Building Physics, Dynamics and Modeling

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Introduction

Buildings are responsible, directly and indirectly, for ~40% of US carbon dioxide emissions. Reductions of ~70% in energy use in buildings are required to achieve emissions reduction goals for the building sector set by a number of organizations, including the California Public Utilities Commission.

To realize DOE's strategic vision of cost-effective Net Zero Energy Buildings (ZEB), increased integration is required during the building life cycle among domain disciplines, design tools and processes in order to reduce the energy utilization by 60% to 80% (and to cover the remaining energy demand with renewable energy). Current simulation tools (EnergyPlus, etc) are written for analysis by *one* domain expert. Integrating these tools with tools from other domains, such as for complex fenestration, thermal solar systems, or controls design, is difficult. Thus, using these tools in a holistic way across all of the systems that buildings are composed of is hard.

Existing modeling tools largely assume course, lumped parameter, time-averaged, or steady state conditions that simplify the underlying physics within buildings. These coarse assumptions limit the fidelity of models and hamper interoperability between models that could simulate simultaneous states of different components in a building (e.g., energy systems, natural ventilation and control systems).

Different modeling tools are not coupled to each other; for example, energy and CFD model coupling is typically ad hoc. Modeling tools focus on one particular metric – energy or air flow, surface lighting, or duct lay out etc. There are currently no comfort or IAQ modeling tools for buildings except at the simplest single zone level.

Today, simulation tools are written for simulation, not analysis. The HiPerBRIC vision is that given state-of-the-art systems theory that the level of sophistication of simulation will extend from the low resolution single domain solution to multi-domain models that analyze multiple thermal and environmental conditions at a level of sufficient granularity to resolve temporal and spatial variability to enable fine distinction between slightly different building design. It will also need to zoom between fine granularity for design optimization to a much coarser level for system load specification, and even coarser granularity for system control specification and software and hardware development in support of a Platform Based Design methodology.

The exact specification of the level of the range of model granularity is currently unknown. It is a matter of research to define the ranges for different domain simulation

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tools and how they can be coupled to each other. This research will in some cases require investigation into first principles and laboratory science. In other cases the science may be well demonstrated, but the state equations or chemistry have not been translated into mathematical algorithms that can be codified for computer simulation.

The purpose of this document is to outline the gaps, and needs, an approach to simulation tool development, and ultimately development of an integrated set of modeling tools that can feed into a HiPerBRIC building design and operating platform

Situation

Modeling

Current building simulation programs lack the capability to properly model emerging building energy systems, adding new models takes months to years and the controls is idealized to a point where it lacks to resemble actual control systems. Furthermore, creating a model for a building and its energy system is time-consuming and expensive which is a barrier for more widespread use of simulation as a tool to reduce energy consumption and peak power. Models intended for building design that provide information about pollutant transfer and their physical and chemical properties, and their implications on health and productivity, are almost completely lacking. Risk exposure to water damage and microbial growth due to space usage, material selection, and/or change in ventilation rates are not being quantified. Models to limit pollutant sources and provide ventilation requirements to meet occupant health and comfort requirements are lacking.

Current building simulation programs typically do not allow integration of domain specific tools that may be used by different people of a design team. For example, a mechanical engineer may use TRNSYS to design a solar thermal systems, while an architect may use EnergyPlus to design the building envelope because EnergyPlus can assess daylight availability for different facades. For computing the site energy use, these two models would have to be integrated which is currently at best possible by an expert user. Similarly, when simulating a building with a large atrium, separate tools need to be used to assess the air stratification inside the atrium and the operation of the HVAC system that may provide cooling for the atrium.

Regarding integration of modeling tools into the design process, one has to recognize that current building simulation programs have been written to compute the performance of a building system (such as energy use or room temperature) for a given set of input data. The converse question of what input data (design parameter or control sequence) provides a desired performance is hard to address with existing tools that have not been designed for such use cases.

Exergy Analysis

The current approach to achieve net zero energy buildings (NZEB) is based on energy

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analysis and does typically not include exergy analysis, which quantifies the *quality* of the energy relative to an environment condition. Exergy analysis is an additional tool that can help achieving NZEB. In contrast to energy analysis, exergy analysis can quantify the *system internal* irreversibilities, such as due to heat transfer, thereby providing a physics-based guidance for *where* to improve the system design or operation in order to reduce its primary energy consumption. Exergy can also be used to trade-off different forms of energy such as electrical and thermal energy.

Exergy analysis can give insights into which quality levels of energy supply and energy demand are matched. For instance, the majority of today's HVAC systems operate with large temperature differences (e.g. between the HVAC plant and the room), to provide for room temperatures that are very close to the external environmental temperature; hence these are very low exergy efficiency processes. For instance, 5C water temperature from the chiller is used to provide room cooling to temperatures around 21C. This process could be achieved with other systems with lower temperature differences such as trombe walls or radiant ceilings. Another typical example are boilers with very close to 100% energy efficiency, but about 5% exergy efficiency. Zmeureanu and Wu (2005) show comparisons between environment indices, COP and exergy efficiency of different systems, and concludes that exergy is the best measure for quality developments and impact to the environment.

Exergy analysis provides an additional tool to analyze where the largest irreversibilities occurs in buildings, but it can also be used for equipment evaluation. In many cases the use of exergy in assessing different system is advantageous because with energy metrics, electricity and heat are given the same weight. With energy only analysis, environmental and economic potential of alternative systems are missed. (Ref. 5) [Stella to provide reference]. In the same reference, Table 1 [Stella to provide table] provides several real example of the differences in conclusions that can be attained by comparing several cogeneration systems by comparing energy and exergy efficiencies for different systems. For example, a steam cogeneration is compared with geothermal cogeneration. While steam cogeneration has a better energy efficiency because of the low input temperatures in geothermal, the exergy efficiency of geothermal cogeneration is much better which is consistent with a more thorough thermodynamic and economic comparison of both systems. Hence, for new cogeneration systems and also for building design, energy analysis may not be enough to provide a thorough comparison.

After the International Energy Agency Annex 37 recognizes that exergy-efficient buildings with low-exergy systems and equipment will be the most important step for the next generation of sustainable development and environment, there have been a number of ongoing research efforts to promote the use of exergy measures for buildings and building equipment analysis. The International Society of Low Exergy Systems in Buildings was formed to investigate and promote the filed of energy use and sustainable buildings (www.lowex.net).

Design Support Methods and Tools

NOTE: THIS SECTION DESCRIBES AN EXAMPLE – NOT GENERAL SITUATION FOR DESIGN SUPPORT METHODS.

Natural dynamics are ignored or "fought against" e.g with pressure driven flows, forced mixing. Costs ~10% for fan energy in typical building. Passive HVAC systems offer significant energy savings but their implementation is not done correctly. Passive HVAC systems have been applied in several commercial buildings showing potential of 60-80% energy savings when combined with high performance lightning, envelope, and equipment. Examples include radiant cooling and heating systems, natural, and hybrid (mechanical and passive) ventilation (ref. Harvey 2006).

Underfloor air distribution systems represent an alternative efficient technology to conventional overhead mechanical ventilation systems (ref. Bauman and Webster 2001, using similar cooling, heating and air handling equipment but differ in some important respects involving vertical displacement of indoor air. These are the use of an underfloor air supply plenum, warmer supply air temperatures, and localized air distribution and resultant floor-to-ceiling airflow patterns. Displacement ventilation systems are similar to these underfloor systems but are employed for cooling purposes only and rely on 100% outside air, achieving improved ventilation and cooling energy savings. Such systems are estimated to be 20% more efficient than traditional overhead systems (ref. Lehrer and Bauman 2003) while providing better comfort and air quality in the occupied space (ref. Oguro et al. 1995). Room level energy and comfort are evaluated using models that represent average room environment dynamics evolving in minutes. Spatial inhomogeneity of temperature, humidity, and airflow (pressure, density and velocity) field within the room is not captured as well as their time scales of response to disturbances.

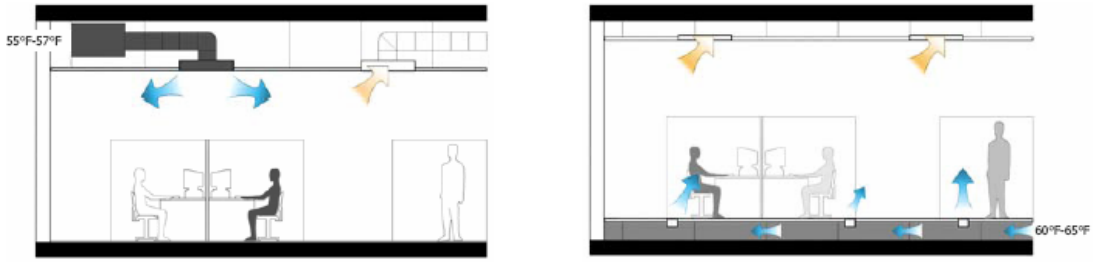

Figure 1. Schematics of conventional overhead ventilation system (see left) and and underfloor air distribution (UFAD) and ventilation system (see right). Ref. Bauman 2006.

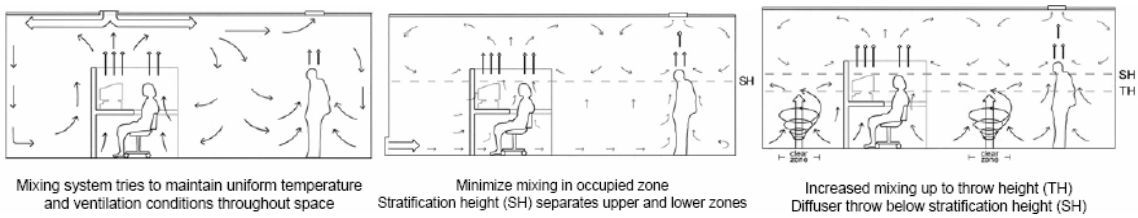

Figure 2. Schematics showing the indoor airflow patterns realized via conventional (see left) and alternative ventilation schemes (e.g. displacement ventilation and UFAD). Ref.

