Performance-Risk Analysis
For the Design of High-Performance Affordable Homes

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Abstract

Net-zero energy, emissions, and carbon sustainability targets for buildings are becoming achievable with the use of renewable energy technologies and high-performance construction, equipment, and appliances. Methodologies and tools have also been developed and tested to help design teams search for viable strategies for net-zero buildings during the early stages of design. However, the risks for underperformance of high-performance technologies, systems, and whole buildings are usually not assessed methodically. The negative consequences have been, often reluctantly, reported. This paper presents a methodology for explicitly considering and assessing underperformance risks during the design of high-performance buildings. The methodology is a first attempt to formalize extensive applied research and industry experiences in the quest for net-zero energy homes in the U.S., and build on existing tools and methods from performance-based design, as well as optimization, decision, and risk analysis. The methodology is knowledge driven and iterative in order to facilitate new knowledge acquired to be incorporated in the decision making. As a point of departure in the process, a clear definition of the project vision and a two-level organization of the corresponding building function-performance objectives are laid out, with objectives further elaborated into high-performance targets and viable alternatives selected from the knowledge-base to meet these. Then, a knowledge guided search for optimized design strategies to meet the performance targets takes place, followed by a selection of optimized strategies to meet the objectives and the identification of associated risks from the knowledge-base. These risks are then evaluated, leading either to mitigation strategies or to changing targets and alternatives, and feeding back to the knowledge-base. A case study of affordable homes in hot humid climate is used to test the methodology and demonstrate its application. The case study clearly illustrates the advantages of using the methodology to minimize underperformance risks. Further work will follow to develop the underpinning mathematical formalisms of the knowledge base and the risk evaluation procedure.

1. Introduction

High-performance buildings optimize major functional attributes including energy efficiency, durability, and comfort. Recently, however, energy has become the main, and often the only, driver for high-performance buildings, with the other attributes often not being explicitly considered. The consequences of the energy efficiency drive on building durability and comfort underperformance have been reported elsewhere. This paper presents a formal methodology to help explicitly consider the risk for underperformance in all building functional attributes when only few performance targets drive the search for high-performance designs.

The value of the methodology is that it attempts to optimize the design of high-performance <u>affordable homes</u>, which unlike other buildings, involve particular constraints, such as social ones, that transcend the purely technical boundaries. Furthermore, even though the case study focuses on affordable homes in the hot and humid southeast region of the U.S., the methodology is expected to be applicable to other regions and contexts. For example, in the case study presented in this paper the home air conditioning system (AC) is both a "curse" (energy) and a "blessing" (comfort). However, in many countries, having an AC is a luxury out of

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reach for most homeowners, and more vernacular methods to maintain comfort are permitted such as opening windows and using purposely leaky envelopes. Furthermore, in temperate climates, having an AC or heating system is not even contemplated. In both cases, comfort sacrifices may exist, but the energy "curse" is eliminated. No matter the context, the trade-offs that may lead to prioritize affordability over other functional needs, such as structural safety or health, will always exist. The methodology describes how to address these trade-offs systematically.

The quest for energy security over the last 10 years has spurred impressive efforts in the United States to research and develop homes leading to net-zero energy with promising results. To support this cause, extensive government programs are now in place, notably the Energy Star Homes program by the U.S. Environmental Protection Agency (EPA, 2011) and Building America program by the U.S. Department of Energy (US-DOE, 2011a). Energy Star defines strict guidelines and targets for energy efficiency, which if satisfied, certify a home as Energy Star, and qualify it for government incentives. Building America is an industry-driven research program designed to accelerate the development and adoption of advanced building energy technologies in new and existing homes. The Building America program forms research partnerships with all facets of the residential building industry to develop cost-effective solutions to reduce energy use of housing with consideration to comfort and quality.

Whole-house energy performance is assessed throughout the U.S. with the Home Energy Rating System (HERS) index developed by the Residential Energy Services Network (RESNET, 2011) in which a home built to the specifications of the HERS Reference Home, based on the 2004 International Energy Conservation Code (IECC), scores a HERS Index of 100, while a net-zero energy home scores a HERS Index of 0. The lower a home's HERS Index, the more energy efficient it is in comparison to the HERS Reference Home. Each 1-point decrease in the HERS Index corresponds to a 1% reduction in energy consumption compared to the HERS Reference Home. Both, Energy Star and Building America programs use the HERS index to measure the whole house energy performance. Energy Star certification requires third-party construction plans verification and on-site inspection of construction, equipment, and appliances, as well as duct and envelope performance air-tightness testing. The data is then entered into a customized interface software built on top of an accepted whole building energy simulation engine, such as DOE2 (LBL, 1980) or EnergyPlus (Crawley, et al., 2000) to obtain the HERS score.

Green homes rating systems attempt to produce high-performance homes through a pre-determined point system that gives credits to improvements in all aspects of home performance over standard practice. The Builders Challenge program developed by the U.S. DOE (US-DOE, 2011b) overlaps significantly green home programs, but is based on the guidelines set out by the Building America research. In general, green homes rating systems in the U.S. rely on the Energy Star rating and the HERS index to evaluate energy performance. The first author was a HERS and green home certifier for new affordable homes for Habitat for Humanity (HFH) of Greater Miami. HFH receives Government incentives for each house that is certified as Energy Star and green. However, the existing guidelines for high-performance and green homes are general and cannot deal with the specific needs of particular projects. For example, for hurricane, flooding, and termite protection, south Florida homes are built with concrete masonry unit walls as opposed to the wood-frame construction used in the rest of the country. Affordable homes also pose particular challenges that constrain the search for optimized energy solutions.

A formal methodology is lacking to assist building project teams in selecting affordable optimized energy solutions without compromising quality. Such methodology should be general

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to be applicable to countries with less stringent building codes and standards. This paper presents a performance-risk methodology to address this need. The paper describes the methodology and demonstrates its application with a case study. The paper is organized as follows. Section 2 describes the performance-risk methodology. Section 3 demonstrates the use of this methodology with a case study of typical affordable homes in the hot humid climate of the greater Miami. Section 4 discusses the findings, limitations and further directions to improve and implement the methodology.

2. Performance-Risk Methodology

The goal of the methodology is to be generic so as to be used by affordable housing teams for the selection and optimization of design strategies for high-performance affordable homes. As illustrated in Figure 1, the methodology defines five iterative steps in which strategies that pose high risks to a house performance are eliminated or the risks mitigated. After the vision, goals, and objectives of the project have been determined, an iterative synthesis-analysis (SA) loop follows in which performance targets are determined and strategies to meet these selected (synthesis), and then evaluated and optimized (analysis). A strategy is a combination of viable alternatives. Performance models are developed for the analysis according to the criteria determined in steps 1 and 2. The analysis process may lead to more realistic targets and improved strategies (synthesis). The SA loop continues until the strategies selected are satisfactory. Step 2 is knowledge-based in order to narrow the search for realistic, low-risk strategies. In the final step possible under-performance risks are evaluated which may lead to selecting new targets and strategies or mitigating the risks on the selected ones.
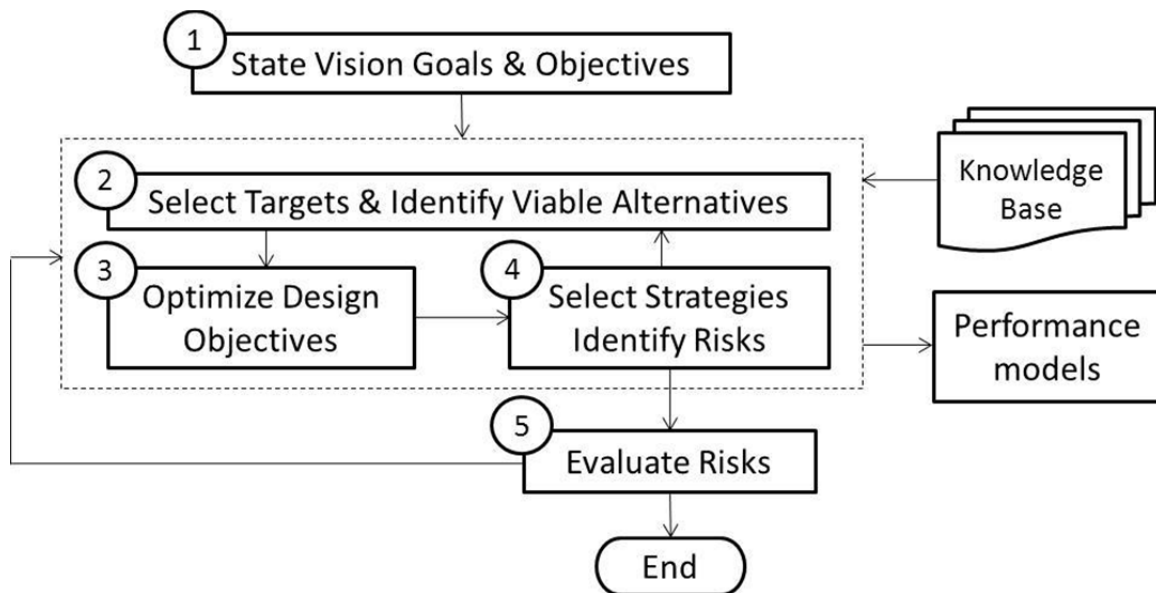

