed to one of the local departments, we have several hundreds of square meters of unused rooftop space. This phenomenon seems relatively common in urban environments, as rooftops are designated as technical areas and left unused.

By moving the servers from the clouds to the rooftops, we can solve social and political problems which have hindered placing user data away from local administrative boundaries. As the geographical distance decreases, so do the communication latencies dictated by the speed of light. From a green or sustainable ICT perspective, the major benefit is free air-side cooling.

Instead of depending upon computer-room air conditioning units, the servers can be directly air-cooled for the larger part of the year, local weather conditions permitting. In Helsinki, no cooling has been necessary for the past two and a half years. To our knowledge, our experiment is the longest continuous scientific endeavour taken to discover and measure the limits of direct, free air cooling [6, 7].

In this paper, we extend our previous work by harvesting the exhaust heat from our free air-side cooling prototype. This heat is used to warm a directly adjacent greenhouse, which we custom-built for this specific purpose. We grow mainly edible plants, e.g., tomatoes and chili peppers. During 2012, our main research goal has been to show the feasibility of this combination. We consider the goal successful, as our local university cafeteria has already committed to serving our chilis in their 24 local restaurants.

Our key contributions and results are:

- We demonstrate the feasibility of supplying the required additional heat for a greenhouse in our climate using the exhaust heat of only one rack of servers.
- We experiment with many different plants, identifying which of them do thrive in our greenhouse and which do not.

UrbaNE'12, December 10, 2012, Nice, France

Our results show that exploiting unused roof space and free air cooling can enable growing of edible plants in urban locations, close to where they are consumed.

This paper is structured as follows. Section 2 reviews related work. Section 3 describes how we constructed the greenhouse and supply heat to it, while Section 4 details which plants have thrived in such a synthetic environment. We discuss these results and make projections for a much larger DC-adjacent greenhouse in Section 5. Finally, Section 6 concludes this article.

2. RELATED WORK

In this article, we extend the micro data centers proposed by Church et al. [2] by harvesting the server exhaust heat and reusing it in a greenhouse. This idea has previously been described by Brenner et al. [1]. We expand their idea by relying on the servers as our only synthetic heat source, placing the whole setup on an already existing office building, growing edible plants in the greenhouse, and using our yield for the benefit of local restaurants.

As the feasibility of our approach is dictated by the local climate, perhaps the closest related work comes from the previously unrelated field of greenhouse production. Scientists from the local universities and MTT Agrifood Research Finland have experimented and calculated the energy requirements for modern and future greenhouses [3–5].[1] Their calculations include the heating requirements per square meter of nearby greenhouses, which roughly match the heat signature of our prototype (see Sect. 5.3 for details).

3. HEATING A GREENHOUSE

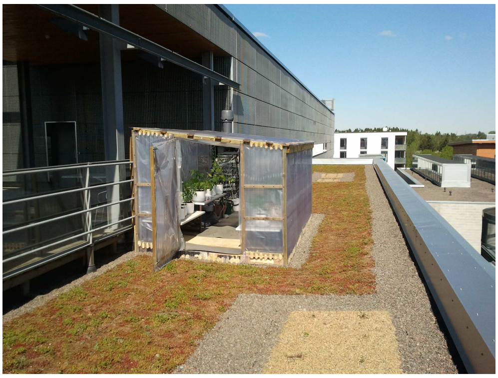
As server exhaust heat is too low-temperature for efficient conversion back into electricity using currently available methods, we have been looking for a direct application for the past two years. The idea to build a rooftop greenhouse came from local green roof installations. The key research questions we set out to solve were feasibility and whether we could extend the growing season of our plants. An important secondary objective was to raise public awareness about the amount of energy wasted by many DCs.

3.1 Heat source

In order to shield the servers we employed an existing prototype chassis called the *Helsinki Chamber* (HC), which is detailed in our earlier work [6]. Briefly, the HC contains 14 servers in a 26U 19” rack. The servers draw ca. 3.4–3.6 kW during normal operations, almost all of which is turned to heat. The HC is visible as a separate unit in Fig. 1(a). The transparent plastic cover in the front shields the server intakes from snow and rain. Intake and exhaust chambers are separated, forcing heated air to flow into the greenhouse.

