Creating a Sustainable IT Ecosystem: Enabling Next-Generation Urban Infrastructures

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***Abstract*—In this paper, we describe an integrated design and management approach to creating a *sustainable IT ecosystem*: a physical infrastructure where information technology has been seamlessly interwoven to improve environmental efficiency while achieving lower cost. Specifically, we describe five principles to achieve such integration: ecosystem-scale life-cycle design; scalable and configurable resource microgrids; pervasive sensing; knowledge discovery and visualization; and autonomous control. Application of the approach is demonstrated for the case study of an urban water infrastructure, and we find that the proposed approach could potentially enable reduction of life-cycle energy use by over 15%.**

***Index Terms*—information technology, physical infrastructure, sustainability, urban design**

I. Introduction

The United Nations has estimated that 3.3 billion people live in cities and towns, about half of the world population, and the U.N. projects that this will increase to nearly 5 billion people by 2030, which by then will be approximately 60% of humanity [1]. This population growth will require the creation of a new generation of cities in emerging economies and around the globe. This new physical infrastructure will require significant amounts of materials and energy for construction, operation and disposal. The resulting risk to the carrying capacity of the biosphere – including the threats of climate change and growing scarcity of water, food, and fuel – necessitates appropriate choices of least-material, least-energy design and operation for next-generation infrastructures.

Unlike the previous generation of cities built during the Industrial Age, the next generation will have access to technologies from the Information Age. While the need for information and the ability to communicate have always been mainstays of cities, we can now embed information and communication technology into *everything*. While researchers, city planners, and others have been working on such concepts as intelligent cities and spaces [2], as well as the integration of computing and sensing technologies with the physical world [3], [4], a concise framework for achieving such integration of IT into the physical infrastructure is lacking. This paper provides such a framework: *sustainable IT ecosystems*, which are alternatives to conventional physical infrastructures that are more sustainable due to integrated design and management with IT. We propose five principles for achieving this:

1. Ecosystem-Scale Life-cycle Design (Section II)
2. Scalable, Configurable Resource Microgrids (Section III)
3. Pervasive Sensing (Section IV)
4. Knowledge Discovery & Visualization (Section V)
5. Autonomous Control (Section VI)

As shown in Fig. 1, we propose uniformly applying these principles across each of the different urban infrastructures. Using the same structure in the design and management of all the different infrastructures provides the opportunity to take advantage of any interdependencies, while potentially eliminating many inefficiencies and redundancies across the different verticals. Such an approach has been previously discussed for improving the sustainability of large-scale IT infrastructures, such as data centers [5]; in the present work, we describe how these principles could be applied to physical infrastructures for the creation of sustainable IT ecosystems. Section VII illustrates this for the case study of water microgrids, while we summarize the conclusions of our study in Section VIII.

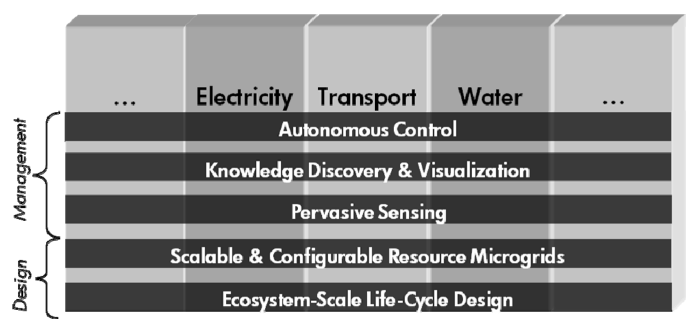

Fig 1. City 2.0 Architecture for a Sustainable IT Ecosystem.

II. Ecosystem-Scale Life-cycle Design

A critical challenge in creating sustainable IT ecosystems will be ensuring that choices made at design time do not result in detrimental behavior downstream during the life-cycle. Life-cycle assessment (LCA) provides a useful approach in such Design for Environment (DfE).

The notion of LCA is not new [6], [7] and has been successfully applied for many decades in various fields.

