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Understanding and Mitigating the Effects of Device and Cloud Service Design Decisions on the Environmental Footprint of Digital Infrastructure

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ABSTRACT

Interactive devices and the services they support are reliant on the cloud and the digital infrastructure supporting it. The environmental impacts of this infrastructure are substantial—and for particular services the infrastructure can account for up to 85% of the total impact. In this paper, we apply the principles of Sustainable Interaction Design to cloud services use of the digital infrastructure. We perform a critical analysis of current design practice with regard to interactive services, which we identify as the *cornucopian paradigm.* We show how user-centered design principles induce environmental impacts in different ways, and combine with technical and business drivers to drive growth of the infrastructure through a reinforcing feedback cycle. We then create a design rubric, substantially extending that of Blevis [6], to cover impacts of the digital infrastructure. In doing so, we engage in design criticism, identifying examples (both actual and potential) of good and bad practice. We then extend this rubric beyond an eco-efficiency paradigm to consider deeper and more radical perspectives on sustainability, and finish with future directions for exploration.

Author Keywords

Sustainability; Interaction Design; Green Computing; Cloud Computing; Sustainable HCI

ACM Classification Keywords

H.5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous.

INTRODUCTION

The importance of incorporating sustainability principles in the design of digital products and services is becoming increasingly recognised by both academia and industry. Such principles should be applied both when considering how a product is made, but also when considering how a product might be used. Many companies now incorporate reviews of energy efficiency of products, including models of expected user behaviour, and reviews of substances which are potentially hazardous (to people and the environment) in their design process. They also incorporate consideration of the end-of-life of a product—how to encourage recycling of products, and in some cases refurbishment for reuse [27]. In the perspective of Sustainable Interaction Design, Blevis [6] argues that designers of digital products must also be responsible for explaining how resource use is impacted by the artefacts and services they design, as an intrinsic part of the design. As an instrument of fulfilling this responsibility, designers may minimise resource use by moving away from a paradigm of 'invent and dispose' towards one encouraging longevity and sharing of digital devices.

However, one area has received relatively little consideration in the design process—the environmental impact of the infrastructure that grows in support of interactive devices and the cloud services they use. A service on a device does not live in a vacuum. Infrastructural support is required to create the service, to create or source associated content supplied through the service, and to deliver the service over time. Doing this requires use of servers, core and edge network equipment, and potentially content creation equipment such as cameras, sensors etc. We refer to this as the *digital infrastructure*.

People increasingly use digital services for socialising, communicating, organising and entertainment, and such services are often cloud-based. As a result, the infrastructure is a significant contributor to the environmental impact of a device and the services it supports. Furthermore, with the nascent Internet of Things, the impact is likely to increase.

Based on figures for 2007, Malmodin et al. [39] estimate the greenhouse gas impact of the manufacture and running of this digital infrastructure to be 253 Mt CO_2e per annum, of similar order of magnitude to that of computers and other end user devices (278 Mt CO_2e p.a.).[1] Hence a focus on the impact of a device is only considering half the problem.

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[1] The infrastructure figure quoted here excludes the share of the fixed telecoms network associated with non-broadband customers.

Furthermore, with the growth of streamed media and cloud services, the impact is increasing rapidly. More recent studies of specific digital services [1],[61] show that, especially with the trend towards smaller end-user devices, the infrastructure can account for up to 85% of the environmental impact.

The impact of this infrastructure has begun to draw attention of policymakers, campaigners and researchers. The US EPA [70] identified the growth of energy consumption by data centers as a cause for concern, and Greenpeace [24] has campaigned on the issue. What has drawn less attention in the public eye is the network. This is despite the fact that the network is responsible for over half the impact of the infrastructure [39]. Furthermore, although data centers are used for a number of applications besides the provision of consumer services, the network is primarily used for this. Consumer services, in particular video, make up by far the largest category of data traffic, accounting for 80% of throughput [9].

Design decisions taken when creating an interactive device or service can have a significant impact on the use and development of this digital infrastructure—and hence on the environmental impacts it creates through resource consumption and energy use. Despite this, it has received relatively little consideration in the Sustainable HCI literature, and impacts of infrastructure use do not form part of design considerations used within companies.

In this paper, we apply the principles of Sustainable Interaction Design to cloud services use of the digital infrastructure. We perform a critical analysis of current design practice with regard to interactive services. We show how user-centered design principles induce environmental impacts in different ways, and combine with technical and business drivers to drive growth of the infrastructure through a reinforcing feedback cycle. We then create a design rubric, extending that of Blevis [6] to cover impacts of the digital infrastructure. In doing so, we engage in design criticism, identifying examples (both actual and potential) of good and bad practice. We then extend this rubric beyond an eco-efficiency paradigm to consider deeper and more radical perspectives on sustainability, and finish with future directions for exploration.

RELATED WORK

The work in sustainability related to HCI has mainly focused on front-end interactions between people and digital devices rather than with issues of infrastructure. However, on the level of theory, philosophy, and politics, we as a community have aspired to wider coverage. In this section, we trace the history of notions of sustainability in HCI to support our understanding of digital infrastructure in relation to this.

Origins of the Notion of Sustainable Interaction Design

The notion of Sustainable Interaction Design (SID) originates in Blevis [6]. With respect to infrastructure, Blevis appealed to Kumar et al.'s [36] reformulation of the IPAT equation [8] to show the need to address per-capita energy consumption in our global collective future. In the same year, the *Environmental Sustainability and Interaction* [40] workshop built on notions like VSD [19] to advocate sustainability as a key concern in a values-rich conception of HCI.