Figure 1. Performance-Risk Methodology

For the risk evaluation a typical risk analysis approach is adapted from (Modarres, et al., 1999). In Figure 2, the initiating events are those that cause risks for house unsatisfactory performance according to the criteria determined and evaluated in the previous steps. Again, the whole process is knowledge-based, which, as discussed below, for risk analysis must be statistically based.

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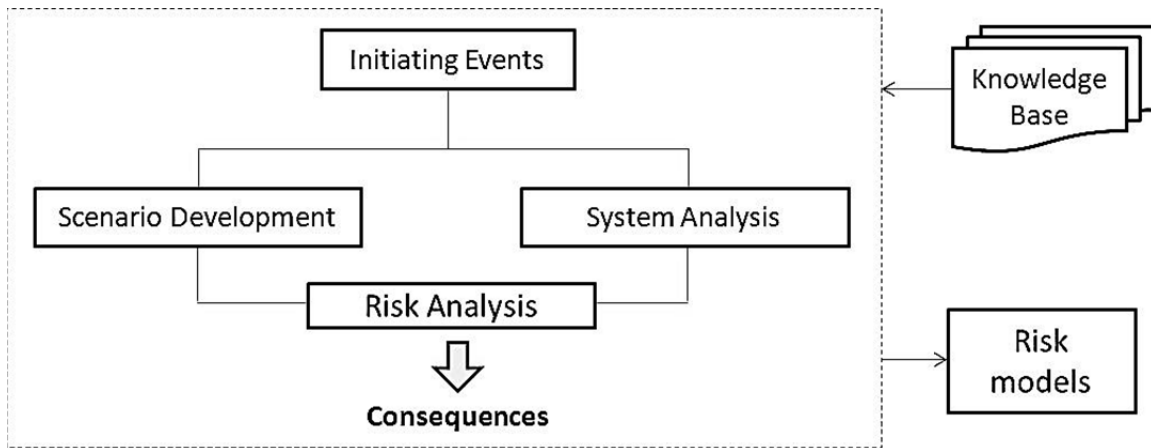
Figure 2. Risk Evaluation Process

Risk evaluations are inherently probabilistic as they permit the calculation of the odds of various levels of loses. In building science the uncertain factors involved in the hygrothermal processes are grouped in the following categories: a) climate (outdoor boundary conditions); b) occupants density, activities, and home use (indoor boundary conditions); c) the construction (mainly the envelope); and d) the mechanical system that alters indoor responses to the indoor and outdoor loads. Over the past few years, there is been a trend to use the statistically robust reliability theory in building science (Pietrzyk, 2000; Carmeliet, et al., 2009; Alfano, 2010; ANNEX-55, 2011), following the lead from the field of structural engineering, which has implemented this theory in practice as a limit state design approach (CSA, 1981). In general, and depending on the problem at hand, a probabilistic risk evaluation selects relevant factors from the ones described above as random variables, based on sufficient data available and judgment on how these factors impact the result. Then it uses standard probabilistic methods to process the random inputs to produce probabilities of poor performance. Due to a lack of actual performance data, this paper follows a deterministic approach to risk evaluation.

3 Case Study

Greater Miami HFH homes are typically one story, detached, slab-on-grade (i.e. bungalow) air conditioned (AC) homes located on generous plots of land. Six similar types of homes are built with conditioned area ranging between 1,000 ft^2 and 1,200 ft^2 in a compact rectangular shape. For hurricane and termite resistance, the homes are built with concrete masonry units (CMU), except for the interior walls and roof that are wood-framed. The roof is shingled, pitched hip-type with a 5/12 slope extending 2 feet around the perimeter of the house, except for the entrance porch that provides extended sun and rain protection. The attic is non-conditioned and vented, and houses the supply ventilation ducts. The case study home has a conditioned floor area of 1,109 ft^2.

The indoor environmental conditions for the case study home are mainly determined by the AC operation during 10 months of the year, which is typical for South Florida. Reducing the AC operation period in favor of natural ventilation is not explored in this project due to constraints imposed by the developer. As an anecdotal note, one of the authors suggested to HFH to consider changing the architectural designs and increasing the land occupation density to achieve greater impacts on energy and sustainability of whole HFH residential communities. These recommendations will hopefully take place in future developments. A secondary goal of this paper is to demonstrate that a more radical, community-based, approach is needed to break the trend for incremental improvements, and lead towards more significant ones.

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3.1 State Vision Goals and Objectives (Step 1)

This step of the methodology draws on work at the U.S. National Renewable Energy Laboratory (Deru, et al., 2005). However, it departs from it in two fundamental aspects: 1) it is function-performance centered, therefore it breaks down a project vision directly into the functional categories of a building; and 2) by explicitly referring to the building's broad functions it facilitates identifying and evaluating the risks associated to these. As indicated in Figure 1, the process starts with a vision statement, which for the HFH affordable homes is the following:

"To build energy efficient affordable homes in the Greater Miami area that meet the Energy Star incentive requirements, while maintaining the indoor environmental health, comfort, and construction safety and durability standards."

Note that the vision above explicitly includes important aspects of a building functional performance to permit a holistic performance evaluation of a building, and help to avoid "missing the forest through the trees" The vision is then broken down into the broad building functional objectives, which are categorized as primary and constraining objectives. These can be further decomposed as needed. Figure 5 illustrates the vision broken down into functional categories for the affordable homes project.
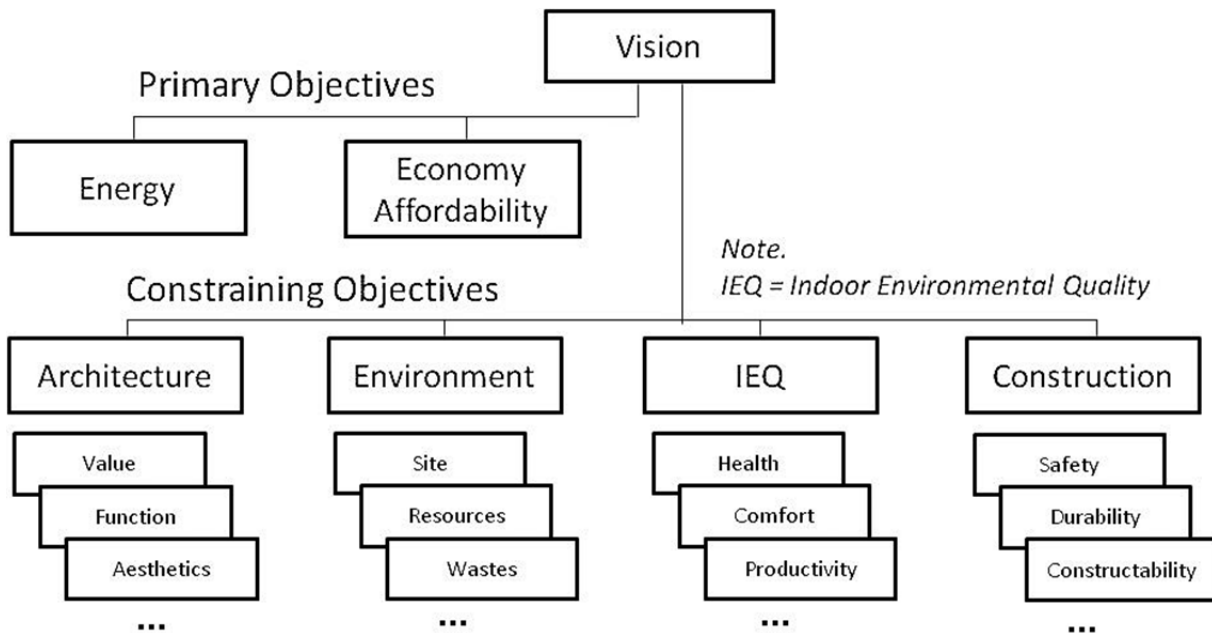

Figure 5. Project vision and objectives

In Figure 5, Energy belongs to the environmental resources category, but is identified as a primary objective in the project vision and therefore treated separately. The constraining objectives are equally important to high-performance design as the primary ones, and need to be stated explicitly; however, according to the project vision these are not the primary drivers of the design process.