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Traditional LCA approaches have involved building detailed inventories of unit processes and products flowing across the entire life-cycle – from extraction of raw materials and manufacturing through distribution and retail to operation and end of life. Having aggregated these inventories through proxy indicators [8] such as mass, energy, exergy or in terms of unit processes and products, standardized or documented impact factors can then be applied across the inventory to obtain the environmental impact along a multitude of impact categories [9], [10]. Many off-the-shelf software packages [11]–[14] are available for implementing LCA.

Unfortunately, most of these LCA approaches are focused on product- or system-scale implementation (on the order of hundreds to thousands of components) using standard assessment methodologies. To create sustainable IT ecosystems, more advanced design tools that enable a higher degree of hybridization in LCA will be required; such tools will also need to deliver improved validation, rapidity and scale to the design methodologies. Such hybridization may include a combination of streamlined methodologies [15], economic input-output techniques [16], traditional process LCA [7], object-based modeling [17], and other approaches including Design of Experiment techniques [18] along with innovations in computational LCA approaches [19]. Once successfully integrated, such a toolkit would enable designers with a multi-stage layered approach that allows an initial narrowing of the design space into discrete subsets of parameters, whose resolution is then gradually increased for the most sensitive objects as the size of the design space is expanded. While the analytical and computational complexity of such an approach previously prohibited its widespread deployment, we have now reached a point where the IT infrastructure – including software development, programming techniques, and computational hardware – enables such large-scale analysis and design exploration using commodity systems. By using such technology to create a library of domain-specific methodologies and metrics, an integrated approach for ecosystem-scale life-cycle design can be achieved, and be applied to the use of IT in urban infrastructures.

III. Scalable and Configurable Resource Microgrids

To take advantage of the resources consumed during construction of the physical infrastructure, the sustainable IT ecosystem must provide high utilization in spite of shifting population and resource availability patterns. An agile infrastructure will be required to effectively adapt to changes during its long, extended operational life-cycle. As population growth expands urban centers, including megacities, scalability is a key attribute of infrastructures. Just some examples of urban infrastructures where security, configurability, and reliability are important characteristics include: power supply and distribution [20], and public safety/civil defense [21], [22]. We propose that the desired security, quality, reliability and availability for next-generation urban infrastructures be achieved by enabling integrated supply-side and demand-side management through systems of resource microgrids.

Such microgrids essentially consist of multiple discrete sources interconnected to provide an available resource pool, which can be depleted or replenished (supply-side management) as required to provide flexibility and a higher degree of customizability for meeting user needs (demand-side management). The concurrent emergence of smaller heat/power generating systems and other scalable technologies also provide novel options to create solutions that improve the reliability and scalability of supply-side infrastructures in the urban environment. The physical layer is comprised of microgrids of small (micro) sources and demand centers with flexible attributes; a rich intelligent monitoring layer continually provides information on the state of these entities. Fig. 1 shows the needs-based provisioning of resources using measurement and control. Policies driven by human interaction and automation guide the resource management within and across the verticals. (Note that the architecture is generalized so that it could easily be applied to other verticals, like food and health care, which have not been described in this paper for brevity.)

To cite an example, a grid of regional water storage reservoirs could store rainwater for energy and human use. Water supply could be regulated from these reservoirs based on usage patterns and monitored state. In the current centralized distribution system, urban water distribution can consume close to 1.2MWh of electrical energy for every million gallons of water. This energy use can be significantly reduced through the use of distributed and coordinated water microgrids, as discussed in Section VII. A similar analogy can be drawn for delivery of other goods and services like power, transport, food, etc.

IV. Pervasive Sensing

With recent advances in semiconductor technology and circuit design, we have seen the deployment of autonomous, low-power, low-cost, wireless sensor nodes throughout the environment and especially within urban spaces. These deployed nodes automatically form a robust ad hoc network known as a wireless sensor network (WSN).

System-on-chip methodologies have enabled the deep, on-chip integration of microcontrollers, memory, radio transceivers, and even antennae [23]. This has driven down the cost of wireless sensor nodes dramatically. These new economics allow for large numbers of nodes to be deployed widely and densely to achieve so-called “pervasive sensing.” These same economics also allow for a low labor strategy to deal with node failure: *fail-in-place*. An intelligent networking stack and system software that “routes around” failed nodes along with judicious over-provisioning make the system essentially maintenance free. This is imperative, as the cost to repair and/or replace deployed nodes would be prohibitive for many applications.

