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SUPPLEMENTARY MATERIAL

What is the resource footprint of a computer science department? Place, people and pedagogy.

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1. Place – the built environment

1.1. Present state of affairs: three geographically distinct locations

1.1.1. Multi-site organisation

UCL Computer Science is spread over three mixed-use multi-story 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 ~130m^2 but the resources consumed by this specific space cannot be determined. The 2016 US Energy Information Administration's Commercial Buildings Energy Consumption Survey 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" [1]. Since the Department's data centre space is likely to use orders of magnitude more electrical energy than standard office space, we expect a similar disparity between our buildings.

1.1.2. Data centre

The data centre is the Department's most important wired/wireless network domain. As the major infrastructure component powering the networked computer system, it is key to not just productivity but also its financial and environmental sustainability. Data Centre Energy Productivity (DCEP) quantifies the 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 [2]. Global metrics for different aspects of a data centre include Power Usage Effectiveness (the ratio of the total energy of the data centre to the ICT energy consumption), Green Energy Coefficient (the portion of a facility's energy that comes from green sources), Energy Reuse Factor (the portion of energy that is exported for reuse outside the data centre), and Carbon Usage Effectiveness (assessment of the total greenhouse gas emissions). How best to use these metrics to compute the Department's DCEP requires further enquiry. Given baseline values, we could assess the efficacy of interventions such as 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 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.

1.1.3. Cloud computing services

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 data centre efficiencies and the true environmental cost of using cloud computing services is an open question [3, 4]. 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 integrate seamlessly local services with the on-demand elastic resource, that is, improving a network's ability to scale up and down as traffic demands ebb and flow.

1.1.4. Keeping bits alive

In many respects, the core function of the Department's infrastructure (software, hardware, and physical floorspace) and operation (services and people) is to ensure the survival of bits. In principle, we could partition the complete cost of maintaining one byte over a period of time such as a month or a year into the costs of storage (£/Mbyte), computing (£/CPU cycle), and networking (£/bit). Our challenge is finding, applying, and evaluating models for computing these quantities.

1.2. Ideas for the future: architectural works designed with nature for resource conservation and quality of life

1.2.1. Integrating the built and natural environments

An integrated viewpoint is needed to understand the diverse and complex building-related factors that influence human health and performance [5]. Although "green buildings" tend to be discussed 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 people's 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 [6]. 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 [7–11].

The overall design, construction methods, building materials, and geospatial organisation of the Department's facilities are key determinants of its land, carbon, energy, and water usage. 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. Creating a more resilient, healthy, and sustainable Department will require investigating the mutually instructional relationships between a building's physical infrastructure, what is in it, what is around it, and how the (a)biotic components of this triad influence the quality of life of the building's occupants. For example, microorganisms can drive indoor air quality because although they are found on surfaces and throughout the water and other systems of buildings, air is likely to be the most important medium for their dissemination. Thus, whilst our facilities have a basic instrumental value (their function), they promote also the set of values expressed by the socio-political system in which they are embedded: they themselves are a value-laden technology.[1]

1.2.2. Passivhaus

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" [13]. The fabric first approach of this robust, proven and cost-effective construction concept produces energy efficient, comfortable and affordable buildings [14]. 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 [15].

A passivhaus building housing a computer science department needs to accommodate the unique yet often contradictory (electrical and heat) energy and other requirements of machines as well as humans, e.g., cooling [16, 17], heating [18], and the interior volume of a space [19]. Other challenges range from understanding building physics through cost implications during the design, build, operation, and whole life cycle to quality assurance and on-site delivery. A bespoke building designed for the Department's geographic location that is also part of a solar oriented university campus, neighbourhood, and city could make important contributions to reducing energy usage as well as enhancing human and environmental health [20–22].

1.2.3. 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 [23]. Problems with the modern bathroom and sanitation

[1] "Technology both raises general questions about values and it is value-laden due to its very function. However, although technology is value-laden, it does not necessarily give an imperative mandate. One reason for this lies in our responsibility. We are inevitably responsible for all aspects of technology, i.e. development, construction, production, commercialization, implementation, and use." [12]

systems [24] 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 or sullage) thereby reducing water consumption substantially, nearly eliminating pollution, and producing a valuable plant fertiliser and soil amendment product [25]. 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 [26]. 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 of sites in Norway, California and worldwide [27–31], ecological sanitation systems capable of achieving nearly zero emission and almost complete recycling in London are feasible. Hence, it should be possible to design compact and technically simple blackwater and greywater treatment systems [32] for the Department. Bathrooms [33, 34] 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 hence contribute to a cleaner city and river Thames [35].