Due to the limits of the local climate, the growing season of plants is capped by the cold (nighttime) temperatures for much of spring and autumn. In other words, there is enough sunlight but the plants freeze to death. Thus, local greenhouse operators have turned to using heaters in addition to the greenhouse lamps. By calculating the amount of harvest gained, this technique ends up being more energy-efficient per kg than an unheated approach [4, 5].

(a) Greenhouse during winter, direction south-east.



(b) Greenhouse during summer, direction north-west.

Figure 1: Exactum greenhouse during winter and summer 2012, pictures taken from opposing directions.

3.2 Greenhouse construction

We emulated local greenhouse operators by constructing a small greenhouse just next to the already-existing HC. The greenhouse was built upon 10 standard European logistics pallets (120x80 cm) and it spans a floor space of 9.4 m^2. The total volume is only under 16 m^3 due to the modest height of the slanted roof. The roof is diagonal, rising to 154 and 182 cm in the opposite sides. Figure 2(b) shows the height difference of the roof, while Fig. 2(a) details the floor area and door sizes, which are further explained in Sect. 3.4.

The major difficulty we had to solve was the weight of the greenhouse. Due to local construction laws, any rooftop area has to be built to withstand the *maximum* weight of snow during pathological conditions. According to our building’s construction blueprints, this translates to 630 kg/m^2. Our architects were concerned that the greenhouse would add too much weight in combination with the snow, causing the roof to collapse. As the greenhouse leaks excess heat through its roof, any snow falling on its roof melts. Thus, we gain the weight difference, but must still design for a lightweight structure due to the added weight of the plants and turf.

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[1] Although these articles are published in Finnish, to the best of our knowledge, they are the only articles covering climate conditions similar to our greenhouse.

3.3 Total power

Our greenhouse is built with an unidirectional slanted roof visible in Fig. 1. The supporting frame is built using 2x4" and 2x2" boards covered with 0.8 mm thick polycarbonate plastic wave sheets. The inner walls are covered with 0.15 mm thick polyethen film, forming an insulating air pocket between the double plastic walls. Figure 1(a) shows the greenhouse without the inner plastics, while Fig. 1(b) includes both layers. The insulating layers reduce the transparency of the greenhouse and the amount of sunlight passing through it. This is in fact beneficial, since the greenhouse might else collect too much sunlight for the plants.

Currently, the extra heating provided by the servers to our plants varies between 362–383 W/m^2. While this extra heating is very beneficial during the colder seasons, it is equally problematic during summer. In addition to the server based heat we have tried to measure the effects of the sunlight, including its attenuation caused by our construction materials. We measured the photosynthetic photon flux (PPF) directly outside the greenhouse and spotwise inside it. The measurements were repeated with direct sunlight during the pre-noon hours and then with indirect sunlight after the greenhouse and its surroundings were shadowed. Our quantum sensor was an Apogee model[2] SQ-110.

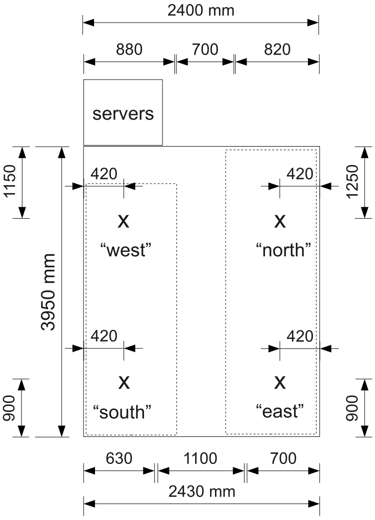
Getting consistent readings showed out to be notoriously difficult. Due to diffusion caused by our materials, the spotwise PPF readings were sometimes larger when sunlight penetrated both wall layers cf. only one layer. By measuring the PPF readings at the same positions where our temperature sensors are located, we obtained direct readings of 535–625 PPF, with an outlier on the east position of 385 PPF. With indirect sunlight, the corresponding readings were 57.5–97.5. We repeated the measurements in many different positions to figure out the attenuation factors of the materials. The full story is available from our website[3].

