From Moore's Law to the Carbon Law

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ABSTRACT

In society in general and within computing in particular, there has, and continues to be, a focus on faster, cheaper, better etc. Such perspectives clash with the fact that impeding climate change and the need for radically decreased CO2 emissions (c.f. the Paris Agreement) will have fundamental and far-reaching ramification *for computing and for all other sectors of society* during the coming decades.

In the call for the first Computing within Limits workshop, it was stated that *"A goal of this community is to impact society through the design and development of computing systems in the abundant present for use in a future of limits and/or scarcity."* There have since been several contributions to Computing within Limits that have accepted the challenge of discussing and imagining what such systems as well as what *"a future of limits and/or scarcity"* could look like. Despite this, there is currently no consensus about what exactly such a future entails and the community can consequently only offer hazy ideas about exactly what systems we should strive to design and develop. The basic problem can be summed up as follows: we know that fundamental changes are necessary and will come, but we still struggle with envisioning what a post-growth/decarbonising society looks like and what computing systems need to be designed and developed for use in such futures, or, to support that transition.

In this paper we argue that the work of imagining an actionable "future of limits" could benefit from using the "carbon law" as a starting point. The carbon law is based on work in the environmental sciences and we exemplify how it can be used to generate requirements that can guide the development of computing systems for a future of limits. While these lessons are general, we exemplify by describing a research project that aims to support the KTH Royal Institute of Technology's goal of - in line with the carbon law - radically reducing CO2 emissions from academic flying over the next decade. We give examples of how computing can aid in this task, including by presenting visualisation tools that we have developed to support the KTH carbon abatement goals. We also discuss the role of computer science in general and of Computing within Limits in particular in supporting the transition to a more sustainable (or at least a less unsustainable) future.

CCS CONCEPTS

• **Human-centered computing**;

KEYWORDS

academic flying, computer science, carbon law, carbon emissions, sustainability

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1 INTRODUCTION

In the call for the first (2015) and the second (2016) Limits workshops, it was stated that *"A goal of this community is to impact society through the design and development of computing systems in the abundant present for use in a future of limits and/or scarcity."* The call for papers for the first two workshops are no longer available online, but the call for papers for the third (2017) Limits workshop[1] states that *"We envision two broad categories of papers: "discussion papers" and "systems papers""*. It is further specified that discussion papers *"explore the nature of limits and computing"* and *"contributions will detail the nature of the limits of interest, describe their impact on computing, and present directions for future research"* while *"Systems papers describe the design, implementation, and evaluation of computing systems that work within or help cope with limits."*

Over the years the discussion papers have far outnumbered the systems papers and while many discussion papers have been both interesting and insightful, there is as of yet little agreement about what exactly constitutes or characterises *"a future of limits and/or scarcity"*. If we aim to develop systems *"for use in a future of limits and/or scarcity"*, what does such a future look like? What exactly are we aiming for? What more specifically are the important challenges and what are the parameters that help us by both limiting and supporting the design of concrete systems that will be useful in a future that has broken away from the idea of economic growth - an idea that has been a cornerstone of economic thinking for many

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[1]See https://computingwithinlimits.org/2017/

decades? How do we even go about to imagine such a future and much less design computing systems for it?

We hope this paper will help contribute to the formation of a consensus view of what an actionable "future of limits" could mean. We will here more specifically propose a frame for thinking about futures of limits and/or scarcity by relating them to the carbon law [29]. We also believe that if (or when) there is more agreement about the future we are imagining, aiming or heading for, it will become much easier to contribute to the Limits community with systems paper that *"describe the design, implementation, and evaluation of computing systems that work within or help cope with limits"*.

In this paper, we present a concrete and actionable "future of limits" that is based on work in the environmental sciences, and more specifically on the idea of a "carbon law" [11, 29]. The carbon law specifies a CO2 emissions reduction trajectory that is compatible with reaching the Paris Agreement's goal of keeping global average temperature *"well below 2°C"* (e.g. aiming for an average 1.5°C temperature increase above pre-industrial levels) [2]. We then exemplify how the carbon law can form a framework that supports the specification of actionable goals in one specific area, namely business-related (academic) flying. With set goals that are compatible with the Paris agreement, it then becomes possible to imagine computing systems that would support attaining that goal. We exemplify this by describing a research project, "Decreased CO2-emissions in flight-intensive organisations", that aims to support KTH Royal Institute of Technology's goal of reducing CO2 emissions from academic flying by 60% in the ten years between 2020 and 2030. This ambitious goal is used to develop a travel scenario that constitutes a concrete example of *"a future of limits and/or scarcity"*. We then discuss visualisation tools that have or are been developed to support the KTH carbon abatement goals and end the paper by discussing the role of computer science in general and of Computing within Limits in particular in supporting the transition to a more sustainable future in line with the Paris agreement.

