What is the resource footprint of a computer science department? Place, People and Pedagogy.

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Abstract

Our goal is formulating policies and developing guidelines that create a more resilient and healthier Department of Computer Science at University College London: a living laboratory for teaching and learning about resource constrained computing, computation and communication. Here, we outline a roadmap and propose high-level principles to aid this effort. We focus on how, when and where resources – energy, (raw) materials including water, space and time – are consumed by the building (place), its occupants (people) and their activities (pedagogy). We describe practical difficulties associated with identifying, acquiring and analysing relevant data. Beyond technical challenges, we find a need to rematerialise the information society: to reveal the full costs of Internet and Communication Technology and electrical and electronic equipment by, for example, undertaking life cycle analyses of end-user paraphernalia such as smartphones and demonstrating the corporeal nature of seemingly immaterial entities such as the "cloud." We outline routes to realising three interlinked aims: cap the power consumed and greenhouse gas emitted per person per year, become a zero waste institution, and rejuvenate and (re)integrate the natural and built environments. We propose two maxims to aid policy making and guideline preparation: resource use needs to be minimised *and* minimal (reduced in relative as well as absolute terms), and responsible research and innovation encompasses decreasing the Department's resource footprint *and* considering non-technological solutions to complex real-world problems.

Keywords: resource footprint; energy; water; internet and communication technology; electrical and electronic equipment; e-waste; resource constrained-computing, computation and communication; rematerialise the information society.

1 Introduction

The digital economy is said to define a new industrial and social paradigm, one based on a complicated mixture of software, hardware, operations and networks. Replete with terms such as cloud computing, social media, (digital) platform economy, algorithmic decision-making, Artificial (General) Intelligence (A(G)I), Big Data, machine learning, digital ledger technology and the grid, this digital realm is neither ephemeral nor immaterial[1]. That is, the underlying Internet and Communication Technology (ICT) and electrical and electronic equipment (EEE) have myriad direct and indirect impacts on the lithosphere, biosphere, atmosphere and hydrosphere. Typically, ICT- and EEE-related products, processes, services and infrastructure are downstream outcomes of research and development performed at universities, companies, the military and other organisations. As such, the Department of Computer Science at University College London contributes to the expansion and

[1] Dematerialisation is the reduction in the quantity of materials required to deliver the same level of functionality, to produce something useful over time. "The information society promises to dematerialise society and make it more sustainable, but modern office and knowledge work has itself become a large and rapidly growing consumer of energy and other resources." [1] A simple, quantitative, predictive model for dematerialisation and an empirical examination of 57 case studies found "there is no dematerialization occurring even for cases of information technology with rapid technical progress. Thus, a fully passive policy stance that relies on unfettered technological change is not supported by our results." [2]

impacts of the ICT/EEE ecosystem[2]. Here, we take measure of the Department's resource footprint: the energy, (raw) materials including water, space and time utilised by the building, its occupants and their activities.

This paper is organised as follows. First, we provide the broader context for this place-, people- and pedagogy-related study of the Department (Section 2). This is followed by a top-level model of the Department and an example of the complexity and indeterminate as well as ever changing nature of the challenges we face (Section 3). Then, we describe the current state of affairs with respect to the resources consumed by the building (Section 4), its occupants (Section 5) and their activities (Section 6) and discuss ideas for the future. Next, we sketch three interlinked paths in our roadmap to a more resilient and healthier Department (Section 7). Finally, we discuss limitations of this investigation (Section 8). What policies and guidelines do we need to transform the Department into a living laboratory for teaching and learning about resource constrained computing, computation and communication? To help answer this question, we need data pertaining to the technical aspects of how to reduce resource consumption in relative and absolute and terms as well as information relevant to the architectural, human and philosophical dimensions of the task.

2 Background

In the public sphere, there is increasing awareness of the vast quantities of power consumed by ICT/EEE individually and collectively: from consumer devices and goods, through Computer Numerical Controlled machine tools (3D printers) and cryptocurrencies[3] to machine learning[4], data centres[5] and networks[6] [13, 14, 15, 16]. If demand for data services such as video continues to grow, the total energy use by communications networks is projected to rival all other energy use [17]. Based on estimates of current trends, U.S. data centres (servers, storage, network equipment and infrastructure) are projected to consume ∼73 billion kWh in 2020 [18]. One illustration of the ICT/EEE-energy-water nexus is the vast quantities of water consumed by data centres: during generation and transmission of electricity to the site as well

[2] In this paper, we ignore cultural, socio-political and similar impacts. For example, digital technologies can reshape the individuals and communities manufacturing and using them [3]. Also, "new patterns of consumer behavior (increasingly built upon access to mobile networks and data) force companies to adapt the way they design, market and deliver products and services. ··· The Fourth Industrial Revolution, finally, will change not only what we do but also who we are. It will affect our identity and all the issues associated with it: our sense of privacy, our notions of ownership, our consumption patterns, the time we devote to work and leisure and how we develop our careers, cultivate our skills, meet people and nurture relationships." [4]

[3] The key sectors of the global cryptocurrency industry (exchanges, wallets, payments and mining) are resource intensive and have large energy footprints with miners recognising the negative environmental externalities of their activities [5]. Whether decentralised blockchains can be scaled to match the performance of mainstream payment processors is an open questions. Although estimates vary, a recent calculation suggests that the electricity consumption of the Bitcoin network is roughly 1.075 GW, approximately one third of the electricity consumption of the entire country of Ireland [6]. With respect to latency (time for a transaction to confirm), a Visa credit card takes seconds to confirm a transaction but today's Bitcoin requires at least 10 minutes. The former processes 2,000 transactions/sec on average (with a peak rate of 56,000 transactions/sec) whereas the latter achieves a maximum throughput of 7 transactions/sec [7]. This performance gap is accompanied by high resource consumption. In the Bitcoin network of 5,400 full nodes, the cost per confirmed transaction may be as high as $6.20 – the operational costs (mainly electricity) and capital equipment costs (mining: proof-of-work and hardware, transaction validation, bandwidth and storage: running cost) [7]. Thus, "fundamental protocol redesign is needed for blockchains to scale significantly while retaining their decentralization." [7]

[4] Although machine learning algorithms are attractive solutions for diverse problems, there is increasing interest in analysing data locally on a sensor or device rather than remotely on a cloud. This shift of A(G)I towards the edge is fueled by issues such as the high cost of communication, limits on network capacity and architecture, constraints on latency, privacy, cybersecurity, global availability and the volume and velocity at which data are being generated [8]. Whether data processing occurs locally or remotely, the joint design of algorithms and hardware can produce energy-efficient dataflows (reducing data movement conserves energy) whilst maintaining accuracy, throughput and cost [9].