Bauman 2006.

Controls, Networking and Sensing

Existing controls are not currently part of design but rather are arrived at heuristically, typically based on a set of design rules. Controls are not performance-based, which works against meeting energy saving goals [Haves et al.??]

Achieving the overarching HiPerBRIC goal will require a system of interconnected efficient components including the building façade, lighting and daylighting, ventilation, renewable energy systems including thermal storage, and the use of high efficiency heating and cooling systems. Control of these systems by themselves are often more challenging than conventional whole-building systems, and an additional constraint is the need for interconnected control between these subsystems.

For a wide range of innovative heating and cooling systems, their enhanced efficiency depends on the storage of thermal energy. Examples include radiant-slab cooling systems [1], systems that use novel building materials that exhibit phase changes near room temperature [2], stratified tank systems, under-floor air distribution systems and systems that use natural ventilation during the night to remove heat stored in the building materials.

Controls design for decoupling
Network not used for feedback.
Local feedback loops within PICs.
Regulation, disturbance rejection.
c.Control designed assuming control loops are decoupled, nonlinearities ignored
Large oscillations develop because of coupling and large gain
d.Sensing and estimation – no estimation. There are design rules for sensor placement but ad hoc.

Building Information Models

The concept of BIM and its implementation are the crucial elements in changing how software is used in the AECOO industry in general and within the HiPerBRIC building design, delivery and operation process in particular. A BIM constitutes the instantiation of a data model of buildings with data specific to a building, which then serves as the authoritative repository of information for that building. Software interoperability enables access to and the use of data in a BIM; thus interoperability is a key to process integration and to how the AECOO industry will conduct its work much more efficiently in the future (Eastman et al. 2008).

At this point in time no BEP simulation software is directly and fully interoperable with a "lifecycle" data model of buildings (Bazjanac 2005). The lack of software interoperability that costs the building industry at least $15.8B/yr (Gallager et al. 2004) obviously also affects BEP simulation and analysis. Traditional manual reentry of

already existing data during input preparation is very time consuming and extremely prone to error, omission and misrepresentation, and deprives BEP simulation projects from using usually limited project resources more effectively (LBNL 2008).

Problems and Implications

Implication is that the energy savings are not uniformly realized over a broad range of operating and boundary conditions. Sub-standard comfort prevents wide adoption. The design methods and tools that describe the passive schemes discussed above are not scalable to a larger stock of commercial buildings. Observability and controllability of the inhomogeneous temperature, humidity, and airflow patterns, and time scales introduced by passive ventilation and associated disturbances are not known. Hence comfort requirements cannot be guaranteed in design and implementation phases.

Modeling

Current building simulation programs (DOE-2 [Winkelmann et al., 1993], EnergyPlus [Crawley et al., 2001]) are monolithic tools that tightly integrate physical models with solution algorithms and program flow logic. These makes it hard to integrate models from different disciplines, to extend the modeling capabilities to better address emerging thermal, controls and communication systems and even to model standard control sequences more realistically because of inherent limitations of the program architecture (data structure, solution methods, lack of model encapsulation). In fact, the “controls” in today's building energy simulation programs is based on energy requested by the rooms that ought to be met by components of the secondary and primary HVAC system, which is a large disconnect of how controls are implemented in actual buildings. Due to the increased importance of part load performance, a condition at which equipment operates in most of the time, system controls and energy simulations for ZEB need to properly resolve the non-linear dynamic behavior of building energy and control systems. This mandates, for computational efficiency, the use of algorithms for symbolic computer algebra (such as partitioning and tearing) and numerical solution algorithms for differential equations that exhibit large separation in time constants (stiff solvers). Using these mathematical tools is however not possible with the imperative model formulation of today’s building energy simulation programs.

Furthermore, since building simulation is very time-consuming, it is used primarily for high profile projects. Although building data are increasingly available in electronic format in the form of a Building Information Model (such as in Industry Foundation Classes), automatic translation of these data into a building simulation program is currently only possible for simple buildings. Large gaps exist in particular for the translation of HVAC systems and even more so for controls.

Energy required to maintain acceptable air quality cannot be simulated using current design tools. This leads to over-ventilated buildings and therefore oversized equipment and energy inefficiency; or if materials with high pollutant emissions are used, buildings with the same outside air flow rate are under-ventilated leading to poor occupant health

and productivity. Providing models for management of indoor conditions is particularly difficult in hot and humid climates.

Poor indoor air quality is known to have adverse affects on building occupants. These can range from chronic building-related symptoms such as lower respiratory symptoms and headache, to potential long-term risks such as cancer, to reduced work performance and absenteeism. Also, moisture condensation due to poor humidity management can lead to building damage and risk of mold growth. Building designs must consider this factor at many system levels as well as at the level of supervisory control and integrate systems to meet occupant needs at the lowest achievable energy expeniture.

The verification of new HVAC technologies and controls sequences currently must rely on cost-prohibitive on-site full-scale testing and tuning due to lack of robust and scalable energy analysis tools. This leads to slow development of innovative system concepts for buildings. Many modern HVAC systems[1] can, at best, only be simulated by an expert model user with a significant time investment. The required time and cost investment is not aligned with the building delivery cycle which impedes the deployment of modern HVAC systems. Another impedement to adoption of new technologies is the avoidance of unquantified risk associated with using an unfamiliar technology.

Because of the interrelations between different program modules, adding models for emerging systems typically takes more than a year. The loop structure underlying the EnergyPlus program architecture also makes it impossible to automatically translate certain HVAC systems from a Building Information Model into an energy simulation model. This will impede the use of Building Information Models for HVAC system. An even larger problem is anticipated if Building Information Models shall also contain specification of control systems since modeling of realistic controls is not possible with today's building simulation programs.

Since the importance of integrated controls was not recognized when today’s building simulation programs were designed, they cannot properly represent local loop controls. Their supervisory control framework is too restrictive for developing novel control algorithms that integrate façade, lighting and HVAC system controls, and that may utilize optimization algorithms to minimize energy or peak electrical demand. Because controls models are too simplistic and equipment is modeled steady-state, there is no provision for testing sequences of controls with building simulation programs such as EnergyPlus.

Reusing models created for building design for use in controls during operation, commissioning and fault detection and diagnostics is not practical with today’s tools as

1 Examples include Microencapsulated Phase Change materials with embedded capillary heat exchangers as part of the building construction [Koschenz and Lehmann, 2004], liquid desiccant systems for dehumidification [Liu et al., 2006], and Model Predictive Controls for demand response and optimal free cooling.

the program architecture with its integrated solution algorithms and fixed data flow does not allow for extraction of submodels. Furthermore, existing control approaches are too idealistic and most component models consider steady-state conditions. This is too big a disconnect with actual system operation to be of practical use.

A further limitation is that the data and code structure of today's tools do not possess the functionalities required for expressing complex systems, such as hierarchical modeling, class inheritance, object instantiation and different models of computations that are needed to properly represent communication and control systems. Consequently, large complex systems are very difficult and in many cases even impossible to model and simulate in today's tools. This poses significant challenges not only for managing the complexity in a large domain-specific model, but also for integrating models that stem from different domain disciplines and that may evolve using different dynamics (e.g., continuous time for heat transfer, discrete time for direct digital control and event-driven for wireless networks). How to model and simulate such heterogeneous systems is not well understood.

The software architecture of today's building simulation programs do not allow researchers to drive innovation using rapid prototyping, a method that is key in many industrial research processes in which system integration and exploiting system dynamics for higher efficiency is essential.

Exergy Analysis

Energy-based building design and operation requires energy flow analysis, computational speed and visualization that are not provided by the current tools. On the other hand, there has been enough evidence to demonstrate that the energy conservation principle alone is not adequate for gaining a full understanding of the energy utilization process. Energy flows are available in nearly all the current engineering and building management tool, but not always at a level of detail and analysis required for decision making. In the case of exergy, this is a property that is not even considered, and needs to be included and extended to all components of the building shell and building systems.

The inclusion of exergy and environmental performance metrics, besides energy efficiency, requires a change in the way the building systems are controlled, which is not longer only based on energy savings, that may be a combination of both –energy and exergy, or one of them depending on the specific case.

Decision making for design and for building diagnostics requires visualization, decision-support tools and analysis based on a combination of metrics that include energy and exergy, economic and environmental performance.

Design Support Methods and Tools

Andrzej to add?

Controls, Networking and Sensing

The goal is to determine whether, and how, advanced control methods can significantly improve the performance of these systems. Improved performance would include reduced energy consumption, reduced peak demand, tighter regulation for thermal comfort, and model-based fault detection and diagnosis.

Slab-coupled radiant cooling systems use a large evaporative cooling tower to cool water at night. This water is circulated through pipes embedded in the concrete floor or ceiling slab, cooling the slab. During the day, the slab absorbs heat from the occupied space that otherwise would have to be removed by a conventional vapor compression cooling system. In suitable climates, the energy used by the cooling tower fans and circulation pumps is substantially less than the energy that would have been used by a conventional cooling system, though it is not negligible. Shifting electricity consumption from the afternoon to the nighttime has the additional benefit of reducing peak electricity demand. In addition, several chillers (which can be connected in series or in parallel) can be operated each night to recharge the cooling tower which meets the cooling demand for the following day.