3.4 Sensors and ventilation

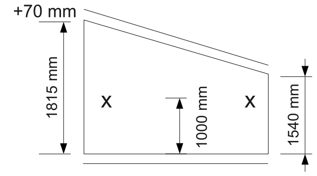
We measure temperatures from four different positions within the greenhouse as depicted in Fig. 2. Our sensor solution is custom-built and detailed in [8]. Each sensor is positioned roughly 1 m from the floor and resides in the middle of the plants. In addition, we measure the ambient temperature from a sunlight spot from outside of the greenhouse. We are able to calculate both absolute temperatures and ambient-indoors differences with 1-minute granularity.

For the cold winter period, we aim for a minimum indoors temperature of 10°C. With this target temperature, our plants would be able to survive the winter period in a suspended state. So far, we remain some 5–10°C of the target temperature during the worst combinations of darkness and temperatures dropping to −30°C. With improved insulation and additional computational load on the servers, reaching the target temperature still seems possible. We are currently in the process of replacing the polyethen sheets with much more airtight polycarbonate windows.

Conversely, during the warmer periods the added insulation becomes a burden. Our greenhouse was designed with two opposite doorways to function as a wind tunnel whenever ventilation was required. The doorways are visible in Fig. 1(b) and Fig. 1(a) respectively. Passive door-opening mechanisms used in greenhouses employ wax-like mediums that are designed to expand with heat and open ventilation windows. These levers remain too weak for the wind surface of our doors, while smaller windows would not be able to exhaust the heat from both sunlight and the servers.



(a) Greenhouse, doorway, and growing table sizes, temperature sensor (N,E,S,W) locations, top view.



(b) Greenhouse and sensor heights

Figure 2: Greenhouse schematics and temperature sensor positions, side view.

Thus, stabilizing the indoors temperature remains one of the key difficulties in our environment. With manually regulated doorways, we have been able to separate the indoors-ambient temperature difference to roughly three different plateaus. The plateaus correspond to door configurations where both doors are either closed, partially open, or fully open. The matching temperature differences are roughly 20–25°C, 10°C, and 0–5°C. Note that the differences are calculated with an ambient sensor positioned in sunlight: differences to a shadowed ambient would higher. Real-time and historical temperature graphs are available from our website[4]. Further analysis of the internal temperatures has been omitted both for brevity and due to the unique nature of our installation. Individual differences in construction would mean that the results would not carry over to other installations.

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[2] For details, see http://apogeeinstruments.co.uk/quantum/.

[3] See http://wiki.helsinki.fi/display/Exactum5D/Sensors for additional PPF measurements.

[4] http://wiki.helsinki.fi/display/Exactum5D/Home

4. HEAT AND PLANTS

For our plants, the key benefit of the added heat is the lengthening of the growing period between spring and autumn. During 2012, we have tried to figure out the edible plants most suited to our synthetic environment. As we knew in advance that the summer-time temperatures would be higher than normal, we selected the initial set of plants to be very diverse. Emphasis was placed on plants with higher temperature requirements, e.g., tomatoes and chili peppers.

It was fully expected that some of the plants would not to make it, and indeed, this has been the case. The temperatures inside the greenhouse reached well over 30°C during the summer, with occasional peaks reaching 40°C. These temperatures were too high for some of the plants in our experiment, even though we had chosen plants with higher temperature requirements.

Excessive transpiration slows or even stops the growth of many plants and can kill them by dehydration. In addition to dehydration, overly high temperatures can also prevent CO^2 intake. Plants have stomata in the epidermis layers of leaves and stems which allow CO^2 to enter and water vapour from the transpiration system to exit. The CO^2 is needed for photosynthesis and thus for the growth of the plant. Stomata can close to prevent the loss of water, but this also prevents the entry of CO^2 into the leaves. Thus, both too much and too little sunlight can kill the plants.

4.1 Plant lifetimes

In our environment there is sufficient sunlight from roughly the beginning of March to allow net growth. Our initial set of plants were planted on March 20th as seeds and then left in the greenhouse to sprout. Of the initial set of seeds, only our habañero chili peppers refused to sprout. The probable reason for this is the source of seeds, as they were retrieved from peppers sold in a local grocery shop. On April 4th, we replaced the unsprouted seeds with sprouts bought from a local greenhouse operator.

