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Smart Connected Buildings Design Automation: Foundations and Trends

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Abstract

Buildings are the result of a complex integration of multi-physics subsystems. Besides the obvious civil engineering infrastructure, thermal, electrical, mechanical, control, communication and computing subsystems must co-exist and be operated so that the overall operation is smooth and efficient. This is particularly important for commercial buildings but is also very relevant for residential buildings especially apartment buildings. Unfortunately, the design and deployment of these subsystems is rarely synchronized: lighting, security, heating, ventilation and air conditioning systems are often designed independently. However, simply putting together a collection of sub-systems, albeit optimized, has led to inefficient buildings of today. Worldwide, buildings consume 42% of all electrical power – more than any other asset – and it can be proven that much of this can be reduced if a holistic approach to design, deployment and operation is taken.

Government agencies, academic institutions, building contractors and owners have realized the significant impact of buildings on the global environment, the electrical grid, and the mission of their organizations. However, the economic impact for all constituencies is still difficult to assess. Government regulations can play a fundamental role, as it has been the case for the transportation industry where regulations on emission and fuel consumption have been the single most important factor of innovation in automotive design.

We are convinced that by leveraging technology and utilizing a system-level approach to buildings, they will provide comfort, safety and functionality while minimizing energy cost, supporting a robust electric grid and mitigating environmental impact. Realizing this vision requires adding intelligence from the beginning of the design phase, to deployment, from commissioning to operation, all the way to the end of the building's life cycle.

In this issue, we attempt to provide an overview of the activities in the field of smart connected building design automation that attempts to make the vision a reality. The overarching range of such activities includes developing simulation tools for modeling and design of buildings, and consequently control algorithms proposed to make

buildings smarter and more efficient. Further, we will review real-world and large-scale implementation of such control strategies on physical buildings. We then present a formal co-design methodology to design buildings taking the view that buildings are prime examples of cyber-physical systems where the virtual and physical worlds meet, as more traditional products such as thermostats are able to connect online and perform complicated computational tasks to control building temperature effectively. We complete the presentation describing the growing role of buildings in the operation of the *smart grid* where buildings are not only consumers of energy, but also providers of services and energy to the smart grid.

The audiences for this monograph are industry professionals and researchers who work in the area of smart buildings, smart cities and smart grid, with emphasis on energy-efficiency, simulation tools, optimal control, and cyber-physical systems design for the emerging and connected power markets.

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1

Introduction

The term *intelligent* or *smart building* refers to the next generation of buildings that provide new levels of comfort to the occupants with minimum possible energy consumption. They not only follow commands, but also proactively learn from occupants' behavior and adapt their operation based on the indoor and outdoor conditions. These buildings are no longer solely consumers of energy, but also significant players in the ecosystem of smart grid, in that they provide regulation services to the grid as well as energy if equipped with solar panels or other green sources. Intelligent buildings not only are safe by design, but also react in the case of a fault, system malfunction, or cyber-attack to steer the system into a safe operating region. There has been much research in academia and industry towards this goal. Companies such as Nest (https://nest.com/), recently acquired by Google, have been formed over the last few years to bring new technologies in this space to the public. In this paper, we present an overview of the work done in this domain over the last two decades.

1.1 Why Buildings?

But why buildings are so important? According to an Environmental Protection Agency (EPA)[1] survey, on average, Americans spend approximately 90% of their time indoors. Commercial Buildings Energy Consumption Survey (CBECS)[2] estimates that there were 5.6 million commercial buildings in the United States in 2012, comprising 87 billion square feet of floor-space. This level represents a 14% increase in the number of buildings and a 21% increase in floor-space since 2003, the last year for which results are available. Between the first CBECS (conducted in 1979) and the latest 2012 CBECS, the number of commercial buildings in the United States has increased from 3.8 million to 5.6 million, and the amount of commercial floor-space has increased from 51 billion to 87 billion square feet. On the residential side, nearly 130 million residential housing units existed in the U.S. in 2010. Approximately 7.188 million new housing units were built between 2005 and 2009, according to the American Housing Survey (AHS [2008]). The total primary energy consumption in the United States increased from 35 quads[3] in 1950 to 78.3 quads in 1980 to over 98.5 quads in 2014 as shown in Figure 1.1 by the Energy Information Administration (EIA)[4]. In 2014 the building sector accounts for 39.87% of this total consumption according to the EIA as shown in Figure 1.2. The industrial and transportation sectors represent the remaining 31.33% and 27.12%. Electrical energy consumption of buildings doubled in the last 18 years, and another 25% growth is projected through 2030. Residential buildings accounted for 54.6% of the total energy consumption in the building sector, while commercial buildings accounted for the other 45.4%. The building sector is also responsible for almost 40% of greenhouse gas emissions and 70% of electricity use. The energy consumption by Heating Ventilation and Air Conditioning (HVAC) systems is 50% of the total energy usage in buildings and 20% of the total national en-

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[1] Buildings and their Impact on the Environment: A Statistical Summary. http://www.epa.gov/greenbuilding/pubs/gbstats.pdf

[2] http://www.eia.gov/consumption/commercial/

[3] A quad is a unit of energy equal to 1.055×10^{18} joules.

