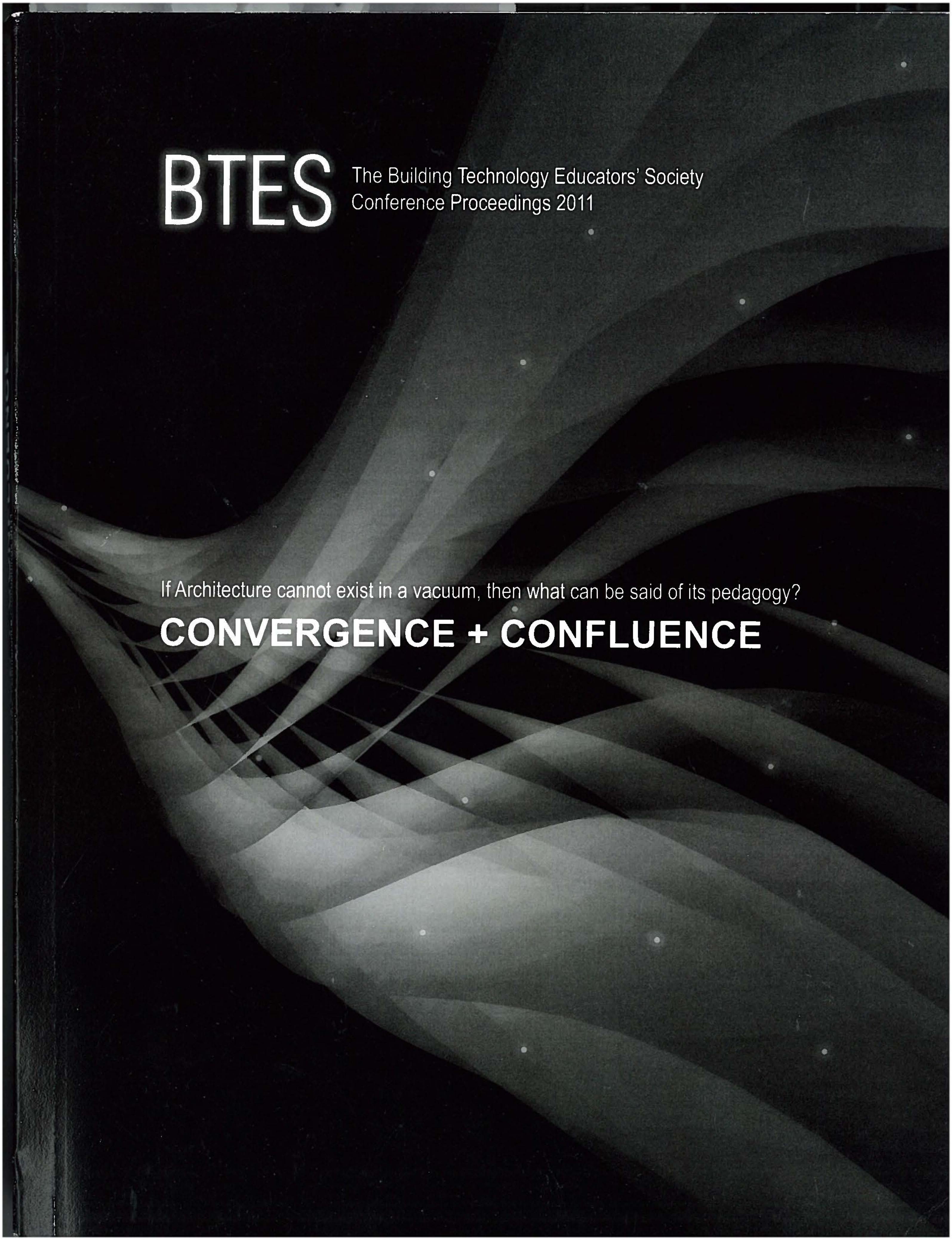

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If Architecture cannot exist in a vacuum, then what can be said of its pedagogy?