While many plants have thrived, others have clearly grown too fast due to the high temperatures. This effect was enforced during spring, when there was too little sunlight compared with the temperatures. For example, the beans *Phaseolus vulgaris* 'Carminat' and the coriander *Coriandrum sativum* first elongated to a considerable height, but their growth later weakened. Then, the beans died altogether. The corianders were induced to flowering very early on, which also tends to indicate too high daytime temperatures. One of the corianders later fell prey to pests detailed in Sect. 5.1.

Similarly, our zucchinis *Cucurbita pepo* 'Gold rush' have been mostly unsuccessful. Possible causes for this could be the pot size being too small, too high temperature, or pest problems. Zucchini leaves tend to be very large, so that the amount of water they evaporate can easily grow too high.

4.2 Yields and harvest

As containers for our plants, we chose individual self-watering pots because of the unknown survivability of each chosen species. The pots' water reservoirs function as buffers, enabling us to reduce watering requirements to every 3 or 4 days[5]. The pots are 20 and 25 cm in size and filled with turf. Into the turf we have mixed fertilizer as slowly dissolvable grains. Each of the pots is numbered 1–33, carrying exactly one plant and identifying it uniquely.

ID	Scientific name 'Cultivar'	Common name
17	*Beta vulgaris* 'Detroit 2'	beetroot
18	*Beta vulgaris* 'Detroit 2'	beetroot
23	*Citrus sinensis*	orange
27	*Coriandrum sativum*	coriander
8	*Cucurbita pepo* 'Gold Rush'	zucchini
9	*Cucurbita pepo* 'Gold Rush'	zucchini
4	*Lavandula angustifolia*	lavender
5	*Lavandula angustifolia*	lavender
6	*Lavandula angustifolia*	lavender
7	*Lavandula angustifolia*	lavender
31	*Ocimum basilicum*	basil
30	*Pelargonium fragrans*	pelargonium
1	*Rosmarinus officinalis*	rosemary
2	*Rosmarinus officinalis*	rosemary
3	*Rosmarinus officinalis*	rosemary
29	*Tropaelum*	nasturtium

Table 2: Unharvested plants.

With the exceptions detailed in Sect. 4.1, all of the remaining plants have thrived relatively succesfully in our synthetic environment. Table 1 details our current yields as of Aug. 2nd, 2012. The table describes the scientific name and cultivar, measured plant height, amount of leaves remaining and lost, yields, and yield sizes. Note that in Table 1 we have measured only those plants for which similar data is easily available for comparisons. The other plants are listed in Table 2. Also, the yield counts are minimums. At the time of writing, we have a crop of over 500 chili peppers, and some of the plants are still producing chili in October.

4.3 Benefits of rooftop gardening

One of the major benefits or rooftop gardening is the relative ease of access that comes with a shortened distance to the garden's urban operators. In our case, the first author is the primary gardener while the second author supervises all gardening work. As mentioned in the previous section, the plants do not need watering every single day. As a normal watering cycle takes only 15–20 minutes, tending the rooftop greenhouse actually *feels* like recreation, not work. However, in a larger scale setup the distance benefit could easily be lost, as tending multiple rooftops could become a burden without a private car. Transporting plants, pots, and turf, for example, would quickly become problematic using only bicycles etc.

Instead, scaling upwards might be enabled by tempting more volunteers to form new greenhouses. With only 9 m^2 of greenhouse space, and using only 9/33 of our growing pots, we are able to far overgrow the local demand for our chilis. If multiple greenhouses could be co-operated using the heat of many small-scale DC nodes, each greenhouse could conceivably grow its own specific products. In this manner, the products could form a micro economy, where each team could barter for the crops from the other teams. Similar economies are already in place on larger, open-air gardening patches.

Finally, in an urban environment, exhaust heat is also provided by other A/C units than DCs. Large supermarkets

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[5] Although this seems very much a minimum requirement for our *Solanum lycopersicum* tomatoes.