In standard implementations, manipulated control variables are cooling fluid flow rates, cooling tower fan speeds, cooling tower evaporation water flow rate, variable speed chillers, fans and pumps and the operation of HVAC secondary systems. The salient measurements include inlet and outlet temperatures, slab temperatures, ambient temperature and humidity, and conditions within the cooling tower. It is envisioned that in the future the aforementioned control variables and measurements will be spatially distributed across the building and thus include: cooling fluid flow rates in each slab, multiple wireless temperature, humidity and airflow sensors in each room (or thermal zone) as well as people presence detectors and motion predictors. Because thermal energy is stored actively within the water tank and passively within the building fabric, minimizing energy consumption is an optimal control problem meaning the optimal value of a set-point at any time t0 depends on the future thermodynamic state trajectories for time t > t0, which in turn depend on the future value of disturbances such as coil loads and weather.

Current Industrial Solution and Implication:

The existing controls are designed and implemented as follows…
TO BE DETAILED BY SCOTT AS PER OUR DISCUSSION.
As an example, chillers are sequenced manually in a manner optimized for full load to produce an amount of stored chilled water estimated to be required for the following day. Although the storage tank enables load shifting to off-peak hours to reduce peak demand, the lack of an optimized automation results in conservatively over-charging the tank where conductive losses erode efficiency, and possibly to producing chilled water in an non-optimal manner because the existing sequence is optimized for peak loads.

Building Information Models

In practice, one often encounters building energy systems and control sequences that a given simulation tool cannot model or cannot model properly. Thus one must define "work-arounds," if such are possible: substitute building energy systems that approximate what the simulation software is not able to model directly. As these "work-arounds" require human expertise that is difficult if not impossible to encode in rules that are valid for all special cases, one can currently only automatically generate a simulation from a BIM for HVAC systems that are available in the selected energy simulation software.

Also, Building Information Models do not contain sufficient language elements that allow representations of actual control systems. The current controls specification in Building Information Models are primarily oriented on the controls representation in building simulation programs which are far removed from how controls is implemented in an actual building.

In view of this, a more modular system simulation is needed that allows connecting component models for simulation in the same way as components are connected in actual buildings, and that allows controlling components in simulation similar to how components are controlled in actual buildings.

Additional Stuff

Coupling and dynamics across subsystems.
Complex facades are challenging. Impacts HVAC, lighting, materials, building usage. Not well understood, modeling tools immature.
Growth of embedded and networked systems → Not necessarily integrated.
Interfacing modeling tools with diverse models of computation. (PBD) How to do this? Ptolemy II.
Compling of design decisions. System architecture, component sizing all depend on dyamic response, which is affected by controls. Sequential design flow doesn't work.
Data formats and streams incomopatible. Archiving, BIM
Control-oriented point of view
Reduction of loop gains
Higher influence of disturbances.
Larger numbers of interactions

Modeling tools
1970s vintage fortran, monothic, not scalable.
Not useful for optimization, innovation. Difficult to extend.
Narrow – focus on only energy, comfort but not dynamics.
Loop structure of existing simulation tools makes translation from BIM impossible if actual system do not have a loop structure.

Examples

Displacement Ventilation

Displacement ventilation systems are not robust. With HVAC involving passive ventilation concepts, the thermal comfort and indoor air quality cannot be satisfied over large range of operating and boundary conditions and disturbances. In fact, unlike in the case of case of conventional mechanical ventilation schemes (involving mixing-type air distribution), the temperature distribution and airflow pattern used for passive ventilation are fragile, uncontrollable, and not robust to disturbances like people movement, door and window opening, weather, etc. Understanding of the controlled/optimized thermal stratification becomes critical to provide designers with a reliable energy-estimating tool. Furthermore, the time scale in which the passive HVAC schemes can adapt to disturbances (tens of minutes) is an order of magnitude slower than that of forced ventilation. In fact, the inhomogeneous temperature, humidity, and airflow patterns and time scales created by passive ventilation and disturbances are not modeled or sensed. No energy modeling tools are available for assessment of whole building energy performance between the above-mentioned systems. Currently employed models such as from EnergyPlus assume idealized indoor environment, such as fully mixed room state, and are unable to describe accurately the physics of stratified air temperatures and conditioning in the occupied spaces and enable the optimization of the flow patterns to realize the full benefits of the energy savings.

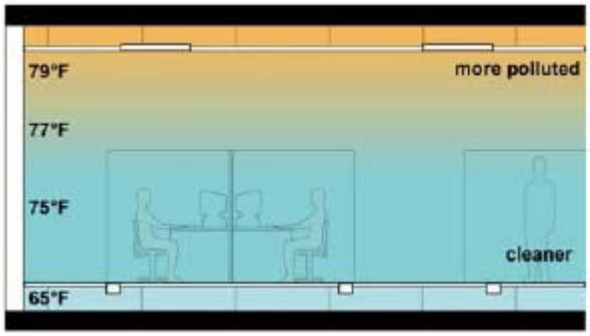

Figure 3. Schematic showing benefits of improved indoor environment achieved via thermal stratification in an underfloor air distribution system. Ref. Bauman 2006.

Add large atrium example (Andrzej)??

Needs

Modeling

The need for modeling and simulation is two-fold: For R&D, and to routinely model novel HVAC systems using Building Information Models and to use models during operation in five to ten years, a more modular modeling and simulation environment is needed. To address the immediate need for carbon dioxide reduction, waiting for this environment to fall into place is however not an option for the building industry. Parallel to new developments, existing energy simulation tools need to be further developed, with

a successive phasing in of new system modeling methods that are developed for R&D and matured in this user segment. Due to the pre-competitive R&D focus of HiPerBRIC, this report primarily focuses on the need for a new environment for modeling and simulation.

Functionalities that a new environment for modeling and simulation need to provide to address the needs for ZEB design and operation include:

- Provide to innovative companies and researchers a platform that stimulates innovation in energy efficient building systems, using virtual prototyping as a means for rapid concept evaluation within a large trade-space to select promising alternatives for subsequent concept refinement and product development.
- Allow researchers to quickly add models of emerging technologies into a computational environment for building systems to do annual performance assessment and system sizing.
- Allow controls engineers to extract subsystem models from models used during the building design in order to embed them within building control systems for model-based controls, fault detection and diagnostics.

This modeling and simulation environment will be one tool of the Building Informatics Repository shown in Figure XXX. The figure shows the Building Design and Operating Platform that consists of platforms for design and operation. These two platforms use tools from the Building Informatics Repository, such as model libraries, modeling environments, simulation tools, tools for optimization and uncertainty analysis. In view of this, item 1 and 2 are applications within the Building Design Platform, and item 3 is an application within the Building Operating Platform both drawing models and simulation environments from the Building Informatics Repository.

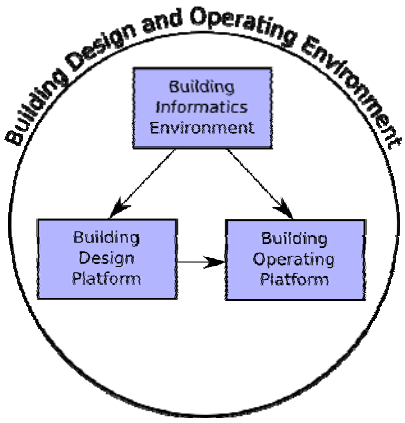

Figure XXX. Building Design and Operating Environment with Building Informatics Environment that provides tools for the Building Design Platform and the Building Operating Platform.

To address the need of using models within different processes, a modular, flexible approach for system modeling and simulation is required that can rapidly be extended by the modeler to analyze innovative technologies and system integration approaches. In

addition, model libraries need to be available that include models with various fidelity. For example, for a chiller there need to be a steady-state model based on performance curves for annual energy simulation, a dynamic model for controls design and a detailed model that models the refrigerant loop for fault detection and diagnostics.

We recognize however that there is no single modeling platform that should and will be used by all users. Users may prefer to use domain specific tools such as for computational fluid dynamics, daylight analysis or controls design. Furthermore there is value in reusing existing programs for applications for which they have been designed, as the programs matured and are validated for these applications.

To address the need for use of heterogeneous tools, a software environment that allows users to link different simulators *during run-time* with each other is needed. An example of such an environment is the Building Controls Virtual Test Bed, a software currently under development at LBNL that links EnergyPlus (for thermal simulation) to MATLAB/Simulink (for controls algorithm development) and, in the future, to building control systems and to the Modelica simulation environment Dymola. Further R&D is needed in this area to also couple other domain simulation programs such as computational fluid dynamics for modeling of air stratification, tools for active facade design, and tools for optimization of materials selection.

R&D is also needed to define semantic aware interfaces between tools for co-simulation that are robust even if the individual tools advance from one version to another.

To truly integrate Building Information Models into the building life cycle, extensions of BIM are needed to allow more realistic controls representation. Next, to generate from a BIM an energy simulation model, the BIM and the energy simulation program need to allow the same component modularization and connectivity. This mandates a mechanism for constructing HVAC systems from HVAC component models in a similar way as one would for built up systems in reality.

At least in the early project phases, the flexibility of these tools comes at the price of complexity in their use. R&D is needed to “package” these flexible tools for specific use cases to make them accessible for non-experts. That such a packaging is possible for modular environments has been demonstrated for example RESFEN, a tool developed to provide a user-interface overlay for the DOE-2 modeling platform to simulate fenestration options.

Exergy Analysis

As illustrated in the above discussions, exergy analysis need to be included in the design and operation of buildings. The specific requirements for performing this analysis are:

1. Include energy and exergy analysis -1st and 2nd law of thermodynamics- in building and equipment models to be used in building and building systems

design, equipment design, or for estimation purposes during building operation

2. Develop new methodologies to support the understating on when exergy and when energy are important, and their impact on the building economics and environmental aspects.
3. Analyze the impact of new architectural concepts or envelope designs that would allow to minimize exergy destruction, subject to comfort and cost constraints
4. Design new "low exergy" HVAC and power generating and storage technologies.
5. Extend the capability described above to support diagnostics and prognostics during building operation, self-tuning controls based on selected optimal metrics, and easy visualization of operating conditions, that would include energy and exergy on-line efficiency estimation.