[4] Annual energy outlook 2015. http://www.eia.gov/totalenergy/

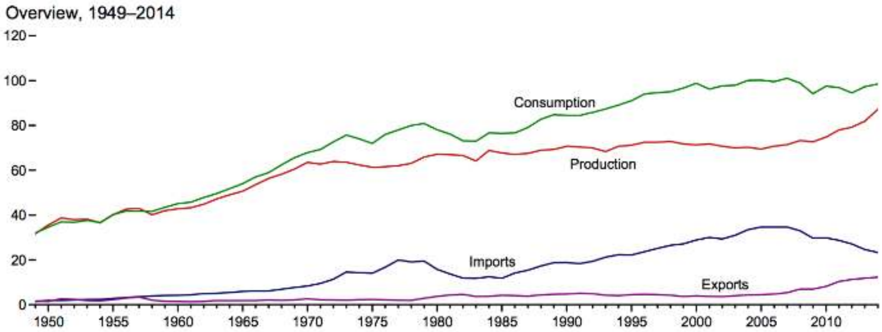


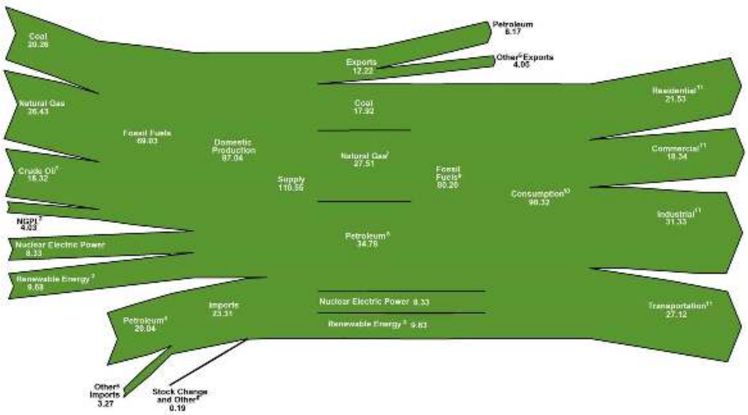
Figure 1.1: US Primary Energy Overview (Quadrillion Btu).

ergy usage in European and American countries Pérez-Lombard et al. [2008]. HVAC energy consumption can exceed 50% of the total energy usage of a building in tropical climate Chua et al. [2013].

The industrial sector has always been optimizing its processes to reduce cost and increase profit. In the transportation sector, in the last 30 years a great amount of work has gone into emission and fuel consumption reduction via better engine control, and efforts are already well under way to find suitable alternatives to oil. Bio-fuels are one possibility. Alternative types of vehicles – hybrids, electric vehicles, and vehicles powered by hydrogen fuel cells, for example – all have the goal of reducing our dependence on oil. The Corporate Average Fuel Economy (CAFE) standards, initially adopted in 1975, made more stringent in 2007, and strengthened again in pending legislation, require automobile manufacturers to build cars with higher average fuel economy. On the other hand, historically, not much has been done to improve the energy efficiency of buildings.

Growth in population, increasing demand for building services and comfort levels, together with the rise in time spent inside buildings, assure that the upward trend in energy demand will continue in the future. For this reason, energy efficiency in buildings is a prime objective today for energy policy at regional, national and international levels.

U.S. Energy Flow, 2014
(Quadrillion Btu)



[1] Includes lease condensate.
[2] Natural gas plant liquids.
[3] Conventional hydroelectric power, biomass, geothermal, solar/photovoltaic, and wind.
[4] Crude oil and petroleum products. Includes imports into the Strategic Petroleum Reserve.
[5] Natural gas, coal, coal coke, biofuels, and electricity.
[6] Adjustments, losses, and unaccounted for.
[7] Natural gas only; excludes supplemental gaseous fuels.
[8] Petroleum products, including natural gas plant liquids, and crude oil burned as fuel.
[9] Includes -0.02 quadrillion Btu of coal coke net imports.
[10] Includes 0.16 quadrillion Btu of electricity net imports.
[11] Total energy consumption, which is the sum of primary energy consumption, electricity retail sales, and electrical system energy losses. Losses are allocated to the end-use sectors in proportion to each sector's share of total electricity retail sales. See Note 1, "Electrical Systems Energy Losses," at the end of U.S. Energy Information Administration, *Monthly Energy Review* (March 2015), Section 2.

Notes: • Data are preliminary. • Values are derived from source data prior to rounding for publication. • Totals may not equal sum of components due to independent rounding.

Sources: U.S. Energy Information Administration, *Monthly Energy Review* (March 2015), Tables 1.1, 1.2, 1.3, 1.4a, 1.4b, and 2.1.

Figure 1.2: US Energy Flow in 2014 (Quadrillion Btu).

1.2 Why *Smart* Buildings?

Given that we spend on average more than 90% of our time in buildings and the fact that 40% of total energy consumption is being consumed in buildings, it is crucial that these systems are safe and comfortable while consuming the minimum amount possible of energy. In order to achieve these objectives, we need to make buildings smart about the way they operate. Studies such as the American Housing Survey for the United States by EnergySTAR, have shown that 30% of energy consumption of commercial buildings is wasted and could be saved by continuously monitoring and adjusting operations of these buildings. Achieving safety, energy efficiency and comfort is only feasible if all subsystems in the building continuously sense the environment, communicate between different parts of the system and make the right decision both individually and collectively.

Buildings of the future are perceived as entities for real-time energy trading, as opposed to passive energy consumers. In this scenario, buildings not only need to be aware of and responsive to the internal conditions, but also need to be able to operate their subsystems (e.g. HVAC, and lighting) in coordination with the grid. Real-time pricing combined with the intelligence of the Building Energy Management System (BEMS) to operate the building in a cost-effective way, is an example of such scenarios. More sophisticated scenarios would involve buildings operating in a cost-effective way given not only the real-time energy prices, but also *rewards* that a utility or system operator may offer buildings to provide *flexibility* in their energy consumption. The latter scenario would require a fundamentally different building control design; operating a system in the most cost-effective manner does not typically lead to much flexibility around the operating trajectory. In a scenario where the objective is defined not only by the goal of reducing energy cost, but also by the reward for operating in certain regions, the optimization problem becomes multi-objective and nontrivial.