CONVERGENCE + CONFLUENCE

COMPUTATION AS CATALYST FOR SUSTAINABILITY: Environmental Stewardship through Interdisciplinary Research and Design

AIMEE P. C. BUCCELLATO
School of Architecture, University of Notre Dame

PAUL R. BRENNER, P.E., PH.D.
Center for Research Computing and Department of Computer Science and Engineering, University of Notre Dame

DAVID B. GO, PH.D.
Department of Aerospace and Mechanical Engineering, University of Notre Dame

ABSTRACT

Because of accelerating advances in computational systems capability and efficiency, architects and building systems engineers must contend with growing – and thus far unregulated – heat loads generated by centralized data systems and the associated energy waste involved in cooling them[1]. Current efforts to regulate, recapture, and/or distribute computer waste heat have not yet been met with comprehensive, whole building design solutions. The authors' contribution is Environmentally Opportunistic Computing (EOC), a sustainable computing concept that enables distributed computing hardware to be integrated into a building – or a network of buildings – to optimize the consumption of computational waste heat in the built environment.

Utilizing data from full-scale EOC experiments using a pioneering building-integrated operational prototype, faculty and students from Architecture, Computer Science, and Engineering are working together to develop a unified design methodology along with implementation and delivery methods that merge engineering and architectural concerns related to the design of buildings that involve EOC technology as part of an integrated design process. The potential for EOC to provide a new paradigm in sustainable building in which the distribution framework for computation serves as a catalyst for integrating a novel, essentially passive thermal system with current building practices necessarily involves the consideration of various interrelated design considerations. Among them: a sensor-controlled balance between computational user demand, hardware capability, and building performance; occupant expectation, and the myriad potential impacts of the technology on architectural form and spatial dynamics.

In this work, we describe the early success of the EOC concept and the trans-disciplinary research opportunities that have been developed by the authors to engage both undergraduate and graduate-level students in the advancement of this potentially transformative energy conservation concept.

KEYWORDS

sustainable design, building systems and technology, innovation in energy conservation, interdisciplinary research

INTRODUCTION

In the US we spend billions of dollars annually to power and cool data systems[1]. These systems have become a large and growing part of modern life, supporting everything from commerce to global communication, scientific simulations to gaming; they help feed our ravenous hunger for information and our need for instantaneous feedback. In addition to our myriad devices, our cars and our houses, our very daily lives are inextricably tied to information and communication technology (ICT). And while we're wired-in, they put out tremendous amounts of heat; the thermal equivalent of the input electrical power they consume. And so regardless of streaming advances in systems capability and efficiency – *or perhaps even as a direct result of them* – architects and engineers will always have to contend with the heat loads generated by computational systems, and the associated costly, involuntary energy waste required to cool them.

Today, it is typical for large ICT systems to be housed in a centralized data center facility – think: Google warehouse. These data centers are typically remotely located and highly conditioned in order to maintain optimal operating conditions for the equipment. In most data centers, heat generated by the ICT is considered merely as a heat load to be overcome by the building's HVAC system.

Instead of treating the heat generated by ICT as a negative consequence of computation, what if computational exhaust heat could be capitalized upon – harnessed and effectively consumed within a building – and the machines more passively cooled to reduce energy cost and demand on traditional energy infrastructure? Could a more integrated, symbiotic relationship be formed between our buildings and the computational infrastructure that has become omnipresent in our modern age? In other words, can computational infrastructure and its associated by-products become part of the discourse on sustainable design, change the way that structures interact with their occupants and the outside world, and by extension, create new opportunities for form-making in architecture?

THE VEILED "COSTS" OF EFFICIENCY

In the computational world, as in the built world, optimized performance along with growing systems efficiency and capability is fast-approaching a zero-sum game: despite evolving low power architectures (in the computational sense), demands for increased systems capability are driving up utility power consumption for computation towards economic limits on par with capital equipment costs; or, as Douglas Alger from Cisco points out: top-end performance often translates to top-end power demand and heat production[2]. Not surprisingly, the faster and more efficiently we are able to compute, *the more we grow a culture and economy requiring greater computation,* simultaneously increasing power utilization for system operation and cooling while placing added pressure on an electric grid that at present time is almost entirely fueled by non-renewable resources.