2 FROM MOORE'S LAW TO THE CARBON LAW

Economic growth has been an integral part of societal development since the beginning of the industrial revolution and, in the post-WWII period, economic growth has become not just a means but also a goal in society. Cumulative growth in the post-WWII era has created "the great acceleration" of just about everything [20, 34]; paper consumption, electricity use, air traffic, number of fast food restaurants and so on. Economic growth has become expected - the normal condition - and we take for granted that energy and mineral "reserves" (that are economically justifiable to extract) in combination with an "extractivist paradigm" will continue to yield all resources we need to maintain a high level of material throughput in society and to continue to grow the economy [24]. We have come to expect, welcome and assume economic growth and interpret its absence in terms of dysfunctionality. Ideas of a non-growth steady-state economy [8] or of negative economic growth, "degrowth" [7] are an anathema to mainstream economists and usually gets a short shrift.

If society in general treats economic growth as a "natural fact" (that is not possible to question), the closest to an equivalent in computing would be Moore's law. Originally formulated by Intel CEO Gordon Moore in 1965 [22, 32], Moore's law states that the number of transistors on an integrated circuit doubles every 18-24 months. From having been a descriptive statement with some predictive power (slated to be valid for at least another decade, i.e., until the mid-1970s), Moore's law has for decades become a goal and a benchmark that has guided the semiconductor industry. While the validity of Moore's law has been questioned by some [32, 38], it is beyond doubt that cumulative developments in computing have been beyond explosive. The general public has come to perceive Moore's law as a rule-bound law, and the explosive exponential growth that is embodied in Moore's law has come to represent the raw (and increasing) force of computational power - an unstoppable tsunami of power that nothing can withstand and that is currently being heralded by Big Data, the Internet of Things (IoT) and Artificial Intelligence (AI).

Computing has for decades progressed along a trajectory that has seen explosive growth in everything that matters to techo-utopians of all stripes. Most computer scientists see little reason to reconsider the trajectory, the speed or the direction of change. However, the rules have changed. The boundless developments that we have seen in our globalized world are starting to push up against equally global boundaries, as exemplified by [35]. Naturally occurring weather events happen at a higher frequency and with larger amplitudes, leaving societies injured and vulnerable. Recent examples are the 2017 record year of hurricanes in the Atlantic basin [14], the 2018 heatwave in Northern Europe and the 2019 bushfires in Australia. There is growing realisation and unrest among the general public in regards to the lack of sufficient political action to mitigate the effects of climate change, as exemplified by the Fridays For Future school strikes and the Extinction Rebellion civil disobedience campaigns. Political and economic leaders observe this unrest and start to make commitments and argue for action. Public campaigns and popular movements move in tandem with climate researchers [13] who are becoming more concerned and more outspoken about the current situation. Researchers stress that rapid decarbonization is needed to attain the 1.5 degree target of the Paris agreement [2] and to avoid the consequences of fatal climate change. Earth is currently heading down a destructive path - a path that is hard or impossible to break away from if we do not change the trajectory soon. We urgently need to change course before tipping points and reinforcing feedback loops are activated [36].

There has, and still is, a lack of consensus about what needs to be done and when. The 2016 Paris agreement primarily concerns greenhouse gas (GHG) emissions and the 189 signatories have agreed on the end goal of keeping the global average temperature increases below 1,5 degrees Celsius compared to pre-industrial times. The Paris agreement does however not specify how we are to attain this goal. It points to a "sustainable level", but it does not specify how to reach that level nor how fast GHG and CO2 emissions need to be reduced. The cumulative effect of CO2 in the atmosphere means that the longer we wait for reductions to be made, the faster we need reduce emissions [11].

One way to concretize what needs to be done is to work with carbon budgets, that is, calculating the remaining space in the atmosphere for additional CO2 emissions while still managing to uphold the goals that have been specified in the Paris agreement (Millar et al. 2016). This is a helpful tool, but does not clearly communicate the time scale in which we need to act. Another concrete plan of how to approach the transition is "the carbon law", which states that we globally need to curb (increasing) carbon emissions by 2020, and then reduce emissions by 50% every decade between 2020 and 2050. The end goal is to reach (close to) zero emission by 2050 at an aggregated global level [29]. In the report "Exponential Roadmap" [11], the research organization Future Earth exemplifies in some detail how carbon emissions could be reduced by 50% in every sector[2] (in transport, industry, buildings etc.) between 2020 and 2030. It should be noted that the authors of that report emphasize that digitalization and the ICT sector will play an important role in making this happen.

In this paper we will argue that the Carbon Law constitutes a framework that can be used by the Limits community as a scenario for understanding what "a future of limits and/or scarcity" could mean and what such an understanding would entail. The specific limits will in this case be limits to CO2 emissions and such limits would immediately transform CO2 emissions into a scarce resource. In this paper we will exemplify how it is possible to work with the carbon law to guide the development of systems by describing our efforts in a research project that aims to curb the emissions from academic flying within KTH Royal Institute of Technology and will next give some background to academic flying in general.