1.3 Areas of research

According to the building energy data book of the US Department of Energy (DOE)[5], about 50% of the energy consumption in buildings is directly related to space heating, cooling and ventilation as shown in Figure 1.3. As such, reducing building energy consumption by designing smart control systems to operate the HVAC system in a more energy-efficient way is critically important to address the worldwide energy and environmental concerns. With the advent of smart, easily-controllable and remotely-accessible thermostats, smart meters, and two-way broadband communication infrastructure between occupants and buildings via smart devices such as smartphones and next generation connected electric cars, as well as between the buildings as consumers of energy and utility companies as providers of energy, the role of buildings in the operation of the smart grid will be even more significant and crucial compared to the current state-of-the-art.

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[5] http://buildingsdatabook.eren.doe.gov/default.aspx

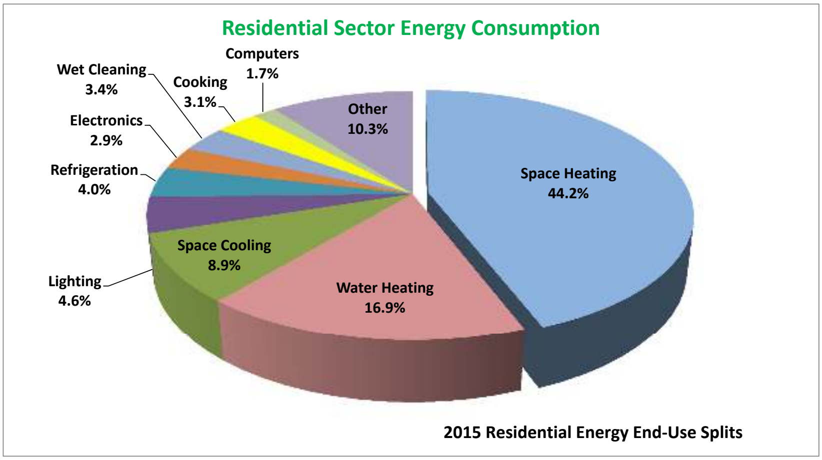

Figure 1.3: Breakdown of energy consumption in a typical building. Over 50% of energy consumption is related to HVAC systems.

In the last decade a significant amount of work has been done in areas that, directly or indirectly, have contributed to achieving improved performance, reliability and efficiency of buildings. We categorize this work into the following areas:

- Simulation tools;
- Building models;
- Building control design;
- Test-beds and real-scale experiments;
- Buildings as cyber-physical systems;
- Smart buildings in the smart grid ecosystem.

In this monograph, we provide an overview of what has been achieved in each of these areas, and we highlight emerging or existing areas for research.

1.4 Organization

The remaining chapters of this monograph are organized as follows:

We start by reviewing the simulation tools that have been developed over the years in Chapter 2. We cover EnergyPlus and Modelica Libraries among other building simulation tools.

We then present our work in modeling buildings. In particular, we first present Resistor-Capacitor (RC) models, which are the building blocks of the majority of building simulation tools. Next, we show how we use related available information from additional sensors such as CO2 sensors, outside air temperature, and Global Horizontal Irradiance (GHI) to infer quantities that are not measured, such as internal and external heat gains and un-modeled dynamics.

Furthermore, we show how the proposed modeling framework can be enhanced by introducing a Parameter-Adaptive Building (PAB) model. The proposed PAB model leverages a Kalman filter-based state estimation algorithm to simultaneously estimate the states and parameters of the system, resulting in a parameter-varying model.

We first provide an overview of classical building HVAC controllers. We then present a hierarchical control scheme in which the high-level controller optimizes a cost function and sends the optimal set-point to the local low-level PID controllers. The majority of Chapter 4 is devoted to obtaining and studying Model Predictive Control (MPC), Robust Model Predictive Control (RMPC), Stochastic Model Predictive Control (SMPC), and Exergy-based Model Predictive Control (XMPC), and studying the performance of each in the presence of model uncertainty. At the end of this chapter we provide a guideline for selecting the most appropriate control strategy based on the accuracy of the building model.

In Chapter 5 we review some of the outstanding efforts in this domain, and present some findings on how effective new control techniques are when implemented on real buildings. We focus on real-scale implementation of novel control algorithms on buildings and classify the studies according to the system that was controlled (e.g. whole building, test cell), the actuators, the total experiment time, and the MPC model.

After presenting various control strategies in Chapter 4, and reviewing real-scale implementation of such algorithms on real, physical buildings, we present a framework to co-design the control algorithm and the embedded platform for building HVAC systems in Chapter 6, thus treating a building as a cyber-physical system. As complex cyber-physical systems, HVAC systems involve three closely related subsystems – the control algorithm, the physical environment and the embedded implementation platform. In this chapter, we propose a co-design approach that analyzes the interaction between the control algorithm and the embedded platform through a set of interface variables, in particular the sensing accuracy. Based on the proposed models, we explore the design space of the control algorithm and the embedded platform to optimize a system with respect to energy cost and monetary cost while satisfying the constraints for user comfort level.