Low power design and careful budgeting and scheduling of energy use throughout the system facilitate operation by *energy harvesting* [24]. This greatly extends the range of application, as it eliminates the need for grid power or prohibitively labor intensive battery replacement. Whenever nodes are grid powered, they can help other nodes in the network conserve energy.

Pervasive sensing has many applications throughout urban spaces. Though this is a nascent technology, the literature already contains numerous useful applications in fields such as intelligent transportation systems [25], [26], air quality management [27], homeland security [28], [29], flood control [30], and the monitoring of civil engineering structures [31]. Furthermore, the potential of nanoscale sensors [32] raises the possibility for such sensors to get embedded in the infrastructure during the manufacturing process itself. This type of progression would eliminate the need for sensor installation. Such sensors could be inserted in the pavement at intersections for traffic sensing and control; injected in the concrete or paint of buildings, bridges and overpasses to measure stress; affixed to the coating on water and sewer pipes for monitoring flow and leakage; or embedded in the sheathing or insulation of electric cables to monitor and control power usage.

Sensing serves three broad purposes. The first is the detection of events of concern to the owners and managers of infrastructure. Events can be normal or abnormal occurrences and may vary in severity. Many are ignorable, but some require immediate remedial action. Events can be simple and directly sensed, such as the case of a failed component, or they can be complex and even synthesized from other sensors.

The second purpose of sensing is to supply data to tools that aid management. These tools include visualization of the operating conditions, knowledge discovery algorithms that can pore over sensor readings to find hidden faults or poor operating points (discussed further in Section V), and decision support systems.

The final purpose of sensing is in the implementation of autonomic control systems. Section VI discusses this implementation in further detail.

The volume of data generated by the plethora of sensors in a WSN is large and necessitates a scalable architecture for collecting and aggregating the data while disseminating it to multiple consumers. Data from the sensing layer must feed a number of "downstream" subsystems, including historical data recorders, event detection and alarming mechanisms, data analytics, visualization tools, decision support systems, and autonomic control algorithms.

Thus pervasive sensing requires a software stack that not only makes the sensor data available to consumers, but also describes the sensors and data produced sufficiently so that it can be placed in context. Some aspects of context are fixed for any class of sensor: measured quantities, precision and accuracy of those measurements, measurement range, measurement rates or bandwidths, and so forth. Others are a function of deployment. A common example of the latter is a node's location in three-dimensional space. This is ideally determined automatically by the sensor nodes' radios.

Many applications require timely delivery of sensor data. The requirements for timely delivery fall along a continuum with the need for real-time data at one end and the need for a historical record of data at the other. Real-time data feeds are particularly important for autonomous control, online data mining, decision support systems, and visualization dashboards. Offline data mining relies on historical archives.

V. Knowledge Discovery and Visualization

Knowledge discovery refers to statistical, data mining and machine learning techniques that transform and analyze data collected from various sources – including (but not limited to) pervasive sensing networks. An IT ecosystem generates large volumes of data related to its physical and operational state, including environmental sensor data (e.g. temperature), operational state of systems and devices (e.g. utilization values), and user demand (e.g. user requests sent to a data center, or load at a power distribution site). Broadly, these techniques, which can be applied to real-time data streams or to archival data, can enable six classes of outcomes: (i) event and anomaly detection, diagnosis and prediction; (ii) causality inference; (iii) discovery of patterns, rules, and associations; (iv) models for automated control; (v) automated planning and scheduling; and (vi) summarization and visualization of operational state and metrics through dashboards. These techniques have been widely applied to various components of existing urban infrastructures, including transportation, power, water, telecommunication, and networking. For example, intelligent transportation systems [25] rely heavily on knowledge discovery techniques for achieving cost-effective, high performing, safe and sustainable systems pertaining to land, water, air and space travel. These techniques are also being applied to assist in agent-based autonomous and distributed control of traffic [25], traffic flow prediction, inference of human behavior (e.g. if a driver is drowsy), identification of crash patterns for better future designs, and, automated resource allocation and scheduling [33].