A similar trend is emerging in the building sector, where efforts to minimize a building's operating footprint by optimizing raw energy consumption are supported by studies from the US Environmental Protection Agency which reveal that the building sector accounts for nearly 40 percent of US energy consumption[3], not including energy tied to construction processes or building materials. Similar data from the Department of Energy and studies by the National Institute of Building Sciences reveal that, on average, upwards of two-thirds of the energy/carbon impact of buildings is tied to process and operating energy – or energy used for heating, cooling, and ventilation. And like energy use tied to powering and cooling ICT, energy expenditures to heat and cool buildings are predicted to rise exponentially over the next twenty years, on the order of $100 billion dollars by 2030[4].

Recognizing that power resources for traditional, centralized data centers are not infinite, several professional entities within the technology industry have begun to explore the systems-side energy problem, such as the High-Performance Buildings for High Tech Industries Team at Lawrence Berkley National Laboratory[5], the ASHRAE Technical Committee 9.9 for Mission Critical Facilities, Technology Spaces, and Electronic Equipment[6], the Uptime Institute[7], and the Green Grid (http://www.thegreengrid.org). At the same time, efforts by corporations, universities, and government labs to reduce their environmental footprint and more effectively manage their energy consumption have resulted in the development of novel waste heat exhaust and free cooling applications, such as the installation of the Barcelona Supercomputing Center, MareNostrum, in an 18th century Gothic masonry church[8], and novel waste heat recirculation applications, such as a centralized data center in Winnipeg that uses re-circulated waste heat to heat the editorial offices of a newspaper directly above[9]. Similar centralized data centers in Israel[10] and Paris[11] use recaptured waste heat to condition adjacent office spaces and an on-site arboretum, respectively. However, despite systems-side optimization of traditional centralized data centers and advances in waste heat monitoring and management, current efforts in computer waste heat regulation, distribution, and recapture are focused largely on immediate, localized solutions, and have not yet been met with comprehensive, whole building design solutions.

In order to overcome the staggering energy use tied to our information-geared culture, and meanwhile reduce its consumption to support our highly conditioned buildings, progress in sustainable building design and computations each must reach beyond traditional systems-side advancement. The aggressive growth in computational users[12] and the demand capability of those users[13] must necessarily be met with new energy-focused, integrated design paradigms; traditional, single-facility data systems isolation must give way to integration; and as it is in the built world, advances in technology and computational capability and efficiency must be met with efforts to reduce associated environmental and economic costs.

THE SOLUTION: ENVIRONMENTALLY OPPORTUNISTIC COMPUTING (EOC)

The authors suggest that if the current consolidated ICT model could be decentralized, broken down into smaller nodes and integrated into the built environment, 'waste' heat generated by data systems could then be used to offset a building's energy demands, thereby enabling energy hungry, heat producing data systems to become service providers to buildings in much the same way that renewable energy sources like wind, solar, and geothermal can be integrated into a building's design and infrastructure to offset non-renewable source energy consumption. Instead of expanding active measures (i.e. mechanical systems) to contend with the thermal inequities of space, Environmentally Opportunistic Computing utilizes *existing* technology (ICT) and the associated waste by-product of computing – heat – to reduce or potentially eliminate a building's dependence on traditional fossil fuel-powered heat systems. At the same time, decentralization of these data systems promotes more efficient and effective ventilation and cooling of the systems themselves, resulting again in lower energy consumption to offset cooling loads.[14, 15, 16]

EOC utilizes a grid heating concept – the optimized consumption of low-grade 'waste' heat within a building – to perform as a "system-source" thermal system, with the capability to respond to a building's heating demands by raising baseline air or water temperature to decrease outside energy consumption for heat. Further, when fully integrated, EOC can utilize aspects of a building's existing heating, ventilation and air conditioning infrastructure (HVAC) to "locally cool" ICT data servers with little cost to the building. For instance, it may be possible to use return, relief, or exhaust air up to levels permitted by ASHRAE to cool the ICT hardware. Integrated designs developed around this concept essentially reduce or remove cooling requirements (and associated energy use) for computational systems and enable cost sharing on primary utility expenditures because input electrical energy that is consumed by the data servers also produces a usable by-product.