3 ACADEMIC FLYING

Aviation is a large and growing source of greenhouse gas emissions. Global CO2 emissions from aviation has been predicted to grow to 22% of the global carbon budget by 2050 if efforts within this sector to combat climate change are further postponed [3]. IEA data from 2018 suggests that direct emissions from aviation represents around 2.5% of global energy-related CO2 emissions[3], but that number does not include aviation-related emission sources such as embodied energy costs of manufacturing airplanes, energy costs for operating airports etc. [19]. Nor does it take into account the radiative forcing (RF) or high-altitude effect of aviation [16, 18]. Taken together, aviation could easily be attributed 5% or more of human climate impact. This is remarkable if we also take into account that only a few percent of the world population travel by air any single year. Aviation can easily account for a large or even the major part of an individual's carbon emission[4]. The average (consumption-based) CO2e emissions for a Swede are, according to the Swedish Environmental Protection Agency, around 9 tons per person and year[5] while *a single round trip from Sweden to North America* racks up CO2 emissions of 2-3 ton (depending on the destination[6]).

Carbon emissions can be particularly high for researchers since participation at conferences, workshops and in international collaborations can be a prerequisite for advancement in an academic system where flying has become established and intertwined with cultural and normative expectations of what constitutes a successful researcher (Hopkins et al. 2019). Flying can thus easily be the single largest source of CO2 emissions at a research-intensive university.

In this paper we regard the effects of (academic) flying, or rather the resultant CO2 emissions, as deeply problematic and as something that needs to be "handled" (e.g. decreased). We realise that it is possible to bring other perspectives to the issue of academic flying and to argue that there are many legitimate reasons to fly; that many people like to fly, that flying represent "freedom", that junior academics need to fly to build networks and to get their academic career started, that senior academics need to fly to teach at schools that don't have experts in their particular area or to provide support for emerging programs etc. It is certainly true that decreased flying will have adverse effects on current conceptions of academia, but so will catastrophic climate change. When all has been said and done, one irrefutable truth still remains and that is that however much we like to fly and whatever the "importance" of each trip, we still need to decrease CO2 emissions from flying (*and from everything else*) if we are to attain the 1.5 degree target of the Paris agreement.

Despite the link between flying, networking, bolstering your CV and academic advancement — all recurrent arguments in [10] — it is uncertain if there is a real correlation between extensive travelling and academic excellence. Wynes et al. [39] analysed air travel data from the University of British Columbia and found no relationship between emissions from air travel and "hla", a weighted h-index [15]: *"Neither total citations, nor citations normalized by academic age and authors per paper had a correlation with trips taken, distance travelled, or emissions from air travel"* [39, p.963]. More extensive but as of yet unpublished results by Ciers, Mandic and Toth suggest that there is no correlation between 18 different academic performance indicators and CO2 emissions from air travel of 411 senior researchers at École Polytechnique Fédérale de Lausanne (EPFL) in Switzerland. These conclusions are based on a data set with all trips that were booked through the university's official travel agency between 2014 and 2017.

There are also large differences between the (air) travel patterns of people in academia. In a study by Ciers et al. [6], analysing data between 2014 and 2016 that came directly from EPFL's travel agency, it was shown that 10% of the researchers were responsible for 60% of the total emissions from business travel. More senior researchers (e.g. full professors) were on average responsible for 10 times higher greenhouse gas (GHG) emissions from air travel than PhD students. Similar findings have also been reported by others [17, 39] and preliminary data from our own project at KTH indicate similar patterns. We next turn to our case which is academic flying at KTH Royal Institute of Technology.

4 FLYING AT KTH ROYAL INSTITUTE OF TECHNOLOGY

KTH Royal Institute of Technology is a research-intensive technical university situated in Stockholm, Sweden. KTH has decided to become a leading technical university in sustainable development

[2]Every sector with the exception of food production which is slated to increase its emissions due to population growth [11].
[3]See further https://www.iea.org/reports/tracking-transport-2019/aviationabstract.
[4]For one particular detail-oriented Belgian PhD student [1], it was calculated that 74% of the climate change impact of the whole PhD project could be attributed to mobility and that mobility in this particular case for the most part was equivalent to air travel (which constituted 95% of this PhD student's mobility-related climate change impact).
[5]See further https://www.naturvardsverket.se/Sa-mar-miljon/Statistik-A-O/Vaxthusgaser-konsumtionsbaserade-utslapp-per-person/
[6]See further https://flightemissionmap.org

and to actively contribute to attaining the UN sustainable development goals (SDGs). This includes being a leader in mitigating climate change and to work actively towards a transition to a more sustainable society. KTH's efforts span education, research and collaboration with surrounding society and includes developing and executing an action plan to curb CO2 emissions that is in line with global climate targets.

An initial baseline of travel related emissions at KTH was established in 2016. It shows that the average emissions per full-time employee were 4800 kg CO2/year, which is about half of the total annual emissions of the average Swede. Consequently, an action plan that also included regular follow-up routines of employee travel habits was launched in 2018, based on the modelling framework and process tool CERO [27, 28]. The CERO process tool has been implemented in many organisations, but in contrast to more than 100 other organizations, aviation and in particular long-distance (intercontinental) travel was by far the most significant source of travel-related emissions at KTH. No less than 99% of the total emissions from business travel (including car, rail and boat transport) came from flying. The climate target scenario that was developed at KTH was therefore designed to mainly emphasize substituting domestic and international aviation with trains and digital meetings in order to meet desired target levels.

