Data Center Heat Recovery Models and Validation: Insights from Environmentally Opportunistic Computing

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ABSTRACT

Residential and commercial buildings account for nearly 40% of United States (U.S.) energy consumption and related carbon emissions as well as 72% of total electricity consumption. Tangentially, the U.S. Environmental Protection Agency estimated the U.S. spent over $4.5 billion in 2006 to cool and power data centers and this expenditure grew by 56% from 2005 to 2010, on par with U.S. EPA, The Green Grid, and International Data Corporation predictions. Clearly, there is an urgent need to rethink the paradigms for both building energy consumption and data center energy management from a combined economic, environmental, and energy perspective. While the established optimization of buildings and data centers individually is one approach toward energy efficiency, harvesting the heat produced by data centers for use in buildings that need heat addresses both these problems in a holistic, integrated, and more effective manner. Our approach to more efficient operation of information and communication technology (ICT) infrastructure is Environmentally Opportunistic Computing (EOC), an energy conservation concept under development at the University of Notre Dame. The primary goal of EOC is to distribute computing resources such that the waste heat produced by the computational equipment can be used to reduce the heating demands of an integrated facility and the facility's exhaust air can cool the ICT equipment. However, the implementation of EOC is inherently interdisciplinary, requiring elements of data center managements, thermal analysis, and building design. In this work, we present the various perspectives that must be considered when exploring EOC and studies conducted to date that demonstrate and evaluate EOC. In particular, we focus on computer science, engineering, and architecture challenges and how these are considered through the lens of our proof-of-concept prototype, the Green Cloud, integrated with a local greenhouse

INTRODUCTION

In our finite physical world of growing population, sustainable development and societal planning have complex and debated global benefits, where the absence of objective, sustainable processes has debated global consequence. The complexity arises from both social (economics, psychology, sociology, etc…) and scientific (biology, chemistry, physics, etc…) aspects over temporal and physical scales unfamiliar to the majority of our growing human population. It is within this "Grand Challenge" that we have evolved our sustainability research over the past 5 years, with a focus on the applied engineering, architectural, and economic aspects of sustainable information and communications technology (ICT) infrastructure. Increasingly, societies around the globe utilize ICT in every part of their lives [1] and the large, diverse, and exponentially growing data sets [2] that underlie our interconnected societies require a robust infrastructure to meet the growing demand for access and computational speed. The estimated energy demand to power and environmentally condition this infrastructure grew from ~$4.5 billion in 2006 to ~$7 billion in 2010 [3,4] *despite* suppressed global economic conditions.

The economic and environmental importance of this challenge has been recognized by numerous commercial, professional, government, and academic organizations; who are working to make ICT infrastructure more sustainable while meeting the growing capability demand. ICT service (software and cloud) providers such as Google, Yahoo, Amazon, Microsoft, and Facebook are

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working aggressively to reduce the energy demands of their data centers through greater system utilization and better facility design in order to improve their bottom-lines and lower their corporate carbon footprint [5,6,7,8,9]. ICT hardware providers (Intel, AMD, NVIDIA, IBM, Dell, HP, Cisco, etc..) have invested heavily into new lower-power computational technology to improve the number of floating point operations (FLOPS) and input/output operations (IOPS) per watt. Data center utility component manufacturers such as Emerson, Schneider Electric (APC), and Trane are working at the interface of ICT and facility engineers to deliver power and cooling solutions as close to computation as possible for efficiency optimizations. Operating system and application software vendors such as Microsoft, Apple, RedHat, and Oracle have re-engineered software frameworks to remain fast and responsive while allowing for more automated and dynamic low power sleep states for sporadically idle hardware components. Professional organizations such as ASHRAE (Technical Committee 9.9), The Green Grid, and IEEE are bringing together facility engineers, ICT engineers, and administrators to develop and catalog metrics and best practices for sustainable ICT infrastructure construction, renovation, and operation [10,11,12]. Government organizations have also taken an active role in funding, educating, and regulating data center efficiency through activities such as those administered through the DOE (Energy Efficiency and Renewable Energy, DC Pro) and EPA (EnergyStar) programs.