Similarly, in telecommunication and networking systems, knowledge discovery techniques have been used extensively for applications including resource allocation based on demand prediction, detection of call fraud [34], [35] (including through visual analytics [36]), intrusion detection [37], [38], detection and diagnosis of failures [39], and customer relationship management based on customer behavior prediction [40]. In power systems, some tasks that use knowledge discovery techniques are planning and forecasting of power infrastructure extensions, involving estimation of future peak and minimum demand levels, future costs related to generation, fuel consumption, transportation and transmission of power; fault diagnosis; models for voltage control; and alarm processing [41], [42].

A key contribution of the current work is the recognition that – with the help of information technology – pervasive sensing and knowledge discovery methods can potentially be integrally deployed across different infrastructure verticals to obtain a more unified view of the urban environment. For example, the discovery of trends sensed within the water infrastructure could potentially inform operational choices related to the power infrastructure, which in turn might alter fuel demand and supply patterns. Another innovation required in the creation of a sustainable IT ecosystem will be the incorporation of sustainability metrics into knowledge discovery techniques.

VI. Autonomous Control

Ultimately, the goal of the physical infrastructure is to meet the needs of end users. Realizing this goal requires continual attention to sensor data reflecting the system behavior and the manipulation of actuators that modify that behavior to keep the system within a proper operating envelope. Failures in system regulation can result in disruption of services and even serious damage to the infrastructure itself.

In traditional urban infrastructures such as the electrical grid or potable water system, a control center staffed by humans performs this work. Given the complexity of such systems, human operators spend the bulk of their effort on maintaining the overall stability of the system. Their ability to optimize the system or to respond to local disturbances is limited.

Autonomous control is an attractive alternative. It is a mechanism by which a sustainable IT ecosystem can connect the sensed demands of users to the pool of supply-side resources available for consumption and can manage the infrastructure to deliver those resources efficiently. Autonomous controllers can often operate on larger volumes of sensor data, with larger numbers of actuators, and at faster rates than a human control center. This opens up the possibility of increasing efficiency and reliability of physical infrastructures, even to the point of being able to "do more with less."

To illustrate the applicability of autonomous control, we consider the vision of 'smart homes' – a key component of the urban infrastructure. As discussed previously, sensors will be pervasive throughout this infrastructure: to monitor light, temperature, power and water consumption, room entry and exit (including unauthorized entry for security monitoring), and movement. The sensor network would likely be wireless and connected to one or more cooperating nodes to enable coordination throughout the home.

Convenience is often mentioned as a benefit of control (e.g., [43]), but ultimately the most compelling reasons for autonomous control would be management of expenses and conservation of resources. Reducing heating or cooling in unoccupied rooms, detecting and controlling ambient lighting then reducing or extinguishing artificial lighting, and control of instantaneous load are likely benefits of distributed autonomous control. "Leakage" is a subtle but non-trivial contributor to expense, and it is estimated that 5-26% of a home's annual electricity use is the result of standby power consumption for televisions, set-top boxes and printers [44]. A control system could mitigate this, for example, by temporarily reducing the voltage for powered-off devices.

A final example of smart home autonomous control comes from the home health care field. The accelerated growth of health care costs has driven a need for distributed care giving. The ability to couple bio-sensing of vital signs with environmental and activity sensors will transform home health care and assisted living. Continuous monitoring and the ability to learn about a patient's normal activities will enable emergency situations to be detected and reported immediately, both reducing health care costs and improving quality of life for those in need [45].

Essentially, control theory provides a pathway to customize policies that govern the flow of resources through the ecosystem in accordance with inhabitant-driven needs.

VII. Case Study: Urban Water Distribution

To demonstrate the framework described in Sections II-VI for creating sustainable IT ecosystems, we consider the case study of water distribution for a city with a population of 1.5 million spread over 1500 km^2. Our baseline case uses a single reservoir for the entire city, which we compare against an ensemble of micro-reservoirs. The EPA estimates that the fresh water consumption for such a city is upwards of 150 MGD (million gallons per day) [46], including outdoor usage for swimming pools and landscaping with moderate evapotranspiration demand. As shown in Fig. 2, the phases of the water use cycle include *conveyance* from the source to the treatment plant, *treatment* itself, *distribution* from the treatment plant to the end users, and *wastewater treatment*. Summing the energy consumption per gallon across each of these phases determines the *embedded energy* for a gallon of water, of which distribution accounts for almost 30% in our baseline case, and wastewater treatment (including pumping) is nearly 60% (note that desalination is not considered in the present study). While treatment plants benefit from economies of scale, distribution systems are generally less integrated. They can be optimized at design phase to reduce the embedded energy content.