Here emerges the potential for a truly symbiotic building-systems relationship: if designed well, the building gets 'free' heat, and the machines get 'free' cooling.

Not only does EOC have the potential to boost energy efficiency worldwide, but technological solutions such as EOC may provide a new paradigm for sustainable building in which the distribution framework for information technology serves as a catalyst for integrating an *existing*, essentially passive thermal system with current building practices.

An optimal implementation of EOC would be as depicted in Figure 1. EOC nodes would be distributed across the various buildings of a municipality or community (campus, industrial park, etc.). In lieu of a centralized data center, computing jobs would be moved between nodes based on the requirements of the building. If, for example, an office building required a large amount of space heating during the day, those nodes would have primary job access in order to maximize the heat delivered to the building. In the evening, those jobs could then be migrated to a hospital and the heat would be used to pre-heat the water supply. Similarly, if an industrial plant has a significant amount of relief air to deliver 'free' cooling, jobs could be migrated to that node when computational loads are greater than the need for waste heat. One can even envision a large EOC network established across multiple municipalities across the nation in order to take advantage of local time of day and climate, energy costs, and operational efficiency. Ultimately, by moving the computing jobs to where energy is needed and cheapest, EOC presents not only a sustainable ITC/building approach but an economically beneficial one, as well.

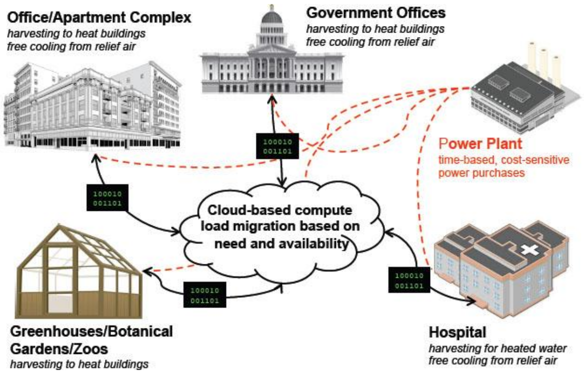

Figure 1: Illustration of EOC Implementation and Energy Conservation Concept

EARLY SUCCESS IN INTEGRATION: EOC IN ACTION

The success of early lab-based, simulation experiments of the concept led to the expansion of EOC into a novel operational prototype called the Green Cloud, a distributed node of data servers that has been integrated into South Bend's Ella Morris/ Meussel Ellison Botanical Conservatory and Greenhouse in order to help offset growing costs to heat the facility during the fall, winter, and spring months.

The Green Cloud prototype http://greencloud.crc.nd.edu/) is a shipping container-style EOC node that houses three racks of high performance computing servers that are directly connected to the University network and used for running typical University-level research computing jobs. The prototype is situated immediately adjacent to the facility, where it is ducted into one of the large public conservatories (Figure 2). The heat generated from the hardware is exhausted directly into the conservatory to offset a portion of wintertime heating requirements – which average $15,000/ month during peak winter months.

Figure 2: Operational Prototype, Green Cloud, installed at the Botanical Conservatory and Greenhouse

The 20' wide x 8' long x 8' high data server container was fabricated and installed at the Botanical Conservatory and Greenhouse in the summer of 2009 and commissioned in January 2010 during peak winter demand. After the data server container was secured, the data servers were connected to a high-speed Internet network. Initial experiments on the EOC prototype demonstrated its capability to securely run scientific simulations, meeting the needs of the computational user, and generate heat to help offset demand for heat from the facility's existing boilers. Because there are only 100 servers in the prototype container, they require little active cooling by air conditioning. During its first full winter of operation (2010-2011), the Green Cloud continuously supplied nearly 80° F heat to the conservatory at no cost to the municipality. Initial estimates predicted that the EOC offset peak winter heating costs by as much as 15%, though final data analysis is still ongoing.