Our approach to more sustainable ICT infrastructure is rooted in the concept that the energy used by data centers manifests itself as waste heat and that this waste heat is both usable and useful. Environmentally Opportunistic Computing is an apporch to sustainable ICT infrastructure where data centers are decentralized and integrated directly with other-purposed buildings and facilities, acting as a heat provider directly to the building they service. The effective use of low-grade waste heat from a variety of industrial and commercial sources is a well-known engineering challenge that has been under investigation for decades. Our EOC research seeks to balance the reutilization of waste heat from ICT infrastructure with effective ICT infrastructure operations in new energy-efficient building designs. In short, we aim to identify the optimal integration of ICT infrastructure with facilities or processes that can effectively utilize the waste heat without sacrificing ICT performance. To this end we have evolved the concepts over the past five years through multiple prototypes [13,14,15,16,17,18] moving from small scale thermal control of office room temperatures through dynamic computation scheduling (Grid Heating) to the integration of a partial rack of servers and ultimately a containerized data centers into a greenhouse as proof-of-concept (GreenCloud). In this paper we provide our validation metrics as applied to both our physical prototypes and more generalized larger-scale future deployments. We do so from three primary professional perspectives: computer systems engineering, mechanical engineering, and architectural design.

EOC COMPUTATION AND SYSTEMS ADMINISTRATION: A COMPUTER ENGINEERING PERSPECTIVE

ICT end users and systems engineers focus on application/computation service reliability, speed, responsiveness, security, and cost. Customer prioritization of these factors varies based on service (bank transaction, database query, delivery of a news feed, scientific computation, etc.) and, to a lesser extent, on delivery device (desktop, laptop, tablet, or mobile phone). Thus there is considerable flexibility in infrastructure deployment characteristics (location, type of building, distribution scale, etc…), which are effectively obscured from the end user except through their impact on those user experience factors that matter to them. With a focus on ICT waste heat reutilization, our target is then to locate infrastructure as close to a persistent thermal demand for the waste heat to capitalize on energy reutilization to reduce cost and carbon footprint while not degrading the user experience. The validity of EOC from a computer engineer's viewpoint is therefore twofold: (a) Is EOC technically viable, meaning does the technical software/hardware capability exist, and (b) is EOC practically viable, meaning will reliable, fast, responsive, and secure computational services be delivered at lower cost (where cost includes additional capital and operational overheads)?

First we discuss the technical viability from a computer engineering perspective; leaving a technical discussion of the thermodynamics for the mechanical engineering section. Our first prototypes, called "Grid Heating" appliances, configured existing software tools for distributed computation to dynamically control local space heating demands. We added 6 computational servers (12 CPUs) to a standard office space fitted with temperature sensors and isolated from the facility's central air system. We then configured the Condor distributed/grid computation framework [19] and our test servers to dynamically schedule and execute work load while also meeting the thermal targets of the office space. As demonstrated in Figure 1, we were successful in scheduling (executing, idling, and evicting) compute load to provide a waste heat source (proportional to the degree of computation) that met defined temperature targets for the space within a fine degree of granularity (+/- 1 degree). The results provided a baseline validation that computation and its dynamic scheduling over various server components could provide a tunable thermal load.