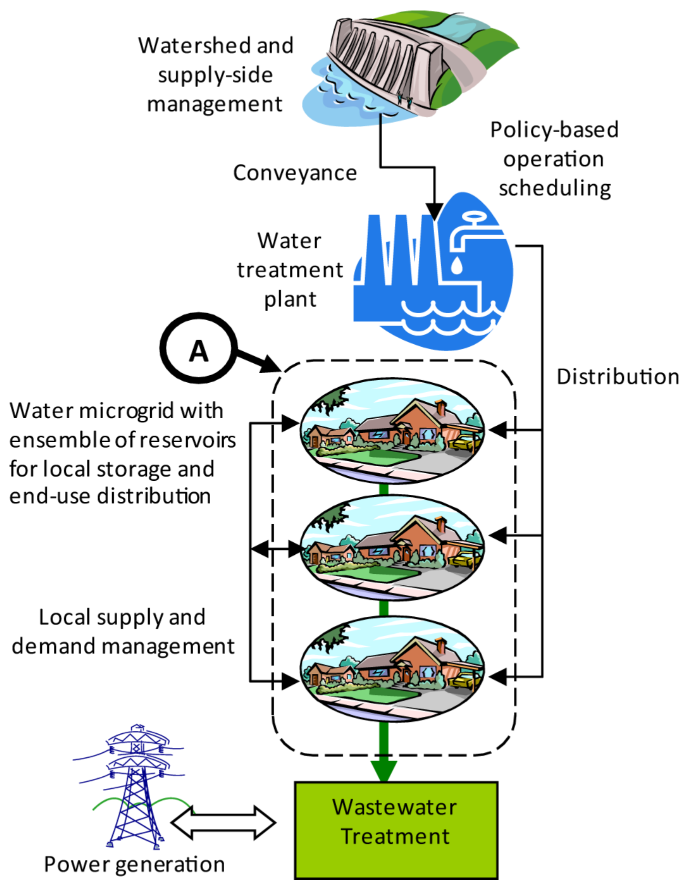

Fig. 2. Water Microgrid Architecture.

Small multi-purpose reservoirs are common for domestic water use and small scale irrigation in rural regions with highly variable rainfall that experience droughts and floods. A reservoir ensemble may be hydrologically linked by the streams or aquifers that feed them. We propose that this approach can be applied on a city-scale, as shown in detail

"A" of Fig. 2, to reduce the energy cost of water distribution. Such a configuration is scalable in the sense that additional reservoirs can be brought online to cope with growth in demand, and a wider variety of resources within the same network improves availability of water resources. Water can be traded between neighborhoods to balance supply and demand across the district. Moreover, since the proposed distribution system is tiered, there is no single point of failure, allowing water to be available during local power outages, assuming that each reservoir has sufficient static pressure head. Water microgrids also ease the isolation and containment of pathogenic elements in the water supply.

The location and size of reservoirs can vary; in the present study, we assumed a total of 50 reservoirs, each servicing a population of 30,000 with a capacity of 6 MGD. This microgrid approach enables the water to be stored closer to the end-users, so that small inline pumps can distribute water on-demand to local neighborhoods, as opposed to operating central pumping stations around the clock. Such a configuration has the potential to reduce the embedded energy for distribution by about 50% (i.e., a 15% reduction in total embedded energy), based on our estimates for pumping distances, which scale with the square root of the reservoir service area. Embedded energy could be further reduced by suitably locating the reservoirs at higher elevations. IT is an effective tool for simulating the results of design changes to large-scale infrastructures [47].

Although our current focus is on distribution only, other components of the water use cycle can also be implemented at the microgrid level. As the use of reclaimed water rises, a similar infrastructure of gray water microgrids can reduce demand for fresh water and the associated costs of conveyance and treatment. A water microgrid infrastructure also lends itself to integration with small-scale distributed energy resources. Such measures can reduce the emissions footprint of the water use cycle.