Additional related efforts include user-friendly tools that can be used to analyze and visualize energy and exergy flows in buildings structures and systems to facilitate the detection of unnecessary losses during the design phase. New controls and supervisory systems that would include energy and exergy metrics -besides systems reliability and costs- will need to be developed.

Physics / chemistry domain knowledge (science) – write the equations, assumptions.

Thermodynamic
Models of transport, reactions (chemistry) of indoor pollutants. Streams.
Models of energy flows, energy storage, transfer, fluid transport

Model construction – libraries & architecture.

Data structures, database management, BIM structures. Standards.
Legacy problem – buildings last 100 years.

System level model integration – establishing and enforcing a common semantic domain (e.g. Ptolemy)
Object oriented. Acausal. Physics based but multiphysics problems.
Separation of concerns.
Languages. Semantic translations, translation tool, compilers.
Common semantic domains. (see fusion work).

Model reduction for different uses e.g. controls.
Multiscale, Applicable at different time / length scales and different parts of the design process. Multi-Scale: A major objective of this project is to develop a family of physics-based models spanning various time and length scales. This multi-scale approach to modeling is important because different scales are relevant to different control objectives, disturbances, and sensing and actuation technologies. As an illustration, changes in room-level solar gains and internal heat gains would affect the fast time-scale behavior of room temperatures while variations in the outside air temperature would be effective over slower time scales. Multi-scale modeling is thus critical for designs that systematically

distribute control effort over the relevant spatial and time scales, thus simplifying the design process and reducing the total control effort.

An important problem in multi-scale modeling is understanding how the scales couple and to exploit this understanding to develop reduced models. To address this problem we plan to employ several aggregation schemes that take advantage of the differing strengths of subsystem interactions. One such aggregation scheme was developed in the 70's for large-scale power networks in which differing strengths of interactions between the generators led to a decomposition of network models into slow and fast reduced-order models [Chow]. A recent result [Biyik & Arcak] extended this decomposition to networks that exhibit densely-connected clusters with sparse links across them. Our goal is to combine the strong/weak and dense/sparse decompositions and extend them to air flow, thermal, and contaminant source, transformation, and sink models of building systems.

For airflow and transport - how scales couple – multiscale modeling. (Andrzej / Murat)
Control oriented models.

Design Support Methods and Tools

Design of Dynamics
Sensor / actuator placement; shaping dynamics using means aside from an "active" computer control.
Airflow, building mass, lighting, passive thermal storage – exploiting dynamics to achieve requirements. Methods for implementation of passive ventilation concepts that lead to observable, controllable, optimal and robust systems are needed. This includes the need for tools and analysis methods to help optimize sensing and actuator placement and distribution strategies. We need to establish fundamental limitations of achievable energy savings, subject to comfort constraints. Design methods that provide practical guidelines and guarantee required level of energy savings and comfort over the large range of operating and boundary conditions are needed. Recent work at the Center for the Built Environment (UC Berkeley) and LBNL are addressing this tool gaps by proposing suitable modifications to existing tools such as EnergyPlus (ref. www.cbe.berkeley.edu/research/briefs-ufamodel.htm).

Controls, Networking and Sensing

Control algorithms / theory / implementation (networks)
Multivariable, optimal. MPC. We need to establish fundamental limitations of achievable energy savings, subject to comfort constraints. The described system typically depends on direct use of natural heat sinks/sources for their enhanced efficiency. These systems are characterized by: uncertain process dynamics; time-varying behavior; multiple objectives (cost functions) which change in time (primary energy, water usage for evaporative cooling, peak electrical power); and environmental effects (disturbances), such as ambient temperature and humidity, solar radiation and user behavior. Furthermore, the storage system's limited capacity necessitates the use of a control

methodology that directly deals with state and input constraints. It is for such complex systems that the potential benefits of advanced modeling and control methods are most significant.

Extremum seeking.
Robustness analysis
Control architectures
Installation / commissioning – rules.
Diagnostics
Estimation.
HIL
Networks / distributed control implementation.
PBD.
Models for bus utilization, CPU capacity & utilization, impact on closed loops (delays), control over networks.

Building Information Models

BIM need to be extended to allow specifications of control sequences that allow automatic translation of control sequences into models for simulation and into instructions for actual building automation systems.

Translators need to be developed that generate from a BIM a model that can be used for simulation of the HVAC system and the control system. This translators will be distinct from the currently existing translators in that they

a) allow a *modular component-based* HVAC system representation instead of pre-configured HVAC topologies. The HVAC systems need also include systems for renewable energies such as solar thermal systems that may be integrated into the building façade.
b) allow generating *controls representation* that can be linked to the above HVAC systems for simulation and that can be uploaded to actual Building Automation Systems.

Barriers and Enablers

Modeling

Limited experience exists in how to formulate large differential algebraic equation DAE systems so that solver always converges. Pricing and license terms of commercial tools (Dymola) are barriers to wide-spread deployment. There is limited awareness of modern modeling approaches in the building energy community. No data are available for dynamic equipment performance and part load data only available for limited operating ranges. Building scientists who rely on old monolithic tools underutilize computer science.

Modular system architectures for modeling environments allow for dealing with large heterogeneous systems (cf. Edward Lee's characterization of Systems and Signals). It has been shown that well designed modeling languages such as Modelica for physical systems and Ptolemy for heterogeneous systems enable modeling and analysis of large heterogeneous systems.

For modeling of physical systems, the Modelica language is well-positioned to become the de-facto open standard. Its object-oriented design provides a formal method for implementing equipment models with different fidelity (for example steady-state vs. dynamic, and performance-curve based vs. detailed physical models) in such a way that they can, within a system model, easily be replaced by the corresponding model that is most applicable for answering specific design and operation questions. The standardized component interfaces and model encapsulation also facilitates designing schematic model editors that allow users to assemble system models graphically. Furthermore, because in Modelica, models can be assembled as a contractor would assemble real components to form an HVAC system, there is a direct path for a one-to-one mapping between HVAC system models expressed in a Building Information Model and expressed in Modelica.

An approach that enables managing complexity in large system models is the *object-oriented modeling paradigm*, described by Cellier [1996] as follows:

- *Encapsulation of knowledge:* The modeler must be able to encode all knowledge related to a particular object in a compact fashion in one place with well-defined interface points to the outside.
- *Topological interconnection capability:* The modeler should be able to interconnect objects in a topological fashion, plugging together component models in the same way as an experimenter would plug together real equipment in a laboratory. This requirement entails that the equations describing the models must be declarative in nature, i.e., they must be acausal.
- *Hierarchical modeling:* The modeler should be able to declare interconnected models as new objects, making them indistinguishable at different hierarchical levels from the basic equation models. Models can then be built up in a hierarchical fashion to manage complex systems.
- *Object instantiation:* The modeler should have the possibility of describing generic object classes, and instantiating actual objects from these class definitions by a mechanism of model invocation.
- *Class inheritance:* A useful feature is class inheritance, since it allows encapsulation of knowledge even below the level of a physical object. The encapsulated knowledge can then be distributed through the model by an inheritance mechanism, which ensures that the same knowledge will not have to be encoded several times in different places.
- *Generalized Networking Capability:* A useful feature of a modeling environment is the capability to interconnect models through *nodes*. Nodes are different from regular models (objects) in that they offer a variable number of connections to them. This feature mandates the availability of *across* and *through* variables, so that power

continuity across the nodes can be guaranteed.

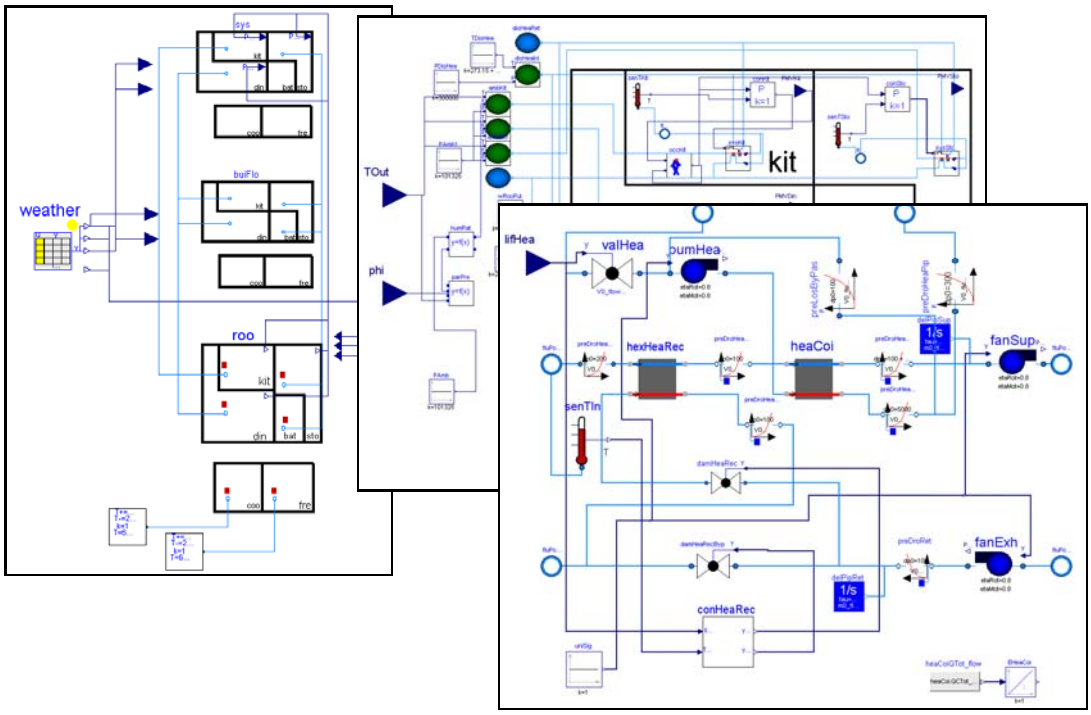

Figure 1: Schematic view of a building system model in Modelica that was constructed using different hierarchical layers to manage the model complexity, and that decomposes different domain. On the left, there is a model for the HVAC system (top), for the interzonal air flow (middle) and for the building envelope heat transfer (bottom), which are connected to each other by fluid loop and signals to form a coupled system of equations. The top right shows the inside of the HVAC system definition for each thermal zone, with an icon for the HVAC secondary loop, for the controller and for the user that may adjust the set points to maintain comfort. The bottom right shows the actual implementation of the HVAC secondary loop with the heat exchanger, the fans and pumps. (Figure from (Wetter 2007).)