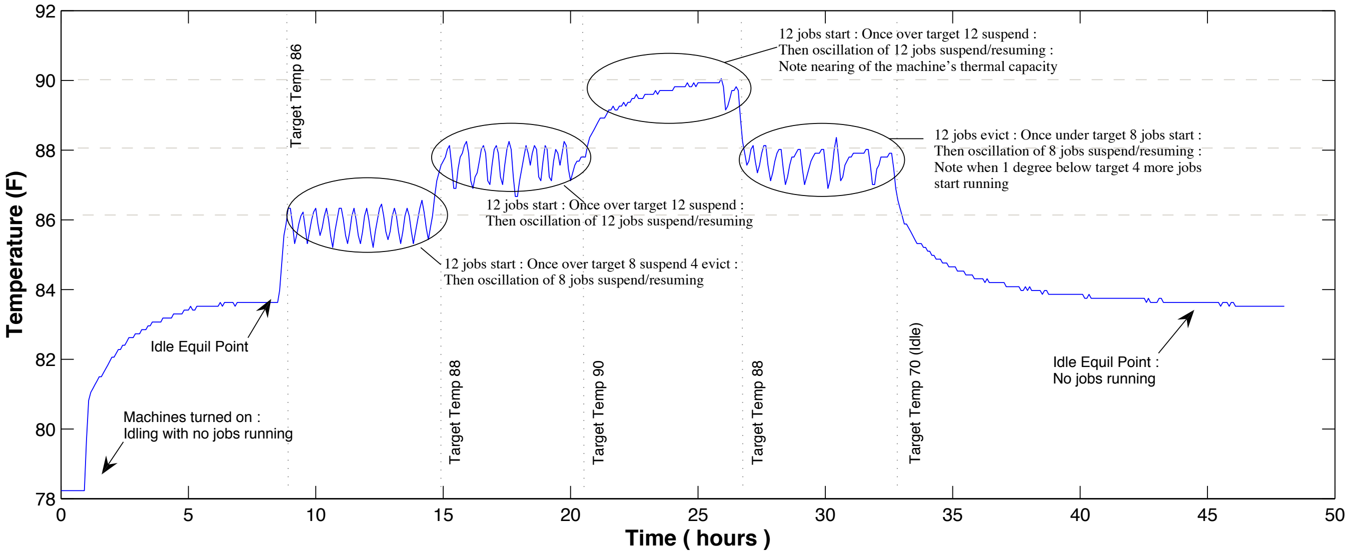
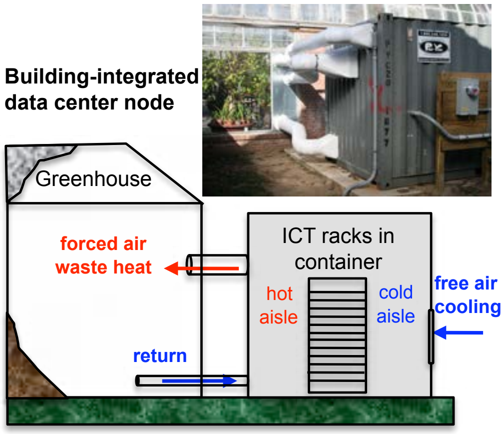


Fig. 1. Schematic and photo of our experimental platform – a data center node integrated with the local Greenhouse.

The next step was to expand EOC to larger practical deployments. To this end we partnered with the South Bend Botanical Society, which was struggling with costs to heat their greenhouse. Because ICT infrastructure was foreign to botanists, we started with a small 1/3 rack server deployment located directly in the greenhouse's "desert dome". Sufficient power existed locally for the ~2 kW ICT deployment. The networking challenge was met by contracting a commercial satellite dish network provider. Within a few months the computers were online, connected to the Notre Dame computational network, and running computational chemistry simulations as scheduled by Condor, while acting as a small space heater in the desert dome. To increase the scale by another order of magnitude we needed to address a number of practical issues: acoustics, ~50 kW of dedicated power availability, network bandwidth at 1 Gbps, and secure access. The secure access and acoustic concerns were met by locating the ICT in a container external but adjacent to the greenhouse. The power needs were met through coordination of a new dedicated power panel. Finally the 1 Gbps connectivity was enabled via fiber optics tunneled underground to the nearest City of South Bend MetroNet connection point, which provided a dedicated path to the Notre Dame network. The container was ducted to the greenhouse and outfitted with fans that drew ambient air into the container, heated it via three server racks, and then pumped it into the greenhouse as space heat. The "Green Cloud" prototype was born (Figure 2 next section) and became an active test bed for EOC research. Direct space heat has been delivered to the greenhouse during cool months at variance between ~15-40 kW of power depending on the tests at hand. In warm summer months the Green Cloud has served as a platform to test various Condor control algorithms that control the number of active servers ensuring that operate within a set of prescribed temperature limitations. The largest practical limitations to viability have been the distance from system engineer offices (making server maintenance difficult) and the absence of a cooling infrastructure for warm summer days (currently free cooling only). Our EOC team is now in the development stages for the next generation prototype "Green Cloud 2" that will address these limitations.