[5] "Everyone prefers to talk about the efficiency of individual data centers, or the proportion of renewable energy they use. No one talks much about total energy used by data centers because the figures you get for that are annoying, depressing and frustrating. ··· The plain fact is that, no matter how efficiently we run them, data centers are expanding uncontrollably, and consuming increasing amounts of power. In fact, the efficiency improvements are contributing to the rapid growth." [10]

[6] Nearly all signals are transmitted over optical fibres at some point along their route. Communication networks will need to deploy techniques of scarce resource management to overcome technical limitations (wireless spectrum, common public radio interface, network management and switching and software) as well as societal and economic influences (network neutrality, innovation with the creative industries, latency and energy) [11]. To control congestion within a data centre network, new approaches are being developed to coordinate transfers of data among large populations of servers [12].

as by cooling systems at the site itself [18].

ICT/EEE utilise resources across their entire life history: from mining (exploration, extraction and processing) of non-renewable materials[7] and manufacturing, through production and transportation to utilisation and disposal[8] [21, 22, 23]. Concerns about day-to-day operational use include the increasing demand for power, the growing need for raw materials[9], the generation of ever larger amounts of plastic waste [25] (including by 3D printers [26]) and the emission of greenhouse gases [27].

According to the Solving the E-waste Problem (StEP) international initiative, the term "e-waste" covers all types of EEE items and their parts that have been discarded by the owner as waste without the intention of re-use [28]. E-waste[10] is a product of the largest and fastest growing manufacturing industries: ∼41.8 million metric tonnes (Mt) was generated in 2014 and this number is estimated to increase to 50 Mt by 2018 [30]; the total may escalate to 100 Mt by 2020 – probably even more given current research and development in areas such as the Internet of Things and wearable technology [31, 32, 33]. A study of 50 countries in the pan-European region found that an increase in the gross domestic product at purchasing power parity generates additional e-waste that requires management [34].

The ICT/EEE ecosystem affects not just human health and environmental health [35, 36, 37] but also (agricultural) biodiversity. Heavy metals and persistent organic pollutants produced as a result of (in)formal e-waste recycling activities can contaminate soil at the recovery site as well as the soils and water of nearby farmland threatening crops and livestock [38, 39, 40]. In 2017, the United Nation's Food and Agriculture Organisation (FAO) will issue the first report on *The State of the World's Biodiversity for Food and Agriculture* [41]. Although healthy soils are essential for ecosystem (and human) well being [42], current energy and raw material consumption, land use and pollution are key factors contributing to the degradation and contamination of this non-renewable resource whose preservation is essential if current and future generations are to meet their food, feed, fibre, dye, medicine, fuel and other needs [43]. Therefore, it is imperative that resources be used in ways that do not undermine the integrity, stability and beauty of natural (agro)ecosystems today as well as tomorrow – particularly since agrocology provides solutions to the multiple crises of climate, environment, public health, livelihoods and economies [44, 45, 46, 47]. Policies at the nexus of ICT/EEE, energy, raw materials (including water), and whole food systems contend with shifting forces spanning multiple spatial, temporal and social scales – for example, technology advances, governmental regulations, consumer preferences, environmental conditions, and large infrastructure such as transportation networks, energy grids, and water, sewer and storm water systems.

In order to determine the resource footprint of the Department, we require full cost accounting models for every activity, product and process: systematic approaches that identify, sum and report the costs involved in the complete life cycle – from direct private costs, through indirect private costs to social, environmental and other costs [48]. Clearly, enunciating what we need models for, pinpointing appropriate models and applying them in the real world are non-trivial tasks. Beyond quantifying the current footprint are the qualitiative, human, challenges of mitigating and reducing resource use. Below we describe the first steps along this path.

3 The Department of Computer Science at University College London

In order to comprehend the breadth and depth of the task that lies ahead of us, a bird's eye view of the Department and a brief explication of the activities that take place in pursuit of its goals is useful. These activities take place in defined locations and/or utilise various defined ICT/EEE services. The locations in and of themselves consume resources such as water, space and electrical energy. Every ICT/EEE service consumes resources and requires other hardware and software for its operation. The manufacture, transportation, installation and decommissioning of physical hardware generates greenhouse gas emissions and waste. For each activity, the agents or actors involved include not just Departmental staff and students but also external providers such as the higher organisa-

[7] The percent of tungsten, tin, tantalum and gold consumed by ICT products in 2018 is projected to reach 4%, 0.3% 27% and 5% of global shipments respectively [19]. [8] A study of the recycling of desktop and laptop computers in Belgium found that it saves 80% – 87% of the natural resources compared to landfill and that base metals but not precious metals and plastics were recycled efficiently [20]. [9] In 2011, the number of digital electronic and radio-frequency identification-chipped devices connected wirelessly to the internet was projected to reach 50 billion by 2020, or ∼ 7 per person [24].
[10] Any household or business item with circuitary or electrical components with power or a battery supply such as computers, mobile telephones, televisions, monitors, laptops, tablets, smartphones, printers, MP3 players, games and gaming equipment, white goods (refrigerators, washing machines, dryers, air conditioners and so on), robots, drones, cables and routers [29].

tional and academic structures in which the Department is embedded. Some factors can be quantified fairly precisely (for example, the electrical power consumed by a server and the number of bits through a network port), others can only be approximated because they pass outside the control of the Department (for example, hardware manufacturers), and many, if not most, cannot be measured at all (but it may be possible to estimate their contribution to the total).