At the first follow-up in 2019, flight emissions (as registered by KTH's travel agency) had unfortunately increased by 28% per capita since 2016. Part of the increase could be explained by the fact that employee compliance with travel routines had increased, e.g., employees had become better at booking trips (only) through KTH's contracted travel agency (as stressed by policy measures that were specified in the new action plan). In 2016 a larger proportion of trips were booked in ways that were not registered and were subsequently not included in the baseline numbers. It is hard to retroactively determine how much of the increase in per capita CO2 emissions from business travel can be explained by the fact that the 2019 data represents a more complete data set than the 2016 data.

Based on the follow-up results from 2019, an updated target scenario and action plan has been developed and firmly established by KTH's chancellor. As of January 2020, KTH's climate objectives for 2020-2045[7] include an emission reduction plan which stipulates that KTH will decrease its business travel related CO2 emissions by at least 60% during the present decade (2020-2030) in terms of carbon dioxide equivalents per annual workforce. This means that CO2 emissions from flying has to decrease by 9% per year for 10 years in a row. These are bold but necessary goals and they have been formulated against the backdrop of KTH's lack of success in attaining the earlier (2016-2020) CO2 reduction goals. Our conclusion is that something - perhaps radical - must happen if KTH is to change the direction of its hitherto increasing travel related CO2 emissions. Data from 2016-2019 has hitherto been broken down and presented only at a low-granularity high level (e.g. per school). A deeper understanding of travel patterns have this far been lacking (e.g., who flies where, when and why). In order to fully understand the possibilities and the conditions for changing employee travel activities, there is thus an urgent need for better data, for tools to make sense of this data, and for a better understanding of travel and meeting-related practices at a school, division, department and at the individual level. Concretely we need to understand how flying is distributed over the various schools, departments and positions at KTH in order to be able to discern who, what and where reductions are most attainable, e.g. what flying needs to decrease, whose flying needs to decrease and what the existing obstacles are to reducing academic flying.

[7]https://www.kth.se/en/om/miljo-hallbar-utveckling/klimatramverk/kth-s-klimatmal-1.926003

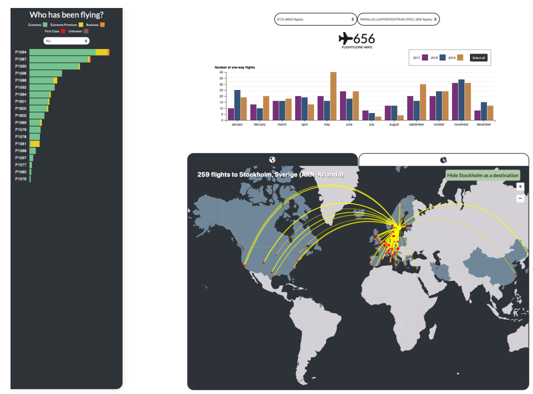

Figure 1: A map of all flights at a specific department between 2017-2019 by month (top), by destination (bottom) and by individual (left)

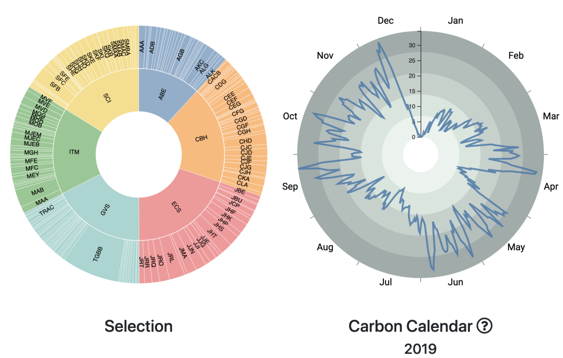

Figure 2: KTH's CO2 emissions from flights during 2019 in ton/day (based on distance and duration of trips)

The authors of this paper are working on providing KTH with such data and suitalble tools to analyse this data in a 2019-2022 research project, "Decreased CO2-emissions in flight-intensive organisations: from data to practice". In this project, the authors are working together with departments at KTH in order to study work-related (air) travel habits of individuals and departments with the aim of creating change toward more sustainable travel behaviour. Through a series of workshops together with employees at specific departments, the plan is to discuss, reflect upon and mediate negotiations about departmental and individual CO2 emissions, and follow up the results on a regular basis. Additionally, the project team is working together with students at KTH to develop and evaluate visualization tools using a dataset containing all registered business trips conducted by KTH employees during 2017-2019. These tools explore different perspectives when they interrogate the data set, from investigating when and where employees fly (see figure 1) to describing the carbon intensity of departments and individuals across a calendar year (see figure 2). The purpose of developing these tools is to explore and create an understanding of who flies when and where, and what impact this has in terms of CO2 emissions. The tools are also being evaluated by different stakeholders, both within the university and outside, who might be interested in understanding the emissions from air travel in their own organisation. Next we will give an example of why and where these tools are needed.