EOC HEAT RECOVERY MODELS: A MECHANICAL ENGINEERING PERSPECTIVE

While the Green Cloud serves as an essential experimental demonstration of the EOC concept and an excellent platform to test new Condor control algorithms and configurations, optimal design and scaling issues can only be reasonably addressed through suitable thermal models. Ideally, a comprehensive thermal model would model not only the ICT data center containers, or nodes, but also the adjacent building or facility the model could then be used to predict the overall energy consumption of the combined data center nodes/building. Such a comprehensive model might be organized as shown in the schematic in Figure 3, where the data center nodes and building are treated as separate zones that are analyzed individually but where variables are passed between them based on the nature of their coupling. Aspects such as the weather, which affects free cooling and thermal losses through the envelop of the nodes and building, the dynamic Condor control algorithms, which affect the heat provided by the servers q_{ICT}, and the control of the building's native heating, ventilation, and air conditioning (HVAC) system can all be simulated to understand the dynamic nature of reutilizing waste heat from the data center nodes and the impact on energy consumption. As laid out in Fig. 3, existing mathematical software such as Simulink by MATLAB [20] is ideally suited for such a task. We have recently begun building this comprehensive thermal model in Simulink focusing on the data center node zones and the building zones.



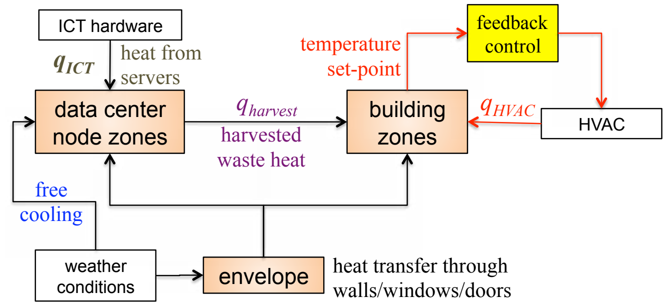


Fig. 2 and 3: 2) Schematic and photo of our Green Cloud experimental platform – a data center node integrated with the local Greenhouse. 3) Schematic of a comprehensive modeling strategy for an integrated ICT data center node/building thermal analysis.

Our first priority has been developing a thermal model that predicts the waste heat generated by the ICT hardware. With the Green Cloud prototype, we can calibrate and validate the thermal model against actual temperature measurements. The ideal approach to the thermal model would be three-dimensional computational fluid dynamics and heat transfer (CFD/CHT) simulations [21]. However, these are computationally expensive and time consuming, limiting their utility for design optimization or simulations of a wide variety of configurations and conditions. A more reasonable method, and one which easily fits within the overall simulation architecture of Fig. 3, is a control volume or thermal network approach. In these approaches, the primary features are treated as lumped masses and the thermal gradient across the features are considered negligible.