The following exemplar illustrates these interconnected factors. The Department has decided to provide a new undergraduate module on Machine Learning. This decision is expected to enhance the teaching provision and reputation of the Department as well as the University. This new module is likely to attract an additional 20 students in the 2017 – 2018 academic year, a number that may increase in subsequent years if the course proves popular. The students require physical space in the form of, for example, classrooms that require heating, ventiliation, cooling and electrical power. The ICT/EEE services they need will consume resources.

To facilitiate teaching, two new GPU servers are to be provided: these require 6U of rack space and add an extra 3kW to the power drawn by the Department. This in turn requires an equivalent amount of cooling. Whilst the resources consumed during their production and transportation are not disclosed by the manufacturer, their packaging consists of approximately 25 kg of cardboard, expanded polythene foam, and the pallet on which they are transported. These are disposed of by the University through an external recycling company. The servers also utliise a portion of the existing network and storage infrastructure. The course uses a cloud software package, provided free of charge by the vendor, but this adds additional network load throughout the path, and consumes resources wherever the vendor is hosting the cloud application. The bandwidth consumed by the application can be measured on the Departmental router, allowing an estimate of Watts per bit to be established.

The servers will be used for the course for 3-4 years, after which point they will be replaced by the next generation of server. The Department will continue to operate the hardware as part of a general compute/GPU cluster for an additional 3-4 years. As this period will exceed the hardware's "normal" lifespan, each component will be out of warranty and so not replaced as it fails. Any useful parts which are compatible with other devices (such as power supplies) will be kept – but these need to be stored and is often the case, may never see usage again. On final removal from the Department, UCL central Estates & Facilities disposes of the hardware through an external e-waste company. In the absence of information about the company's practices, it is unknown how much material is ultimately extracted, whether this is recycled into the manufacturing process, and the energy costs of either or both.

As demonstrated above, an activity, product, service or infrastructure consumes resources both directly and indirectly. When quantifying the contribution of a particular ICT/EEE, considering these as "fixed" and "proportional" costs will help us to "understand the real energy and cost behaviour of the data centre and how that impacts the cost and energy use of operating IT equipment within the data centre." [49] The heterogenous nature of the Department's research and funding sources is reflected in the bespoke nature of the research infrastructure and data centre. It is no surprise therefore, that whenever we wish to calculate a metric such as data throughput, CPU cycles, power, and temperature when attempting to ascertain consumption of a particular resource, we need to expend a substantial amount of time and effort gathering consistent and relevant information from a plethora of agents and actors.

4 Place – the built environment

4.1 Current: Malet Place Engineering Building and Gower Street building

Multi-site organisation The Department is spread over two mixed-use multi-storey buildings with one containing a data centre that operates round the clock. We have access to the size of individual spaces – shared offices, laboratories, cubicles, conference rooms, lifts, lobby areas, kitchen/break rooms and so on – but only the water or energy used by the entire building is available. For example, the data centre occupies a total floor area of $\sim 130m^2$ but the resource consumed by this specific space cannot be determined. The most recent Commercial Buildings Energy Consumption Survey from the U.S. Energy Information Administration showed that "office buildings with data centers have significantly higher computing, cooling, and total electricity intensity (consumption per square foot) than office buildings without data centers." [50] Since the Department's data centre space is likely to use orders of magnitude more electricity than standard office space, we expect a similar disparity between our two buildings.

Data centre As the major infrastructure component powering the networked computer system, the data centre is key to the Department's productivity and sustainability, both financial and environmental. Data Center Energy Productivity (DCEP) is an equation that quantifies useful work that a data centre produces based on the amount of energy it consumes where "work" is defined by and specific to an organisation [51]. Various global metrics quantify different aspects of a data centre: Power Usage Effectiveness (PUE, the ratio of the total energy of the data centre divided by the ICT energy consumption), Green Energy Coefficient (GEC, the portion of a facility's energy that comes from green sources), Energy Reuse Factor (ERF, the portion of energy that is exported for reuse outside the data centre) and Carbon Usage Effectiveness (CUE, assessment of the total greenhouse gas emissions). Given a baseline value for the Department's DCEP, we could assess the efficacy of interventions – for example, whether particular building-dependent design measures (especially for the rooms containing cooling equipment and servers) reduce electricity use and save money without compromising reliability, availability and resiliency. Practical issues preventing us from determining values for the global metrics include the lack of data, the incomplete and uncertain nature of the data we do have, the pace of change and the paucity of suitable assessment tools.

Cloud Many organisations are turning to cloud computing as the way to solve some environmental issues. By utilising resources managed and run by multi-national organisations whose *raison d'être* is profit, the prevailing view is that in order to offer competitive pricing to prospective customers, the company needs to reduce its financial costs by ensuring its computing is as energy efficient as possible. However, this assumption of green computing may not always be a simple matter of comparing datacentre efficiencies and the true environmental cost of using cloud computing services is an open question [52, 53]. Nonetheless, there are some benefits to be had for correctly scaled elastic computing. Bursts of high demand can be moved to regional resources where demand can be evened out. The primary challenge is software: getting workflows to seemlessly integrate local services with the on demand elastic resource – improving a networks ability to scale up and down as traffic demands ebb and flow.

Keeping bits alive In many respects, the core function of the Department's infrastructure (energy, network and server hardware, physical floorspace) and operation (service, people) is to ensure the survival of bits. The complete cost of maintaining one byte over a period of time such as a month or a year could be partitioned into the costs of storage (£/Mbyte), computing (£/CPU cycles) and networking (£/bit). Our challenge is finding, applying and evaluating models for computing these quantites.

4.2 Future: architectural works designed with nature for resource conservation and quality of life

Integrating the built and natural environments Given the dynamic reciprocity between a building, what is in it and what is around it, the relationships within and amongst the components of this triad play a critical role in the health, sustainability and resilience of the Department. Although "green buildings" are discussed often from the perspective of their use of environmentally friendly materials and energy-saving techniques, such practices have the added benefit of boosting indoor air quality thereby improving human health and people's sense of well-being. For example, residents who moved from conventional low-income apartments to "green" homes report substantially fewer "sick building syndrome" symptoms such as headaches and itchy or burning eyes, ailments commonly linked to indoor air pollution [54]. Microorganisms are one component of indoor air and although they are found on surfaces and throughout the water and other systems of buildings, air is likely the most important medium for their dissemination.