PURSUING A FULLY-INTEGRATED DESIGN APPROACH

The early success of the greenhouse emplacement shows the great potential for EOC. However, in order for distributed data servers and facilities (i.e., buildings) to become truly integrated, the technology must advance beyond merely considering the aggregated interactions between computational users and a building's heat consumption. Ultimately, the integration of EOC nodes within a building must involve the consideration of a host of other localized design factors or "Market Forces" (see Table 1). Among them:

- Variable occupant loads and demands: is the technology nimble enough to respond to individualized climate response?
- Return on investment related to installation including retrofitting existing structures and expanding infrastructure to support a decentralized computational node-based system (including ductwork, plumbing, fiber optic distribution, etc.)
- Logistics of decentralized data server access: hardware maintenance and issues of data/ computing privacy
- Integrated space planning that considers usability of space and perception of space where EOC nodes are placed, including acoustics, vibration, and the perception of heat quality.

Beyond these practical concerns, there are the less obviously quantifiable issues of aesthetics that must also be studied. Before practical wide-spread EOC implementation is possible, there are engineering and architectural issues that must be studied, evaluated, and addressed.

EOC IN THE STUDIO AND IN THE LAB

In partnership with EOC researchers, students in architecture and engineering at the University of Notre Dame have begun to study the concept's potential to migrate from prototype scale to whole building integration through their design of an EOC-enabled, state-of-the-art experimental research and education facility, the St. Patrick's Experimental Ecosystem Center – Notre Dame (SPEEC-ND). Collaborating with counterparts in engineering and computer science who are working simultaneously on the development of EOC infrastructure and guidelines for its implementation, eleven upper-level undergraduate architecture students incorporated EOC technology into their designs of research and education buildings for SPEEC-ND as part of a holistic, integrated design process; and meanwhile studied the technology's potential to contribute to optimized form generation in concert with other existing passive design strategies (e.g., building location, orientation, massing, materiality, and other bioclimatic responses).

Utilizing performance data taken from the Green Cloud prototype since 2009, students integrated EOC nodes into their designs given that the heat produced by the hardware is low-grade (less than 90º F); therefore, it must be harvested and utilized locally, such that EOC nodes must either be coupled directly to a building's ducted forced air or heat recovery system (to pre-heat water, for example) or distributed as radiant heat sources tied to other localized passive cooling and ventilation sources.

Table 1: Relevant Market Forces for Integrating HPC/ICT into the Built Environment

1.	User demand for computational capability ▪ Iterative examination of unitization patterns for various applications (science, business, entertainment, education, etc.) ▪ Iterative correlation of utilization characteristics with developing software, hardware, and network capabilities
2.	Computational capability mobility and associated security concerns ▪ Evolution and adoption of grid/cloud computing and virtualization technology ▪ Security algorithms and implementations to allow sensitive/classified information transfer
3.	Hardware thermal and environmental limits (temperature, humidity, particulate, etc.)
4.	Facility concerns ▪ Integration with existing or novel active HVAC and/or passive systems ▪ General thermal performance variables (building materials, orientation, size, location of openings, etc.)
5.	Facility occupant demands/concerns ▪ Thermal control (minimum user expectations and current standards and guidelines) ▪ Indoor air/environmental quality and perception of heat source (radiant computer heat)
6.	Temperature variability (indoor/outdoor; day/night; seasonal)
7.	Return on investment, total cost of ownership, and carbon reduction cost benefits/avoidance

Using the Green Cloud prototype as a model, the design guidelines for the EOC node (or nodes) that were integrated into the studio-based study were based upon the prototype node dimensions (1280 ft3) and estimated thermal output of 75 MBTU/hr (22 kW) to produce an "area of efficacy" of 2,500 ft2 per node. Along with these guidelines, which continue to be refined as the research progresses, students also considered in their designs the basic laws of thermodynamics and principles of heat transfer in conjunction with more specific constraints related to physical configuration and implementation.