5 ENVISIONING AS TROUBLESHOOTING

To further exemplify how the consequences of following the carbon law can become very concrete, we provide a detailed analysis of an example where data (e.g. lack of data) and the need for better computing systems are elaborated upon. As stated above, KTH aims to decrease its business travel related CO2 emissions by at least 60% between 2020 and 2030. These reductions correspond to annual reductions of CO2 emissions from business travel by 9%. Based on current CO2 emissions and stating the obvious, KTH's emissions in 2030 should correspond to 40% of current emissions.

Current emissions can be broken down into two categories: emissions that are generated by KTH employees and emissions that are generated by non-KTH employees. A surprisingly large proportion of the current emissions (31% of total 2019 KTH emissions but rounded off to 30% in the example below) are generated by non-KTH employees. Examples of such trips are when KTH pays for an opponent and multiple members of a grading committee to fly to KTH to participate in a PhD dissertation, trips by KTH PhD students who have a scholarship and are not formally employed by KTH as well as other trips such as first (bachelor's) or second (master's) cycle students whose trips are paid by KTH. An example of the latter are for example students who take a project course that is organised by KTH Global Development Hub. Such courses give KTH students the opportunity to participate in a project that focuses on global challenges in local (African) contexts.

While KTH's travel agency can provide detailed information about each trip made by an employee, little is known about non-KTH employees' trips. It has proven to be hard to find out who paid and for what purpose such a trip was made beyond basic information about which of the five schools paid for the trip and when it was made. It is thus currently not possible to find out which division or department "generated" a specific trip by a non-KTH employee nor for what purpose such a trip was made unless significant manpower is invested in the task of manually going through very large numbers of travel requisition forms. It goes without saying that the less we know about non-KTH employees' trips, the more difficult it will be to reduce the number of such trips (or rather the carbon footprint from these trips). Let us therefore illustrate the effects of attaining the overarching KTH CO2 reduction goals in two different scenarios (further see Table 1 below):

- **2020 (baseline)**: current proportions between KTH employees' and non-KTH employees' CO2 emissions from business air travel
- **2030a**: KTH and non-KTH employees' CO2 emissions are reduced (proportionally) by 60%.
- **2030b**: non-KTH employees' CO2 emissions remain a "black box" , their carbon footprint has not been reduced and all carbon reductions instead have to be made by KTH employees.

Table 1: Current (2020) and future (2030) projections of CO2 emissions from KTH business travel in per cent of current CO2 emissions from KTH business travel

CO2 emissions from air travel	KTH employees	non-KTH employees	Total
2020	70%	30%	100%
2030a	28%	12%	40%
2030b	10%	30%	40%

Attaining the 2030a goals constitutes a major challenge as both categories (KTH employees and non-KTH employees) must reduce CO2 emissions from business air travel by 60% between 2020-2030. Attaining the 2030b goals constitute a radical challenge for KTH employees. If KTH fails to reduce non-KTH employees' CO2 emissions from business air travel between 2020 and 2030, KTH employees instead need to reduce their CO2 emissions from business air travel by 86% in a ten-year period (from 70% to a measly 10% of current emission levels). This would become necessary if overall KTH goals are to be attained and in order to "make up for" the non-reduction of non-KTH employees CO2 emissions from business air travel.

Several lessons can be learned from this example despite the fact that it is based only on simple calculations and hypothetical projections:

- The Carbon Law implies fundamental, tough and probably also potentially painful changes to academic (travel, career) practices also on a time scale of only 5 or 10 years.
- Binding goals - such as a 60% reduction of CO2 emissions in 10 years - clarifies trade-offs, conflicts of interests and dilemmas, but also suggests necessary courses of action.
- In this particular case a simple calculation exercise adds an urgent impetus to collect information about something that KTH has hitherto failed to pay attention to (e.g. non-KTH employees' air travel). This small exercise also implies that collecting this information should be a top priority, e.g. current routines should be changed as soon as possible and not doing so would make already tough goals even tougher for, in this case, KTH employees.

We argue that this scenario of carbon emission reductions from academic business flights constitutes a concrete *"future of limits and/or scarcity"*. By specifying a climate-related goal in terms of limits to CO2 emission, CO2 emissions become a scarce resource to be husbanded and distributed among co-workers at departments (according to some agreed-upon but yet-undecided criteria). This particular scenario hints that KTH might soon face tough discussions about “who gets to fly” both within and between departments. We will not further discuss this topic here but it might become the topic of future research.