ID	Scientific name 'Cultivar'	Common name	Shoot ht.	Leaf no.	Fruit no.	Fruit ∅
19	*Brassica oleracea var. sabellica* 'Half Tall'	kale / borecole	33 cm	18		
20	*Brassica oleracea var. sabellica* 'Half Tall'	kale / borecole	46 cm	30		
12	*Capsicum annuum* 'Apache'	c. pepper			118	5–50 mm
32	*Capsicum annuum* 'Apache'	c. pepper			102	5–50 mm
33	*Capsicum annuum* 'Apache'	c. pepper			100	5–50 mm
14	*Capsicum annuum* 'Jalastar'	c. pepper			6	60–75 mm
11	*Capsicum annuum* 'Rawit'	c. pepper			44	30–50 mm
15	*Capsicum annuum* 'Short Yellow Tabasco'	c. pepper			89	10–20 mm
10	*Capsicum annuum* 'Topepo Rosso'	c. pepper			8	40–50 mm
13	*Capsicum baccatuum* 'Aji Cristal'	c. pepper			45	60–90 mm
16	*Capsicum chinense* 'Pimenta da Neyde'	yellow lantern c.				
21	*Solanum lycopersicum* 'Black Russian'	tomato	140 cm	41 (-3)	6	
22	*Solanum lycopersicum* 'Black Russian'	tomato	103 cm	30 (-3)	6	
24	*Solanum lycopersicum* 'Gardeners Delight'	tomato	122 cm	60 (-10)	5	
25	*Solanum lycopersicum* 'Gardeners Delight'	tomato	130 cm	36 (-10)	22	
28	*Solanum lycopersicum* 'Little Sun Yellow'	tomato	38 cm	10 (-2)	16	
26	*Solanum lycopersicum*	tomato			2	

Table 1: Plant nomenclature, heights (ht), leaf numbers (no, incl. dropped), fruit yields and diameters (∅) as of 2012-08-02. (c = chili)

may require similar chilling towers due to their refrigeration units. Thus, supermarket and mall roofs could not only operate using similar techniques as those outlined for the micro DCs, but also provide a very local vendor channel for the harvest.

5. DISCUSSION

In this section we review some of the problems we have encountered, outline difficulties with building on a rooftop, and make a projection of the possible yield of a much larger greenhouse installation.

5.1 Insects and pests

For the major part of operation, the upkeep of the greenhouse has been surprisingly easy. Most problems stem from four types of pests: aphids (*Aphidae*), spider mites (*Tetranychus urticae*), whiteflies (*Trialeurodes vaporariorum*), and pigeons (*Columbidae*, probably *Columba livia*). Of these, the worst problems have been the whiteflies and the pigeons, while the others have succumbed quite easily to household pesticides based on piperonyl butoxide and pyrethrines.

Whiteflies are notoriously resistant to weaker pesticides. Fortunately, whiteflies are also not the most aggressive pests, and plants can survive smaller infestations. In order to refrain from using too many poisons on our edible crops, we initially tried biological countermeasures. We experimented with a known parasite of the whitefly family, the *Encarsia formosa*. Unfortunately, the parasite was unsuccessful in combating the whiteflies. This is probably a result of employing the parasites too late after infestation had begun. We have now switched over to a pesticide consisting of a very mild mixture (0.15–0.3%) of a biological pine oil-based cleaning fluid and water. The results seem more positive, but the task needs to be repeated for at least 12 days in order to eliminate all whitefly larvae.

City-bred pigeons have shown out to be very reckless in their attitudes towards humans and human constructions. As the greenhouse is constantly heated and ventilated for extended periods of time, it has attracted the pigeons' attention as a suitable nesting place. As bird droppings are hardly a welcome addition, we have experimented with multiple types of hindrances in the forms of wires etc. The pigeons have been quick to learn, and in the end we had to reinforce all doors with wire nets in order to fully block avians from entering.

5.2 Rooftop construction

Even though a rooftop may seem like an odd solution at first, many rooftops are relatively unused and thus prime targets for urban construction. As rooftops are inherentely dangerous places, they combine well with the access control requirements of data center environments. Conversely, we have noted two inherent problems with rooftop greenhouse construction.