In the context of the studio-based study, various strategies for the integration of EOC have been considered in-line with a complex building program and the prioritization of passive technologies over active means. Through this building-specific design process, we were able to advance our understanding of select Market Forces related to the technology (Table 1) – specifically, the potential physical and aesthetic impacts of the EOC node/module emplacement on a building – and consider ways to either mitigate or amplify those impacts.

For example, how the nodes, when placed optimally for heat transfer within a zone might impact horizontal circulation in a building and influence the overall depth and configuration of the floor plate (see Figure 3); or if placed optimally to take best advantage of passive, free cooling, might impact vertical organization and building massing (see Figure 4).

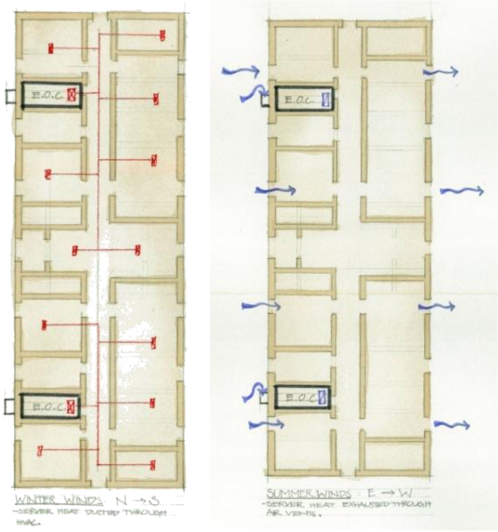

Figure 3: Schematic Design showing zoned arrangement of EOC nodes in a single floor plate (summer operating conditions on left; winter on right). Image: Cristina Gallo-McCausland

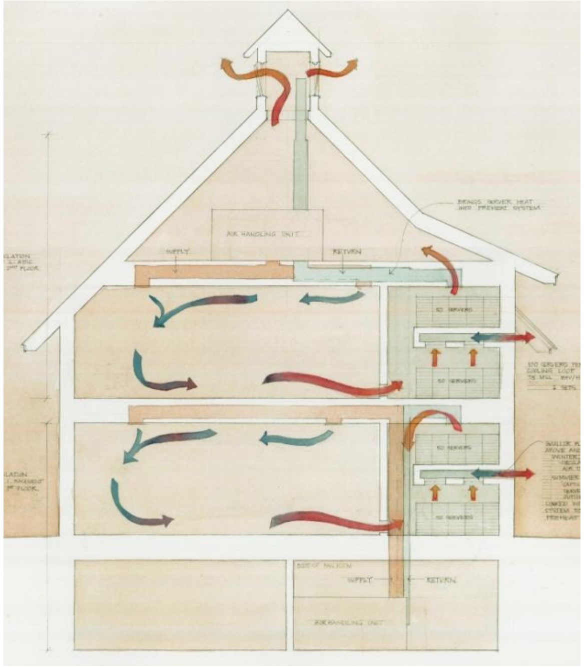

Figure 4: Schematic Design showing hybrid EOC emplacement; designed for direct exhaust in the summer and coupled with building HVAC system for winter-time pre-heating. Image: Gina Paietta

Some of the students' solutions centered on functionally specific uses for the EOC nodes; in one case, arranging server nodes below a second story greenhouse to take best advantage of free cooling from below and convection to draw air through the servers for use in the greenhouse above (see Figure 5). Alternately, locating server nodes around exterior entries to passively condition air locks and allow for direct exhaust at the building perimeter during the warmer months (see Figure 6).

And because efficiency of floor plate is fundamental to sustainable design, the impact of EOC emplacement on the overall size of building footprint (and therefore cost, in terms of construction cost in dollars and energy/carbon impact) has been considered in each of the eleven designs, providing data to further study the correlation between initial EOC building-cost impact, lifetime operating impact, and energy conservation potential. Based upon the designs generated by the students that involve EOC, our preliminary analysis reveals that the average increase in floor plate related to the incorporation of EOC is 3.6% (as compared to a design without integration of EOC).