Even though the project vision does not mention the natural environment, as a functional requirement of a building it must be evaluated. Codes and standards address the local environmental risks, as well as the structural safety ones. However, in many countries these are not strictly enforced, particularly for affordable housing. In the environmental category, resources and wastes are evaluated from a life-cycle point of view at the local, regional, and global levels, in which wastes refer not only to solid wastes, but also to contaminants to soil, air,

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and water. The three dots indicate that more objectives can be included in each category; for example, another important architectural objective for affordable housing is universal design for accessibility and adaptability to the occupants' own needs. Systems maintainability is also critical, as its lack resulted in failed solar technologies in HFH homes in the past (Bass, 2010).

Finally, it should be noted that all these broad building functional categories are interdependent; for example, the site affects energy, comfort, and durability. Central to high-performance designs, these interdependencies need to be captured by the performance models during the evaluation and optimization processes. This paper focuses on evaluating the energy, affordability, health, comfort, and durability functional requirements, given that the structural safety requirements, stated in the project vision, are strictly enforced by the Florida Building Code Residential.

3.2 Select improvement Targets and Identify Viable Alternatives (Step 2)

As illustrated in Figure 1, selecting performance targets and the likely strategies to meet these, requires an accessible knowledge-base of alternative viable solutions to make sure that the targets are realistic and achievable and the strategies viable. For the case study, the Florida Solar Energy Center (FSEC) and the Building America (BA) Program reports and guidelines are the best knowledge sources, as well as the Energy Star program.

3.2.1 Targets

Energy

The benchmark government program for home energy performance in the U.S. is Energy Star. Home builders and homeowners receive government incentives for obtaining Energy Star certification, which are particularly critical for affordable housing. The challenge, however, is that Energy Star has been gradually raising the standard towards 50% HERS energy savings by 2015 and to net-zero energy by 2020, based on a 2004 IECC standard home. Reaching the 50% energy savings target seems achievable, considering that the HFH homes build by 2010 are already scoring as low as HERS 70 (30% savings). However, generating energy from the sun on site is not an option for HFH of Greater Miami due to unaffordability and unproven safety by South Florida hurricane standards.

In this project, for convenience, a typical 2010 HFH home (HERS 70) will be used as a reference home to compute energy savings. The reason for this reference change is that it provides a more realistic and meaningful benchmark for the builders because it gives improvements over their current construction standard. Nevertheless, the decision on the reference home is not expected to alter the outcome of the study, which is a comparative one. An ambitious target of 50% energy savings based on the typical HFH home built in 2010 will then be pursued. If unattainable, this objective can be re-evaluated as illustrated in Figure 1. Therefore, the energy goal and performance objective are as follows.

Goal: to minimize home energy consumption.

Performance objective: to reduce annual energy consumption by us much as 50% by 2015 based on a typical HFH home built in 2010, with enclosure performance ready for net-zero energy by 2020.

The second part of the objective seeks to guarantee, subject to affordability constraints, that the enclosure is built to best possible standards in order to avoid expensive future enclosure upgrades to meet the net-zero energy target by 2020.

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Affordability

The aim of this project according to its vision is to reduce the cost or at least maintain cost neutrality for the alternatives/strategies to be studied. However, the cost evaluation has to consider the time value of money because mortgages are amortized over a period of time, usually 30 years at a mortgage interest rate, and energy improvement investments usually increase the cost of a home, which is also reflected in the mortgage payments. Most importantly, the premise behind energy improvements is that energy investments are recovered as savings in the monthly utility bills.

There are several standard methods and indicators to evaluate the cost effectiveness of investments. A convenient method to evaluate home energy investments is to represent the investment costs as equal annualized or monthly mortgage amortizations at a mortgage interest rate, over a study horizon, which corresponds usually to the mortgage period, combined with the annual/monthly utility payments, at an assumed utility rate (cents/kWh). Representing and adding together annualized/monthly mortgage costs and utility payments/savings, is a convenient way to estimate and compare the impact of different alternatives on the monthly or yearly income of the consumer. Therefore, the affordability goal and performance objective are as follows.

Goal: *to improve or at least maintain affordability*

Performance objective: *to improve home affordability or maintain cost neutrality based on a typical home built in 2010, using an annualized mortgage plus utility costs method over a period of 30 years.*

3.2.2 Alternatives

Viable alternatives to meet the performance targets over the current standard are first identified from a knowledge-base (KB). Table 1 presents the current HFH case study home as the "Reference Home", as well as technically viable energy improvement alternatives from various sources. The set of alternatives titled "Building America" have been extensively tested in prototype homes under the Building America program (BA, 2004) for the hot-humid climate region. Alternatives under the "Various Sources" heading are also technically viable, and have been collected mainly from publications by the Florida Solar Energy Center (FSEC, 2006), Energy Star (EnergyStar, 2010), and the Florida Green Building Coalition (FGBC, 2011), as well as from actual energy efficient construction projects.

Note that most sources assume wood-frame wall construction when specifying insulation levels because, except for South Florida, this system is dominant across the US. Added insulation levels are usually not required for CMU construction in this climate zone. Nevertheless, highly insulated and air tight construction systems such as insulating concrete forms (ICF) and various types of panelized systems, such as structural insulated panels (SIPs) are also gaining ground in South Florida. As indicated in Table 1, the current level of insulation of HFH home wall assemblies is about R-6 to R-7 because the inside face of CMU the walls is furred vertically leaving a ¾" gap that is covered with radiant insulating paper.

Water heating contributes about 15% to the energy consumption for a typical South Florida home (Fairey, 2007), which is why solar water heating is widely promoted in Florida. A viable alternative is to use integrated heat-pump/tank electric water heaters (HPWH). HFH of Greater Miami started installing HPWHs in new homes by recommendation of the first author. These have been tested (EPA, 2008) and demonstrated up to 30% energy savings in hot water heating. HPWHs draw heat from the air to pre-heat the water in the tank, while providing extra indoor space cooling capacity (if located inside). The use of these systems has improved the overall energy performance of the HFH homes by about 5 HERS points (5% energy savings).

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Table 1 Reference home and technically viable energy efficiency alternatives from the KB

Systems	Reference Home	Building America	Various Sources
Walls & Floor	CMU/reflective foil/gap	wood-frame	wood-frame, ICF, SIP
* Effective R-value (IP units)	R-6 to R-7	R-15	R-19 to R-22
* Solar absorptance	0.75 exterior	NA	0.5 int./ext.
* Floor slab	4" slab on grade/6 mil poly	NA	NA
Windows	Single/impact	double/Low-e	
* Window to floor area	16%	NA	12%
* U-factor (IP units)	1.09	0.32	0.6
* SHGC	0.5	0.27	0.27, 0.3
Ceilings	Fiberglass batt		
* R-value	R-30	R-30	R-38
Roof/Attic	Shingles light		
* Solar absorptance	0.8	-	0.3, 0.4
* Roof deck insulation	NA	-	Radiant
* Attic type	Vented	Conditioned	Conditioned
Space conditioning	Central AC/Heat split		
* SEER / HSPF	14.5/Heat coils @ AHU	15/8.8	17/
* Capacity/SHR/Airflow	21 Kbtu-h/0.75/630 CFM	-	-
* Ducts location	Attic	AC conditioned	AC conditioned
* Ducts leackage Qn/CFM	0.05/50 (tested)	-	-
* Ducts insulation	R-6	R-4 to R-8 if in attic	R-6 if in attic
Air movement			
* Leackage (ACH@50pa)	5 (tested)	3	-
* Mechanical ventilation	Kitchen & bath exhaust fans	Controlled central supply	Controlled central supply
* Ceiling fans cover - eff.	75% - 130 CFM/watt	-	-
Supplemental dehumidification	No	stand-alone/humidistat Energy Star 1.2 - 1.5 l/kwh	Stand-alone
Water heating	Heat pump/52 Gal tank	Solar/tank 64 sf cl-loop	Solar
Lighting	10% CFL	100% CFL	-