Sustainability through Design & Sustainability in Design

This workshop also introduced a distinction between *Sustainability in Design* and *Sustainability through Design*. Sustainability in Design [40]:2122 is characterised as *'how to take account of sustainability as part of the material design of products.'* This is contrasted with Sustainability through Design [40]:2123, which is characterized as *'how to support sustainable lifestyles and decision-making through the design of technology.'* These terms *Sustainability in Design* and *Sustainability through Design* owe to another distinction: that of *Research in Design* and *Research through Design* [16],[75].

Sustainable Interaction Design and Sustainable HCI

In 2010, diSalvo et al. [13] published a survey of the 157 papers on sustainability and HCI to that date, adopting the term *Sustainable HCI. Sustainable Interaction Design* and *Sustainable HCI* have become near-synonyms. Nonetheless, the authors of [13]:1977 make a distinction: *'Sustainable Interaction Design (SID)… describes papers oriented around using sustainability as a 'critical lens'* [25] *…[which]…tend to see a need to fundamentally rethink the methods of HCI in order address sustainability…[and]… see designers as complicit in the unsustainability of current interactive products, aiming to change design to encourage more sustainable effects.'* They contrast this approach with other Sustainable HCI research that *'take known approaches in HCI and apply them to sustainability as a problem domain.'* Our work is clearly situated in this tradition: we will firstly provide a critique of the current design paradigm and highlight its shortcomings, and then propose alternative paradigms illustrated with examples of good and bad practice.

Research in Sustainability in Design

As noted in diSalvo et al. [13], research on sustainability in design has focused primarily on the issue of material use and waste reduction associated with interactive devices. It has studied people's attitudes and practices with regard to mobile technology to guide design in this direction [25],[28]. Remy and Huang [55] categorize research approaches used to encourage device longevity. Some of these are focused on encouraging attachment to the device in different ways, encouraging users to keep them for longer [7],[21],[48],[50],. Others focus on the re-using of old devices by passing them on to others [29],[25], repurposing them in different ways [48],[29],[38] and reusing their subcomponents [30],[74].

In addition to the issue of resource use, some attention has been paid to the energy impacts of design decisions in IT systems. McLachlan and Brewster [41] explore the energy implications of alternative interaction techniques with a laptop computer. Tarzia et al. [67] conduct an in-the-wild study of display power management practices.

More recent work has focused on understanding practices that develop around domestic digital technology, and their resulting impact both in terms of resource and energy usage [4]. This work is notable for adopting a holistic, practice-based perspective on environmental impact, rather than focusing on a single device. It identifies the higher impact associated with 'connoisseurs' who create larger 'constellations' of devices and domestic infrastructure.

Despite the significant impact associated with the digital infrastructure, relatively little research has been conducted by the Sustainable HCI community in this area. It is interesting to note that a sustainability framework developed based on literature study and expert interviews provides thorough coverage of device issues but no mention of broader infrastructure issues [12].

Pan et al. [49] frame key sustainability issues associated with trends in cloud computing of relevance to the HCI community. Bates and Hazas [3] estimate the climate impact of the domestic infrastructure associated with home sensing equipment. Preist and Shabajee [54] quantify the long-term increase in energy use by the internet that results from current trends in user behavior, and propose possible design interventions to mitigate this. Lord et al. [37] identify practices associated with tablet use, estimate the associated infrastructural energy use, and propose design interventions to mitigate this. Bates et al. [5] identify practices which grow ownership and usage of domestic digital technology, including demand on digital infrastructure. Schien et al. [60] model end-to-end energy use of a digital media service, quantify its annual impacts, and estimate reductions in impact enabled by different design interventions. Our work builds on the insights from these, situating them within a wider perspective based on the principles of Sustainable Interaction Design.

Recent Studies and Visions

Our work aligns with many of the recommendations made by Silberman et al. [63]. In particular, we are concerned with both an immediate and a longer timescale understanding of the drivers and impacts of digital infrastructures. In understanding digital infrastructure, we appeal to much work that is outside of HCI, particularly industrial ecology and systems modeling, to contextualize and scope the problem and its components. Like Knowles et al. [34], we also draw inspiration from political science [14] to identify existing discourse within design paradigms, and explore more radical alternatives to this. As alternatives to the current status quo in design thinking with regard to the infrastructure, we firstly consider a reformist, eco-efficiency paradigm and then more radical paradigms. Our inspiration for the latter comes from recent work on collapse informatics [69], computing within limits [51] and sustainability 2.0 [35], which we discuss in more detail later in the paper. Firstly, in the critical tradition of Sustainable Interaction Design, we turn our attention to current design practices and their inadequacies.

THE CURRENT DESIGN PARADIGM AND ITS IMPACT

User-centered design and customer-driven business, together with societal values of individuality, choice and convenience lead to designers working to provide ever faster, richer and more pervasive digital services. They do this through both the design of device ecosystems offering richer functionality and more varied affordances, and through the design of services that exploit such ecosystems. In doing so, designers make the implicit assumption that the digital infrastructure is abundant, relatively cheap to the end-user and will expand to meet future demand. As Lord et al. [37] observe, this means that designers, users and providers assume that 'devices have access to certain intensities and continuities of network service'. Innovation in infrastructure provision tends to support this perspective, with Nielsen's law [45] observing that bandwidth available to a high-end user is increasing by 50% every year.