The architecture, construction materials and geographic organisation of the (multi-site) facilities comprising the Department are key determinants of the land, carbon, energy and water usage of the building. Accounting for direct and indirect use of resources requires an integrated approach, one that recognises multiple interdependent challenges: for example, water is used in all phases of energy production and energy is required to extract, pump and deliver water for use by humans, to heat and cool buildings and equipment and to treat wastewater before it is returned to the environment. Biotic as well as abiotic factors affect a building's physical infrastructure and influence the life quality of its occupants. For example, incorporating indoor and outdoor vegetation into building projects, whether new or renovations, reduces energy use, noise, operation costs and resource consumption whilst improving occupant comfort, well-being and productivity [55, 56, 57, 58, 59].

Passivhaus[11] is a robust, proven and cost-effective construction concept whose fabric first approach produces energy efficient, comfortable and affordable

[11] A passivhaus is "a building in which thermal comfort can be achieved solely by post-heating or post-cooling the fresh air flow required for a good indoor air quality, without the need for additional recirculation of air" [60]

buildings [61]. For example, the Bagley Classroom at the University of Minnesota Duluth campus serves as a multi-purpose assembly space and environmental studies centre and is used by engineering students as a "living" laboratory to monitor the performance of a passivhaus building and to learn about its construction and systems [62]. A passivhaus building for our Department would need to accommodate the unique and often contradictory energy (electricity and heat) and other needs of both machines and humans – for instance, cooling computer hardware as opposed to people [63, 64], local systems that take into account the interior volume of a space, the number of people who occupy it and how frequently the space is used [65], and hybrid heating systems [66]. Other challenges range from understanding the basic building physics and their application through the cost implications during the design, build, operation and whole life cycle to quality assurance and onsite delivery. A bespoke building designed for the Department's geographic location and that is part also of a solar oriented university campus, neighbourhood and city would make important contributions to reducing energy usage as well as enhancing human and environmental health [67, 68, 69].

Ecological sanitation Between 1879 and 1883, UCL's Main Building was host to the Parkes Museum, an institution which featured a display of over 30 toilets and provided education about hygiene and public health issues to both professionals and the general public [70]. Problems with the modern bathroom and sanitation systems [71, 72] highlight the importance of ecological sanitation, the design and operation of hygienically safe, economical and closed-loop systems to convert human excreta and urine into nutrients and water to be returned to the soil and land, including for sustainable food production. For example, a system in a student dormitory in Norway treats in the same process wastewater from toilets (blackwater) and from kitchens and showers (greywater) thereby reducing water consumption substantially, nearly eliminating pollution and producing a valuable plant fertiliser and soil amendment product [73]. A decentralised urban greywater system installed below-ground in the courtyard of a large multi-apartment building in Oslo Norway requires about $1m^2$ of space per person and includes an above-ground flow form system for additional aeration in the summer that adds aesthetic value – part of the treatment area is utilised also as a playground [74]. The need for a secondary sewer collection system is reduced because the high quality effluent is suitable for use in urban settings, discharge to small streams or open waterways, irrigation or groundwater recharge.

Given the first-hand knowledge and practical experience in Norway and worldwide [75, 76, 77], ecological sanitation systems capable of achieving nearly "zero emission" and almost complete recycling in London are possible, the design of compact and technically simple blackwater and greywater treatment systems requiring a holistic approach [78]. Hence, departmental bathrooms [79, 80] able to generate effluent that could be received by local bodies of water would reduce the need for a secondary piping and pumping system to transport untreated wastewater and contribute to a cleaner city and river Thames [81].

Rainwater harvesting Rainwater harvesting is the process of intercepting rainfall for its eventual beneficial reuse [82, 77]. Rooftops, concrete patios, driveways and other impervious surfaces of buildings and landscapes can be designed to maximise the catchment area. The collected, detained and retained water can be routed for use in evaporative coolers, toilet flushing, irrigation and so on. This alternative water source reduces water (and indirectly energy) consumption and costs by helping to conserve potable water supplies and the amount of runoff the municipal stormwater management infrastructure needs to handle. A rainwater harvesting system would be both advantageous to the Department and contribute to making London more resilient to flooding [83].

Agroecologically productive landscape Similar in many ways to agroecology [44], permaculture is an approach to sustainable development that integrates land, resources, people and the environment through mutually beneficial synergies by imitating the no waste, closed loop systems seen in diverse natural systems [84]. Demonstration permaculture projects for students and/or staff exist at the Department of Educational Sciences Middle East Technical University [85], the University of Massachusetts Amherst [86], and the University of Sussex [87]. A departmental and UCL-wide agroecology initiative could transform marginalised landscapes such as underused grass lawns into diverse, educational, low-maintenance and edible gardens that have the added virtue of increasing biodiversity across the campus. Water-wise buildings and surrounding bountiful landscapes could be achieved by efforts such as reusing greywater, collecting rainwater, installing waterless composting toilets and implementing smart horticultural changes.

Microbiomes Both biological and non-biological ecosystems provide habitats and residences to microbial communities: tremendous numbers and diverse species of microorganisms colonise not just the surfaces and inner tissues of plants and animals but also settle on the inside and outside of man-made infrastructure: buildings such as offices and hospitals, modes of transport such as cars and trains and conduits conveying fluids and electrical cables [88, 89, 90]. Although the (a)biotic host, climate, geology and geography affect the composition, dynamics and impacts of microbiota, microbiomes are interconnected, form a continuum. For example, there are at least ten times as many microbes as there are cells of the human body and whilst most are harmless and many are beneficial, the consortium is characteristic also of the individual: indeed, bacteria swabbed from the surfaces of computer keys, computer mice and mobile telephones match the microbes on their owner's skin more closely than those from other people [91, 92].