3.3 Optimize Design Objectives: Energy and Cost (Step 3)

The optimization process is conducted in the BEopt 1.1 building energy optimization software (NREL, 2006). BEopt was initially developed to run on DOE2.2 (DOE-2.2, 1998) and TRNSYS (TRNSYS, 2011) energy simulation engines. The latest version of BEopt transitions from DOE2.2 to EnergyPlus (US-DOE, 2011c). The energy performance of the reference home as obtained with BEopt was cross-validated with results from EnergyGauge (EnergyGauge, 2011), which is the software used for Florida Residential Code compliance verification and residential energy performance assessments. BEopt cost database was also updated to reflect the current South Florida costs. Government incentives in favor of solar thermal and photovoltaic technologies are not included in the cost analysis because these are highly variable.

Boundary Conditions

The outdoor boundary conditions used by energy simulation software are based on data from weather files including typical meteorological year data (TMY3) tailored for energy calculations. The weather files represent most representative weather conditions, including clear and cloudy days, for energy calculations rather than extreme, worst case conditions, occurring at the location. Therefore, the weather files do not include any rain data for example. The indoor boundary conditions are typically based on assumed occupancy from the number of bedrooms and bathrooms, and the schedules for home operation.

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Optimization

As explained in section 3.3.1, the metric used to measure affordability is based on the projected total annual or monthly costs (mortgage + utilities), which considers the effect of energy improvement capital investments in increasing the mortgage payments for the buyer, but saving energy consumption and lowering utility bills. Figure 6 presents the source energy and cost optimization results obtained using the BEopt software. In Figure 6, the lower boundary delineates optimized energy and cost strategies to achieve different levels of intended energy savings. As indicated, the reference point for energy and cost savings corresponds to the reference home.

Consistent with EPA and the BEopt software, the source energy metric (MBtu) is used here for the energy evaluations of alternatives as opposed to the site energy (kwh) consumed. The argument by EPA to recommend using source energy is to account for the varying systems efficiencies in converting and distributing energy from the source(s) (natural gas, coal, etc.) to the end-uses (cooling, heating, lighting, power, etc.), so as to provide equivalent and thermodynamically correct assessments. For the case study, given that all the alternatives use the same source of energy, the site energy evaluation provides results comparable to the source evaluation. Furthermore, the site energy metric is more useful for a homeowner because it can compare directly to utility bill payments. Source-to-site ratios are provided by EPA for different energy types.
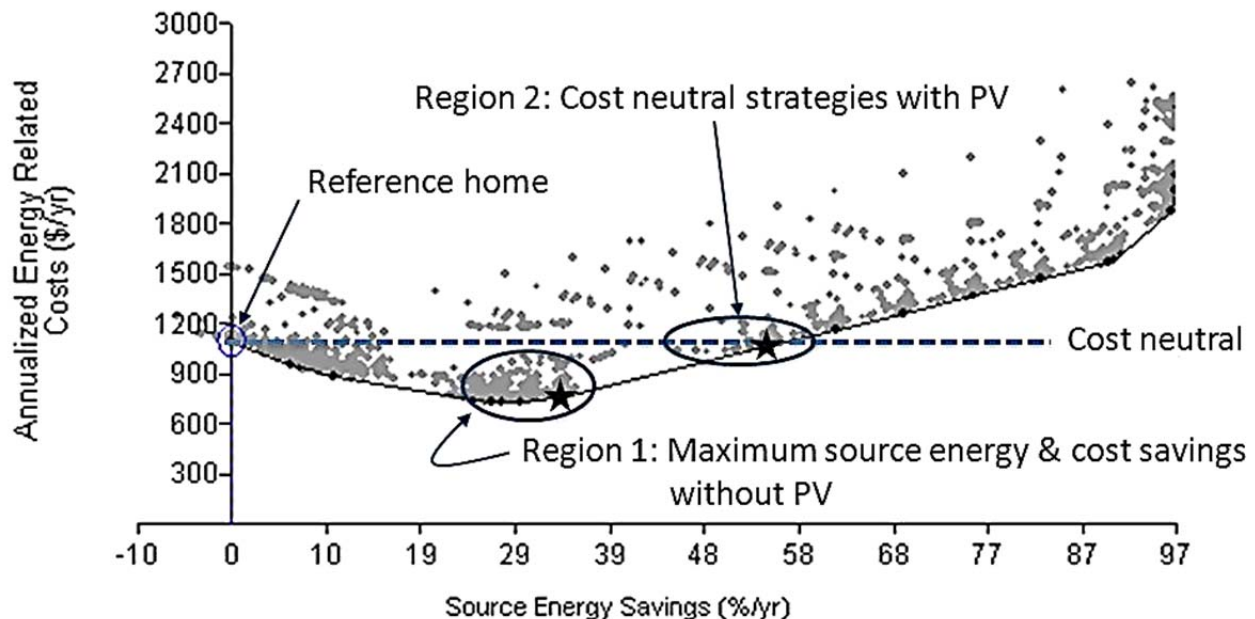

Figure 6. Energy and cost optimization using BEopt software

In Figure 4, strategies falling on the "Cost neutral" line are cost neutral, while those under that line have improved cost performance due to lower utility bills and/or smaller size of the air conditioner. In Figure 4, two, arbitrarily sized, key regions are shown, indicating that, given the uncertainties inherent in the energy and cost analysis, any point within a region could replace the star as the optimum energy-cost performance strategy. Region 1 includes strategies that achieve maximum source energy and cost savings without the need for a PV system to replace source energy. Region 2 includes strategies that achieve maximum energy savings and cost neutrality with PV. However, as indicated in section 3.3.1 PV systems are risky solutions for affordable housing in terms of hurricane safety, cost, maintainability, and long term

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performance, and therefore will not be considered further in this study. Section 3.4 takes a closer look at the strategies in Region 1.

3.4 Select Strategies and Identify Risks (Step 4)

In Table 2 eight parametric alternatives (p1-p8) are explored within region 1 in Figure 4, using knowledge from the knowledge-base on local, affordable, maintainable, and safe construction. From these eight, three promising strategies are selected (s1-s3) to meet the energy performance and affordability targets. Strategy "s1" corresponds to the "star" within Region 1 in Figure 4. In Table 2, the improvements with respect to the reference home are shaded. As indicated, all the alternatives place the ducts inside the conditioned space (p1), which is not only recommended from a performance point of view, but also buildable and affordable even for slab-on-grade homes (FSEC, 2010).

The results from the energy and cost analysis are shown in Figure 7 with uncertainties indicated. In the figure, a vertical arrow denotes first-costs uncertainty, a skewed arrow denotes energy performance uncertainty that is reflected in energy savings and in annualized energy costs, and an arrow-arc denotes unevaluated uncertainties.