The majority of innovation in interactive device ecosystems and their associated services focuses on provision to such high-end customers, under the assumption that these are the early adopters of new technologies. Such customers are encouraged to buy increasingly rich device ecosystems, which in turn are reliant on a rich and bandwidth-intensive set of services in the cloud. This strategy also makes the (currently correct) assumption that innovation in the infrastructure, resulting in increased bandwidth and reduced price over time, will allow the majority of users to access such services in the future.

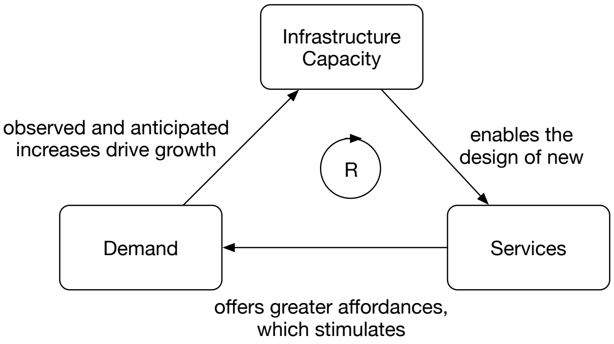

Figure 1: Reinforcing feedback stimulating Infrastructure Growth

Effectively, the provision of digital services to high-end users stimulates latent demand in mainstream users for such services, which means there is a market for infrastructure expansion provided it goes alongside cost reduction in bandwidth provision. The mainstream users then pick up devices and services which were formerly high-end, and they become embedded in everyday practice. Services that most users were happy without become essential to everyday life for the majority of the populace in developed countries. This results in a reinforcing feedback loop encouraging growth of the digital infrastructure.

The (Undesirable) Cornucopian Paradigm

This dominant paradigm, which we refer to as the *cornucopian paradigm*, is reinforced both by faith that Moore's law will continue to hold and deliver efficiency improvements, and by discourse around the cloud which emphasises the 'infinite scalability' [43] of services. The cornucopian paradigm has a number of (often implicit) design principles. We now present the first explicit consolidation of such principles and identify the ways each principle drives increase in infrastructure demand. Elements of these principles are often referred to in academic, design and product advertising literature; we give pointers to examples of this literature to illustrate each of them.

(C1) PERSONAL: Some services are necessarily personal—such as email—but users increasingly expect services traditionally shared by groups of people (family TV, home sound system) to be available on an individual basis: a move from an ideal of a 'happy family' to 'happy individuals' [52]. This means that the infrastructure must deliver more services simultaneously, meaning that more servers and network capacity are required than for shared services.

(C2) VARIETY: Users expect a very large choice of service to be available. Based on this, because of the cheapness of storage, service providers 'make everything available and let the customer decide' [2]. Given the amount of content available, particularly with the rise of user-created content, it means a large amount is never used again. This increases the amount of storage devices required, and hence both use of raw materials to create them and energy to power them.

(C3) INSTANT: Users expect to receive a service straight away, with almost no noticeable access time [44]. To provide this, both servers catering for the individual service and the network infrastructure catering for the combined load of all services must be sufficient to cater comfortably with peak demand, resulting in the need for more servers and network capacity than would otherwise be necessary.

(C4) SHAREABLE: Users want to create content that is available to others, and share it with them [22]. This increases cloud server and storage infrastructure needs, and bandwidth demand to view the content.

(C5) HIGH QUALITY: Users expect increasingly high quality, in the sense of audio, image and video resolution, and services respond by offering increasingly higher resolution video and fidelity of sound [68]. This increases the demand on the network infrastructure, and servers and storage involved in the provision of services. Increasing resolution of user devices means that user-generated content is higher resolution, leading to increased storage requirements both for personal cloud storage services, and also for services that publically share user generated content such as YouTube. The desire for higher quality services also affects content creation equipment, leading to the deployment of new higher resolution cameras (both amateur and professional) and associated infrastructure.

(C6) PERVASIVE: Users increasingly expect each service to be available from any of their devices, transparently [23]. This means that services that historically would be provided locally (such as word processing, diary and music provision) now must be provisioned either partly (through synching of data) or wholly through the infrastructure. This increases server, storage and network provision requirements.

(C7) CONTINUOUS ACCESS: Users expect to access services at any time, anywhere. They want to be able to contact others (increasingly often via video) or view entertainment in any 'down time' [37], wherever they may be. This stimulates the growth of network coverage—particularly mobile networks and Wi-Fi, which are energy intensive components of the infrastructure.

(C8) ETERNAL: Users expect content that they generate to be 'always alive and always available' [58] (unless they choose otherwise) to themselves and others. This increases cloud server and storage infrastructure needs.

(C9) EPHEMERAL: Users create and save content without regard to whether they (or others) will actually use it again. It is easier just to save it just in case than to think about whether it may or may not be used again. Hence a lot of what is saved is ephemeral and never used again. This increases demand on storage infrastructure.

(C10) RICH, CROSS-MODAL AND UBIQUITOUS: Users increasingly look for, and businesses encourage, a collection of services that interact and support each other, providing a richer experience overall [46]. They also increasingly use services in the 'background' of their attention to provide ambient experiences and/or control through the Internet of Things [10]. Hence users use services more often, and use multiple services simultaneously. This increases the demand for services in general, and so amplifies the impact of the other nine factors.