In Chapter 7, we address the future role of smart buildings in the context of the smart grid. We first propose a means to define and quantify the flexibility of a commercial building. We then propose a contractual framework that could be used by building operators and utility companies to declare flexibility on one side and reward structure on the other. Subsequently, we design a control mechanism for the building to decide its flexibility for the next contractual period to maximize the reward, given the contractual framework. Finally, we perform at-scale experiments to demonstrate the feasibility of the proposed algorithm.

Finally, Chapter 8 draws the conclusions of the monograph with a discussion on the possible directions for future work.

References

American Housing Survey for the United States. *U.S. Department of Housing and Urban Development and U.S. Department of Commerce.*, 2008.

C. Agbi, Z. Song, and B. Krogh. Parameter identifiability for multi-zone building models. In 51^{st} *Annual Conference on Decision and Control (CDC)*, pages 6951–6956. IEEE, 2012.

S. Ahuja, A. Surana, and E. Cliff. Reduced-order models for control of stratified flows in buildings. In *American Control Conference (ACC)*, pages 2083–2088. IEEE, 2011.

B. Aksanli, A. Akyurek, M. Behl, M. Clark, A. Donzé, P. Dutta, P. Lazik, M. Maasoumy, R. Mangharam, and T. Nghiem. Distributed control of a swarm of buildings connected to a smart grid: demo abstract. In *Proceedings of the* 1^{st} *ACM Conference on Embedded Systems for Energy-Efficient Buildings*, pages 172–173. ACM, 2014.

B. Arguello-Serrano and M. Velez-Reyes. Nonlinear control of a heating, ventilating, and air conditioning system with thermal load estimation. *IEEE Transactions on Control Systems Technology*, 7(1):56–63, 2002. ISSN 1063-6536.

ASHRAE. Standard 62.1. *Ventilation for acceptable indoor air quality*, 2004.

ASHRAE. Standard 55-2004. *Thermal environmental conditions for human occupancy*, 2004.

A. Aswani, N. Master, J. Taneja, D. Culler, and C. Tomlin. Reducing transient and steady state electricity consumption in hvac using learning-based model-predictive control. *Proceedings of the IEEE*, (99):1–14.

M. Balandat, F. Oldewurtel, M. Chen, and C. Tomlin. Contract design for frequency regulation by aggregations of commercial buildings. In 52^{nd} *Annual Conference on Communication, Control, and Computing (Allerton)*, pages 38–45. IEEE, 2014.

M. Behl, T. Nghiem, and R. Mangharam. Model-iq: Uncertainty propagation from sensing to modeling and control in buildings. In 5^{th} *International Conference on Cyber-Physical Systems*, pages 13–24. IEEE Computer Society, 2014.

S. Bengea, V. Adetola, K. Kang, M. Liba, D. Vrabie, R. Bitmead, and S. Narayanan. Parameter estimation of a building system model and impact of estimation error on closed-loop performance. In 50^{th} *Conference on Decision and Control and European Control Conference*, pages 5137–5143. IEEE, 2011.

S. Bengea, A. Kelman, F. Borrelli, R. Taylor, and S. Narayanan. Implementation of model predictive control for an hvac system in a mid-size commercial building. *HVAC&R Research*, 20(1):121–135, 2014.

T. Bergman, F. Incropera, and A. Lavine. *Fundamentals of heat and mass transfer*. John Wiley & Sons Incorporated, 2011.

W. Bernal, M. Behl, T. Nghiem, and R. Mangharam. MLE+: a tool for integrated design and deployment of energy efficient building controls. In *Proceedings of the Fourth ACM Workshop on Embedded Sensing Systems for Energy-Efficiency in Buildings*, pages 123–130. ACM, 2012.

D. Bertsekas. *Nonlinear programming*. Athena Scientific, 1999.

Y. Bi, X. Wang, Y. Liu, H. Zhang, and L. Chen. Comprehensive exergy analysis of a ground-source heat pump system for both building heating and cooling modes. *Applied Energy*, 86(12):2560–2565, 2009.

V. Bradshaw. *The building environment: Active and passive control systems*. John Wiley & Sons, 2010.

J. Braun. Load control using building thermal mass. *Journal of solar energy engineering*, 125(3):292–301, 2003.

B. Bueno, L. Norford, G. Pigeon, and R. Britter. A resistance-capacitance network model for the analysis of the interactions between the energy performance of buildings and the urban climate. *Building and Environment*, 54:116–125, 2012.

M. Castilla, J. Álvarez, M. Berenguel, F. Rodríguez, J. Guzmán, and M. Pérez. A comparison of thermal comfort predictive control strategies. *Energy and Buildings*, 43(10):2737–2746, 2011.

M. Castilla, J. Álvarez, J. Normey-Rico, and F. Rodríguez. Thermal comfort control using a non-linear mpc strategy: A real case of study in a bioclimatic building. *Journal of Process Control*, 24(6):703–713, 2014.

Y. Cengel, M. Boles, and M. Kanoğlu. *Thermodynamics: an Engineering Approach.* 8^{th} Edition, Chapter 8, McGraw-Hill, New York, 2015.

S. Chatzivasileiadis, M. Bonvini, J. Matanza, R. Yin, Z. Liu, T. Nouidui, E. Kara, R. Parmar, D. Lorenzetti, and M. Wetter. Cyber physical modeling of distributed resources for distribution system operations. *arXiv preprint arXiv:1505.00078*, 2015.

R. Chengqin, L. Nianping, and T. Guangfa. Principles of exergy analysis in HVAC and evaluation of evaporative cooling schemes. *Building and Environment*, 37(11):1045–1055, 2002.