The bacterial makeup of a building housing a college of business is affected by the number, type and layout of its spaces (offices, classrooms, restrooms and hallways), the number and variety of their occupants and the activities occuring within them [93]. Since overall architectural design (notably heating, ventilation and air conditioning systems), intended human use pattern for spaces and local horticulture affect the biogeography of microbial communities, careful attention needs to be paid to such factors when designing, constructing or renovating a Departmental building. For example, mechanical ventilation is likely best suited for unoccupied and/or infrequently used spaces: (un)filtered inside or outside air is supplied via dedicated mechanical air handling units to areas needed for office and building support (machine and server rooms), storage spaces, mechanical equipment rooms, janitor closets and so on. However, natural ventilation is necessary to promote a healthy indoor environment and to enhance the life quality of building occupants and visitors: unfiltered outdoor air is supplied via window, louvers or other means to areas needed for specific functions (classrooms, hallways, atria, common rooms, restrooms and so on).

5 People – the building's occupants and visitors

5.1 Current: education and engagement

Environmental Responsibilty Co-ordinator The Department's Green Champion addresses risks from activities and sets policy and standards for topics ranging from sustainable working (issues such as recycling, disposal and energy use) through co-ordinating, reviewing and ensuring that students are taught relevant environmental and sustainability issues (*cf* the duties of an Health and Safety Officer). Open to all members of the department, the Green Team considers short-, medium- and long-term issues and initiates actions such as encouraging users of the communal coffee machine in the staff common room to empty the grounds into the adjacent bin thereby facilitating horticultural use of this organic matter by other people. Another example is making representations to UCL authorities about shared datacentre inefficiencies.

Staff The Technical Support Group (TSG) supports the teaching and research needs of faculty. Examples include repairing equipment so it can be reused, designing high performance computing (HPC) flows to minimise idle times incurred by waiting for external task such as accessing storage to be completed, and moving the majority of services to virtual servers.

Students Since resource use by and in buildings is intimately tied to the behaviour of its occupants, the TSG provides information and instruction for undergraduate and post-graduate students, especially those just entering the Department. Examples include implementing a printer quota, discouraging unnecessary printed material whilst promoting double-sided printing as default, collecting spent batteries and using renewable batteries for student robots. Decommissioned equipment is generally offered to students for re-use before final disposal. A hot-desking office space is available to post-graduate students and staff, allowing access to services via a thin client, or direct connection of a laptop. This saves the need for a permanent desk and personal computer.

5.2 Future: curricula, modules, materials and activities

Developing new and/or distributing extant practical information, hosting events and fostering discussion of broader more philosophical issues can increase awareness of problems, promote potential solutions and identify topics which dovetail with existing teaching- and research-related classes and courses. Illustrative examples include the following.

"Meetups" for staff, students and visitors – primary, secondary and tertiary level teachers and pupils The Department could organise informal gatherings where topics ranging from hardware and software through data centres to growth in data from sources such as social media, mobile devices, sensors, and science would be discussed. One subject that crosses many areas is the rebound effect, a behavioural change or other systemic response that partly or completely offsets expected savings from the implementa-

tion of new technologies or other measures that seek to lower energy use or greenhouse gas emissions [94]. Mobility provides one forum for probing this subject: in the transport sector, three strategies for achieving sustainable mobility are travel more efficiently, travel differently, and travel less[12] but all three are associated with the rebound effect [94].

Informational resources and material created elsewhere We could produce our own versions of extant EEE/ICT-related flyers, documents and information for dissemination to staff, students and visitors. Three examples are as follows. The Electronic Product Environmental Assessment Tool (EPEAT) [95] is an easy-to-use repository utilised by public and private entities in more than 42 countries – federal agencies, state governments, universities, hospitals, hotels, businesses and so on – to make informed purchasing decisions about electronic products based on standards that cover reduction/elimination of environmentally sensitive materials, use of preferable materials, design for reuse, recyclability and longevity, energy conservation, responsible end-of-life management and corporate performance and reduced and preferable packaging. StEP has a brochure describing its activities such as developing and implementing e-waste strategies on a local, national and international level: reducing the materials used in manufacturing, reusing equipment or components when practical, refurbishing where possible, recovering materials from obsolete equipment and recycling the highest possible level of material [96]. Engineers without Borders Spain has a brochure posing questions to ask before buying an ICT/EEE item: Do I really need it?, Does the price include the real cost?, What is behind the brand?, What if I don't find an ethical product but I still need it?, and What do I do with the device when I want to replace it? [97].

ICT/EEE community clinics and cafés The StEP initiative has added Refurbish and Recover [96] to the traditional "Rs" of Reduce, Reuse and Recycle. Regular hands-on events can be held to diagnose malfunctioning, repair broken and repurpose neglected items. A natural partner for this practical activity is UCL's Institute of Making, a multidisciplinary research club for making, breaking and repairing everything from jewellery to robots that has close ties to the Engineering faculty [98]; the facility is located in the ground floor of one of the buildings housing the Department.

Show-and-tell sessions centred on "ethical" ICT/EEE Discussions about the entire physical, financial and resource life cycle of a specific product or item can provide a concrete way to probe broader questions such as socioeconomic impacts, alternatives and social, environmental, ethical, health and labour issues [99, 100, 101, 102]. These can range examining the earliest stages of design [103] to defining Life Cycle Sustainability Assessment impact categories related to social and economic issues [104]. For instance, the Fairphone [105] is the first smartphone marketed as free of minerals sourced from conflict zones (for example, gold, tin, tantalum and tungsten) and is manufactured in factories that meet stringent ethical and environmental standards (for example, fair labour conditions for the workforce along the supply chain). The level of e-waste associated with this mobile device is reduced by the use of micro-USB charging standards that allow the battery to be replaced and two SIM slots permitting the same handset to be used for home and work.