Cloud-based services are at times (particularly in a corporate context) able to reduce energy and resource consumption by consolidation and more efficient use of servers stored in state-of-the-art green data centers [71]. However, in the consumer context, the design principles described above result in growth both of energy consumption by the infrastructure, and in demand on raw materials for infrastructural construction.

In many ways, these principles are desirable to the user. This contrasts with design approaches such as Choreographed Obsolescence [72] and Disposable Technology [28], which arguably encourage waste primarily to improve revenue rather than to benefit the user. A human-centered design process would identify these principles as giving an improved user experience, and offering services to make life easier and more pleasurable. However, as design theorists have observed [20], a human-centered design process is not necessarily humanity-centered. The choices that an individual user may make can result in collective longer-term outcomes that are detrimental to the overall sustainability of the system [57].

Having considered the current design paradigm, and its consequence on the digital infrastructure, we now consider approaches to mitigate its environmental impact.

STRATEGIES FOR 'SOLVING' THE PROBLEM

Broadly, there are two approaches to trying to contain this problem without addressing user interaction.

1. Efficiency improvements in the underlying infrastructure.

Network equipment is increasing both in the bandwidth it can provide and also the energy (and, to a lesser extent, resource) efficiency with which it does this. Similarly, servers within data centers provide computational power more efficiently. Such efficiency improvements can be used to partly offset the increasing demand.

2. Smart use of the infrastructure

As well as improving efficiency of the underlying infrastructure, the infrastructure can be used more efficiently through appropriate algorithms and architectures. On a local level, compression algorithms partly compensate the growth of bandwidth from increases in resolution and use time. Video streams can adapt to the resolution of a device to ensure that unnecessarily large images are not sent. Peer-to-peer architectures can reduce the need for data centers by exploiting unused compute resources [32]. Local caching and the use of content delivery networks can reduce the load on the core network [59]. Such interventions are already taking place as increased efficiency of services has the potential to provide better performance and thus improve user experience.

Both of these approaches have value, and are already making significant contributions to the efficiency of the infrastructure. Despite this, the overall infrastructure is growing too fast for the efficiency gains to offset this growth, and there is currently an unsustainable absolute growth in energy consumption. If this is not adequate, then something else will need to change to reflect this future reality: the design paradigm discussed above.

A DESIGN RUBRIC: ALTERNATIVES TO THE CORNUCOPIAN PARADIGM

If we are to move interaction design away from the cornucopian paradigm, it is important to reflect on the consequences of a design of a digital product or service on the wider infrastructure and develop an awareness of the resulting environmental impact of such consequences. We now present a design rubric, in the form of a number of questions for designers to reflect on, which aims to do this. Our rubric, the Rubric of Infrastructural Effects (RoIE) is intended as an extension of Blevis' [6] Rubric of Material Effects (RoME). Following Blevis, we use two core principles to generate a set of questions to encourage reflection on the environmental consequences of design decisions and how to mitigate them. Blevis identified the *invention and disposal* of new types of device as being a driver of increased ownership and therefore material use and waste generation. The corresponding principle behind RoIE is *infrastructural expansion and obsolescence*: to what extent does a device, and the services it enables, encourage deployment of new infrastructure or the replacement of existing infrastructure as no longer adequate. Blevis' second principle, *renewal and reuse*, identifies the use and replacement of existing devices as a source of material and energy impact, and the potential for reuse to reduce this. The RoIE equivalent of this is *infrastructural use and sharing*: the energy consumption in the infrastructure to support services a device enables, and the more efficient use of the infrastructure through sharing to reduce energy and material use. The resultant questions that emerge from these two principles are:

(E1) *Does the design encourage infrastructural expansion or obsolescence?*

(E2) *Does the design encourage increased infrastructural use?*

(E3) *Does the design mitigate or reduce infrastructural use in some way?*

(E4) *Does the design encourage digital waste, or avoidance of it?*

(E5) *Does the design promote the sharing of infrastructure?*

We now discuss each question in more detail, and illustrate them through a number of examples—both potential and actual. Through these illustrations, we engage in design criticism, pointing to existing practice both positive and detrimental, and giving examples of potential new positive practice. We also refer back to principles in the cornucopian (C) paradigm where relevant.

(E1) Does the design encourage infrastructural expansion or obsolescence?

There are broadly three ways in which a new service can strongly encourage or require new infrastructure to be deployed: (a) It can require new functionality of the infrastructure. (b) It can require greater reach of the infrastructure. (c) It can require larger capacity in the infrastructure. We consider each of these in turn.

When a new interactive digital service requires new functionality of the infrastructure, it can require new infrastructural equipment to be deployed. This infrastructure will have environmental impacts, resulting from materials used in its deployment, energy consumption during its use, and impacts of equipment disposal associated with its ongoing maintenance and renewal.

For example, the 'Surfcam' service [64] provides real-time and continuous views of surfing beaches (C5,7). Uptake of this service is resulting in the new deployment of cameras around the world, together with local access network connectivity, primarily or exclusively for the provision of this digital service. As another example, cloud gaming services provide a local high-end gaming experience (C3,5,7,10) with the rendering and game logic taking place in remote data centers. This is resulting in the deployment of additional specialised graphics rendering hardware.