By making the goals of the Paris agreement actionable by way of the global carbon law (and as specified in the Exponential Roadmap [11]), it is possible to develop a roadmap for any specific area (for example flying) and at any level (individual, department, organisation, country, globally). If a specific area is deemed particularly important (for example healthcare) and/or if it is particularly difficult to reduce emissions by 50% per decade in a particular area (for example food production), this means that *other areas need to reduce emissions by more than 50% in a decade*. We believe that flying is an area where it would be, if not relatively easy, then at least *comparatively* easy to reduce carbon emissions by more than 50% in a decade compared to for example healthcare or food production. By setting up an actionable goal for 2030 it becomes possible to work both forwards from where we are today (e.g. carbon emission reductions of 9% *this* year) as well as backwards from where we would like to be in 2030 (e.g. 40% of current CO2 emission from academic business travel). This implies that it would be possible to make use of a combined forecasting/backcasting methodology to flesh out the scenario that is outlined here (e.g. “who gets to fly where?”). We also argue that it becomes easier to discern what the contribution of computing could be when it is based on such scenarios, making it easier to *“describe the design, implementation, and evaluation of computing systems that work within or help cope with limits”*, e.g., Limits “systems papers”. We will below discuss computing systems that we suggest are relevant in our specific case, e.g., how computing systems could support the goal of reducing carbon emissions from flying at KTH by 60% between 2020 and 2030.

6 HOW COMPUTING CAN MAKE A DIFFERENCE

Now that the goal has been spelled out and we know what we are aiming for, e.g. reducing CO2 emission from academic flying at KTH by 9% every year between 2020 and 2030, what then is the role of computing systems in helping us achieve this goal? In other words, how can we *“impact society through the design and development of computing systems [...] for use in a future of limits and/or scarcity”*?

We here suggest a number of solutions that together constitute a “toolbox” of sorts. Some of these solutions involve designing and developing new systems, apps and interfaces, but there are also opportunities for maintaining, developing and enhancing already existing computing systems and the practices they are embedded in. Developing and maintaining existing or new computing systems will be a matter of working together with various stakeholders. The most important partners in that process are in this case those who are responsible for operational tasks in relation to attaining the university’s sustainability goals. At KTH Royal Institute of Technology, the most important stakeholder is thus the KTH Sustainability Office which has the operational responsibility of making sure that the chancellor’s decisions are enacted. This means that our research project closely collaborates with the KTH Chief Sustainability Officer and with the KTH vice chancellor with responsibility for sustainability. Our proposed toolbox consists of the following measures:

6.1 Disseminate information

Find suitable digital or non-digital channels and formats for communicating guidelines, travel policies and meeting policies to all employees.

6.2 Collect relevant data.

KTH Royal Institute of Technology has developed climate objectives for 2020-2045. To decrease carbon emissions from flying is a prioritized area but in order to achieve that goal it is first necessary to collect data about flying. At KTH employees are mandated to order any trips through our procured travel agency and compliance needs to be high to yield high-quality data. It is important that procedures are put into place to collect all relevant data (KTH unfortunately collects almost no relevant data about the *purpose* of each trip, nor about non-KTH employees’ trips, see further above). Extending or adjusting existing systems to get relevant and complete data about the travel habits of employees is important in order to get the full picture.

6.3 Visualization

It is essential to gain a deeper understanding of how schools, divisions, departments and employees travel in order to understand what constitutes "unnecessary" flying and what reductions are needed to reach set targets. Developing visualization tools is important to unveil and communicate information about who flies where and when, to enable decision makers to gain insights about what needs to be done to reach emission reduction targets, to facilitate reflection and discussion amongst employees and to facilitate monitoring and communication of the climate action plan over time. What (kinds of) trips are (un)necessary in relation to job (or career) requirements.

6.4 Decision support

Providing decision support in relation to travelling is another venue of possible solutions to support emission reductions. It would for example be possible to develop systems that compares carbon emissions between different travel modes (e.g. plane vs rail). This functionality could be delivered through a stand-alone application or by enhancing existing online travel booking systems through feedback about emission impacts from different alternatives (e.g. direct flights vs stopovers, different airline companies, airplane types and seat configurations etc.). The Tyndall Carbon Tracker [17] helps assess and score a planned trip based on what emissions are justified in relation to the the purpose and length of the trip, mode of travel and seniority of the traveller (with the assumption that the more senior you are, the less the need to travel in order to establish yourself as a researcher in a field). This kind of tool could inspire policy measures in organizations such as making it mandatory to assess the importance of a planned trip and whether it can be justified in relation to the carbon emissions it generates.

6.5 Follow-up

It is possible to develop emission auditing systems and routines for travel management follow-ups to better understand travel data at different levels in an organization, including offering individuals the possibility of keeping track of their own emissions. The Tyndall Carbon Tracker [17] calculates a carbon footprint for a trip by multiplying the duration of the trip by average emissions for various modes of travel.

6.6 Digital meetings

Digital meeting technologies could be used to replace trips and face-to-face meetings. There is a plethora of meeting tools that can be used, but this is also a field that is replete with opportunities for improvements. Possibly even more important is to develop ways to improve knowledge and to support employees in using digital meeting technologies to the fullest.

6.7 Research

Initiate research projects to study and support carbon emission reductions at universities and other flight-intensive organisations, including by supporting all the measures enumerated above.

6.8 Partnerships to achieve the goal

It will be hard to achieve significant carbon emission reductions without anchoring high-level goals at the highest levels in the organisation as well as with those who are tasked with realizing those goals. We have already outlined how this is done at KTH Royal Institute of Technology above. This is a role that has little to do with computing but that is crucial if the goal is to enact real changes in a real organisation (be it a university or otherwise).