K. Chua, S. Chou, W. Yang, and J. Yan. Achieving better energy-efficient air conditioning–a review of technologies and strategies. *Applied Energy*, 104: 87–104, 2013.

J. Clarke, J. Cockroft, S. Conner, J. Hand, N. Kelly, R. Moore, T. Brien, and P. Strachan. Simulation-assisted control in building energy management systems. *Energy and Buildings*, 34(9):933–940, 2002.

D. Crawley, J. Hand, M. Kummert, and B. Griffith. Contrasting the capabilities of building energy performance simulation programs. *Building and Environment*, 43(4):661–673, 2008.

K. Dalamagkidis, D. Kolokotsa, K. Kalaitzakis, and G. Stavrakakis. Reinforcement learning for energy conservation and comfort in buildings. *Building and Environment*, 42(7):2686–2698, 2007.

S. Dawson-Haggerty, X. Jiang, G. Tolle, J. Ortiz, and D. Culler. sMAP: a simple measurement and actuation profile for physical information. In *Proceedings of the 8^{th} ACM Conference on Embedded Networked Sensor Systems*, New York, USA, 2010. ACM. ISBN 978-1-4503-0344-6.

R. de Dear and G. Brager. The adaptive model of thermal comfort and energy conservation in the built environment. *International Journal of Biometeorology, Springer*, 2001.

R. de Dear and G. Brager. Thermal comfort in naturally ventilated buildings: revisions to ASHRAE Standard 55. *Energy and Buildings*, 34(6):549–561, 2002.

K. Deng, P. Barooah, P. Mehta, and S. Meyn. Building Thermal Model Reduction via Aggregation of States. In *American Control Conference (ACC)*, pages 5118–5123. IEEE, 2010.

I. Dincer and M. Rosen. *Exergy: energy, environment and sustainable development*. Newnes, 2012.

A. Dounis and D. Manolakis. Design of a fuzzy system for living space thermal-comfort regulation. *Applied Energy*, 69(2):119–144, 2001.

B. Eisenhower, Z. O'Neill, V. Fonoberov, and I. Mezić. Uncertainty and sensitivity decomposition of building energy models. *Journal of Building Performance Simulation*, 5(3):171–184, 2012.

EnergySTAR. American Housing Survey for the United States. *http://www.energystar.gov/buildings/about-us/how-can-we-help-you/build-energy-program/business-case*.

M. Fayazbakhsh, F. Bagheri, and M. Bahrami. A resistance-capacitance (rc) model for real-time calculation of cooling load in hvac-r systems. *Journal of Thermal Science and Engineering Applications*, 7(4):041008âĂŤ041017, 2015.

C. Federspiel. Estimating the inputs of gas transport processes in buildings. *IEEE Transactions on Control Systems Technology*, 1997.

C. Federspiel and H. Asada. User-adaptable comfort control for hvac systems. *Journal of dynamic systems, measurement, and control*, 116(3):474–486, 1994.

P. Ferreira, A. Ruano, S. Silva, and E. Conceicao. Neural networks based predictive control for thermal comfort and energy savings in public buildings. *Energy and Buildings*, 55:238–251, 2012.

R. Freire, G. Oliveira, and N. Mendes. Predictive controllers for thermal comfort optimization and energy savings. *Energy and Buildings*, 40(7): 1353–1365, 2008.

M. Goforth, G. Gilchrist, and J. Sirianni. Cloud Effect on Thermal Downwelling Sky Radiance. *Proceedings of Society of Photo-Optical Instrumentation Engineers (SPIE)*, 2002.

M. Gwerder, S. Boetschi, D. Gyalistras, C. Sagerschnig, D. Sturzenegger, R. Smith, and B. Illi. Integrated predictive rule-based control of a swiss office building. In 11^{th} *REHVA World Congress Climate*, 2013.

D. Gyalistras and M. Gwerder. Use of Weather and Occupancy Forecasts for Optimal Building Climate Control (OptiControl): Two Years Progress Report. In *ETH Zurich*, 2010.

ASHRAE Fundamentals Handbook. American Society of Heating, Refrigerating and Air-conditioning Engineers, Inc. Atlanta, GA. 2009.

S. Hanif, D. Fernando Recalde Melo, M. Maasoumy, T Massier, T Hamacher, and T. Reindl. Model predictive control scheme for investigating demand side flexibility in singapore. In 50^{th} *International Universities Power Engineering Conference*, 2015.

H. Hao, A. Kowli, Y. Lin, P. Barooah, and S. Meyn. Ancillary service for the grid via control of commercial building hvac systems. In *American Control Conference (ACC)*, 2013.

U. Helman. Resource and transmission planning to achieve a 33% RPS in California–ISO modeling tools and planning framework. In *FERC Technical Conference on Planning Models and Software*, 2010.

G. Henze, M. Krarti, and M. Brandemuehl. Guidelines for improved performance of ice storage systems. *Energy and Buildings*, 35(2):111–127, 2003.

G. Henze, C. Felsmann, and G. Knabe. Evaluation of optimal control for active and passive building thermal storage. *International Journal of Thermal Sciences*, 43(2):173–183, 2004. ISSN 1290-0729.

G. Henze, J. Pfafferott, S. Herkel, and C. Felsmann. Impact of adaptive comfort criteria and heat waves on optimal building thermal mass control. *Energy and Buildings*, 39(2):221–235, 2007.

B. Jin, P. Nuzzo, M. Maasoumy, Y. Zhou, and A. Sangiovanni-Vincentelli. A contract-based framework for integrated demand response management in smart grids. In *Proceedings of the 2nd ACM International Conference on Embedded Systems for Energy-Efficient Built Environments*, pages 167–176. ACM, 2015.