Qualitative changes in existing services may also require new functionality of the infrastructure. This can result in the obsolescence of existing infrastructural equipment, forcing the upgrading of it by organisations providing content to the service. For example, the potential move to 8K video would result in the obsolescence of existing professional filming and editing equipment in media providers, meaning a large turnover of equipment in a short period of time to meet new user expectations of image quality (C5). This would result in resource consumption and electronic waste.

Secondly, new devices and their associated services can require greater infrastructural reach. This is currently happening in the home. Users look to their personal devices for entertainment anywhere in the home (C1,6,7). Furthermore, the Internet of Things becomes more of an everyday reality (C10). IP-enabled devices and services such as networked TVs, smart home technologies and home audio mean that a home WiFi connection is becoming an essential in many households. As a result, WiFi equipment together with signal boosters are being deployed to ensure good coverage throughout the home. This trend has combined with the trend towards lower power devices (laptops, tablets etc.) so that domestic WiFi routers are often the single largest consumer of energy among IT equipment in UK homes [11].

Thirdly, a new service may require a greater capacity infrastructure to support its wide deployment. An example of the first is the move away from broadcast and cable transmission of home TV/film viewing towards streaming on-demand of such services (C1,2,3). This results in a step-change in demand for internet bandwidth, and so will stimulate significant expansion of the core internet [33] as on-demand moves increasingly into the mainstream.

Another example of a step-change in digital service is the 'always on' remote videoconference [31]. If it becomes the norm in remote working to have high-quality video connections with the rest of one's team (C1,3,5,7), it will significantly increase bandwidth demand.

(E2) Does the design encourage increased infrastructural use?

Some services may not result in a step-change in demand on the infrastructure, but nonetheless may encourage increased use and therefore increased impact. This impact consists of the energy to provide the service, and also the longer-term expansion of the infrastructure to handle this usage along with other new services. For example the move from SD to HD video (C5). While not a step-change service change on its own, it does roughly double the infrastructural demand for each video streamed. Similarly, the deployment of mobile services on smartphones has significantly increased the demand on the mobile network, as it means people are using networked devices more often and more intensively than they used to. This demand for mobile services, particularly those associated with audio and video often connected with the practice of 'filling down time' observed by Lord et al. [37] is driving the move to 4G mobile networks. Such networks, while more energy efficient in terms of the delivery of a given service, use more energy overall.

Another digital product (and it's associated services) that is increasing demand in this way is the Action Cam. Sales of Action Cams are over 5m units per year and increasing [66]. New practices that are developing around their use, e.g. by cycle commuters, extreme sports fans and other communities, are resulting in significant amounts of video content being uploaded to the cloud. A deeper understanding of how these new practices are developing, their associated environmental implications, and what potential there is to 'guide' such practices to be lower impact is a fruitful area for further research.

Services that are used at peak times make stronger contributions both to energy usage and the longer-term drive towards network expansion. The main driver for expansion of network and server infrastructure that support digital services is not the total use over the whole day, but rather the highest (peak) demand requiring servicing at a given time. As peak demand increases, more infrastructure is deployed to ensure continuity of service. Furthermore, the higher peak demand is compared with average demand on a given resource, the less efficiently that resource is used—resulting in waste of energy and material resources. If a service increases demand at such peak times, it is likely to contribute to increased infrastructure deployment over time. For example, the drive for personalised on-demand video (C1,2,3) and other services used at peak times.

(E3) Does the design mitigate or reduce infrastructural use in some way?

Our first two questions in the rubric focus on negative impacts and examples. We now turn to approaches for reducing such impact. Three possible approaches to this are (i) design a service to encourage users to choose less intensive options within it; (ii) design a service to encourage users to use it, rather than other more intensive services; (iii) design a service to reduce or avoid usage of infrastructure at peak times. We consider each in turn.

As noted above, both users and service providers often assume that they want the highest quality possible. For that reason, there is a move towards higher resolution (HD, UHD, 8K) though it may have limited impact on user experience once a certain resolution has been reached. Many video streams will automatically default to the highest resolution available that the end user device will accept. However, some services do not do that. For example, the BBC iPlayer service defaults to standard definition, and the user must explicitly select 'view in HD' if they wish a higher definition image. This is an example of the use of a 'nudge' approach to encourage users by default to use the lower bandwidth option. Audio also can use such an approach. Spotify defaults to 160Kbps as 'normal' with the option of 'high' quality requiring accessing the settings to change. Interestingly, it has different defaults for mobile devices—with 'normal' being 96Kbps. From an impact perspective, this default behaviour will reduce demand on the mobile network—the most energy-intensive part of the network infrastructure.

Secondly, one service can 'compete' with a more intensive service and encourage people away from it. For example, text messaging reduces the number of calls made over the mobile network. Services such as HipChat [26] provide rich (but primarily text-based) environments for collaborative working and so encourage voice or visual connection only when it provides additional value rather than as a default. If these replace regular audio and visual connections, it will reduce infrastructure usage.