Such a modeling paradigm allows that each component only sees boundary conditions that a real object would interact with (such as a temperature and heat flux boundary condition or a data bus). This makes the integration of system models for different physical domains possible on the mathematical modeling layer (by linking model equations) as opposed to the program code and solver layer (by linking executables). This is shown in Figure XXX, where a model for heat transfer in a building, a model for interzonal air exchange and a model for the HVAC system and its control are linked together graphically. While the models have been developed separately from each other, linking the models graphically assures that the equations for heat transfer, mass transfer and HVAC system, including its controls, are solved simultaneously. We believe that such a physics-oriented interface facilitates the integration of mathematical models with

the Building Operating Platform, and enables the use of the models to augment sensor networks with physics-based estimation. The acausal modeling paradigm (embodied in item 2 above) allows not only model reuse in different contexts but also the use of symbolic processing for reducing the size of coupled equation systems [Elmqvist et al., 1995; Mattsson et al., 1999]; this is key to run-time efficiency and enables the simulation of large engineering systems [Cellier and Kofman, 2006].

Developing a building simulation program that embodies these principles is a radical departure from how existing building simulation programs (EnergyPlus, DOE-2, TRNSYS, ESP-r) were developed.

Exergy Analysis

The thermodynamics fundamentals needed for exergy analysis with a fixed environmental state are well understood. Building simulation enables applying these fundamentals for large dynamic systems. A barrier is however how to treat the fact that the environment state is not fixed, but rather changes over a day and throughout the seasons. A further scientific challenge is how to distill the large amount of data that a detailed exergy analysis will provide in order to present the data to a designer or a building controller in a form that is amendable for decision-making. One enabler for distilling such data may be to exploit the tree-structure that is inherent in hierarchical modeling, and use this tree structure to also structure the results of the exergy analysis and collect them for individual subsystems. This may help collecting the results obtained by the fundamental processes of heat transfer, mass transfer and flow friction, which may be at too low a level of detail to make decision for improving the system design or operation.

Building Information Models

Building Information Models enable sharing building data, in an electronic form that can be processed by various applications, among the different stakeholders of the building life cycle. They have become increasingly used by code authorities for electronic code compliance checking. This creates an incentive for architects to provide building data in electronic form which can be used by engineers to accelerate the creation of simulation input files. The only open, object-oriented data model that covers the whole building life cycle are the Industry Foundation Classes, developed by the International Alliance for Interoperability and currently under consideration at the International Organization for Standardization (ISO) to become an international standard (ISO/PAS 16739:2005). This data model can be used for semi-automated building data transformation between BIM authoring tools and energy simulation tools (Bazjanac 2008).

Collaborative Development

Web 2.0 tools allow collaborative development that involves end-users directly in the development process (cf. Linux, Modelica, Ptolemy II). These tools allow continuous review, improvement and innovation by the end-user (see Tabscott and Williams [2006]), thereby providing a path that ensures that the tools better meet application requirements.

Technical Proposal

Our suggested approach can be partitioned into development of new tools for system modeling and simulation, development of co-simulation environments, and advancement of existing domain-specific tools.

Task 1: New tools for system modeling and simulation

To enable HiPerBRIC's Computation Science and Engineering, modeling need to be separated from simulation, as shown in Fig. XXX. This allows using modern modeling languages that follow the *object-oriented modeling paradigm* described above and makes it possible to use modern mathematical tools (symbolic processing and solvers for stiff systems) that are needed to simulate computationally robust and efficient. It will also enable use of Building Information Models for automatic generation of HVAC system and controls models, starting with a *modular* Building Information Model.

For a modeling language we propose to use Modelica as it is well positioned to be-come the de facto standard for modeling of physical systems. The Modelica language is an open standard that is significantly adopted by various industrial sectors. The language enjoys multi-million dollars investments within the ITEA2 framework of the European Union that is funding advanced pre-competitive R&D in software for Software-intensive Systems and Services.

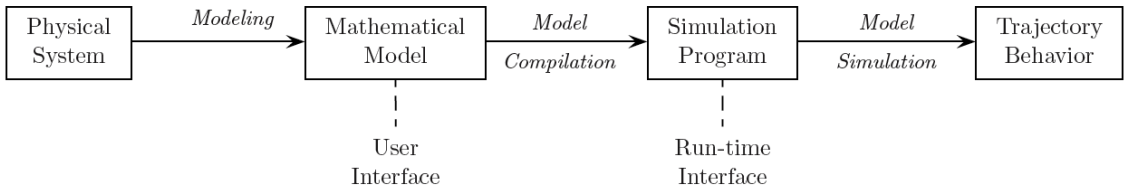

Fig. XXX: Illustration of converting a physical system (hardware) to a mathematical model (that expresses the governing equations) to a simulation program (an executable program code) that can generate the trajectory behavior. Note that in this paradigm, the mathematical model has nothing to do with how the equations are being solved, thereby allowing model reuse for different use cases. (Source: Cellier and Kofman [2006].)

The modeling will be based on the following principles:

a) Separation of models (acausal equations) from data and from numerical solution methods.
b) Separation of modeling and simulation as illustrated in Fig. XXX. This allows end-users to spend their time on defining the system topology, not on figuring out what causality should be imposed to make the system solvable using computer assignments.
c) Representation of models to the modeler in the most intuitive form, e.g.,

   a. for HVAC and power generation systems: Schematic editor.
   b. for control algorithms: Block diagram and finite state machine.
   c. for geometry: 3D object-oriented CAD.

d) Modularization of the environment (such as in Unix, Modelica and Ptolemy II). This will make the environment significantly easier to collaboratively develop and maintain as different models and tools can be separated and individually tested.

The models proposed in this section will also allow computing the exergy destroyed by the various irreversible processes of a building system in order to identify opportunities for system improvements. Thus, the models can be used in conjunction with the exergy analysis tool proposed in Task XXX.

Subtask 1.1: Models for HVAC and renewable energy systems

We propose to port existing models and develop new models in the Modelica language. These models can then be used directly within a Modelica simulation environment, or be translated into program code that can be used by existing building simulation programs.

New models need to be developed that characterize the dynamic performance of HVAC and renewable energy components as only little work has been done to create dynamic models of equipments [Bourdouxhe et al., 1998]. Models of various fidelities will be developed: For preliminary design, typically simple models may be used that reflect the current lack of detailed information. As the design processes, these models will be replaced with models that interface to manufacturer data. During operation, yet another set of model will be needed, for example for a chiller fault detection a model will be needed that can detect loss of refrigerant.

Experiments are necessary to obtain performance data over a larger set of operating conditions, to obtain dynamic performance data and to validate new models as manufacturers only provide steady-state equipment performance for a narrow range of operating conditions.

Subtask 1.2: Models for Active Facade and Lighting

xxxxxxxxxx

Subtask 1.3: Models for IAQ

Unlike the HVAC modeling domain for which there is significant existing simulation capability to work from, indoor environmental quality modeling tools are relatively non-existent. IEQ models can be broken down into sets of mass balance problems that include multi-directional transport and transformation across a network of compartments. The basic solutions for these mass balance problems across time and space are well developed for conservative, non-reactive gases; they have not been implemented in a simulation package to any useful degree.

The characteristics of a needed IEQ simulation tool to meet the goal of this project would include an ability to model the mass concentration of a range of gas phase compounds and particle sizes across time and space within the building. Environmentally relevant scales of these species are dramatically different from those typically encountered in energy modeling: gas phase concentrations can range over nine orders of magnitude and particle are distributed across five orders of magnitude. Relevant time scales vary from those of fast chemical reactions in the millisecond range to compartment air exchange time constants of minutes to hours, to daily and weekly building occupancy patterns.

Model inputs include material selection parameters, material source emission rates for specific IAQ-related compounds, contaminant removal mechanisms including ventilation, filtration, and sink effects (e.g., water condensation, adsorption), contaminant transformation through chemical reactions, contaminant entrainment mechanisms including ventilation, desorption, and re-suspension.

Much information exists on the above parameters in the indoor environmental field, however, basic research is still needed in some fundamental areas. The existing information on the simpler compounds and conditions (e.g., carbon dioxide generated by occupants) may be fairly rapidly implemented into a simulation tool and has the potential to provide early integration into building design process. More complex compounds or particle distribution conditions will require significantly more time and development to be integrated. The interface of these models will be designed such that they can be integrated with existing and concurrently developed models.

Subtask 1.4: Data Bases and Information Retrieval for Equipment Models and Performance Data

Tools need to be developed that allow linking product specification to performance data. Such tools will allow users or BIM translators to search, as in Goolge Product Search, for a specific piece of equipment and retrieve a Modelica model including performance data that allows assessing its performance or integrating the model into a building automation system for model-based controls or fault detection and diagnostics.

Performance data for use in simulation may be published by manufacturing companies, by organizations such as ASHRAE and by individual tool users. Web 2.0 tools may be used to rate the quality of the data, to add new data and to fix erroneous data. For example, if a neutral testing laboratory produced the data, then this data may get a higher quality rating compared to data provided by an individual user.

Subtask 1.5: Control System Description Language and Tools for Code Generation

A Control System Description Language will be developed that allows specification of control sequences that can be used for design and operation. Such a language will consist of a human readable specification and a specification that is suited for code generation.