Figure 4a illustrates our first control volume analysis for the Green Cloud prototype [22]. The entire container is split into two volumes as illustrated in Fig. 2. Outside air initially enters the *cold aisle* and then is drawn over the ICT servers, picking up heat, and exhausted into the *hot aisle*. The air from the hot aisle is then pumped into the greenhouse as space heat. Conservation of energy for the two aisles leads to two first order differential equations for the cold (T_C) and hot (T_H) aisle temperatures, respectively,

$$\rho_C c_C V_C \frac{dT_C}{dt} = \underbrace{\dot{m} c_{in} T_{in}}_{\text{inlet airflow}} + \underbrace{\left(1/R_{mix}\right)\left(T_H - T_C\right)}_{\text{recirculation}} - \underbrace{\dot{m} c_C T_C}_{\text{exiting airflow}} \; ; \quad (1)$$

$$\rho_H c_H V_H \frac{dT_H}{dt} = \underbrace{\dot{m} c_C T_C}_{\text{inlet airflow}} - \underbrace{\left(1/R_{mix}\right)\left(T_H - T_C\right)}_{\text{recirculation}} - \underbrace{\dot{m} c_H T_H}_{\text{exiting airflow}} + q_{ICT} \; , \quad (2)$$

where ρ is the local air density, c is the local air specific heat, $\dot{m}$ is the mass flow rate through the container, T_{in} is the temperature of the air drawn in from ambient, and q_{ICT} is the heat from the servers. The parameter R_{mix} is a coefficient that represents the resistance to recirculation from the hot aisle to the cold aisle, an inherent in efficiency of any containerized data center.

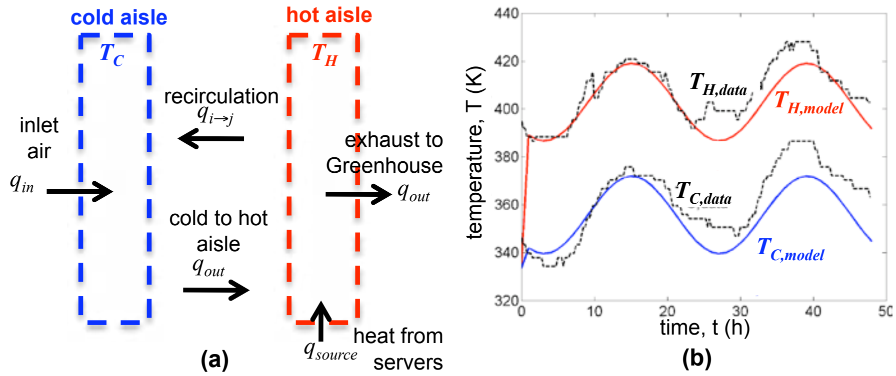


Fig. 4. (a) Schematic of two cold and hot aisle volumes and relevant heat transfer paths. (b) Comparison of model to temperature measurements from Green Cloud prototype.

Equations (1) and (2) can be solved analytically when the ambient air temperature $T_{in}(t)$ and the heat from the servers $q_{ICT}(t)$ are defined as smooth functions in time (*e.g.*, sinusoidal) as shown in Fig. 4b, or they can be solved numerically given real, stochastic T_{in} and q_{ICT} data from the Green Cloud prototype [22]. Critical to the solution, however, is defining the recirculation resistance R_{mix}. Ideally, this parameter is infinite such that there is no mixing and the amount of energy harvested from the container is exactly q_{ICT}. Realistically, R_{mix} is finite and is determined via calibration of the model to temperature data from the Green Cloud prototype. However, we have recently shown that *Rmix* is a strong function of not only the configuration of the container, but other parameters including the ambient air temperature [23]. Figure 5a, for example, shows measured (actual) and predicted temperatures for a set of data from April 2012, where a pre-calibrated R_{mix} value was used in Eqs. (1) and (2). Clearly, the model under predicts the measured temperatures, though it does accurately capture the temperature different between T_H and T_C as shown in Fig. 5b.