Problem-based learning about the impacts of ICT/EEE Small groups of individuals can collaborate to investigate the known and less obvious but nonetheless real-world consequences of specific products or technologies for humans and ecosystems ranging from negative impacts can merely shift from one place to another to genuine efficiency gains arising from their adoption can be usurped by increasing overall production and consumption and hence waste generation [106, 107, 108]. For example, energy efficiency increases in ICT/EEE cause structural changes in households, education, business and the military efficiency that result in a proliferation of devices and thereby increases in energy consumption [109]. This rebound effect is evident also in digital fabrication using 3D printers: the conversion of a digital design into a physical object does not necessarily reduce energy use and transport-associated emissions compared to providing the same products through conventional manufacturing [14]. How ICT/EEE affects the lives of ordinary people – a futurology from below [110] – could be analysed using multicriteria mapping, an interactive hybrid qualitative/quantitative appraisal method for exploring the contrasting perspectives of diverse stakeholders on complex issues [111, 112]. Ecological and economic impacts could be studied through an ecological economic analysis in a problem-based learning setting [113, 114].

As illustration, consider the potential human health problems associated with the normal operation of 3D printers and environmental concerns asso-

[12] (1) Efficiency: environmental problems caused by transport can be improved by developing new and more efficient technologies to replace old, inefficient, and polluting materials and methods. (2) Substitution: a change to less polluting or more energy-efficient means of transport. (3) Volume reduction: efficiency and substitution are insufficient meaning fundamental changes in behaviour and consumption patterns are required – people must travel less, and freight volumes must decrease [94].

ciated with their plastic products. They can use a variety of raw materials ranging from thermoplastics through metal and ceramic powder to cells to produce objects as diverse as trinkets, eye glasses and organs [115]. Typical commercially available desktop machines heat plastic feedstock, extrude it through a small nozzle and deposit it onto a surface to build the object, a process that emits extremely high levels of ultrafine particles (UFPs, particulate matter under 100 nanometres in diameter) [116]. Epidemiologic research suggests that exposure to mass concentrations of atmospheric UFPs increases adverse cardiovascular and respiratory problems and might contribute to pre-term birth [117, 118]. Large, single plastic items degrade ultimately into millions of microplastic pieces and these millimetre or smaller sized particles have the potential to cause physical and toxicological harm to zooplankton, fish and a wide range of other organisms [119, 120]. Based on data obtained from 24 expeditions (2007-2013) across all five sub-tropical gyres, coastal Australia, the Bay of Bengal and the Mediterranean Sea, a minimum of 5.25 trillion plastic particles weighing 268,940 tons are estimated to be afloat at sea [121]. Indeed, "given the concerns over microplastics, the temptation may be to 'clean up the mess,' but substantial removal of microplastic debris from the environment is not feasible. Identification and elimination of some of the major inputs of plastic waste is a more promising route, as is reduced consumption and the recognition of plastic waste as a resource." [119]

Zero waste and ICT/EEE The "ethical, economical, efficient and visionary" goal of zero waste [122] provides a useful lens for ICT/EEE. Zero waste seeks to "guide people in changing their lifestyles and practices to emulate sustainable natural cycles, where all discarded materials are designed to become resources for others to use. Zero Waste means designing and managing products and processes to systematically avoid and eliminate the volume and toxicity of waste and materials, conserve and recover all resources, and not burn or bury them. Implementing Zero Waste will eliminate all discharges to land, water or air that are a threat to planetary, human, animal or plant health." Zero waste has guiding questions[13] and business principles[14] [122]. The Zero Footprint Campus project is an art programme in the public areas of the Utrecht Science Park that examined the (im)possibilities of sustainability [123] – for example, the Human Power Plant[15].

Learning and adapting ideas from other fields Researchers in Cyber Risk and Resilience Management have developed a framework for identifying, analysing and resolving vulnerabilities in an organisation's operating environment [125]. For information assets, the CIA triad is a simple but widely-applicable model used in the information risk industry. The following three key principles should be guaranteed in any kind of secure system: Confidentiality (the ability to hide information from those people unauthorised to view it), Integrity (the ability to ensure that data is an accurate and unchanged representation of the original secure information) and Availability (the ability to ensure that the information concerned is readily

[13] "Rethink: What has led us to our present linear use of materials and thus, what needs to evolve to move towards a closed loop model? How do we re-design systems to avoid needless and/or wasteful consumption? Reduce: What supports the use of less material and less toxic material? Reuse: What supports the better use of those products we already have in ways that retain the value, usefulness and function? Recycle/Compost: How do we ensure materials are put back in the materials cycle? Recover: What was salvaged from mixed waste? Residuals Management: What is still left and why? What do we need to take out of the system that should not have been circulated in the first place? How do we manage what is left in a flexible manner that continues to encourage movement towards Zero Waste? Unacceptable: What systems and policies encourage wasting and should not occur?"

[14] "A commitment to the triple bottom line. Apply the Precautionary Principle before introducing new products and processes. Send zero waste to landfill or incineration. Take financial and physical responsibility for products and packaging. Buy reused, recycled and composted products in all aspects of operation. Prevent pollution and reduce waste by redesigning supply, production and distribution systems. Adopt highest and best use hierarchy (reuse product or materials for their original purpose, for an alternate purpose, for their parts; recycle sustainably inorganic materials in closed loop systems and in single-use applications; and compost or mulch organic materials to sustain soils, avoid use of chemical fertilisers, reduce erosion and litter and retain moisture). Economic incentives for customers, workers and suppliers to maximise the reuse, recycling and composting of discarded materials. Products or services sold are not wasteful or toxic. Use non-toxic production, reuse and recycling processes."

[15] "To find out if human power can sustain a modern lifestyle, we are designing plans to convert a 22 floors vacant tower building on the campus of Utrecht University in the Netherlands into an entirely human powered student community for 750 people. We're also constructing a working prototype of the human power plant that supplies the community with energy. The Human Power Plant is both a technical and a social challenge. A technical challenge, because there's a lack of scientific and technological research into human power production. A social challenge, because unlike a wind turbine, a solar panel or an oil barrel, a human needs to be motivated in order to produce energy." [124]

accessible to the authorised viewer at all times). In order not to incur fines from the Information Commissioners Office, for each new risk, an organisation measures and assigns risk coefficients for CIA which are then evaluated in terms of accept, avoid, transfer or reduce. Similarly, we could assign a number to new ICT/EEE purchases and services based on principles and considerations such as Reduce, Reuse, Recycle, Refurbish and Recover. These figures could be employed to determine whether the item is to be accepted, avoided (use an existing service), transferred (use elastic computing) or reduced (does it need to be operated at all times).