Tools for code generation will be developed that allow generating code from the Control System Description Language for different applications: For the design of HVAC systems, code will be generated that can be linked to a Modelica-based dynamic HVAC models for performance assessment. For the design of the control and communication hardware, different code may be generated that allow synthesis of communication hardware and control implementations. For the operation of building systems, code may be generated that allows uploading control laws to Building Automation Systems.

Subtask 1.6: Modeling Environments

Combined graphical and textual modeling environments will be developed. The environment will allow plug-and-play model assembly, retrieval of performance data from product data bases (developed in a separate task), and model hand-off to translators that may generate a simulation program for performance assessment, for reduced-order model extraction and for controls design, or that may generate static data that can be used to populate a Building Information Model. This will provide a modeling environment aimed at innovative companies and industrial researchers to identify: (i) optimized approaches to reduce energy consumption through component and system-level modifications; (ii) locations and types of sensors and actuators for monitoring, diagnosing and self-tuning controls of buildings; (iii) economics and environmental impacts of these approaches and their respective cost-benefit metrics.

Based on this modular modeling environment, user-friendly tools for A&E firms to design new and retrofit existing buildings will be developed. These tools will link to product libraries for HVAC components and building materials through Building Information Models. It will contain expert systems for component selection and the above modular modeling environment for energy system modeling. Such a tool will embed all the necessary system-level engineering to identify components and system integration strategies to reduce energy consumption, but would not require users to understand details of the underlying engineering and analysis methods.

Subtask 1.7: Simulation Environments

Research is needed for further advancing the symbolic and numerical solvers that are critical for robust and efficient simulation of equation-based models of building systems. Some challenges that require further research are how to deal with systems

- that have time scales from seconds (controls) to days (heat storage)
- that become singular at certain times (e.g., a flow network with zero flow rate)
- that are hybrid (e.g., switching event-driven controls and continuous time dynamics)

While these effects have been dealt with in isolation, the challenge that the building industry faces are

- the systems have hundreds or thousands of differential equations, which often need to be integrated over the duration of a whole year.
- when simulation-based design becomes the norm rather than the exception, the typical tool user have little formal training in mathematics.

- algorithms for optimization and uncertainty propagation often require hundreds of simulations which poses practical challenges with respect to computing time.

In terms of user support during simulation, further research is needed to include better diagnostics into equation-based solvers. Currently, debugging a simulation model that does not converge to a solution can be a formidable task even for experienced users. Furthermore, when a simulation progresses slowly during certain times (e.g., due to an ill-conditioned problem) it can be rather difficult to isolate and fix the root cause for the slow computation time. Better diagnostics from the simulation program may help in guiding a user toward a problem formulation that does not cause the numerical difficulties.

Subtask 1.8: Expert Systems for building system design based on Platform Based Design methodology

This task will develop expert systems that identify components and system integration strategies to reduce energy consumption. While initial versions will require much user decisions, guided by an expert systems, subsequent versions will increasingly employ optimization algorithm and uncertainty analysis to guide the user in the decision making process.

Task 2: Integration of Modelica HVAC System Models into EnergyPlus

As there is currently no detailed building and facade model available in Modelica, we propose, in parallel to a Modelica development, to research how a Modelica-based HVAC system simulation can be integrated with the EnergyPlus building model. This will allow the use of EnergyPlus for envelope and daylighting simulation and Modelica for the system and controls simulation until whole building energy and daylighting simulation models are available and validated in Modelica, which is a significant effort by itself. Such system models may then be automatically generated from a modular BIM, even for building systems that do not obey the EnergyPlus loop structure. It will also allow testing of control sequences described in a product neutral Control System Description Language that is envisioned to become part of a Building Information Model.

A parallel research task will be how to translate Modelica models into simulation modules, for example for EnergyPlus in the form of an EnergyPlus module and for TRNSYS in the form of a TRNSYS TYPE. A similar, although significantly smaller, effort has been done in the past to develop a translator from the NMF equation-based language into simulation models that could be used with various building simulation programs. We propose to research how Modelica could be used for such a model translation, whether the EnergyPlus module structure is applicable for being auto-generated and to develop corresponding translators.

Note that this model integration is an alternative path to the co-simulation environments

proposed below. While the co-simulation environment targets primarily the research audience, this task reduces the risk of not being able to integrate Modelica with EnergyPlus through co-simulation in a way that is simple enough for use by a large user audience.

Task 3: Co-simulation Environments

To enable interfacing domain specific tools during run-time (i.e., co-simulation), interfaces need to be added to existing tools. Initial work has been done within LBNL's Building Controls Virtual Test Bed (BCVTB) software.

Currently the data shared among different programs that are coupled to the BCVTB have no semantics. This puts the burden of correctly configuring the data flow to the user. R&D is needed to design interfaces that semi-automatically configure the data connectivity, thereby reducing the setup time for co-simulation that involve hundreds to thousands of exchanged variables.

Research is also needed for use of adaptive time steps for co-simulation that exploit the fact that during set point changes, short time steps are needed between subsystems (such as the building and HVAC system) while significantly larger time steps may be used during night when the loads are constant.

For well-defined applications with specific requirements, special tailored interfaces can be developed that link domain specific tools and hide the complexity through a user interface. For co-simulating novel HVAC systems, modeled in Modelica, that are linked to the whole building energy analysis program EnergyPlus, a specially tailored interface to the BCVTB, or a direct link between EnergyPlus and Modelica, can be developed. Such a program would hide the complexity of the more modular BCVTB.

Task 4: Advancement of EnergyPlus

Since newly proposed tools will not be ready for use by a larger design community during their early stages of development, we propose to further advance EnergyPlus for simulation of innovative building systems. New models need to be added in order to allow design of established systems for very low energy buildings. Particular gaps include

a) for thermal system design, models for natural ventilation and the associated controls and models that model pressure distribution in HVAC ducting systems, and
b) for envelop design, models for complex window systems that use bi-directional spectral distribution functions.

Task 5: Exergy Analysis

Scientific Foundation

We propose research that shows how to best incorporate exergy analysis into the design

and operation of building energy and control systems. For example, during operation a fan coil unit controller may trade-off airflow rate with supply air temperature such that the exergy destruction is minimized. This will allow using a physics-based metrics to trade-off flow friction versus thermal energy. Thus, the fan coil unit need not be aware of the detailed chilled water plant operating performance which simplifies the implementation of distributed control.

Historically, exergy analysis typically assumes an environment state (dead state) that is fixed in time. However, it is well accepted that low energy systems should take advantage of diurnal and seasonal change in environment conditions. We therefore propose research in how to incorporate dynamics into exergy analysis to form a scientific foundation for use of *dynamic* exergy analysis for building design and operation, including Model Predictive Control that exploits the system dynamics.

Tool Development

Unlike energy, exergy is a physical quantity that is destroyed in a system. The amount of exergy destruction is a physics-based measure of the system-internal irreversibility that ultimately leads to consumption of primary energy. We propose to develop visualization tools that allow building designers and operators to visualize the destroyed exergy in order to find and eliminate the root causes that lead to high consumption of primary energy. These visualization tools will interface the Modelica models proposed in a separate task that compute the exergy destruction, and process these raw data to a form that is easier to comprehend by the tool user. An example of such a visualization is shown in Figure XXX. The figure shows on the horizontal axis the amount of exergy destroyed in various subsystems of a room air conditioning system, and on the vertical axis the temperature level at which the subsystems exchange heat. Here, 30% of the exergy is destroyed because the Carnot efficiency of the chiller is 0.7. Hence, improving the compressor efficiency should *not* be the first priority since a better system design and operation would allow reducing some of the exergy destruction that is caused by heat transfer at large temperature differences, which amounts to 70% in this system.

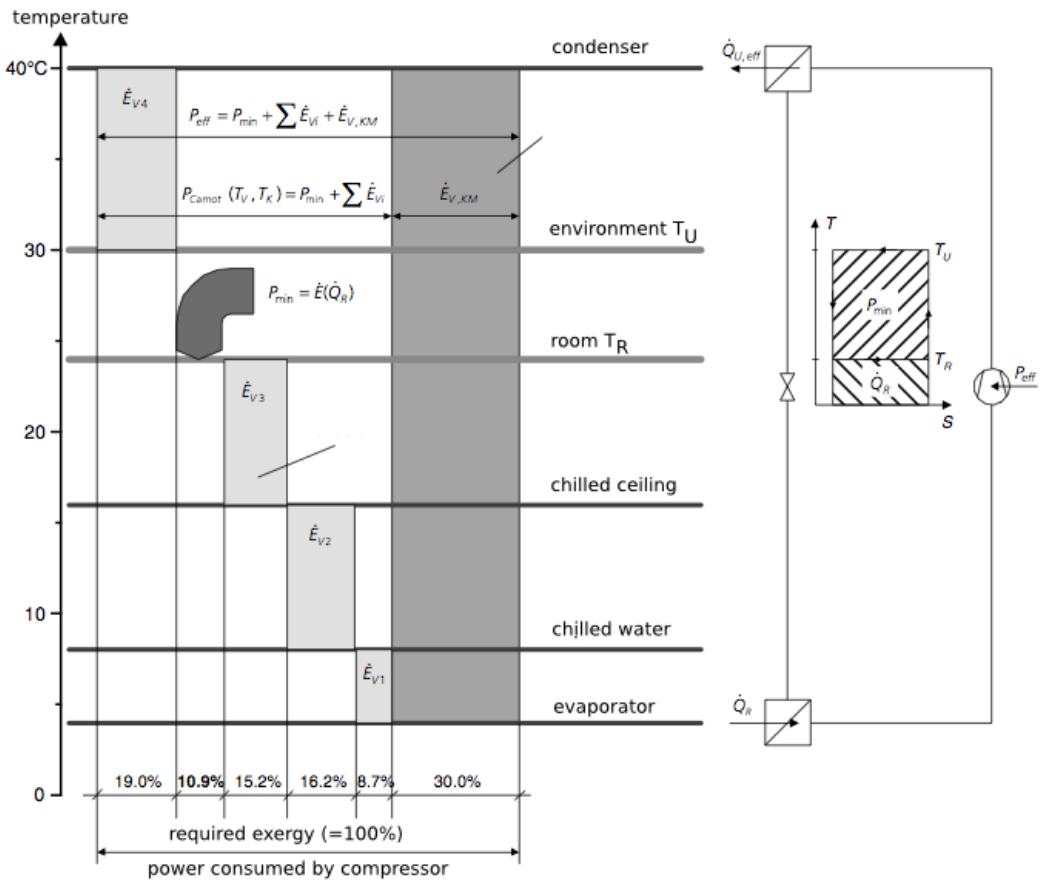

Figure XXX: Schematic representation of temperature differences (vertical axis) of a chilled water plant that serves a chilled ceiling and rejects the condenser heat to the ambient. The horizontal axis shows the exergy that is destroyed in the various heat transfer processes and in the compressor. (Figure translated from Wellig et. al. (2006)).