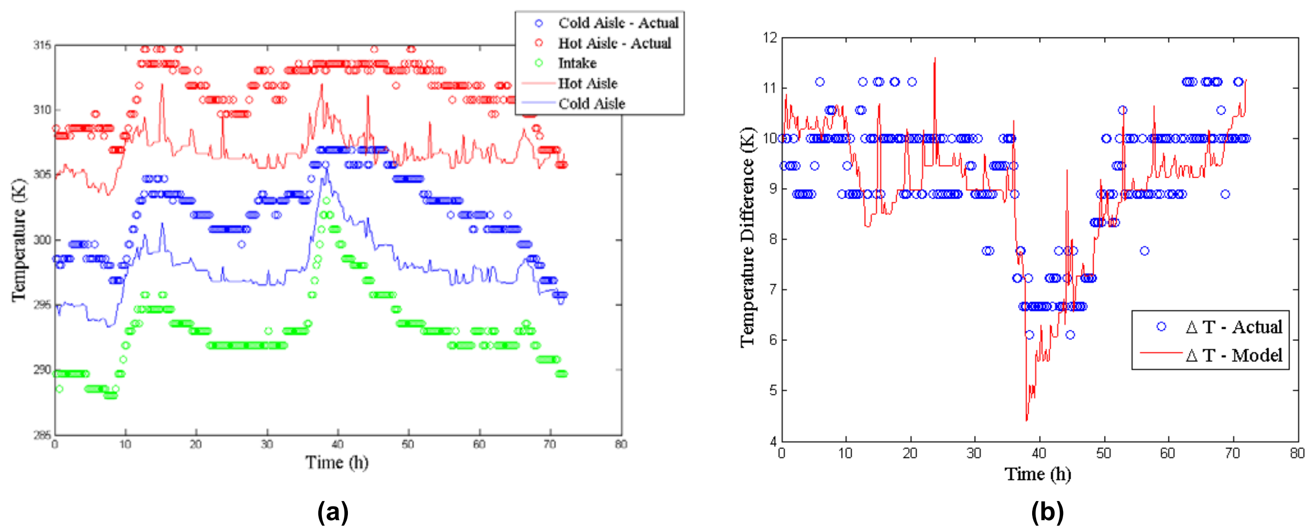


Fig. 5. (a) Measured and predicted temperatures from the GreenCloud prototype from April 2012 using a pre-calibrated R_{mix} coefficient. (b) Comparison of model to measured temperature difference, T_H–T_C.

The difference between the predicted and actual temperatures in Fig. 5a only highlights the complexity of these systems and the limitations of using simplified modeling approaches. In practice, for example, there can be severe temperature gradients that invalidate the lumped mass/control volume approach. Figure 6 shows a snap shot of the inlet temperature to each server in the container on typical day in July. The temperature difference between the bottom and top of racks is nearly 25 °F and there is a similar, though smaller, gradient across racks. These gradients are driven by natural convection in the container as well as the placement of the racks, fans, and inlet vents. A control volume model only treats the average of these temperatures and does not consider the extremes. Thus, such a model is sufficient to understand the influence of various parameters on the cold and hot aisle temperatures and waste heat produced by a data center node, but is insufficient to correctly predict absolute temperatures.