S. Julier and J. Uhlmann. New Extension of the Kalman Filter to Nonlinear Systems. In *International Society for Optics and Photonics*, 1997.

S. Julier, J. Uhlmann, and H. Durrant-Whyte. A new approach for filtering nonlinear systems. In *Proceedings of the American Control Conference*, volume 3, pages 1628–1632. IEEE, 1995.

G. Karmakar, A. Kabra, and K. Ramamritham. Coordinated scheduling of thermostatically controlled real-time systems under peak power constraint. In *Real-Time and Embedded Technology and Applications Symposium (RTAS)*, pages 33–42. IEEE, 2013.

R. Katz, D. Culler, S. Sanders, S. Alspaugh, Y. Chen, S. Dawson-Haggerty, P. Dutta, M. He, X. Jiang, and L. Keys. An information-centric energy infrastructure: The Berkeley view. *Sustainable Computing: Informatics and Systems*, 1(1):7–22, 2011.

B. Kilkis. From Floor Heating to Hybrid HVAC Panel: A Trail of Exergy-Efficient Innovations. *American Society of Heating, Refrigerating and Air-conditioning Engineers Transactions*, pages 343–349, 2006.

B. Kirby. *Spinning reserve from responsive loads*. United States. Department of Energy, 2003.

I. Konstantakopoulos, C. Spanos, and S. Sastry. Social game for building energy efficiency: Utility learning, simulation, analysis and incentive design. Technical Report UCB/EECS-2015-3, EECS Department, University of California, Berkeley, Feb 2015. URL `http://www.eecs.berkeley.edu/Pubs/TechRpts/2015/EECS-2015-3.html`.

M. Kummert and P. André. Simulation of a model-based optimal controller for heating systems under realistic hypothesis. In 9^{th} *International IBPSA Conference*. IBPSA, 2005.

S. Larsen, C. Filippín, and G. Lesino. Thermal behavior of building walls in summer: Comparison of available analytical methods and experimental results for a case study. In *Building Simulation*, volume 2, pages 3–18. Springer, 2009.

P. Levis, S. Madden, J. Polastre, R. Szewczyk, and E. Brewer. Tinyos: An operating system for sensor networks. *Ambient intelligence*, 35, 2005.

J. Liang and R. Du. Thermal comfort control based on neural network for hvac application. In *Proceedings of IEEE Conference on Control Applications*, pages 819–824. IEEE, 2005.

Z. Liao and A. Dexter. An inferential model-based predictive control scheme for optimizing the operation of boilers in building space-heating systems. *IEEE Transactions on Control Systems Technology*, 18(5):1092–1102, 2010.

S. Liu and G. Henze. Experimental analysis of simulated reinforcement learning control for active and passive building thermal storage inventory: Part 1. theoretical foundation. *Energy and Buildings*, 38(2):142–147, 2006a.

S. Liu and G. Henze. Experimental analysis of simulated reinforcement learning control for active and passive building thermal storage inventory: Part 2: Results and analysis. *Energy and Buildings*, 38(2):148–161, 2006b.

J. Löfberg. *Minimax approaches to robust model predictive control*, volume 812. Linköping University Electronic Press, 2003.

Y. Ma, F. Borrelli, B. Hencey, A. Packard, and S. Bortoff. Model predictive control of thermal energy storage in building cooling systems. In *Proceedings of the* 48^{th} *IEEE Conference on Decision and Control*, pages 392–397. IEEE, 2009.

Y. Ma, F. Borrelli, B. Hencey, B. Coffey, S. Bengea, and P. Haves. Model predictive control for the operation of building cooling systems. In *American Control Conference (ACC)*, pages 5106–5111. IEEE, 2010.

Y. Ma, A. Kelman, A. Daly, and F. Borrelli. Predictive control for energy efficient buildings with thermal storage. *IEEE Control System Magazine*, 32(1):44–64, 2012.

M. Maasoumy. Modeling and optimal control algorithm design for hvac systems in energy efficient buildings. Master's thesis, EECS Department, University of California, Berkeley, Feb 2011. URL `http://www.eecs.berkeley.edu/Pubs/TechRpts/2011/EECS-2011-12.html`.

M. Maasoumy. Controlling energy-efficient buildings in the context of smart grid: A cyber physical system approach. Number UCB, EECS-2013-244 - PhD Thesis, Dec 2013. URL `http://www.eecs.berkeley.edu/Pubs/TechRpts/2013/EECS-2013-244.html`.

M. Maasoumy and A. Sangiovanni-Vincentelli. Total and Peak Energy Consumption Minimization of Building HVAC Systems Using Model Predictive Control. In *Design and Test of Computers*, 2012a.

M. Maasoumy and A. Sangiovanni-Vincentelli. Optimal Control of HVAC Systems in the Presence of Imperfect Predictions. In *Dynamic System and Control Conference (DSCC)*, 2012b.

M. Maasoumy and A. Sangiovanni-Vincentelli. Comparison of control strategies for energy efficient building hvac systems. In *Proceedings of the Symposium on Simulation for Architecture & Urban Design*, page 11. Society for Computer Simulation International, 2014.

M. Maasoumy and A. Sangiovanni-Vincentelli. Buildings to grid integration: A dynamic contract approach. In *Proceedings of the IEEE/ACM International Conference on Computer-Aided Design*, pages 473–478. IEEE Press, 2015.