First, an adequate water access is crucial for successfully operating a greenhouse. In our case, the nearest access point was at ground level, some four stories below. Thankfully, the water pressure allowed for a straight-forward solution, which involved running a hose up the side of the building and the remaining 40 m sideways to the greenhouse. An alternative solution would have been to plug into the water drainage pipeline, which ran only a couple of meters from our greenhouse. This solution would have enabled us to use rainwater for irrigation. However, we decided against this due to political reasons. As it was difficult enough to receive building permits due to the weight concerns outlined in Sect. 3.2, we decided not to push our luck.

Second, snow remains a problem in many nordic countries. During many winters, the snowfall accumulates on the rooftops so that specialized crews have to be contracted to safely remove the snow. As our greenhouse does not consume the waste heat of the servers, the radiated heat could be conceivably used to reduce the snow burden on the rooftop. With a larger DC exhaust, more snow could be melted than we currently do.

5.3 Larger installations

By calculating the current yield of our prototype we can now project some rough estimates on what a greenhouse using a larger DC could produce. As mentioned above, local greenhouse researchers [5] have estimated the heating requirements for a greenhouse using LED-based lighting as 300–450 kWh/m^2. Their energy estimates a growing period from February to October. Assuming equal sunlight and that heating is required for only a fifth of May and September, half of June, and none of July or August, this would translate to an average power draw of 68–102 W/m^2. Note that as the sun does shine even during the colder months, the heating load fluctuates over the average during the night, and vice versa during the day. This causes the above calculation to underestimate the worst case for the heating. However, as our prototype's heat signature is currently 362–383 W/m^2 (Sect. 3.3), the servers can easily overprovide the requirements even during the colder months. This adds some confidence that harvesting heat remains feasible for larger greenhouses with relatively fewer servers required.

If we would concentrate only on the most successful chili peppers in our greenhouse, we could extend the yield from roughly 500 to over 1830 chili peppers in our 9.4 m^2 greenhouse. In contrast to our power draw of 3.4–3.6 kW, the local CS Dept.'s data center consumes roughly 80–110 kW during normal and peak operations [6]. Currently all of the heat is wasted, as it is radiated into the air by a cooling tower located in the vicinity of the greenhouse.

If we could harvest a conservative 80% of the Exactum DC's waste heat, we could heat up a similarly constructed greenhouse of ca. 177–230 m^2. Thus, using the available heat we could grow roughly 34,500–44,800 chili peppers. During summer 2012, the market price for *Capsicum annuum* 'Aji Cristal' produced in Finland was 92.50 euro per kg, or roughly an euro per chili pepper.

Finally, as the heat produced is pretty constant, the exhaust must in due time be vented from the greenhouse. After that, the heat could still be reused in a district heating network, to heat local buildings or water reservoirs, or melt snow in the harshest climates.

6. CONCLUSION AND FUTURE WORK

In this article, we have demonstrated the feasibility of harvesting server heat and reusing it in a greenhouse environment. We have successfully extended the growing season of the plants by mimicking the synthetic conditions of larger greenhouse environments. Our prototype is a proof-of-concept installation combining both the urban gardening concept and free air cooling.

In future work, we will further describe our experiences by focusing on the most well-adapted plants, detail the requirements for sunlight, and explain the feasibility of biological pest deterrents. Additional LED lighting should be evaluated as a possibility for the winter season. Starting from 2013, we have plans to extend our co-operation with agricultural researchers and revisit the possibilities for symbiosis of large-scale data centers and greenhouses.

While a lightweight construction similar to ours was feasible on top of the Exactum building, much more power-hungry DC installations exist. These facilities are typically located outside urban environments, can require hundreds of kilowatts of power, and require up to thousands of square meters of space. Interestingly, all of these attributes apply to large-scale greenhouses as well. Thus, very large-scale DC installations could be very successful companions to very large-scale greenhouses in rural environments.

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TIETOJENKÄSITTELYTIETEEN LAITOS
PL 68 (Gustaf Hällströmin katu 2 b)
00014 Helsingin yliopisto

DEPARTMENT OF COMPUTER SCIENCE
P.O. Box 68 (Gustaf Hällströmin katu 2 b)
FI-00014 University of Helsinki, FINLAND

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