Like many design principles and methods based upon the optimization of passive means – i.e. those that brought about the traditions like the courtyard house-type, the malqaf (wind tower), the dog-run or possum-trot plan, the side-yard house, the Chicago mercantile plan, etc. – the intelligent incorporation of EOC technology will necessarily impact building zoning, planning, and form at the very earliest stages of design, potentially leading to altogether new opportunities for context-based form-making.

An integrated design process involving EOC is not remarkably different than a holistic design approach rooted in the optimization of more traditional passive methods, or the synthesis of various localized contingencies (climate, culture, character, and values) with programmatic requirements (occupancy and function) ahead of active (mechanical) intervention. EOC technology simply becomes yet another component, among a host of numerous considerations, of integrated design.

Yet, it is the trans-disciplinary collaboration – a continuous feedback loop between architects and engineers and industry – that will enable this essentially untapped, passive thermal system, to advance beyond the prototype and be optimally deployed in the built world.

Systems engineering concerns must be evaluated in the context of actual building design and deployment, and the impact of the technology on the built environment must be studied and quantified beyond purely thermal measurements. In the same way, architectural concerns (function, usability, scale, character, habitability, etc.) must be assessed and weighed in-line with an optimized engineering solution. When all of these factors can be fully considered together, solutions that are optimal from both engineering and architectural perspectives are likely to emerge.

Through our integrated studies in the lab, in the field, and in the design studio, we continue to

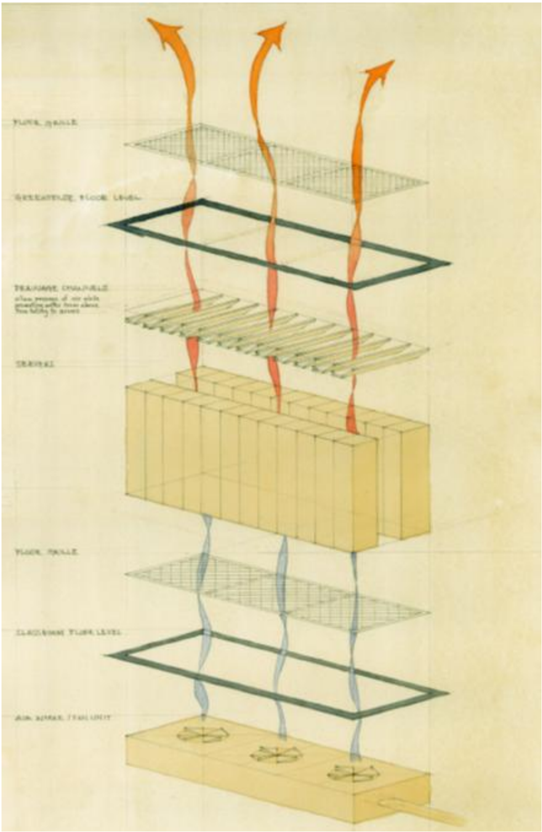

Figure 5: Schematic Design showing EOC design for heating a second floor greenhouse. Image: Evan Possley

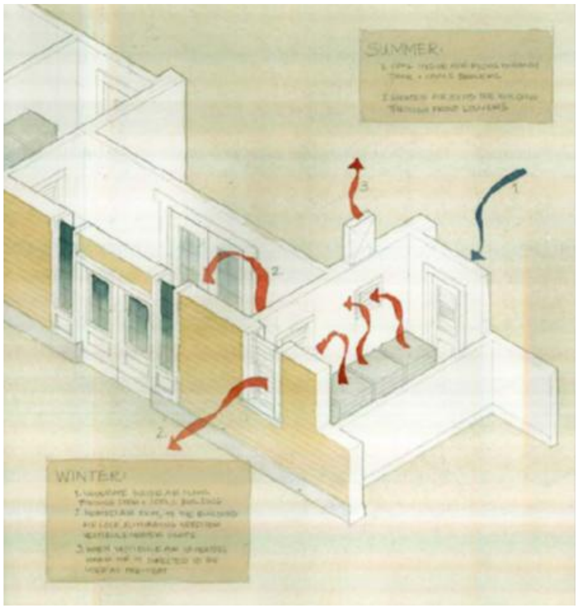

Figure 6: Schematic Design showing EOC nodes integrated into the building to condition air locks at exterior doors. Image: Julie Bujnowski

explore the potential for widespread deployment of this novel technology at various scales: at the level of compartment or single room, a standalone building, or a series of interconnected buildings (e.g., a campus, town, or city). In concert with bench-scale research and full scale, field-based data, our studio-based design investigations support further examination of the many complex, multidisciplinary, and multi-scale technical and operational considerations involved in EOC integration – or the balance of "market forces" that we have identified as critically related to the implementation of EOC technology.