Table 2. Selection of high performance strategies

	Strategies	(1) Ducts location	(2) Roof	(3) Hot water	(4) Walls	(5) Windows	(6) Window area	(7) AC efficiency	(8) Ceiling fans	(9) Ventilation	(10) Dehumidify
ref	Reference	Attic	Shingles light	HPWH	R-6	Single tinted	18%	SEER15	Standard	Kitchen/bath Test 5 ACH50	Through AC
p1	Ducts in AC	Inside	Shingles light	HPWH	R-6	Single tinted	18%	SEER15	Standard	Kitchen/bath 5ACH@50Pa	Through AC
p2	White tile	Inside	White metal	HPWH	R-6	Single tinted	18%	SEER15	Standard	Kitchen/bath 5ACH@50Pa	Through AC
p3	Solar HW	Inside	Shingles light	Solar	R-6	Single tinted	18%	SEER15	Standard	Kitchen/bath 5ACH@50Pa	Through AC
p4	Wall R-14	Inside	Shingles light	HPWH	R-14	Single tinted	18%	SEER15	Standard	Kitchen/bath 5ACH@50Pa	Through AC
p5	Window	Inside	Shingles light	HPWH	R-6	High perform	18%	SEER15	Standard	Kitchen/bath 5ACH@50Pa	Through AC
p6	Window+	Inside	Shingles light	HPWH	R-6	High perform	12%	SEER15	Standard	Kitchen/bath 5ACH@50Pa	Through AC
p7	AC efficiency	Inside	Shingles light	HPWH	R-6	Single tinted	18%	SEER17	Standard	Kitchen/bath 5ACH@50Pa	Through AC
p8	Ceiling fans	Inside	Shingles light	HPWH	R-6	Single tinted	18%	SEER15	Occupancy +4^{0}F setp	Kitchen/bath 5ACH@50Pa	Through AC
s1	CMU+	Inside	Shingles white	HPHW	R-14	High perform	12%	SEER17	Occupancy +4^{0}F setp	Kitchen/bath 3ACH@50Pa	Through AC
s2	CMU++	Inside	Shingles white	HPHW	R-14	High perform	12%	SEER17	Occupancy +4^{0}F setp	Supply ASHRAE 62.2	Yes
s3	ICF++	Inside	Shingles white	HPWH	R-20	High perform	12%	SEER17	Occupancy +4^{0}F setp	Supply ASHRAE 62.2	Yes

The life-cycle cost effectiveness and affordability results illustrated in Figures 6 and 7 are highly sensitive to first cost variations. For example, government incentives included in the costs of high performance windows make them highly affordable (p5 and p6), while a 40 ft2 closed-loop solar water heater (p3) is just below cost neutrality. However, solar water heaters are not considered further as the lack of maintenance have caused system failures in HFH homes in the past (Bass, 2010). Furthermore, the costs of maintenance and repairs are not included in the analysis of Figures 6 and 7, which increases vertical cost uncertainty, and possibly the horizontal energy savings. In Table 2, the solar absorptance of white metal roof is 0.3, and that of white shingles is 0.75 (p3).

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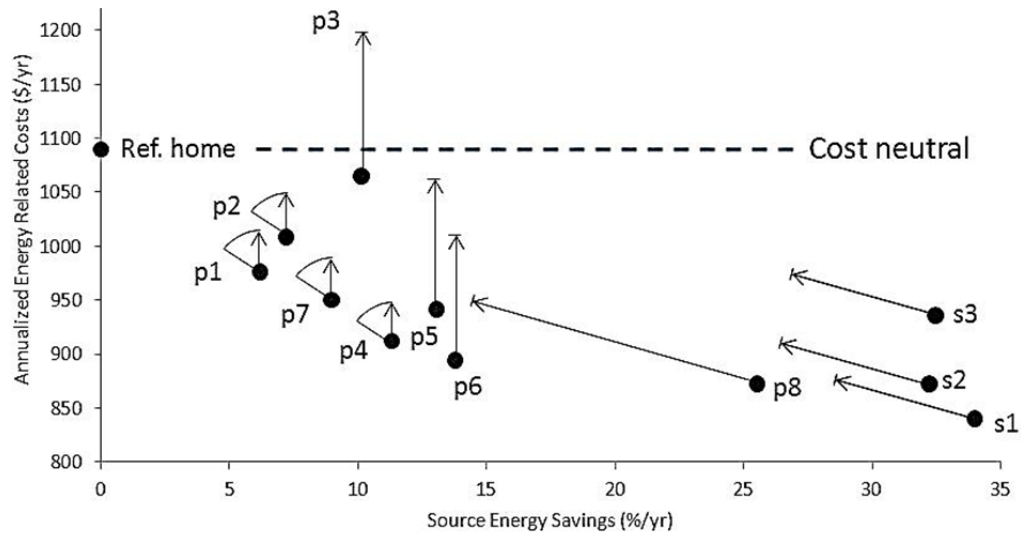
Figure 7. Strategies with maximum energy and cost savings without PV

Figure 8 (a), shows a typical section of a current HFH home, R-6, and Figure 8 (b) one with R-14 insulation. R-14 walls are CMU walls with 2" semipermeable rigid insulation, located inside for hurricane purposes, to permit the envelope to dry towards the interior (p4). Cost effective R-values of walls and ceiling insulation for different climate zones have been calculated and verified for this case project following the economic law of diminishing returns (LDR).
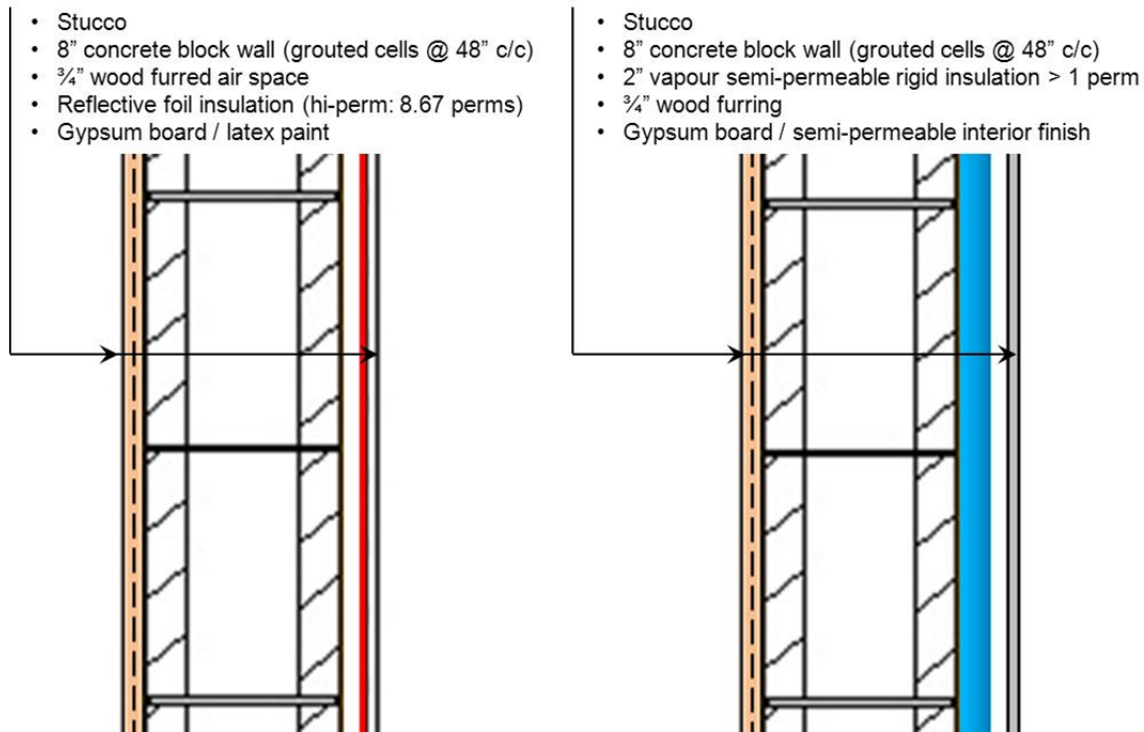

- Stucco
- 8" concrete block wall (grouted cells @ 48" c/c)
- ¾" wood furred air space
- Reflective foil insulation (hi-perm: 8.67 perms)
- Gypsum board / latex paint

- Stucco
- 8" concrete block wall (grouted cells @ 48" c/c)
- 2" vapour semi-permeable rigid insulation > 1 perm
- ¾" wood furring
- Gypsum board / semi-permeable interior finish

Figure 8. Wall section, a) current HFH home and b) Energy efficient home "s1" and "s2"

The LDR measures the progressive decrease in marginal outputs or returns (e.g. energy savings for added insulation) as the amount of inputs, i.e. a product (e.g. insulation), is increased. Figure 9 shows its application in determining the wall insulation for the case study home using the energy simulation data.