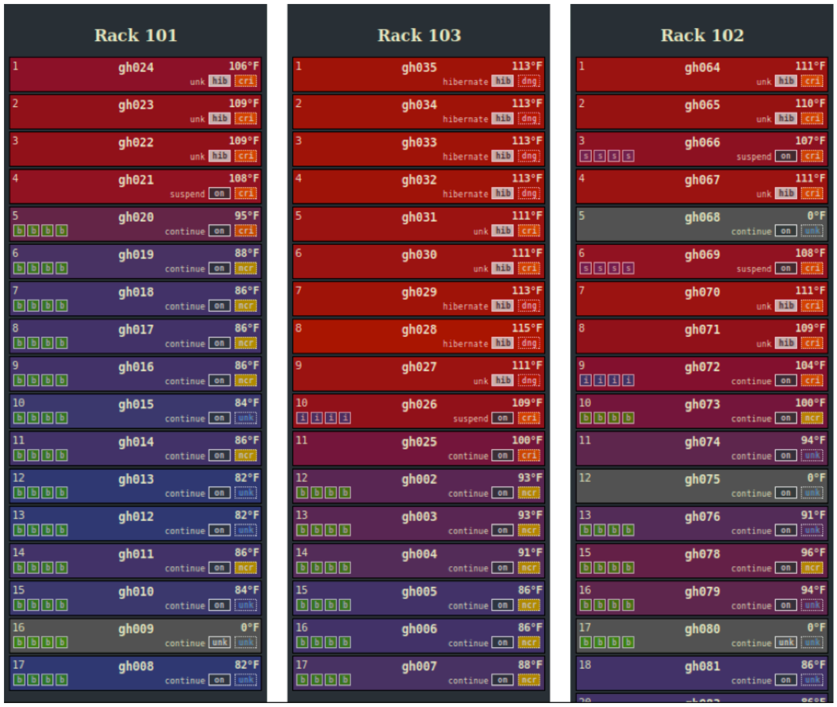


Fig. 6. Inlet air temperatures from the cold aisle to the three racks in the Green Cloud prototype from July 2010.

It is clear that using control volume models, while computationally efficient, are limited in their ability to predict the temperature and heat recovered from a data center node, and it is reasonable to assume that a control volume model of the adjacent building will face similar challenges. Yet, using these simplified approaches in a comprehensive model is suitable for back-to-back comparisons and first level optimization of the ICT node/building configuration. In actuality, because of the wide variety of parameters and design variables that influence the operation of the ICT node/building configuration, optimization is a "wicked" problem with no ideal solution, only better or worse configurations [24]. Our thermal modeling approach will lead us to understand the primary design variables but more detailed thermal analysis, including CFD/CHT, will be required for detailed analysis.

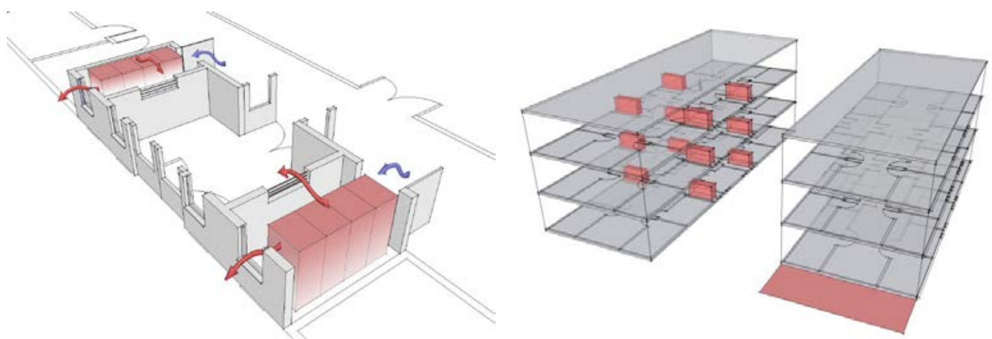
EOC'S CONTRIBUTION TO SUSTAINABLE BUILDING: AN ARCHITECTURAL PERSPECTIVE

While the feasibility of harvesting the waste heat from a data center node for an other-purposed building has been demonstrated through our prototype, the design of an integrated node/building system has not been fully explored. Our research further intends to explore the critical parameters that influence the design of an EOC-enabled structure and how to optimize these parameters while minimizing the net energy impact of the overall building-integrated system. It is important to holistically evaluate all potential benefits and trade-offs associated with EOC. In order to understand the true efficacy of EOC when deployed at the building scale, it is important to evaluate and determine the potential broader impacts. Foremost among these is the net energy impact of a building or structure that has been specifically designed to accommodate data center nodes.

Therefore, our research takes into consideration the physical changes made to a building to accommodate data center nodes and how those changes may potentially increase overall building volume and surface area, compromise spatial relationships (and occupant function and the usefulness of space), and increase material quantities, all of which relate to building net energy consumption. In this way, we consider not only the potential benefits of the technology towards reducing operating energy consumption (by the integrated computational hardware and the building), but also inherent material energy tied to the specific organization, configuration, and construction of an EOC-enabled structure.