7 DISCUSSION

One of the goals of the Limits community is *"to impact society through the design and development of computing systems in the abundant present for use in a future of limits and/or scarcity"*. We have argued that one of the challenges that this community faces is the lack of consensus as to what exactly constitutes a *"future of limits and/or scarcity"* - besides (uncontroversially) less material wealth than what current standards of living in the global North affords. Aside from the fact that a future of limits and scarcity involves "less", does such a future look like something that comes straight out of a Mad Max movie [37] or would we do better to turn our attention to (computing) infrastructure and challenges in a post-earthquake Haiti [25] or in a northern Iraqi refugee camps [31]?

Chen [4] explores parallels between Computing within Limits and Information Communication Technology for Development (ICTD), arguing that both work with similar considerations (simplicity, infrastructure independence and modularity), but Chen [5] suggests that the whole endeavour of *"designing for an unknown future"* might represent an exercise in futility:

"if a system were to be designed beforehand, it would likely be inappropriate given the inevitably different social, political, economic, and technological landscape. Also, the limits scenarios we expect may not occur in the time frame or in the manner that we expect. In these cases, our preemptive efforts and increasingly precious resources would be wasted." [5, p.1].

Chen [5] then suggests that instead of designing for a future we know nothing about, *"future challenges already exist today in their incipient forms"* and we as a community *"should contribute to the facets of limits-aware research that already exist: crisis response, development, and sustainability"* [5, p.1]. This certainly looks like a suggestion that time would be better spent working on real problems today rather than on hypothetical problems that we (most probably) won't encounter in the future. We assume that the corollary to this suggestions is that by solving real problems today, we will be better suited to solve future problems as and when those problems appear.

Others have however tried to find ways to overcome the indeterminability of the future and the *"epistemological asymmetry of historical time: the past is always visible and the future is always unknowable"* [12, p.39]. Eriksson & Pargman [9] argue that while it is easy to reject the folly of endless exponential growth in the economy as well as in computing, it is *"harder to imagine and propose credible, preferable and evocative alternatives"* [9, p.1]. Instead of designing for a specific future, they propose that counterfactual history can help *"liberate our ideas from various preconceptions that hamper them and box them in"* [9, p.1]. Also Silberman [33] attempts to deal with the inherent uncertainty of designing for an unknown future:

responses to global change will require that the global networked information-industrial society become a fundamentally different society: one with different industrial technologies, information technologies, structures and practices of organization and governance, educational institutions and practices, subjectivities, and ideas. Yet one cannot fully map the road from here to there from here, as if from above; rather, the process is one of "navigation," in which we discover the road as we walk it" [33, p.3]).

Silberman's contribution to "limits-aware" computing consists of six pieces of advice, high-level design principles for choosing and succeeding to carry through *"work that contributes substantively to broader efforts to change our society"*[33].

Suggestions for worthwhile research in Computing within Limits thus range from 1) designing for a "collapse that has already happened" (in poor or war-torn countries) and hope that by "doing good" today, we (almost as a side-effect) are also preparing for a future of limits closer to home [4, 5, 25, 31] to 2) more vague ideas about how to go about to design for an unknown future [9, 33]. None of these papers suggest a concrete scenario of what a "future of limits" could look like, nor a trajectory or a roadmap for going from *here* (the present) to *there* (the future). We argue that there is a connection between the absence of concrete future scenarios of what a "future of limits" could look like and the absence of Computing within Limits discussion papers (that *"explore the nature of limits and computing"* and *"describe their impact on computing, and present directions for future research"*) that the community can rally behind. Without a foundation that it's possible to rally behind (or several), it will subsequently be hard to develop systems and produce systems papers that *"describe the design, implementation, and evaluation of computing systems that work within or help cope with limits."*

In this paper we do suggest *one* such a foundation (there can of course be others/several). We propose a scenario that many could rally behind, namely a future where we manage to stop runaway global warming by adhering to The Paris agreement. The Paris Agreement [2] outlines what such a future looks like but says little about how to go from *here* (the present) to *there* (the future). The carbon law [29] does however specify how we can go about to meet the goals of the Paris agreement, namely by decreasing carbon emissions by 50% each decade between 2020 and 2050. These emission reductions should by extension be done in every country, in every city, in every industry, in every organisation and in every household. This scenario, we suggest, describes a future of limits that we imagine many could rally behind.