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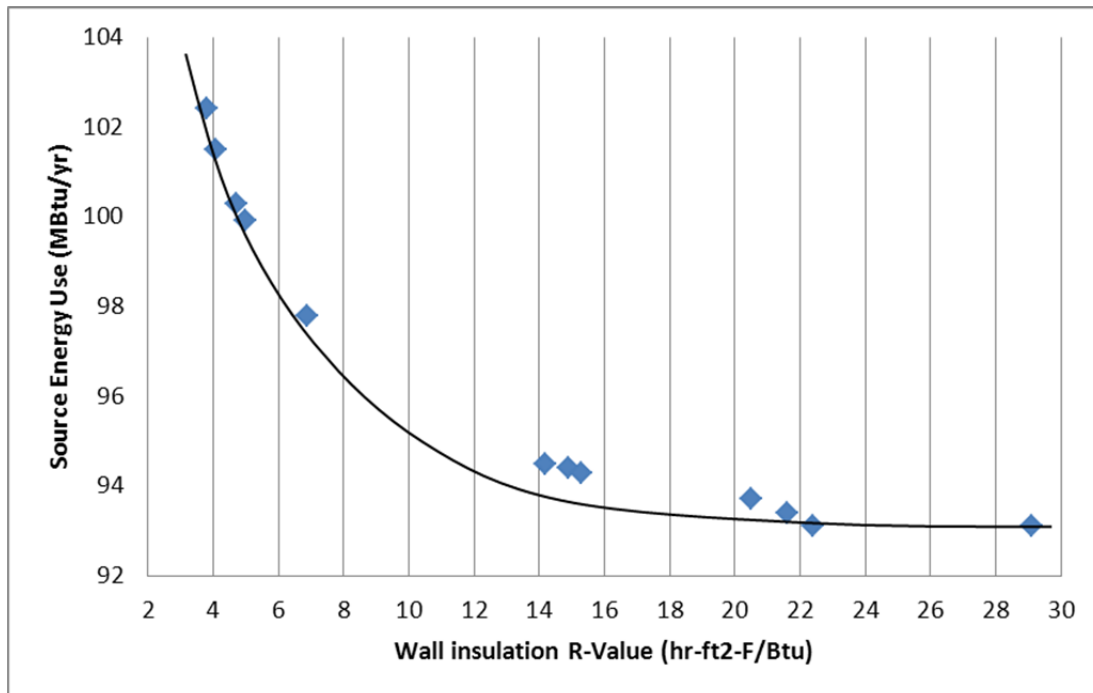[2] Florida International University, Department of Civil and Env. Engineering, Miami, Florida

Figure 9. Diminishing returns for wall insulation R-value

In Figure 9, important energy savings (i.e. reduced energy use) are obtained by adding insulation to the CMU walls down to about R-14 to R-16. After that, the energy savings achieved, using ICF construction, are marginal. It can be argued that the improved air-tightness of ICF (not considered in Figure 9) over CMU further increases energy efficiency. However, the first author tested two affordable ICF homes and obtained comparable air-tightness results to those of air-tightness verified CMU homes.

High performance windows have a U-factor of 0.32 and a solar heat gain coefficient (SHGC) of 0.27 (p5). The reference home has four standard ceiling fans, one per bedroom and one in the living room. As an alternative, smart fans operate based on occupancy and need, and with adequate coverage permit cooling set points up to 4^0F higher (p8). Furthermore, ceiling fans used with natural ventilation could help extend the season without air conditioning. However, this last advantage is not included in the analysis. Figure 7 shows large uncertainties (skewed line from "p8") in energy savings and annualized energy costs derived from the possibility of the thermostat not being raised with the operation of ceiling fans. In Figure 7, these fan-use uncertainties are included in the three strategies selected.

As expected, having a high-performance envelope (p2, p4, p5, and p6) results in reduced AC size and operational energy savings. However, as reported elsewhere, high-performance envelopes reduce sensible heat gains significantly and the need for AC cooling, with the unintended consequence of reducing its capacity for handling the latent loads (i.e. de-humidification), particularly under part load operation. Furthermore, also reported elsewhere, high-performance envelopes are more airtight and, at some point, result in home under-ventilation. However, adding controlled mechanical ventilation alone would exacerbate any moisture-related problems (i.e. ventilation is a latent load in hot-humid climates), and therefore, it has to be accompanied with supplemental dehumidification.

Consequently, three strategies were selected in Table 2 and Figure 7. Strategy "s1" combines all the parameters except for the solar water heater and the metal roof that was replaced by white shingles (metal roofs marginally improve performance at a higher cost). Strategy "s1" also

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increases air tightness from 5 ACH to 3 ACH at 50 Pa. Strategy "s2" includes the same parameters of "s1" plus controlled ventilation and supplemental dehumidification. Strategy "s3" replaces CMU R-14 construction system with ICF R-22 and also includes supply ventilation and supplemental dehumidification. Therefore, strategies "s2" and "s3" are comparable. As expected, notice in Figure 6 that adding controlled ventilation and supplemental dehumidification in strategies "s2" and "s3" results in energy and affordability penalties because these systems are costly and operate on energy. For this reason, strategies "s2" and "s3" fall above the optimization boundary (Figure 6).

Strategy "s3" was added to evaluate the energy performance improvement from changing the construction system at a corresponding cost penalty. For ICF R-22, the energy performance improvement is negligible compared to that of CMU R-14, and the cost penalty is reasonably low. A new construction system needs to demonstrate significant performance improvements to justify the change, while remaining below the affordability line, and involving reasonably low function-performance risks with mitigation measures in place. Informal communications with builders of few affordable ICF homes built recently in South Florida, with no controlled ventilation or supplemental dehumidification, report high indoor humidity levels and condensation, likely due to the increased ICF air-tightness and envelope energy efficiency.

In selecting these strategies, the following risks have been identified in relation to the project vision and corresponding performance objectives: 1) energy savings risks: from uncertainties in the energy modeling assumptions compared to the actual home operating conditions; 2) affordability risks: mainly due to variability in first costs, future utility rates, and mortgage assumptions; 3) health risks: due to uncertain actual ventilation and moisture conditions in strategy "s1"; 4) durability risks: due to uncertain actual ventilation and moisture effects in strategy "s1"; 5) discomfort risks: in the verge of discomfort humans naturally seek to restore comfort. It is therefore expected that home occupants increase the reliance on the AC system to maintain comfort, thus overriding the assumptions of the energy modeling. Figure 7 illustrates uncertainties for the first two types of risks. Section 3.5 addresses the other three types of risks.

3.5 Evaluate Risks (Step 5)

From an energy performance perspective, strategy "s1" is the optimum one. However, as discussed in section 3.4, from the literature (i.e. the knowledge-base), "s1" would likely involve under-ventilation and high humidity risks that could be mitigated with strategies "s2" and "s3" for an energy performance penalty. Therefore, these risks need to be evaluated before selecting the strategy that provides optimum energy and affordability performance with minimized risks. The risk evaluation will follow the process indicated in Figure 2.

3.5.1 Initiating events and Scenario Development

Figure 11 illustrates cause-effect relationships between two initiating events that have been identified for "s1" and the undesirable consequences under four possible scenarios. In the first event, a high performance envelope minimizes energy flows resulting in many possible unintended consequences depending on the climate. The second event, even though not directly related to strategy "s1", has been included because it may aggravate the effects of the first event: a high occupant density expected in small affordable homes results in high moisture generated per house conditioned volume.