Task 6: Building Information Models

IFC need to be extended to allow modular modeling of HVAC and control systems, using a Control System Description Language that is proposed in a separate task. IFC extensions are also needed to provide material properties that affect IAQ, such as mass diffusion coefficients, partition coefficients and partial vapor pressure.)

The translator between IFC and EnergyPlus need to be extended to allow, in addition to building fabrics data translation, the translation of (predefined) HVAC system models and controls schedules between IFC and EnergyPlus.

Translators between IFC and Modelica need to developed. These translators will allow automatic generation of a model for performance assessment, for control system synthesis or for model-based building operation from a Building Information Model that contains a modular representation of the HVAC system and a control specification in the Control System Description Language. Conversely, to populate the BIM, translators need

to be developed that allow populating the BIM with data that have been specified in a schematic model editor such as the Dymola modeling environment. In addition, these translators need to be able to translate HVAC system architectures between a BIM and schematic diagrams that can be used as construction documents to avoid having duplicate diagrams, and associated loss of productivity, for the simulation model and the construction documents.

Task 7: Design support

[Andrzej to add content]
Modeling, analysis, and control of sensitive and complex airflow dynamics in buildings using uncertain models in the presence of unmeasured disturbances, and large, but highly constrained design parameter space.

System complexity: coupled thermal and airflow dynamics models (including Navier-Stokes equation) describing airflow dynamics involve multiple spatial and temporal scales and are highly nonlinear. As a consequence it is difficult to determine airflow patterns that are beneficial for comfort and do not require large control (and hence energy) effort to stabilize.

Sensitivity: established temperature and airflow patterns can easily become unstable due to change in boundary conditions or disturbances.
Uncertain parameters include thermal connectivity of walls, parameters used in subgrid models representing airflow dynamics below the grid size, boundary conditions, etc.
Unpredicable and unmeasured disturbances include weather and people dynamics.
Large design space: there are multiple choices for HVAC devices (positions and sizes of radiators, chilled beams, air vents), sensor, and actuator locations for hybrid systems.
Constrained design space: there are limits on amount of air available for injection, heat or water, cost of devices and implementation, etc.

Enablers:
Fast CFD codes for Reduced Order Model extraction and concept validation.
Methodology for obtaining Reduced Order Models from Navier-Stokes or its Boussinesq approximation using POD/Galerkin methods and Lagrangian Coherent Structures.
Efficient Uncertainty Quantification methods.
Distributed estimation and control theory including “Design then Reduce” approach.
Direct and adjoint-based sensitivity analysis and optimization methods.
Methods for extraction, analysis and control of Lagrangian Coherent Structures.
Design methodology using Platform-Based Design for synthesizing control, sensing, computation, and communication architecture.
Dynamical systems methods for control of mixing.
Wireless temperature, humidity and airflow sensors.
“Compressed sensing” ideas for estimation of spatial and temporal airflow structures .
Experimental techniques and sensors for measuring temperature, humidity, IAQ, and

airflow.

Approach: *Exploit natural airflow dynamics to get most benefits by passive ventilation concepts optimized using models. Use small footprint active control system for augmentation of performance and stabilization.*

Use POD/Galerkin and LCS methods for analysis, and control of sensitive and complex airflow dynamics in buildings.
Use analysis based on reduced order models to identify detrimental and beneficial, stable and unstable temperature and airflow patterns. Utilize the most beneficial and stable patterns as targets for stabilization using combination of passive and active techniques.
Use combination of distributed control, sensitivity analysis to determine passive device locations (air vents location), actuator and sensor points for mechanical HVAC stabilization/augmentation system.
Use PBD methods for finding control architectures that meet comfort and energy requirements, while meeting cost targets, and managing complexity of design process.
Use methods developed under DARPA Robust Uncertainty Management to quantify robustness of the candidate solutions.

Examples

Example of possible new approach: Design of a Robust Displacement Ventilation System

- We will use the example of Displacement Ventilation to illustrate the approach for designing robust ventilation systems, propose a possible design work flow, and show how the enablers mentioned before will be used in the design.

Possible Approach:

- **Select air flow vent location for base and control inflow and outflow.** The idea is to have a robust base flow and a small controlled flow to stabilize the base flow and reject disturbances while saving energy. We would use CFD modeling coupled Navier-Stokes or its Boussinesq approximation and advection diffusion equations for temperature and density [Satish to provide reference]. Use sensitivity analysis (direct or adjoint [Bewley, John to provide other references]) based on linearized PDE models of coupled airflow and temperature dynamics in a room (linearization around solution with a uniform inflow at the floor and outflow at the ceiling as BCs) to select potential vent locations. Alternatively, “design then reduce” approach based on linearized PDE [John to provide a reference] could be used to select vent locations. Insensitive points will be used for a steady injection to provide a base flow that satisfy basic IAQ requirement (based on square footage). Sensitive points will be used for controlled airflow injection to stabilize the base flow and reject disturbances. Alternatively, controllability Grammians could be used to determine most beneficial control

flow vent locations. Adaptation of the flow to the occupancy level could be done through the base flow (pros: more robustness, cons: additional actuation required) or through controlled airflow (pros: no additional actuation required, cons: larger actuators required).

- **Obtain a Reduced Order Model of airflow and temperature field response to design parameters, control inputs, boundary conditions, and disturbances**. Obtain POD modes of airflow and temperature fields from multiple CFD runs corresponding to a wide range of vent locations, vent air mass flow and temperatures, boundary conditions, and disturbances [Lumley, Moehlis, Rowley, …, Guey ACC08]. Use LCS analysis to eliminate POD modes that do not significantly contribute to mixing [Surana ACC 08]. Obtain a parameterized reduced order ODE model (ROM) of airflow and temperature dynamics in the room by a Galerkin projection of the PDE model on the POD modes [Lumley, Moehlis, …, Guey ACC08]. Compare ROM to CFD and possibly adjust parameters to improve mode shape and transient response agreement [Tadmor]. Possibly add "shift modes" [Noack] to stabilize ROM. Linearize ROM and verify controllability of POD modes through control flow (through controllability Grammians). Possibly move the control vent locations to improve controllability. Model neglected modes as uncertain feedback around ROM. Obtain bounds on the uncertain feedback by assessing (in linearized ROM) how much gain and phase neglected POD modes provide.

- **Obtain Pareto curves for base airflow parameters for energy use, comfort, and robustness to disturbances and uncertain parameters.** Use multidisciplinary optimization of base airflow parameters running ROM in the optimization loop to find a set of acceptable comfort solutions. The comfort metric is how far is the base flow (temperature and airflow) in the living zone from the desired one. This could be refined by doing LCS analysis using velocity field from ROM instead of using the Eulerian ROM for temperature and mass flow. The energy metric is a function of the amount of base airflow that needs to be provided. The robustness metric measures how much the comfort and energy metrics vary under disturbances and uncertain parameter variations. Use trend optimization [Sorin to provide references] and other RUM tools such as adaptive coarse optimization [Andrzej to get a reference from Yannis] to avoid getting stuck at local minima. Robustness to uncertain parameters, disturbances, etc. will be evaluated using RUM Uncertainty Quantification methods [Andrzej to provide references].

- **Optimize temperature sensor location.** Optimize temperature sensor location using linearized models and observability Grammians [Rowley] or "design then reduce" approach linearized PDE models [John to provide a reference]. Analyze fundamental limitation of performance of the control architecture [Goodwin] for effect of non-minimum phase effects such as right-half zeros and delays. Look for

pole/zero cancellations. If detrimental pole/zero

- **Build a temperature and airflow estimator.** Construct a nonlinear observer for the temperature and the flow [Rowley, Tadmor, Guey ACC08, Surana ACC 08]. Also, a linearization-based observer design approach could be used. An option is to build an Extended Kalman Filter (EKF) to estimate uncertain parameters such as solar loads, open door airflow, etc [Khalil].

- **Design an estimator-based control law to stabilize desired temperature and airflow**. One would use either robust or adaptive airflow control approach, depending on the range of uncertain parameters and disturbances. Possible robust control approaches include linearization-based approaches like LQG using the same optimization goals (weighted sum of energy and comfort metric) as in Step 3 above. Moreover, ideas from optimal control of mixing could be applied [Igor to provide references]. Alternatively, one could provide optimization of energy while keeping comfort as constraint using MPC applied to nonlinear ROM. The latter would be especially applicable if the occupancy profiles were known and the response to control flow inputs were slow. Adaptive approaches could be indirect (use estimate parameters using EKF) or direct (such as extremum seeking control [Krstic books]). Control input would be mass airflow and temperature at control vent location. To create such flow local PID loops around equipment that controls temperature and mass flow (fans, valves, dampers) would be used. {Scott: review/edit/add to the control approaches}.