1.2.4. Rainwater harvesting

Rainwater harvesting is the process of intercepting rainfall for its eventual beneficial reuse [36, 30]. 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 then (re)routed for use in evaporative coolers, toilet flushing, irrigation, and so on. This alternative and additional water source helps to conserve potable water supplies and the amount of run-off the municipal stormwater management infrastructure needs to handle. The benefits of a rainwater harvesting system to the Department include the potential to reduce water (and indirectly energy) consumption and costs as well as contribute to making London more resilient to flooding [37]. The importance of such actions lies in the need to tackle water resource because "Parts of the country face a significant risk from drought, while neighbouring regions have surplus water. ··· If more concerted action is not taken now, parts of the south and south-east of England will run out of water within the next 20 years." [38]

1.2.5. Agroecologically productive landscape

Similar in many ways to agroecology [39–42], 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 ecosystems [43]. Demonstration permaculture projects for students and/or staff exist at the Department of Educational Sciences Middle East Technical University [44] and the University of Massachusetts Amherst [45]. A 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 landscapes could be achieved by efforts such as reusing greywater, collecting rainwater, installing waterless composting toilets, and implementing horticultural changes.

1.2.6. Microbiomes

Biological and non-biological ecosystems provide place-based habitats and residences to microbial communities. Tremendous numbers and diverse species of microorganisms colonise not just the environs, surfaces, and inner tissues of plants and animals [46–48] but also settle on the inside and outside of buildings such as offices and hospitals, modes of transport such as cars and trains, conduits conveying fluids and electrical cables, and other infrastructure [49–52]. Although the (a)biotic host, climate, geology, and geography affect the local composition, dynamics and impacts of microbiota, microbiomes form a globally interconnected continuum. The number of microbes exceeds the number of cells of the human body and whilst most are harmless and many are beneficial, the consortium is characteristic of the individual: 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 [53, 54]. The bacterial make-up 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 occurring within them [55].

Since a Departmental building's architectural design (notably its heating, cooling, ventilation and air conditioning systems), intended human use pattern for spaces, and local horticulture affect the biogeography of its microbial communities, redesign and/or renovation projects should take such factors into account. 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 such as those needed for building support (machine and server rooms, especially if some microorganisms could physically degrade hardware), storage spaces, mechanical equipment rooms, and janitor closets. In contrast, natural ventilation is necessary to promote a healthy indoor environment and to enhance the life quality of building occupants: unfiltered outdoor air is supplied via window, louvres or other means to areas needed for specific functions such as classrooms, hallways, atria, common rooms, and bathrooms.

2. People – a building's occupants and visitors

2.1. Present state of affairs: education and engagement

2.1.1. Environmental Responsibility 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* a 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 common rooms to recycle food waste and single-use coffee pods and capsules. Another activity is making representations to UCL authorities about shared data centre inefficiencies.

2.1.2. Staff and students

The Department's Technical Support Group (TSG) supports the teaching and research needs of faculty such as repairing equipment so it can be reused, designing high performance computing 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. 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, notably those entering the Department, as well as visitors such as primary, secondary and tertiary level teachers and pupils. This includes 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. Hot-desking office spaces are available to individuals, allowing access to services via a thin client or direct connection of a laptop; this saves the need for permanent desks and personal computers because essentially all students and staff prefer to use their own computing devices. This non-exhaustive list of observations illustrates a few of the practical and logistical matters the TSG handles, its purpose being to give a sense of what a whole systems exploration of resource consumption by people in the Department would entail.

2.2. *Ideas for the future: curricula, modules, materials, and activities*

2.2.1. Meet-ups for staff and students

To increase awareness of problems, promote potential solutions, and identify topics which dovetail with existing teaching- and research-related classes and courses, the Department could organise informal gatherings on topics ranging from the materiality of software through the resource-related aspects of data centres to reasons for the growth in data from social media, mobile devices, sensors, sciences, and other sources. Transport provides a forum for exploring energy efficiency rebound and circular economy rebound [56]. Strategies for achieving sustainable mobility are (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, and (3) volume reduction: fundamental changes in behaviour and consumption patterns such as people travel less often and freight volumes decrease – but, all are associated with the rebound effect [57]. Since the circular economy focuses only on a small part of total resource use [58] and may fail to deliver on its potential once economic realities are considered, it has been argued that “what is truly required to reduce environmental impact is less production and less consumption” [56].

2.2.2. Informational resources and material created elsewhere

The Department could produce bespoke versions of extant ICT/EEE-related flyers, documents, and practical information for dissemination to staff, students, and visitors. We provide three examples. The Electronic Product Environmental Assessment Tool [59] is a repository utilised by public and private entities in over 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. The Solving the E-waste Problem (StEP) Initiative addresses the life cycle areas of design, production, usage, reuse, recycling, and final disposal [60]; its “e-waste world map provides comparable, country-level data on the amount of EEE put on the market and the resulting amount of e-waste generated in most countries around the world” [61]. Finally, *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? [62].