Thirdly, if a service is designed to use less resource at peak times and 'time shift' that use to times of reduced demand, then it will reduce the need for infrastructure expansion and use the existing infrastructure more efficiently. An example of a service that already does this is Apple newsstand. It downloads content overnight, at times when the network is less used for media streaming. Other downloads of content that do not need to be used in real time, such as app updates [37], could also be done in this way. Similarly, uploads of content (such as from an Action Cam) could be timed to take place automatically off-peak. Where data or content is used on-demand, such as media streaming, proactive local caching [54] at off-peak times could be used to reduce peak demand. This would be personalised, based on user behaviour—such as downloading at off-peak times the next episodes in a series that a user is regularly watching. Or, in the case of on-demand music streaming, inserting some previously locally cached tracks known to be acceptable to the user (for example, because they have played them more than once before) into a stream, allowing the rate of download at peak times to be reduced. More sophisticated approaches to reducing peak demand while maintaining a good user experience of different services is another rich area for research.

(E4) Does the design encourage 'digital waste', or the avoidance of it?

Digital waste [54] is the accessing of a cloud-based digital service without actually making use of it, or only making partial use of it. It is the digital equivalent of leaving the lights on in an empty room and can take several forms.

Downloading of content that is never used.
For example, podcast subscriptions that download automatically to allow instant access (C3), but a person no longer listens to or is heavily behind on. More intelligent download strategies, based on the number of prior episodes stored locally and the speed at which the user is accessing them, would mitigate this.

Another example of digital waste through non-use of downloaded content is web page bounce. If a user downloads a page, but leaves it straight away because it was not what they were looking for, this is waste. Sometimes this is simply a necessary part of the search process: the user cannot assess the value of the page to them without actually looking at it. However, at other times it may be because either the source-linking page or the search service used to locate the destination page provides inadequate or misleading information. Hence, the design of web pages and search algorithms that reduce the chance of the 'wrong' content being accessed in the search process will reduce digital waste.

Downloading of content that is already available locally.
For example, users download PDF articles that they have downloaded before because it is easier to locate them online than locally. It would be relatively simple for a browser plug-in to perform an automatic local search for an article downloaded from the same url, and then checking with a conditional request to determine if the article has been modified before commencing the download.

Streaming/downloading content that is only partially used.
A common practice, particularly but not exclusively among teenagers, is the streaming of (free) YouTube videos to provide music, without watching the visuals [37]. This anecdotally widespread practice is likely to be responsible for substantial energy waste, both in Google data centres and in the network. Technically, it would not be difficult to remotely detect such behaviour (e.g. when the page visibility API determines the YouTube tab/window is in the background, or when a user queues a long music playlist.) A 'video on/off' option could be provided to override this detection where it makes an error. However, it may be the case that legal (copyright) issues mean this waste cannot currently be resolved in such a way.

Another example is the partial use of video. Some video players force download from the beginning, so even if you are interested in a late section in it you must download the whole thing. Others encourage 'scrubbing'—resulting not in the whole video being downloaded, but sections of it in an attempt to find the relevant bit. A recent design innovation on YouTube—video scrubber preview images—makes it easier to find the relevant spot in a video (or to assess whether it appears interesting overall) without downloading sections, and so helps reduce associated digital waste.

Web pages have increased to approximately 150 times their size in 1995, now averaging over 2MB [15]. Long webpages may only have the top section of them read, and the rest be 'waste' to the user. The size of a page is increased by the use of scripts and embedded video content (C10)—again often providing content not of direct interest to the user. This may be necessary for the business model of the site provider—advertisements aiming to catch people's attention benefit from animation, even if this uses more energy [62] and are an unwelcome distraction for many users. Awareness of the consequence of web page bloat could be encouraged through the use of an enhanced version of a service such as 'noscript' which blocks plug-ins on a page unless the user chooses to activate them. By providing an estimate of the energy or environmental cost of activating each one, and the total 'saved' on the page through deactivation, it could encourage improved design practices around web page bloat.

Uploading content that is never accessed.

Waste can occur through upload as well as download. With cloud storage and backup now commonplace and automated, content (such as photos) users take are often uploaded automatically (C4,8,9). Some of this content is consciously intended as ephemeral—for example, taking a joke photo to text to a friend, or photographing a whiteboard brainstorm to type up. Other content is not intended as ephemeral, but is uploaded without regard for whether it has sufficient interest and quality to be worth using in the future. Waste occurs both in the use of infrastructure to upload, and also in the ongoing use of infrastructure to store the content.

It may not be straightforward to identify ephemeral content prior to upload. However, research into understanding practices associated with image and video use could identify behaviours associated with ephemeral use. These in turn could be automatically detected, and the user given the option of deleting associated content. For example, if a user regularly sends ephemeral images by text, the sending device could offer the option of deleting the image at the moment of sending. If a user takes a number of similar images, planning on keeping the best few, then automated software could detect those with obvious flaws (such as motion blur or poor exposure) and propose which to keep and which to delete prior to upload.

(E5) Does the design promote the sharing of infrastructure?

The desire to have personalised on-demand entertainment (C1,2,3,5,7) is a significant driver in infrastructure expansion. Techniques that encourage sharing (either overtly or covertly) are of value here. Lord et al. [37] propose encouraging people back to broadcast media. Less radical approaches would be to find ways of synching viewing between people who are accessing the same content to allow multicast. One example of this is micro-registration, where several unicast streams in video-on-demand with approximately similar timings are aligned in order to bundle them into a multicast stream and thus to reduce bandwidth use in upstream network links [17]. This is relatively transparent to users, but more intrusive techniques could be used to combine more streams—for example, by delaying the start of some by inserting some other content (such as adverts, if that is part of the business model). How much delay is acceptable, and techniques to make such a delay more acceptable, is an area for research.