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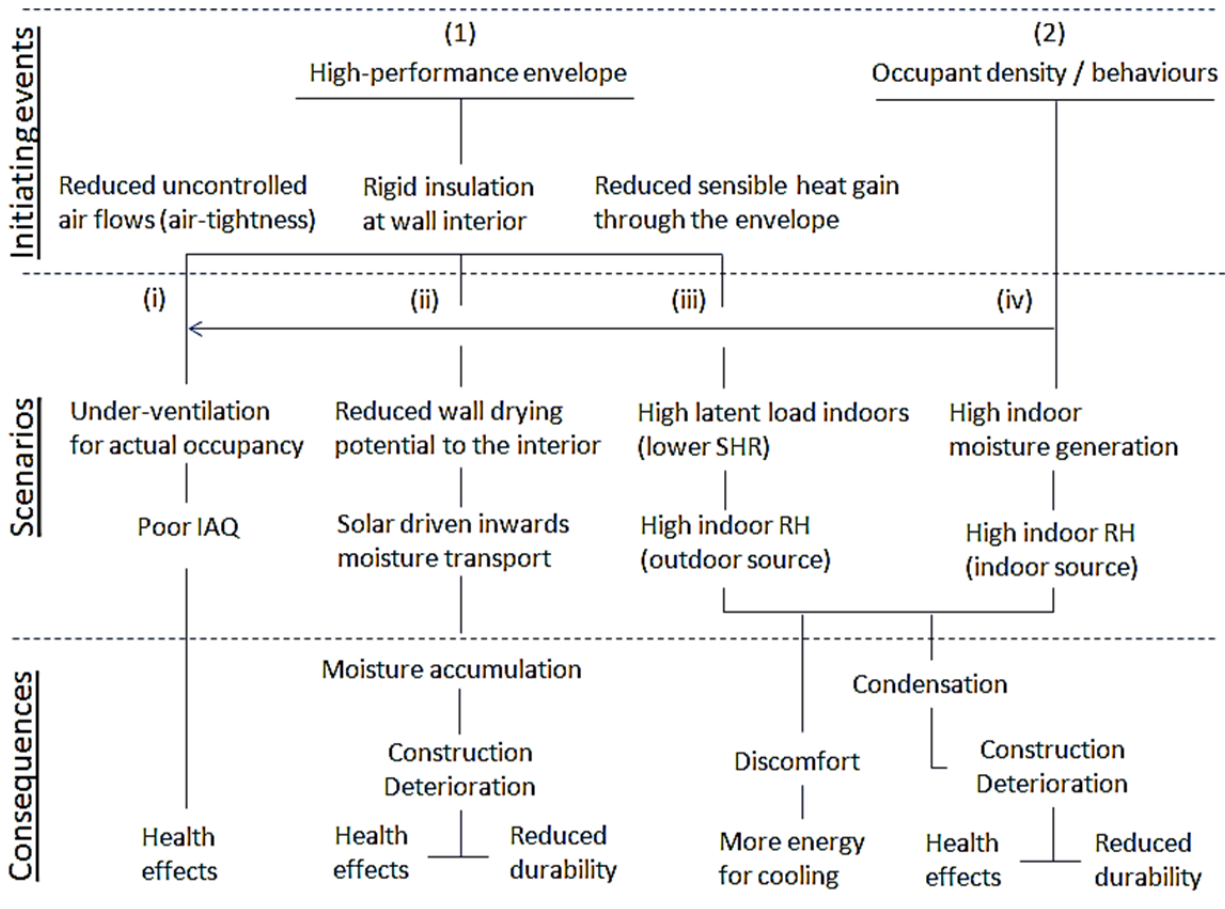
Figure 11. Cause-effect relationships: initiating events, scenarios, and consequences

3.5.2 System Analysis

The goal of the system analysis is to evaluate the risks that the identified initiating events (cause) will produce undesirable consequences (effect) under the anticipated scenarios. Such a cause-effect analysis needs to rely on a heat, air, and moisture (HAM) performance model of the indoor environment. In this project, the whole building hygrothermal model used is HAMFitPlus (Tariku, et al., 2011), which takes into account the dynamic interaction between the indoor environment and the building enclosure. In addition the model incorporates among other things the following: moisture buffering effects of materials which could act as a moisture source and sink; moisture removal due to condensation on cold surfaces such as on windows; moisture addition by evaporation from water reservoirs and from building envelope components that have higher initial moisture content, as well as moisture flow through building envelope components (walls, roof, foundation walls and floor slabs) by diffusion and convection.

The risk model, as indicated in Figure 2, is a performance model (Figure 1) that specifies relevant variables, as probabilistic, random variables. In this case, the risk model is a HAM model with indoor boundary conditions as random variables, namely: the indoor humidity and the indoor air quality as a function of probabilistic occupancy/behaviors and air leakage. The remaining parameters (materials properties, climate, and HVAC) would be considered deterministic. As mentioned in section 2, due to a lack of actual performance data for the case study, only deterministic variables are considered. Figure 12 illustrates the model for HAM

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balance in a room, with variables having a bell-curve type of "hat" representing potential candidates to become random variables.
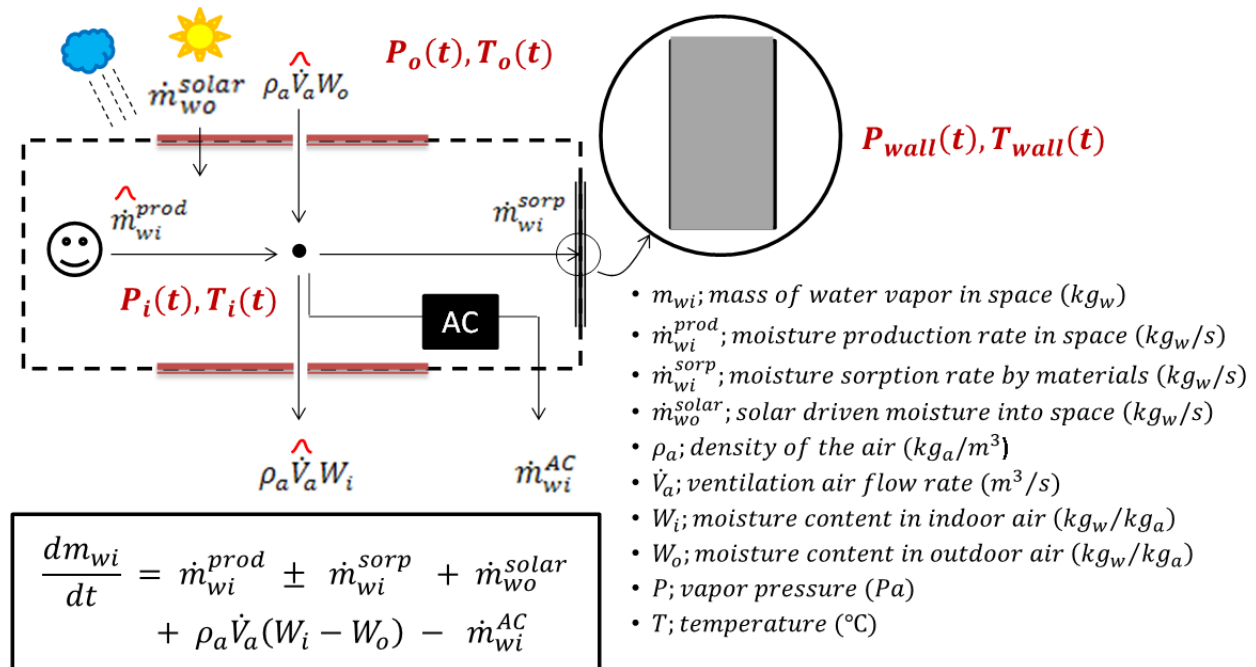

- m_{wi}; mass of water vapor in space (kg_w)
- $\dot{m}_{wi}^{prod}$; moisture production rate in space (kg_w/s)
- $\dot{m}_{wi}^{sorp}$; moisture sorption rate by materials (kg_w/s)
- $\dot{m}_{wo}^{solar}$; solar driven moisture into space (kg_w/s)
- ρ_a; density of the air (kg_a/m^3)
- $\dot{V}_a$; ventilation air flow rate (m^3/s)
- W_i; moisture content in indoor air (kg_w/kg_a)
- W_o; moisture content in outdoor air (kg_w/kg_a)
- P; vapor pressure (Pa)
- T; temperature (°C)

$$\frac{dm_{wi}}{dt} = \dot{m}_{wi}^{prod} \pm \dot{m}_{wi}^{sorp} + \dot{m}_{wo}^{solar} + \rho_a \dot{V}_a (W_i - W_o) - \dot{m}_{wi}^{AC}$$

Figure 12. Overall HAM model with random variables

Boundary conditions

The outdoor boundary conditions include precipitation, wind speed and direction, calculated wind-driven rain, temperature, relative humidity, and directional global solar radiation. Similar to the energy calculations, the indoor environmental loads are determined from the number of bedrooms and bathrooms in the house and the schedules for home operation.

Results

The HAMFitPlus simulations were run for different setpoint temperatures. Experience shows that residential AC setpoint temperatures in Miami vary between 70^{0}F and 78 ^{0}F depending on preference, and mainly on the ability and willingness to pay to stay cool. Typical setpoint temperatures are 75^{0}F and 76^{0}F. For economy reasons, in affordable housing it is expected that the setpoint temperature will be towards the higher end; however, further work is required to evaluate the influence of this and other factors, including occupancy density and habits.