2.2.3. ICT/EEE community clinics and cafés

The Department could hold regular hands-on events to diagnose malfunctioning, repair broken, and repurpose neglected items; practical activities in accord with the StEP initiative’s addition of Refurbish and Recover to the traditional “Rs” of Reduce, Reuse and Recycle [61]. A natural partner could be UCL’s Institute of Making, a multidisciplinary research club for making, breaking, and repairing everything from jewellery to robots – a facility located on the ground floor of one of the buildings housing the Department [63].

2.2.4. Show-and-tell sessions: “ethical” ICT/EEE

The Department could facilitate discussions about the entire physical, financial, and resource life cycle of specific products or items as a way to probe broader philosophical questions such as socio-economic impacts, alternatives, and social, environmental, ethical, health and labour issues [64–67]. Activities could range from examining the earliest stages of design [68, 69] through defining Life Cycle Sustainability Assessment impact categories related to social and economic issues [70] to probing whether “Science Discovers–Humanity Decides–Technology Conforms” should replace “Science

Finds–Industry Applies–Man Conforms" [71, 72]. For instance, a mobile device such as the "Fairphone" [73] could be queried with respect to How free is it of minerals sourced from conflict zones (for example, gold, tin, tantalum and tungsten)?, To what degree is it manufactured in factories that meet stringent ethical and environmental standards (for example, fair labour conditions for the workforce along the supply chain)?, and What features reduce the level of e-waste (for example, charging batteries from a micro-USB port and multiple SIM slots that permit the same handset to be used for home and work)? [74]. Even seemingly nebulous goods such as biodiversity data [75] and biometric data (datafication more widely) could be inspected using the FLE^5SH framework lenses (F = Financial, L = Legal, E^5 = Economic, Ethical, Equity, Environmental, and Ecosystem, S = Socio-political, H = Historical) [76].

2.2.5. Problem-based learning: impacts and implications of ICT/EEE

Small groups of individuals from within and outside the Department could collaborate to investigate the known and less obvious real-world consequences of the ICT/EEE ecosystem: from negative outcomes being shifted from one place to another to genuine efficiency gains arising from adoption being usurped by increasing overall production and consumption and hence waste generation [77–80]. With respect to the rebound effect, energy efficiency increases in ICT/EEE can cause structural changes in households, education, business, and the military resulting in a proliferation of devices and thereby increasing energy consumption [81]. Similarly, 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 [82, 83]. How ICT/EEE affects the lives of ordinary people – a futurology from below [84] – could be investigated using multicriteria mapping, an interactive hybrid qualitative/quantitative appraisal method for exploring the contrasting perspectives of diverse stakeholders on complex issues [85, 86]. Ecological and economic impacts could be studied through an ecological economic analysis in a problem-based learning setting [87, 88].

Consider the potential human health problems associated with the normal operation of 3D printers and environmental concerns associated with their products. These machines use raw materials such as thermoplastics, metal and ceramic powder, and cells to produce objects as diverse as trinkets, eye glasses, and organs [89]. 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) [90]. Epidemiological research suggests that exposure to mass concentrations of atmospheric UFPs increases adverse cardiovascular and respiratory problems and might contribute to pre-term birth [91, 92]. 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 [93, 94]. Data obtained from 24 expeditions (2007-2013) across all five sub-tropical gyres, coastal Australia, the Bay of Bengal, and the Mediterranean Sea indicate at least 5.25 trillion plastic particles weighing 268,940 tons are afloat at sea [95]. 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." [93]

2.2.6. Zero waste and zero footprint

The Department could investigate the questions and business principles of zero waste [96] in light of its own needs and practices. This framework 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."[2] The Department could devise activities built on the Zero Footprint Campus project, an art programme in the public areas of the Utrecht Science Park that examined the (im)possibilities of sustainability [97].[3]

2.2.7. Learning from other fields: information risk industry

Researchers in Cyber Risk and Resilience Management have developed a framework for identifying, analysing, and resolving vulnerabilities in an organisation's operating environment [99]. The CIA triad [100] is a simple but widely-widely model for information assets: any secure system should guarantee confidentiality (the ability to hide information from those people unauthorised to view it), integrity (the ability to ensure that data are an accurate and unchanged representation of the original secure information), and availability (the ability to ensure that the information concerned is readily 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. The Department could assign a number to a new ICT/EEE purchase or service based on principles and considerations such as Reduce, Reuse, Recycle, Refurbish, and Recover [61]. This figure would 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).

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[2] Two zero waste lenses [96] are as follows. "*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? *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."

[3] For instance, "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." [98]

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