It is possible to ask why we have here chosen a singular focus on decreasing CO2 emissions when there are many other aspects of sustainability that it is possible to focus on. Do we then not reduce the myriad of challenges facing all beings on the planet across many different ecosystems? Research on "planetary boundaries" [30, 35] suggests there are nine boundaries we should not overstep, of which climate change is only one. Other boundaries are for example land-system change (e.g. deforestation), ocean acidification (e.g. coral reefs dying), biosphere integrity (e.g. species extinction) and biochemical flows (e.g. use of fertilizers and eutrophication). It is furthermore possible to besides ecological limits also add social limits, and Raworth [26] has extended the planetary boundaries model so that the environmental ceiling in complemented by a social floor (e.g. access to food, education, housing, healthcare, political voice etc.). We however see no direct contradiction between focusing on decreasing CO2 emissions and attaining most other sustainability goals. If CO2 emissions decrease (for example by flying less), it will surely be easier to attain also other sustainability goals. Many goals are linked, but most would agree that many of the sustainability problems we face stem from our use of fossil fuels (coal, oil and gas) and the CO2 emissions that are associated with extracting and burning them.

The scenario we propose here differs from previous attempts at “divining” the future or attempts that abstain from engaging the future. It is instead closer to normative attempts to shape the future by inventing it, e.g. by stating that “this is the future we want, let’s make it happen”. An important difference though is that the scenario we propose is based on a solid foundation from the environmental sciences (or at least as solid as projections about the future come). We have instantiated this general scenario of CO2 emission reductions with a specific case, namely that of reducing carbon emissions from flying in a specific flight-intensive organisation by 60% in the next 10 years, and also outlined what computing can do to help attain this goal. Many other examples are of course possible and we encourage others to explore and flesh them out.

We find that there are several characteristics that make this scenario attractive for Computing within Limits:

(1) The carbon law, by being incremental, “stabilises” the future and makes it concrete. This makes it possible to, as we have done, develop systems that will be deployed in the next few years and with the tangible goal of decreasing carbon emissions in a specific sector or organisation by 50% in a ten year period.

(2) The carbon law stabilises the future not a specific point, but along a limits- and carbon-law-compatible trajectory. It is thus possible to calculate how much CO2 emissions have to decrease in a specific sector or organisation 5, 10 or 20 years into the future and already in the present plan accordingly.

(3) By stabilising the future and by making it concrete, it becomes easier to *“describe the design, implementation, and evaluation of computing systems that work within or help cope with limits”*. We have exemplified this by describing visualizations that we have developed in our own research project, “Decreased CO2-emissions in flight-intensive organisations”.

(4) The carbon law is agnostic and does not specify what a future society that is compliant with the carbon law will look like or what specific changes are/were necessary to reach that state (nor the specific path from *here* to *there*). The carbon law is concerned only with carbon emissions and forms a framework within which it is possible to imagine different paths to different futures (for example in terms of global equity, see for example [24, 26]).

(5) If there is agreement that the carbon law is an attractive pathway, there is a larger chance to develop a consensus about what (normative) future(s) we are “aiming for” in Computing within Limits and together work towards attaining them.

It should be noted that the future scenario we have presented in this paper aims for "graceful descent" instead of describing a collapsing society. It is inherently difficult to plan and prepare for a collapse [21, 23], just as it is inherently hard to "plan for the unexpected". This paper was incidentally planned before the very unexpected Covid-19 virus was deemed to be a pandemic by the World Health Organisation, but it was written during a period when the virus had a large impact around the world - including in Sweden where all authors of this paper live. Many countries have closed their borders and ordered their citizens to stay at home. Everyone who can work from home does, air traffic is at a historic low and there has been an explosion of digital meetings and of online teaching.

As for the academy, all scientific conferences have either been cancelled, been postponed or moved online. What was previously regarded as preposterous has in a very short amount of time become the norm, or at least a viable working option for the time being. It is an open question if these changes are temporary or if new habits are forming that will make digital meetings an attractive option also after things return to normal. The lock-down obviously has many negative effects, but it is desirable to also reflect on the positive effects. There is a chance that new habits are forming that are more in line with the carbon law. Some months into the pandemic, it is now a given that the aims of our 2019-2022 research project will have to be updated or rewritten. Perhaps our aim will not any longer be to help decrease carbon emissions from academic flying, but rather to make sure that carbon emissions from academic flying does not bounce back to previous levels. Whatever happens we will however have the carbon law to guide KTH towards these new goals.

8 CONCLUSION

We have in this paper argued that the Computing within Limits community should embrace the carbon law as a concrete and actionable framework for building "futures of Limits". In a world where growth (and in the case of computer science, Moore's law) has been the predominant narrative, we need to now instead exponentially decrease our carbon emissions to keep the planetary system in a safe space. The carbon law (or in our case, the even more ambitious goal of 60% carbon emissions reduction over 10 years) superimposed on academic flying at KTH Royal Institute of Technology unveil not only interesting knowledge gaps, but also a large number of ways in which computing can assist in the transition to a low carbon university and a low carbon society. In our particular case, different ways of keeping in contact and exchange ideas, for example by video conference meetings, are a low hanging fruits, but it has also become clear in our research project that we need better computer tools to understand the data around flying before we can actually guide any change process and reduce carbon emissions. We believe that the concrete nature of the carbon law (e.g. the fact that it makes it possible to calculate on necessary future carbon emissions reductions) can aid us in addressing and exploring any case in any sector, at any level of society and with different time spans and we welcome other scholars in the Computing within Limits community to explore these scenarios together with us!

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