While reservoir ensembles store a significant quantity of water for convenient use, they also have an effect on downstream flows and need to be balanced against the tradeoffs resulting from the number and density of their structures. Multi-objective optimization using ecosystem-scale life-cycle design provides the framework to evaluate such trade-offs. For example, while a large number of different sources may provide higher operational flexibility, the material and energy required to harness and deliver the water also increases with the number of sources. If the final demand is usually much smaller than the overall water supply, then the additional flexibility enabled by a large number of water sources may never be fully utilized, but the additional embedded impacts – constructing a dam, building and laying out the piping networks, providing electricity to the pumps – will lead to a sub-optimal solution from a life-cycle perspective. Ecosystem-scale life-cycle design may be required to balance between investing the appropriate amount of resources up front and obtaining the highest return-on-investment during the use phase.

Having designed the water infrastructure for optimal life-cycle trade-offs, the resource microgrids can then be instrumented for pervasive sensing. Parameters of interest include direct monitoring of water quality, storage levels, water consumption, evaporative loss, and biological processes; as well as inferred monitoring of aggregated parameters such as hydrological impact and public health indicators. Enhanced sensing can help in improving the monitoring and management of these systems with quick turnarounds and minimal disruption of service.

Knowledge discovery techniques applied to monitored data enable identification of historical trends and prediction for future consumption, as well as the recognition of consumption patterns from which improved distribution methods could be discerned. Knowledge discovery can also diagnose and suggest remedial measures for faults in delivery systems, pumphouses and treatment plants, including faults such as pipeline leaks, pump malfunction, valve failure, and corrosion-related failures. According to UNDP, 30-50% of urban water is lost in leaks [48], so tracking and maintenance of lines is critical as utility districts grow. Knowledge discovery could be further extended to business and sustainability impact assessments.

Active management and control based on monitored and mined data ultimately enables the long-term sustainability of local water supplies and adequate downstream flows. Pumps and valves can be operated at points of peak efficiencies to reduce energy demands and operational costs. Large upstream pumps can run during off-peak hours to fill reservoirs for a predetermined demand period, and downstream pumps can maintain pressure based on real-time end-user requirements. Beyond improvements at the end-use level, the presence of water microgrids can also allow for coupled operation of the water treatment infrastructure, leading to opportunities for savings in the design and management of large plants. For example, water treatment facilities in New York consume more than 3000 GWh of electricity per year [49]. Even a fractional improvement in operation can offset a significant portion of the municipality's energy bill. Isolation of solid wastes before pumping waste water for treatment can also save pumping power; sensing, monitoring, and ultimately controlled removal of solids in the water streams is an example of how the presence of IT can further benefit the physical infrastructure.

VIII. Conclusion

The ability to integrate IT into the physical infrastructures provides a unique opportunity to improve the design and management of physical infrastructures. This paper provides a framework for creating such sustainable IT ecosystems: infrastructures wherein information technology is leveraged in an attempt to achieve sustainability through need-based management of supply-side and demand-side resources. Future work will seek to apply and demonstrate the proposed framework to diverse arrays of urban infrastructures.

References

[1] *World Urbanization Prospects: The 2007 Revision*, Department of Economic and Social Affairs, United Nations: New York, Feb. 2008.

[2] A. Steventon, S. Wright (eds.), *Intelligent Spaces: The Application of Pervasive ICT,* London: Springer, 2006.

[3] J. A. Stankovic, I. Lee, A. Mok, R. Rajkumar, "Opportunities and obligations for physical computing systems," *Computer*, vol. 38 (11), 2005, pp. 23-31.

[4] D. Estrin, D. Culler, K. Pister, G. Sukhatme, "Connecting the physical world with pervasive networks," *IEEE Pervasive Computing*, vol. 1 (1), 2002, pp. 59-69.

[5] B. J. Watson, A. J. Shah, M. Marwah, C. E. Bash, R. K. Sharma, C. E. Hoover, T. W. Christian, C. D. Patel, "Integrated Design and Management of a Sustainable Data Center," *Proc. ASME InterPACK,* 2009 [unpublished].