M. Maasoumy, A. Pinto, and A. Sangiovanni-Vincentelli. Model-Based Hierarchical Optimal Control Design For HVAC Systems. In *ASME Dynamic Systems and Control Conference*, pages 271–278, 2011.

M. Maasoumy, B. Moridian, M. Razmara, M. Shahbakhti, and A. Sangiovanni Vincentelli. Online Simultaneous State Estimation and Parameter Adaptation for Building Predictive Control. In *Dynamic Systems and Control Conference (DSCC)*, 2013a.

M. Maasoumy, J. Ortiz, D. Culler, and A. Sangiovanni-Vincentelli. Flexibility of commercial building HVAC fan as ancillary service for smart grid. In *IEEE Green Energy and Systems Conference (IGESC)*, Long Beach, USA, November 2013b.

M. Maasoumy, Q. Zhu, C. Li, F. Meggers, and A. Sangiovanni-Vincentelli. Co-Design of Control Algorithm and Embedded Platform for HVAC Systems. In *The 4th ACM/IEEE International Conference on Cyber-Physical Systems (ICCPS)*, Philadelphia, USA, April 2013c.

M. Maasoumy, M. Razmara, M. Shahbakhti, and A. Sangiovanni-Vincentelli. Handling model uncertainty in model predictive control for energy efficient buildings. *Energy and Buildings*, 77:377–392, 2014a.

M. Maasoumy, M. Razmara, M. Shahbakhti, and A. Sangiovanni-Vincentelli. Selecting Building Predictive Control Based on Model Uncertainty. In *American Control Conference (ACC)*, 2014b.

M. Maasoumy, C. Rosenberg, A. Sangiovanni-Vincentelli, and D. Callaway. Model predictive control approach to online computation of demand-side flexibility of commercial buildings hvac systems for supply following. In *American Control Conference (ACC)*, 2014c.

M. Maasoumy, B. Sanandaji, K. Poolla, and A. Sangiovanni-Vincentelli. Model predictive control of regulation services from commercial buildings to the smart grid. In *American Control Conference (ACC)*, 2014d.

M. Maasoumy, P. Nuzzo, and A. Sangiovanni-Vincentelli. Smart buildings in the smart grid: Contract-based design of an integrated energy management system. In *Cyber Physical Systems Approach to Smart Electric Power Grid*, pages 103–132. Springer, 2015.

F. Meggers and H. Leibundgut. The reference environment: utilising exergy and anergy for buildings. *International Journal of Exergy*, 11(4):423–438, 2012.

F. Meggers, V. Ritter, P. Goffin, M. Baetschmann, and H. Leibundgut. Low exergy building systems implementation. *Energy*, 41(1):48–55, 2012.

N. Mendes, G.H.C. Oliveira, and H.X. de Araújo. Building thermal performance analysis by using Matlab/Simulink. In 7^{th} *International IBPSA Conference*, 2001.

Modelica. Modelica Building Library. http://simulationresearch.lbl.gov/bcvtb/releases/latest/doc/manual/tit-DymolaCon.xhtml.

M. Modera, T. Xu, H. Feustel, N. Matson, C. Huizenga, F. Bauman, E. Arens, and T. Borgers. Efficient thermal energy distribution in commercial buildings. *LBNL-41365, Lawrence Berkeley National Laboratory*, 1999.

T. Nghiem, M. Behl, R. Mangharam, and G. Pappas. Green scheduling of control systems for peak demand reduction. In 50^{th} *IEEE Conference on Decision and Control*, pages 5131–5136. IEEE, 2011.

T. Nouidui. Validation and application of the room model of the Modelica buildings library. In 9^{th} *International Modelica Conference*, Munich, Germany. 2014.

P. Nuzzo and A. Sangiovanni-Vincentelli. Let's get physical: Computer science meets systems. In *From Programs to Systems - The Systems Perspective in Computing Workshop, European Joint Conferences on Theory and Practice of Software (ETAPS)*, April 2014.

F. Oldewurtel, C. Jones, and M. Morari. A tractable approximation of chance constrained stochastic mpc based on affine disturbance feedback. In 47^{th} *IEEE Conference on Decision and Control (CDC)*, pages 4731–4736, 2008.

F. Oldewurtel, A. Parisio, C. Jones, M. Morari, D. Gyalistras, M. Gwerder, V. Stauch, B. Lehmann, and K. Wirth. Energy Efficient Building Climate Control Using Stochastic Model Predictive Control and Weather Predictions. In *American Control Conference (ACC)*, pages 5100–5105, 2010.

F. Oldewurtel, A. Parisio, C. Jones, D. Gyalistras, M. Gwerder, V. Stauch, B. Lehmann, and M. Morari. Use of model predictive control and weather forecasts for energy efficient building climate control. *Energy and Buildings*, 45:15–27, 2012.

S. Peleš, S. Ahuja, and S. Narayanan. Uncertainty quantification in energy efficient building performance simulations. In *Proceedings of* 2^{nd} *International High Performance Buildings Conference*, number 3592, 2012.

L. Pérez-Lombard, J. Ortiz, and C. Pout. A review on buildings energy consumption information. *Energy and Buildings*, 40(3):394–398, 2008.

G. Platt, J. Li, R. Li, G. Poulton, G. James, and J. Wall. Adaptive hvac zone modeling for sustainable buildings. *Energy and Buildings*, 42(4):412–421, 2010.

J. Polastre, R. Szewczyk, and D. Culler. Telos: enabling ultra-low power wireless research. In 4^{th} *International Symposium on Information Processing in Sensor Networks*, pages 364–369. IEEE, 2005.