- **Quantify robustness of closed-loop system to the disturbances and uncertain parameters.** Use RUM Uncertainty Quantification using nonlinear ROM with estimator and controller to assess robustness of the closed-loop system. Note that we expect that robustness of the closed-loop system will significantly improve relative to the one of the open-loop base system, whose robustness was evaluate in Step 3 above.

Design Flow for a Robust Displacement Ventilation System

- **{Alessandro to contribute}**

- **Control**

Barriers:

- *Predictive and model-based control design using high nonlinear uncertain models (including complex airflow) in the presence of unmeasured disturbances, and constrained state and control input space.*
- System complexity: coupled thermal and airflow dynamics models describing airflow dynamics involve multiple spatial and temporal scales and are highly nonlinear.

- Uncertain parameters include thermal connectivity of walls, parameters used in subgrid models representing airflow dynamics below the grid size, boundary conditions, etc.
- Predictive variables (with uncertainty bounds) include weather and people dynamics.
- Constrained control input space includes limits on air and water flows as well as temperature profiles.
- Constrained state space includes bounds in temperature and humidity for comfort as well as system operational constraints.

Enablers:

- Synthesis of robust, large-scale, distributed, model-based and predictive optimal control of HVAC systems with thermal storage.
- Modulation of operational set-points and modification of sequences of operation (equipment start/stop logic for example) is fundamentally a dynamic optimization problem whose solution depends on the future evolution of a nonlinear and large scale system. Use of computationally efficient, equation-based models in conjunction with nonlinear programming algorithms [3-4], thereby allowing the application of optimal control theory for large scale systems [5], and enterprise-scale web-enabled networked control systems.
- Systematic approach to Control Oriented Modeling (COM). Use existing high fidelity building energy simulation tools [6], such as EnergyPlus, to generate reduced order models (known as control-oriented models) for prediction in the control algorithm
- Ascertain bounds on the disparity between the high-fidelity and the COM models using empirical statistical methods.
- Distributed estimation and control theory

Approach:

Energy-optimal operation of such system requires solution of a complex control/optimization problem which has to be solved using a combination of off-line and real-time (on-line) optimization. Off-line, design optimization is used to determine nominally optimal open-loop time-varying control actions for a collection of typical and descriptive environmental conditions. Linearizations around these nominal trajectories are employed in on-line, real-time optimization, whose purpose is to handle the off-nominal behavior seen on an (approximately) hourly basis due to a variety of unmodeled and uncertain disturbances (e.g. deviations from nominal weather conditions and internal heat gains due to people, light and equipment and uncertainty in building state-variable dynamics).

Model Predictive Control (MPC) is a class of on-line optimization-based methods that are widely used in other industries to solve broadly similar dynamic problems [7-9]. The approach proposed here is to investigate the use of MPC, on its own or in conjunction with other advanced control methods, to solve the aforementioned class of emerging

building control problems.

Examples

Chilled water plant. Describe current state (3), describe opportunities related to multivariable feedback control, MPC, optimization –based controls. Paint a vision for available technology in the future (building scale)
Radiant heating and cooling (room scale). Advantages of this example: Illustrates new technology that impacts controls performance negatively because loop gains are decreased, gains from disturbances increased relative to air-cooled VAV system.
Natural / mixed mode/displacement ventilation. Illustrates fragility and robustness, sensor placement, comfort metrics.
Desired: single example that expresses multiscale nature of the big problem – goes from zonal to campus.

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Project Description

Project: Design of Energy-Efficient Hybrid HVAC systems

Basic science academic projects will provide stable funding for PhD students and will include:
1. Modeling at various scales and fidelity level of coupled airflow and thermal dynamics, including effect of uncertain parameters, disturbances, and control input.
2. Uncertainty quantification, sensitivity analysis, and optimization of architecture of the base airflow delivery, thermal storage system, and low energy feedback control system architecture.
3. Estimation and control algorithm design.

Tools and Methodology projects will go through gated technology maturation process and will include the following stages:
1. In early stages (years 1-2) we will use the results of basic science to construct tools and develop methodology, downselect design and control approach, validate models and design approaches.
2. In later stages (years 3-5) we will mature the technology through sequence of validation in increasingly realistic environment from room-level experimental facility, to floor-level virtual test bed, to floor-level experimental validation.

Specific tasks will involve:

Task 1. Virtual Test Bed development and validation. We will use a library of component models (CFD, Energy+, Modelica, agent-based occupancy models, etc.) and cosimulation environment described in previous sections to provide a floor-level model of airflow and thermal dynamics interconnected room, thermal storage, HVAC equipment, ducts, and occupants dynamics. We will validate the Virtual Test Bed in room level at Berkeley Center for Built Environment (CBE) and in floor level at the HiPerBRIC facility.

Task 2. Base flow and thermal storage architecture design.

This Task will include Concept Synthesis including down-selection of approach for most promising combination of using natural ventilation, displacement ventilation, and thermal storage and corresponding duct layouts that would be possible to test in CBE and HiPerBRIC facility. The concepts will be optimized for performance (comfort), energy efficiency, and robustness (to uncertain parameters and disturbances). Uncertainty Quantification methods, sensitivity analysis, and optimization methods developed at Universities will be used here.

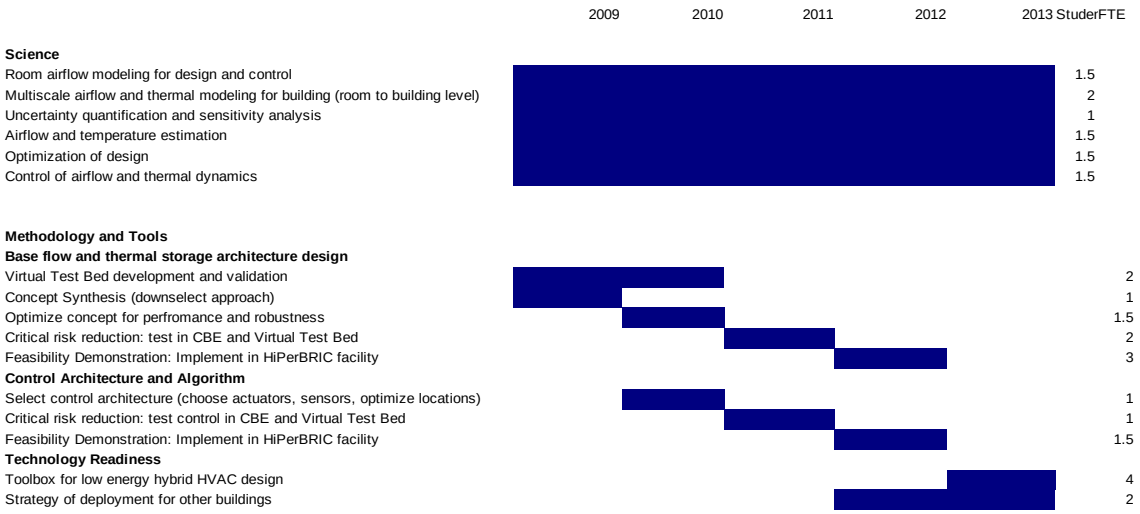
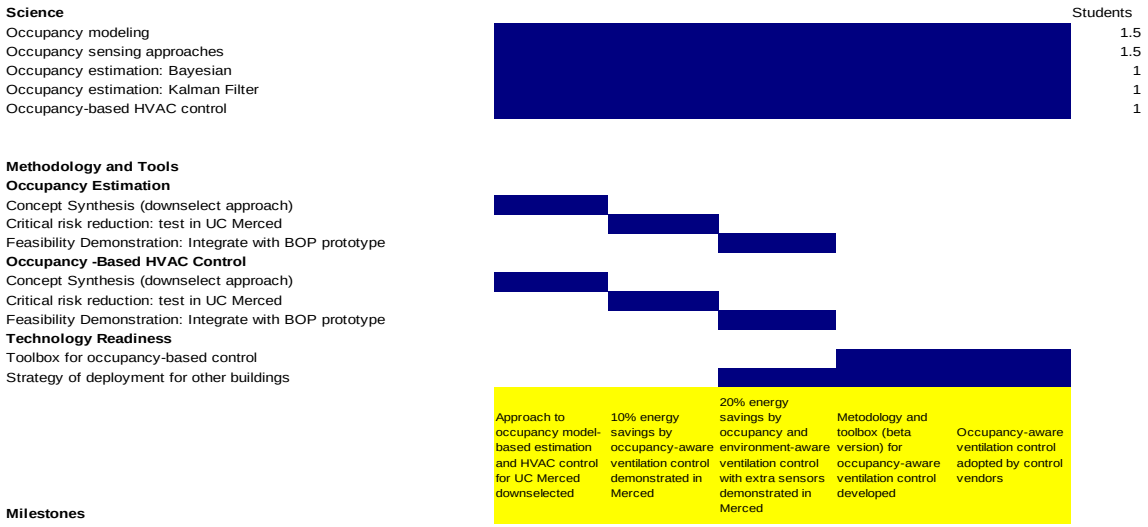
Critical risk reduction will be test in CBE and Virtual Test Bed, while the Feasibility Demonstration will be implementation in the HiPerBRIC facility.

Task 3. Control Architecture and Algorithm.

In this task we will select control architecture (choose vent locations, actuators, sensors, optimize their locations), design temperature and airflow estimators, and control laws. Critical risk reduction will be accomplished by a test in CBE and Virtual Test Bed, while the Feasibility Demonstration will be performed in the HiPerBRIC facility.

Task 4. Demonstrate Technology Readiness

We will provide a design flow and construct a beta version of a toolbox for low energy hybrid HVAC design and provide a strategy of deployment for other buildings.



Project: Occupancy-Based Energy Saving Control