[6] H. Baumann, A.-M. Tillman, *The Hitch Hiker's Guide to LCA*, Studentlitteratur AB: Sweden, 2004.

[7] *ISO 14064: Environmental Management: Life Cycle Assessment – Principles and Framework*, International Organization for Standardization (ISO), 2006.

[8] E.G. Hertwich, W.S. Pease, C.P. Koshland, "Evaluating the environmental impact of products and production processes: A comparison of six methods," *Science of the Total Environment*, vol. 196 (1), 1997, pp. 13-29.

[9] O. Jolliet, et al., "Impact 2002+: A New Life Cycle Impact Assessment Methodology," *Int. J. LCA*, vol. 8 (6), 2003, pp. 324-330.

[10] M. Goedkoop, R. Spriensma, "The Eco-indicator 99: A damage oriented method for life cycle assessment," *Technical Report*, PRé Consultants, The Netherlands, 2001.

[11] *SimaPro LCA* Software [online], PRé Consultants, available http://www.pre.nl/simapro, last accessed March 30, 2009.

[12] *GaBi Software* [online], PE International, available Ihttp://www.gabi-software.com, last accessed March 30, 2009.

[13] Carnegie Mellon University Green Design Institute, "Economic Input-Output Life Cycle Assessment (EIO-LCA)," US 1997 Industry Benchmark model [online], available from http://www.eiolca.net, last accessed February 28, 2009.

[14] *Eco-LCA*, Ohio State University, available http://www.resilience.osu.edu/CFR-site/eco-lca.htm, last accessed March 30, 2009.

[15] T.E. Graedel, *Streamlined Life-Cycle Assessment*, Prentice Hall: New Jersey, 1998.

[16] C.T. Hendrickson, L.B. Lave, H.S. Matthews, *Environmental Life Cycle Assessment of Goods and Services: An Input-Output Approach*, Resources for the Future, Washington DC, 2006.

[17] A. Shah, W. Lugo, C. Patel, "Thermodynamics-Based Object-Oriented Environmental Analysis of an Industrial Air-Conditioner," *ASME Summer Heat Transfer Conference*, San Francisco, CA, 2009 [unpublished].

[18] C. R. Hicks, K.V. Turner, Jr., *Fundamental Concepts in the Design of Experiments* (5th Ed.), Oxford University Press: New York, 1999.

[19] R. Heijungs, S. Suh, *The computational structure of life cycle assessment*, Springer: New York, 2002.

[20] M. P. Ross, B. Kehrli, "Secure super grids: A new solution for secure power in critical urban centers," *Proceedings of IEEE/PES Transmission and Distribution Conference and Exposition*, 2008, pp. 1-7.

[21] M. Portmann, A. A. Pirzada, "Wireless mesh networks for public safety and crisis management applications," *IEEE Internet Computing*, vol.12 (1), 2008, pp. 18-25.

[22] K. Balachandran, et al., "Mobile responder communication networks for public safety," *IEEE Communications Magazine*, vol. 44 (1), 2006, pp. 56-64.

[23] F. Aquilino, F. G. Della Corte, M. Merenda, F. Zito, "Fully-integrated wireless temperature sensor with on-chip antenna," *Proc. IEEE Sensors*,2008, pp. 760-3.

[24] C. Ó Mathúna, et al., "Energy scavenging for long-term deployable wireless sensor networks," *Talanta*, vol. 75(3), 2008, pp. 613-623.

[25] F.-Y. Wang, "Driving into the Future with ITS," *IEEE Intelligent Systems*, vol.21 (3), January-February 2006, pp.94-95.

[26] M. Tubaishat, P. Zhuang, Q. Qi, Y. Shang,. "Wireless sensor networks in intelligent transportation systems," *Wireless Communications and Mobile Computing* vol. 9(3), 2008, pp. 287-302.

[27] J. Woo. "AirScope: A micro-scale urban air quality management system," *IEEE 4th Int. Conf. eScience*, 2008.

[28] J. Yu. "Self-powered wireless sensor balls for homeland security," *Proc. ASME Intl. Mech. Eng. Congress & Exposition (IMECE)*, 2007.