In preliminary studies that incorporated data center nodes into a new institutional-use building (Fig. 7a), we began to evaluate both quantitative and qualitative (functionality, aesthetics) impacts of node emplacement on the building and ways to either mitigate or amplify these impacts. For example, how nodes placed optimally for heat transfer within a zone affect internal building circulation and influence the overall depth and configuration of the floor plate. Or conversely, when placed optimally to take best advantage of free cooling, how nodes affect vertical building organization and overall building massing. Empirical analysis in these studies focused primarily on impacts related to building volume (including increased volume of space to condition) and building envelope (or surface area). Using our prototype as a model unit, we estimate that a 5 rack data center node producing ~30 kW heat (3 server racks) has a physical footprint of ~18 m^3, depending on fan speed (itself an energy expenditure). Recognizing that a data center node has a far smaller energy density than a comparable air heating system but a far larger physical footprint, our design studies reveal that the integration of distributed data center nodes throughout a building may significantly impact the configuration and overall volume of the building; either the overall building footprint must get larger to accommodate the nodes or the overall building footprint may remain the same, but the interior, functional space is impacted (Fig 7b).

As such, our preliminary analyses demonstrate that compromises will necessarily be required – and must be accounted for – in the modification of existing buildings or in the design of new buildings to accommodate EOC heat sources. Increased volume and surface area necessarily correlate to the quantity of materials needed to achieve building structure and enclosure and increased surface area for heat loss, both of which affect net life cycle energy consumption. Further, similar comparative analyses of buildings designed with and without data center nodes will be useful in order to establish a baseline expectation for the energy savings potential of harvesting data center waste heat within other-purposed structures. These analyses will consider not only end user/ building energy consumption, but also the transfer of energy consumption from a traditional, centralized data center model to a distributed, building-integrated model; i.e., the energy impact of a quantity of servers located in a traditional, centralized data center versus the net energy impact of distributing and integrating those servers across a building or network of buildings.



(a) (b)

Fig. 7. (a) Illustration of potential implementation of data center nodes into a single-level building. Two nodes could be integrated in each wing of the building and directly ducted with the heating and ventilation system. In this illustration, the nodes take in ambient air and exhaust heated air into the building (or back to ambient in warm summer months). (b) Conceptual diagram of a representative building with and without data-center nodes illustrating the impact of integration on total building volume (structure and materials).

CONCLUSION

In this work, we have overviewed the principle of EOC and current research efforts to develop and establish EOC as a viable approach to sustainable ICT infrastructure and buildings. As an intrinsically interdisciplinary endeavor, there are many fundamentally different parameters that influence design and implementation of EOC. While the operation of a data center node must take into consideration the performance of the ICT hardware itself, optimal integration with a building requires both operational and design perspectives – that is, thermal analysis and design is required to optimize energy use but architectural study is necessary to understand the influence of a node on the form and function of a building. Here, we have presented various perspectives and progress made along these three disciplines in EOC research.

Ultimately, however, while studying the design and implementation of EOC is a necessary step in translating EOC from concept to practice, a higher-level perspective is important to visualize the future of ICT infrastructure. Our EOC vision is a series of data center "cloud" nodes implemented across a municipality, community, university, or industrial campus. Buildings throughout the municipality are outfitted with data center nodes that either provide space or water heat, depending on the needs and function of the building. Computational jobs are then migrated from node to node based on the computational requirement of the job, the availability of servers in the node, and the waste heat required by the integrated building. Further this vision can be extended across multiple communities where local utility availability and cost also play essential roles in the EOC marketplace. In this implementation, EOC provides a viable solution to the ever-expanding need for ICT capability while simultaneously addressing the need for energy efficient data centers and buildings.

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