6 Pedagogy – teaching, learning, investigating and other activities

6.1 Current: classroom

Green computing Environmental sustainability, the economics of energy efficiency and the total cost of ownership (including that of disposal and recycling) falls under the rubric of "green" computing[16] and includes green networking and energy-aware security [127]. Such ideas are relevant both practically and theoretically: from materials to devices to circuits to complete systems, fundamental limits to computation exist in areas such as manufacturing, energy, physical space, design and verification, and algorithms [128]. Currently, the Department has few undergraduate and/or post-graduate courses, reading groups, or other vehicles that could be categorised as addressing green computing-related problems and solutions.

6.2 Future: resource constrained computing, computation and communication

Resource-efficient computing, algorithms and security Weaving the concept of resource constrained computing, computation and communication into the fabric of instruction, research and development could provide a route to ensuring that resource use is both minimised and minimal. For example, developers of software systems are being encouraged to consider not only their technical and economic requirements but also their social and environmental dimensions [129]. Indeed, addressing topics such as reducing power and raw material consumption, lowering the financial costs of computation and digital preservation, decreasing carbon emissions, lessening environmental impact, improving systems performance and use and saving physical space are deemed necessary for enabling smaller, lighter, faster, cheaper and cooler ICT/EEE hardware and software [130, 131]. Since using less energy produces less heat waste yielding higher clock speed, reversible computing is one way to implement such ideas [132, 133]. Potential topics of interest include quantifying the resources required to achieve a given level of efficiency in hardware (computing), software (algorithms) and security (information transmission in the presence of adversaries and eavesdroppers).

A Living Laboratory for Experimental Computer Science The TSG could explore the feasibility of creating a fully functional machine room that simultaneously enables and facilitates staff and students to observe, monitor and investigate the operation and behaviour of a complex ICT/EEE ecosystem in a real life setting. The resultant data can be used to define, refine and implement solutions for reducing the resource footprint of the Department's computing facilities. Unfortunately, it is difficult to calculate efficency because the latest processors will switch processing speed depending on workloads but will cap these turbo speeds if particular instructions are used [134]. The TSG is performing experiment to ascertain which processor model is best suited to particular job types.

A Back to the Future Interest Group Informal grouping of staff and students could come together to reexamine historical technologies and approaches, extending the range of research and bringing together different strands of computer science to inform the present both culturally and practically. In the late 19^{th} century, for instance, the nature and availability of materials such as rubber, gutta percha, copper and hessian shaped development of the telegraph and transatlantic communication [135]. Similarly, from smartphones to wind turbines to hybrid cars to MRI scanners, virtually every technology invented in the last 30 years uses rare earths (lanthanides) such as dysprosium, neodymium, terbium, europium, and yttrium and rare gases such as helium [136, 137]. Rising demand in the green/clean/alternative technology sectors is depleting rapidly the world's entire supply of strategic materials [138, 139].

Modern subjects such as latency, bandwidth and delay (disruption) tolerant networks can draw on the

[16] Green IT is the "study and practice of designing, manufacturing, using and disposing of computers, servers and associated subsystems – such as monitors, printers, storage devices and networking and communications systems – efficiently and effectively with minimal or no impact on the environment. Green IT also strives to achieve economic viability and improved system performance and use, while abiding by our social and ethical responsibilities." [126]

18th century optical telegraph, a communications network for forwarding coded messages over long distances without the need for wires, electricity, horses or postmen and an e-mail system that could achieve transmission speeds of ∼1,400 kilometres per hour [140]. From early antiquity, private persons, governments, the military, press agencies, stockbrokers and others have used carrier pigeons to convey messages; one unexpected virtue of such systems is pigeon guano [141], a substance prized as a supermanure since the Middle Ages and regarded as more valuable than that of other birds. Indeed, sneakernets – the physical transport of classical information stored in removeable media and used routinely today – have been proposed as a low-latency high-fidelity network architecture for quantum computing across global distances: ships carry error-corrected quantum memories installed in cargo containers [142].

Whereas the environmental and economic costs of digital preservation are known [131], less well appreciated are practical consequences of technical properties such as the "fragility of academic communication in the Web era as opposed to its robustness in the paper era" [17] [143].

7 A more resilient and healthier computer science department

Critical to the development and successful deployment of a roadmap to a more resilient and healthier Department are (a) understanding the basic attitudes, values and patterns of behaviour that are common to staff and students, including patterns of consumption or non-consumption, (b) rethinking discarded materials as resources, (c) reducing waste so that it is diverted from landfills, incerators and the environment (no burial, burning, or emission into air, water and land), (d) promoting the interconnected nature of human and environmental health, (e) questioning and scrutinising concepts such as progress and modernity [144, 145, 146, 147], and (f) avoiding solutionism[18].

Formulating policies and developing guidelines that create a living laboratory for teaching and learning about resource constrained computing, computation and communication will require a unique multi-, trans- and interdisciplinary approach. One potential strategy is the establishment of a resource-aware problem solving laboratory spanning UCL's Department of Computer Science, the Slade School of Fine Art and the Barlett School of Architecture. The resultant Department of (Re)search would be able to investigate problems and examine solutions from novel and diverse angles. Its initial remit could be investigating how to achieve the three aimed outlined below.

7.1 Do not exceed 2,000 W and 1 ton CO_2 per person per year

In the 1990s, researchers at ETH proposed a pragmatic step towards a sustainable Western lifestyle whereby each person in the developed world – primarily the U.S., Canada, Western Europe and Australia – would consume no more than 2,000 W and emit no more than 1 ton of CO_2 per year. Starting with the city of Basel, other regions in Switzerland as well as in Germany have accepted the idea and begun to realise such a society. Assessment of the environmental behaviour of ∼ 4,000 Swiss inhabitants plus a life cycle assessment indicates that whereas restraining energy demand to 2,000 W is possible, limiting CO_2 production to under 1 ton per person per year is more difficult currently [149]. Given the nature and activities of the Department, we suspect it may be almost impossible for a student or staff member to use less than 2,000 W.