A very different approach to sharing infrastructure is provided by Freifunk [18]. It is a non-commercial initiative for free wireless networks. Its members provide free access to their WiFi routers to other members. They operate their routers with a custom firmware that enables additional services. Together the routers form a mesh network over which members can access a variety of services including Internet access. This makes more effective use of (usually underused) WiFi infrastructure through sharing, and will reduce usage of (often overused, and energy intensive) mobile networks for data access.

From Cornucopian Paradigm to Eco-Efficiency Paradigm

These questions provide a rubric, extending that of Blevis [6], to incorporate sustainability considerations related to infrastructural impact within the design process. These move treatment of the infrastructure from a *cornucopian* paradigm to an *eco-efficiency* paradigm: a paradigm in which environmental impacts are considered alongside other factors within design and are reduced where possible. Such a paradigm is already widespread in progressive business practice [73] when applied to a specific product. However, it currently rarely extends further, to the impact of the infrastructure induced by a given product and the services it enables. We believe it would be relatively straightforward, and beneficial, for companies to incorporate infrastructural considerations within Design for Environment guidelines for such products and services.

OTHER PARADIGMS

Many argue that the eco-efficiency paradigm is not adequate to meet the challenges society faces. Hence we now turn to other paradigms from the Sustainable HCI literature and elsewhere, consider how they can apply to the digital infrastructure, and extend our rubric with further questions addressing the issues this raises.

Computing within Limits

The paradigm of computing within limits [51] considers that the Earth's planetary boundaries [56] impose limits within which technical, social and economic development must take place if it is to be sustainable. Information technology must take account of such limits as it is deployed and used in the future.

A global digital infrastructure operating in a world that remains within planetary boundaries would need to (i) take an appropriate (and probably relatively small) share of the total energy generated in such a world; (ii) use an appropriate share of non-renewable resources (such as rare earth metals) in its deployment and maintenance, and use circular economy [47] techniques to wholly reuse these when replacing old equipment with new; (iii) ensure that any new or improved services which require more of the infrastructure (such as higher bandwidth) are only deployed when technological advancement in the infrastructure results in efficiency gains which will at least offset the increased energy use of wide deployment of such services.

If IT is not to become elitist, and to remain something which is available to the majority of the world's population, a further constraint is required: The infrastructure must be capable of providing acceptable levels of service to the global population, within the first 3 constraints. Could current trends with regard to digital service demand be supported in such a world ([54][5])? To determine if this is the case is a key research question. It requires (i) quantifying the infrastructural impacts of existing service demand, and extrapolating these to assume worldwide deployment; (ii) quantifying likely increases in future levels of service demand, including the impact of potential new trends such as Internet of Things and Quantified Self; (iii) understanding and quantifying anticipated technological advancements and the efficiency improvements they bring.

Broadly, the key question is: Are expected efficiency improvements sufficient to allow 'western' levels of service consumption (including its anticipated growth) to take place globally within an appropriate energy and resource budget. It is interesting to note (as has been observed in the context of network use by media services [54]) that such global deployment *may* be feasible within planetary boundaries, based on current technical trajectories. This is very different from many other sectors, such as travel (car, plane) and food (particularly meat) where a qualitatively different breakthrough will be necessary if current western service levels are to be used by all.

However, such 'cornucopia-within-limits' may *not* be possible, and the limits may place restrictions on what service levels can be provided. If so, it is important to understand the environmental costs of different services, and consider what bundles of digital services could be deployed worldwide within environmental limits. Progressive providers could use nudge approaches, 'choice editing' [65] of particularly intensive services and throttling of service levels to encourage or require users to remain within their personal share of the global budget. This leads to questions beyond the eco-efficiency set listed above.

(R1) If this service were to be used by all the world's population, what would the overall environmental impact of the infrastructure be? Can we imagine a future scenario where this would lie within limits imposed by planetary boundaries?

(R2) Is the service able to deal robustly with reduced availability of infrastructure levels?

(R3) Does the business model assume continued growth in infrastructure? If so, what is the risk associated with this?

Collapse Informatics

Collapse informatics [69] can be considered as a more pessimistic version of computing-within-limits: environmental and other pressures risk precipitating a retreat in living standards or even societal collapse. What can Information Technology do to make us more resilient?

From this perspective, in addition to the questions posed above, we must consider what infrastructure might be available in such a scenario, and what services could, or should, run on it. This brings in questions of societal value against the level of infrastructural use of such services. For example, it is likely that the value (to individuals and society) of unlimited text email is worth the relatively low burden in all but the most extreme scenarios. However, the higher infrastructural burden of unlimited video sharing, together with the arguably lesser social value of yet another kitten video, means that such a service may become restricted within many collapse scenarios. This leads to further design rubric questions:

(R4) What is the societal value of the proposed service, and in what scenarios of restricted infrastructure would this justify the resultant usage?

(R5) Can a restricted version of the service be imagined, and what would its value and infrastructural burden be? In what collapse scenarios would this be deployable?