S. Privara, J. Cigler, Z. Váňa, F. Oldewurtel, C. Sagerschnig, and E. Žáčeková. Building modeling as a crucial part for building predictive control. *Energy and Buildings*, 56:8–22, 2013.

P. Radecki and B. Hencey. Online building thermal parameter estimation via unscented kalman filtering. In *American Control Conference (ACC)*, pages 3056–3062. IEEE, 2012.

M. Razmara, M. Maasoumy, M. Shahbakhti, and R. Robinett III. Exergy-based model predictive control for building hvac systems. In *American Control Conference (ACC)*. IEEE, 2015.

R. D. Robinett III and D. G. Wilson. *Nonlinear Power Flow Control Design: Utilizing Exergy, Entropy, Static and Dynamic Stability, and Lyapunov Analysis*. Springer, 2011.

P. Sakulpipatsin, L.C. M. Itard, H.J. Van Der Kooi, E.C. Boelman, and P.G. Luscuere. An exergy application for analysis of buildings and HVAC systems. *Energy and Buildings*, 42(1):90–99, 2010.

A. Sangiovanni-Vincentelli, W. Damm, and R. Passerone. Taming Dr. Frankenstein: Contract-Based Design for Cyber-Physical Systems. *European Journal of Control*, 18(3):217–238, June 2012.

A. Schlueter and F. Thesseling. Building information model based energy/exergy performance assessment in early design stages. *Automation in Construction*, 18(2):153–163, 2009.

D. Schmidt. Low exergy systems for high-performance buildings and communities. *Energy and Buildings*, 41(3):331–336, 2009.

M. Schuss, R. Zach, K. Orehounig, and A. Mahdavi. Empirical evaluation of a predective simulation-based control method. In *Proceedings of the* 12^{th} *International IBPSA Conference*, pages 14–16, 2011.

J. Singh, N. Singh, and J. Sharma. Fuzzy modeling and control of hvac systems-a review. *Journal of Scientific and Industrial Research*, 65(6), 2006.

J. Širokỳ, F. Oldewurtel, J. Cigler, and S. Prívara. Experimental analysis of model predictive control for an energy efficient building heating system. *Applied Energy*, 88(9):3079–3087, 2011.

J. Sousa. Energy simulation software for buildings: review and comparison. In *Proceedings of the international workshop on information technology for energy applications (IT4ENERGY)*. Citeseer, 2012.

G. Strbac. Demand side management: Benefits and challenges. *Energy Policy*, 36(12):4419–4426, 2008.

D. Sturzenegger, D. Gyalistras, V. Semeraro, M. Morari, and R. Smith. BRCM Matlab Toolbox: Model generation for model predictive building control. In *American Control Conference (ACC)*, pages 1063–1069. IEEE, 2014.

D. Sturzenegger, D. Gyalistras, M. Morari, and R.S. Smith. Model predictive climate control of a swiss office building: Implementation, results, and cost-benefit analysis. *IEEE Transactions on Control Systems Technology*, PP (99):1–1, 2015. ISSN 1063-6536. .

D. Todd, M. Caufield, B. Helms, M. Starke, B. Kirby, and J. Kueck. Providing reliability services through demand response: A preliminary evaluation of the demand response capabilities of Alcoa Inc. *Oak Ridge National Laboratory*, 233, 2008.

J. Venkatesh, B. Aksanli, J.-C. Junqua, P. Morin, and T.S. Rosing. Homesim: Comprehensive, smart, residential electrical energy simulation and scheduling. In *International Green Computing Conference (IGCC)*, 2013. .

E. Vrettos, F. Oldewurtel, F. Zhu, and G. Andersson. Robust provision of frequency reserves by office building aggregations. In *World Congress of the International Federation of Automatic Control (IFAC)*, 2014.

A. Wächter and L. Biegler. On the implementation of an interior-point filter line-search algorithm for large-scale nonlinear programming. *Mathematical Programming*, 106(1):25–57, 2006.

D. Westphalen and S. Koszalinski. Energy consumption characteristics of commercial building hvac systems volume ii: Thermal distribution, auxiliary equipment, and ventilation. *Arthur D. Little Inc (ADLI)*, 20, 2001.

M. Wetter, W. Zuo, T. Nouidui, and X. Pang. Modelica buildings library. *Journal of Building Performance Simulation*, 7(4):253–270, 2014.

C. K. Woo, E. Kollman, R. Orans, S. Price, and B. Horii. Now that California has ami, what can the state do with it? *Energy Policy*, 36(4), 2008.

Y. Yang, A. Pinto, A. Sangiovanni-Vincentelli, and Q. Zhu. A design flow for building automation and control systems. In 31st *Real-Time Systems Symposium (RTSS)*, pages 105–116. IEEE, 2010.

Y. Yang, Q. Zhu, M. Maasoumy, and A. Sangiovanni-Vincentelli. Development of building automation and control systems. *IEEE Design Test of Computers*, 29(4):45 –55, Aug 2012. ISSN 0740-7475. .

A. Yildiz and A. Güngör. “Energy and exergy analyses of space heating in buildings”. *Applied Energy*, 86(10):1939–1948, 2009.

M. Zaheer-Uddin and G. Zheng. Optimal control of time-scheduled heating, ventilating and air conditioning processes in buildings. *Energy Conversion and Management*, 41(1):49–60, 2000.

X. Zhang, G. Schildbach, D. Sturzenegger, and M. Morari. Scenario-based mpc for energy-efficient building climate control under weather and occupancy uncertainty. In *European Control Conference (ECC)*, 2013.