As discussed earlier, knowledge of energy efficiency does not necessarily translate into energy savings (technologies designed originally to reduce energy use can give rise to new applications that eventually raise energy consumption as well as technological obsolescence), energy consumption does not equal electricity consumption (an ICT with a given kilowatt-hours of electricity rating requires the production of more than the equivalent amount of energy because the conversion of one form of energy into another is accompanied by loss of energy) and life cycle analyses may be out of date, incomplete or not exist (the com-

[17] The root cause of the evanescent Web [143] has been described as follows: "in the paper world in order to monetize their content the copyright owner had to maximize the number of copies of it. In the Web world, in order to monetize their content the copyright owner has to minimize the number of copies. Thus the fundamental economic motivation for Web content militates against its preservation."

[18] Solutionism is "an unhealthy preoccupation with sexy, monumental, and narrow-minded solutions – the kind of stuff that wows audiences at TED Conferences – to problems that are extremely complex, fluid, and contentious. . . . solutionism presumes rather than investigates the problems that it is trying to solve, reaching 'for the answer before the questions have been fully asked.' How problems are composed matters every bit as much as how problems are." [148]

plex life history of technologies involve a cornucopia of parts, materials and processing techniques, each with its own resource requirements) [150, 21].

Challenges in estimating the energy consumed by today's digital society include the complexity of the infrastructure, the fast-changing nature and rapid evolution of the networks and the methods, assumptions and models employed by researchers. Bearing in mind such caveats, the 2012 global communications network (end-use devices, networks, data centres and manufacturing) is postulated to have consumed 8% of that year's global energy production and coupled with the ever increasing energy consumption per internet user, a "speed limit for the Internet" has been proposed [151]. Furthermore, reductions in the energy intensity of the internet (energy utilised per unit of information sent) are more than offset by ever higher total energy use arising from shifting consumption patterns (system level factors) [151]. Self-imposed limits on the demand side of digital communication is one mechanism for ensuring that resource use is both minimised and minimal.

7.2 Become a zero waste institution

Resource life cycles could be redesigned so that all products are reused and nothing is sent to landfills and incinerators [122]. Higher than the Pollution Prevention Hierarchy, the Zero Waste Hierarchy of Highest and Best Use considers not just the entire carbon life cycle of materials but also the embodied energy used to extract virgin resources, manufacture a product and transport a product to market. In essence, if a product cannot be "reused, repaired, rebuilt, refurbished, refinished, resold, recycled or composted, then it should be restricted, redesigned, or removed from production". Since sustainable resource management is the joint responsibility of producers, communities and politicians, the Department of (Re)search could make contributions in all three areas: industrial production and design at the front end, consumption, discard use and disposal at the back end and a governmental and regulatory landscape in the middle. Another project for the Department of (Re)search could be to articulate what a "zero emission" and "zero energy" building means in the context of the Department [152, 153, 154, 155].

7.3 Rejuvenate and (re)integrate the natural and built environments

In general, increased exposure to and contact with the biome, not least the micro- and macroorganisms, is important for immune development and could reduce several types of diseases and conditions associated with the modern era [156, 157]. Indoor plants provide beneficial bacteria, positively influencing human health [158]. Thus, the Department's indoor and outdoor natural environment is vital to providing a healthy and resilient workplace. An agroecological approach to the building's landscape could enhance the well-being of staff and visitors by for instance, facilitating the flow of beneficial soil- and plant-associated micro- and macroorganisms indoors. Since some microbes can induce deterioration of building materials and artefacts such as compact discs [159, 160, 161], the complex relationships between microbes, animals, plants, humans and the enclosed private and public spaces of the Department warrant investigation. For example, how microbiomes of the built and natural environment affect the day-to-day and long-term operation of ICT/EEE as well as *vice versa*.

More broadly, is it possible to enunciate a "soil-to-soil" [162] approach to ICT/EEE? For example, a hoodie has been grown, designed and crafted using materials from a 150 mile supply chain where at the end of its life, the nutrients in the composted garment (apart from the metal zip) could be returned to pasture or farmland used to produce fibres and dyes and hence raw materials for subsequent hoodies – seed to skin to soil [163].

8 Concluding remarks

The resource footprint of UCL's Computer Science Department is shaped not only by the factors discussed here but also by other forces. Thus, a full accounting will require identifying and enumerating all manner of externalised costs such as off-site data centres, not least their energy, land, raw material and water requirements. Despite such limitations, practical steps towards a 2,000 Watt, 1 ton CO_2, zero waste department where the natural and built environments are (re)integrated do exist. Design philosophies rather than specific technologies are key: for example, passivhaus, ecological sanitation, rainwater harvesting and agroecology are place-based approaches guided by local landscapes, communities, building materials and climate capable of addressing the challenge of ensuring that resource use is both minimised and minimal.

The earlier and faster the Department mitigates its consumption of resources, the less adaptation will be required in the future. Since major infrastructure can last for 30 to 100 years and even academic curricula have a lifespan of many years, it is important to articulate the field of resource constrained computing, computation and communication. A key axiom of theoretical and applied studies in this interdisciplinary field is that resource use needs to be both minimised and minimal – reduced in relative and absolute terms.

Whilst focused on the particular topic of the resource footprint of a university department, this study can be cast an example of "responsible research and innovation". According to the UK's Engineering and Physical Sciences Research Council, "responsible innovation is a process that seeks to promote creativity and opportunities for science and innovation that are socially desirable and undertaken in the public interest" and such an approach should be one that "continuously seeks to anticipate, reflect, engage and act" [164]. Similarly, "ProGReSS" is a European Commission-funded project whose mission is to promote a European approach to responsible research and innovation: "research and innovation which is ethically acceptable, sustainable by avoiding significant adverse effects and drives towards the common good, i.e., societal desirability" [165].

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