Responsible Design and Sustainable HCI 2.0 [19][35]

In their different ways, these paradigms provide an alternative perspective to the techno-positivist assumption that more and richer digital services are necessarily better for individuals and society. They argue that certain forms of technology use can, at times, increase stress and reduce wellbeing in an individual, reduce a sense of community and quality of life, and distance people from the natural environment and so not engender a sense of caring and responsibility to the world. In such cases, it may be better not to design and deploy such services [53]. As with collapse informatics, this is a form of value judgment on different services, but the criteria of what is valued is different. Rather than prioritizing what can support societal cohesion at times of crisis, these paradigms prioritize what encourages improved wellbeing, slow living and engagement with the natural world. (Though, of course, the two are not necessarily mutually exclusive.)

In this context, it is appropriate to question our increasing need to be connected, which at times can feel almost neurotic. Perhaps a healthier relationship with digital technology and the digital infrastructure will be better both for us and the planet. Lord et al. [37] have proposed using techniques to encourage reflection on our relationship with connectivity, and the use of apps to encourage 'filling time' in more healthy ways without the need for connectivity. We incorporate this within our rubric as follows:

(R6) Does the service encourage a healthy relationship with digital technology, and avoid promoting inappropriate dependency on the digital infrastructure?

More generally, the call for Value Sensitive Design, which was one of the original inspirations for Sustainable Interaction Design, argues that designers must bear some ethical responsibility for the broad impact of the services they create on society. This leads us to our final, and most challenging, question:

(R7) Is the service in tune with your values, as a designer? Can you say with heart that the benefits it brings humanity is worth the environmental costs of the supporting infrastructure?

DISCUSSION

Like Blevis' RoME, we are interested in Material Effects; however, the material effects of infrastructural use are often outside the 'boundary' of awareness of the designer. The underlying issues are the same–does it stimulate additional resource or energy use–but are easier to 'not notice'. This explains why so little literature has considered them up to now. It is only through consideration of systems [54] and practice [37] that such questions begin to emerge.

It is not necessary for designers of new devices, new interaction modalities and new services to be unconsciously trapped between the desires of the user and the promises of unlimited infrastructure. The underlying principles of the reformist rubric–namely that resources and energy should be used efficiently–are widely accepted, but not yet applied in the specific domain of the digital infrastructure. We believe that *all* designers have a responsibility to be aware of, and mitigate where practical, the environmental impacts of their work. Blevis advocates reflection on the principles in his Rubric of Material Effects to integrate consideration of the environmental impact of interaction design, specifically the use of physical resources, in the design process. We advocate use of our reformist rubric in exactly the same way, to encourage reflection of the impact of design decisions on the infrastructure–in terms of increased use and expansion–and the resulting environmental effects.

We believe that this is necessary, but may not be sufficient. The more radical additions to the rubric, which consider questions of *limits to growth* and *societal values* as they apply to the digital infrastructure, have less widespread acceptance. Instead, it is vital that *some* interaction designers who resonate with these principles explore them more deeply, question the mainstream assumptions and develop alternative design paradigms, and that consideration of the infrastructure forms part of such work. Such a 'design counterculture' is a key part of the social dialectic, and through the work of 'tempered radicals' [42] will increasingly influence the mainstream position.

CONCLUSIONS AND FUTURE DIRECTIONS

In this paper, we have argued that the cornucopian paradigm implicitly adopted by interaction designers towards the infrastructure is inappropriate. In the short term, it leads to unnecessary environmental impact. In the long term it increases risk—both for individual companies with business models dependent on this assumption but also for humanity as a whole, which needs to find a way of living within planetary boundaries to ensure its long-term survival. We have substantially extended the design rubric of Blevis to consider impacts associated with the digital infrastructure, and provided numerous examples illustrating this—both of bad and potential good practice. We have initially adopted a reformist, eco-efficiency perspective on the problem, to produce a rubric that can be used to inspire enhancements to existing design-for-environment processes used by progressive companies. However, recognizing the many voices that argue that such an approach does not go far enough, we also extend the rubric to encourage designers to incorporate more radical perspectives in their consideration of the infrastructure.

Expanding Sustainable Interaction Design to consider the digital infrastructure significantly broadens the research space. The few papers published so far, though making valuable contributions, only touch the tip of the iceberg. We have highlighted in our discussions above a number of specific research topics our analysis opens up. More broadly, we see four strands of inquiry necessary:

1. Development of accessible guidelines based on the above rubric for designers to take infrastructure into account in design of interactive devices and services.

2. Further integration of Sustainable Interaction Design with the quantification of environmental impact developed in Industrial Ecology can allow the impact of different facets of the problem to be estimated, and how effective different potential interventions may be. This will aid prioritization of research.

3. Development of a more nuanced understanding of user need with regard to cloud services. Rather than treating want as a need to be satisfied through expanding the cornucopian infrastructure, develop an understanding of the value of different service aspects to users, and which of these aspects are more 'negotiable' (e.g. immediate on-demand video vs. wait a minute). Furthermore, development of a theory of design to make compromises in performance or functionality more comfortable to the user.

4. Scenario analysis of potential future trajectories of infrastructure and associated services, considering the spread of service technologies, user practices and improvements in infrastructure technology and efficiency. Through this, development of an understanding of the overall challenge to remain within planetary boundaries, and identification of viable future trajectories and what is necessary to follow them.

By broadening Sustainable Interaction Design to deeply consider the digital infrastructure in this way, we open opportunities for significant environmental improvements in the short term. Furthermore, the improved understanding of the overall impact of IT in the longer term can be used to shape development to move towards sustainability.

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