[29] K. L. Mills, "A brief survey of self-organization in wireless sensor networks," *Wireless Communications and Mobile Computing*, vol. 7 (7), September 2007, pp. 823-834.

[30] E.A. Basha, R. Sai, D. Rus, "Model-based monitoring for early warning flood detection," *Proc. 6th ACM Conference on Embedded Network Sensor Systems (SenSys)*, 2008.

[31] Y. Yu, J. Ou, "Development of a kind of multi-variable wireless sensor for structural health monitoring in civil engineering," *Proc. SPIE*, vol. 5765 (158), 2005.

[32] "Information and Quantum Systems Lab," Hewlett Packard Laboratories [online], available http://www.hpl.hp.com/research/quantum_systems, last accessed March 30, 2009.

[33] S. Tang, F.Y. Wang, Q. Miao, "ITSC 05: Current Issues and Research Trends," *IEEE Intelligent Systems*, vol. 21(2), 2006.

[34] J. Hollmen, V. Tresp, "Call-based fraud detection in mobile communication networks using a hierarchical regime-switching model," *Proceedings of advances in neural information processing systems II*, MIT Press, Cambridge, MA, USA, 1999.

[35] M. Taniguchi, et al., "Fraud detection in communications networks using neural and probabilistic methods," *Proc. IEEE Int. Conf. Acoustics, Speech and Signal Processing*. 1998, pp. 1241–1244.

[36] K. C. Cox, S. G. Eick, G. J. Wills, and R. J. Brachman, "Visual data mining: Recognizing telephone calling fraud," *J. Data Mining and Knowledge Discovery*, vol. 1 (2), 1997, pp. 225–231.

[37] A. Lazarevic, et al., "A comparative study of anomaly detection schemes in network intrusion detection," *Proc. 3rd SIAM Int. Conf. Data Mining*, 2003.

[38] C. Manikopoulos, S. Papavassiliou, "Network intrusion and fault detection: a statistical anomaly approach," *IEEE Communications Magazine*, vol. 40 (10), 2002, pp. 76-82.

[39] L. Vlahavas, et al., "ExperNet: an intelligent multiagent system for WAN management," *IEEE Intelligent Systems*, vol. 17(1), 2002, pp. 62-72.

[40] L. Yan, R.H. Wolniewicz, R. Dodier, "Predicting customer behavior in telecommunications," *IEEE Intelligent Systems*, vol.19 (2), 2004, pp. 50-58.

[41] D. S. Kirschen, B. F. Wollenberg, "Intelligent alarm processing in power systems," *Proc. of the IEEE*, vol. 80 (5), 1992, pp.663-672.

[42] J.R. McDonald, et al., *Intelligent knowledge based systems in electrical power engineering*, Springer: New York, 1997.

[43] B. Zhou, et al., "Novel Wireless Mesh Networking Architectures for Future Smart Homes," *Proceedings of the Future Generation Communication and Networking*, vol. 2, December 2007.

[44] J.P. Ross, A. Meier, "Whole-House Measurements of Standby Power Consumption," *Proceedings of the Second International Conference on Energy Efficiency in Household Appliances*, Naples (Italy), September 2000.

[45] M. Lamming, B. Denis, "Specs: Another approach to human context and activity sensing research, using tiny peer-to-peer wireless computers," *UbiComp 2003: Ubiquitous Computing 5th Int. Conf. Seattle Proc.*, 2003.

[46] "Outdoor Water Use in the United States", Environmental Protection Agency, August 2008, available http://www.epa.gov/OW-OWM.html/water-efficiency/pubs/outdoor.htm, last accessed March 27, 2009.

[47] R. Farmani, G. A. Walters, D. A. Savic, "Trade-off between total cost and reliability for Anytown water distribution network," *J. Water Resources Planning and Management*, vol. 131 (3), 2005, pp. 161-171.

[48] J. Barry, *Watergy: Energy and Water Efficiency in Municipal Water Supply and Wastewater Treatment*, The Alliance to Save Energy: Washington D.C., 2007, pg. 4.

[49] "Focus on Water and Wastewater", New York State Energy Research and Development Authority (NYSERDA), available http://www.nyserda.org/programs/Environment/muniwaterwwt.asp, accessed March 27, 2009.