CONCLUSIONS AND OUTLOOK

In the long run, waste heat generated from computational systems can no longer be ignored. A traditional data center consumes one hundred times the amount of energy than a standard office building, and only fifteen percent of the original source energy is consumed by the hardware itself[17], meaning that most of the energy used is devoted to just cooling the hardware. Ultimately, when these statistics are coupled with those that describe building sector operating energy consumption, a unique opportunity to study energy conservation emerges for engineers and architects. **Essentially, how can we use one energy use problem to solve another?**

Today, we must contend with technology – and its by-products – on a scale previously unimaginable. **And yet, at present, we have not yet found a way to capitalize on what is perhaps one of our largest untapped and underutilized thermal resources: information and communications technology.** We can harvest heat from the sun and the earth to warm our buildings, passively cool them with wind catchment structures, and harvest energy from the tides, but the successful and useful integration of ICT into the built world is a design challenge that has not yet been sufficiently explored.

In order to arrive at a sustainable solution and move EOC technology forward, faculty and students across the disciplines of architecture, engineering, and computer science will continue their analysis and testing of theoretical EOC integration with existing buildings and in the design of new, EOC-enabled buildings, leading ultimately to the development of an evaluative model, dynamic optimization toolset, and a series of facility integration guidelines designed to 1) assist engineers and architects in the selection of EOC as a viable and competitive integrated building system, and 2) serve as a resource to guide the design and implementation of EOC in buildings. The integration guidelines will also serve to facilitate and accelerate recognition of the evaluation model as an assessment tool for sustainable energy source integration and EOC technology, specifically, by organizations like ASHRAE and the International Code Council (ICC) that establish and maintain prevailing energy standards and design guidelines (e.g., like ASHRAE's Standard for the Design of High Performance Buildings 189.1[18] and the model International Energy Conservation Code[19]), and those that promote sustainable building practices like the USGBC through its LEED building accreditation program[20].

Another important aspect of this research is the necessity to assess the efficacy of EOC technology in conjunction with traditional mechanical systems, including the development of enhanced pathways between computational hardware and those existing distribution systems, and possibly the design of altogether new, EOC-inspired systems. Therefore, theoretical testing and practical, full-scale implementation of EOC technology also has the potential to contribute more broadly to sustainable building and system design practices by inspiring the development of novel distribution systems and innovative, hybrid structural/ delivery systems related to the energy conservation concept.

As early data from the Green Cloud prototype demonstrates, and the unique conservation partnership between a municipality and an institution that it fosters, the ability to calibrate EOC technology to meet the needs of a single building or a network of buildings means broad potential for buildings and organizations to mutually benefit from this new energy conservation concept. By treating high performance ICT equipment not as an isolated entity, but as an available and *useful* heat source, EOC has the potential to transform current sustainable building practices and create a critical paradigm shift where the question will no longer be *how to cool data centers* but rather, *how to most effectively utilize computational waste heat* in the built environment.

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NOTES

Figure References

Figure 1: Illustration by Author

Figure 2: Photo by Author

Figure 3: Illustration by Undergraduate Student Researcher/ Studio Participant Cristina Gallo McCausland

Figure 4: Illustration by Undergraduate Student Researcher / Studio Participant Gina Paietta

Figure 5: Illustration by Undergraduate Student Researcher / Studio Participant Evan Possley

Figure 6: Illustration by Undergraduate Student Researcher / Studio Participant Julie Bujnowski

Table References

Table 1: Table by Authors

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