Figures 13 and 14 show indoor temperature and relative humidity profiles from HAMFitPlus simulations for setpoint temperatures of 70^{0}F and 75^{0}F. In Figure 13, the AC unit works mostly from April through November for the 75^{0}F setpoint temperature, and almost all year round for the 70^{0}F setpoint temperature. The simulations were run under the assumption that no heating is used in cooler months.

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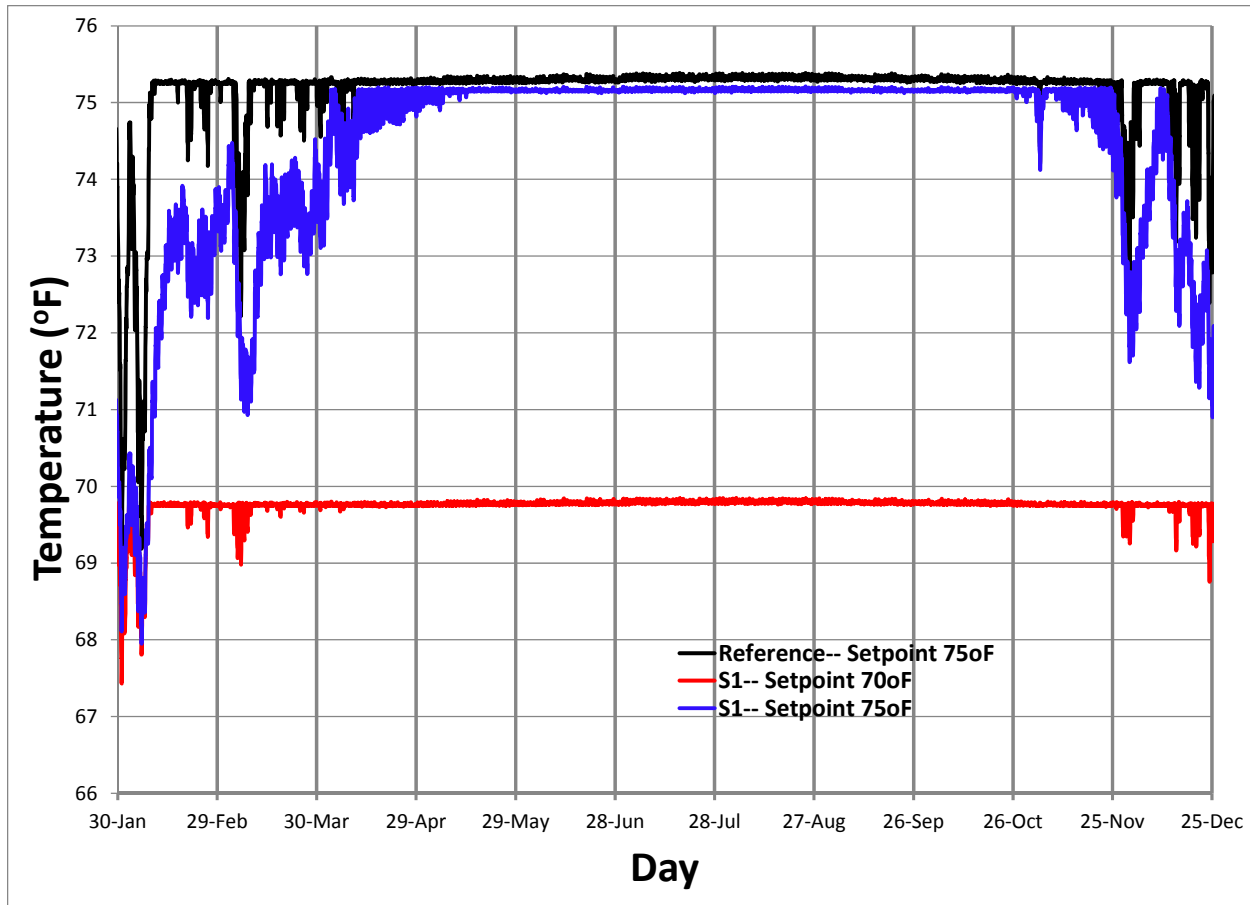[2] Florida International University, Department of Civil and Env. Engineering, Miami, Florida

Figure 13. Indoor temperature profile

Figure 14 shows that dehumidification is strongly tied to the cooling demand for the 70^0F setpoint temperature. However, in the high-performance home for the 75^0F setpoint temperature the AC unit operation is not sufficient to reduce the latent load from space, and therefore the relative humidity is maintained above 80% all year round. The results are not surprising due to a notable reduction in sensible loads from increased envelope insulation levels, use of high-performance windows, reduced window areas, and improved air-tightness. By contrast, for the current, low-performance, home (i.e. reference in Figure 14) the AC unit is more-or-less sufficient to dehumidify the air.

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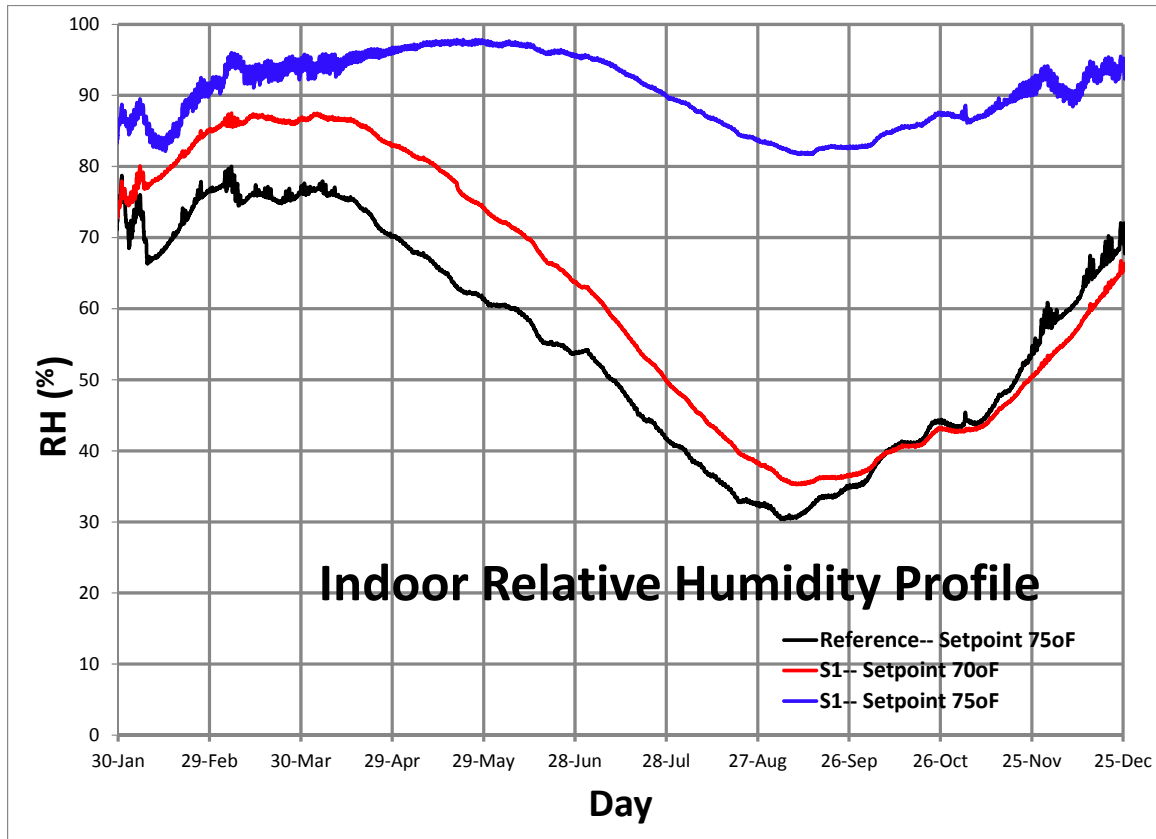[2] Florida International University, Department of Civil and Env. Engineering, Miami, Florida

Figure 14. Indoor relative humidity profile

3.5.3 Risk Analysis

Table 3 illustrates the overall risk performance evaluation criteria for the three aspects in the case study in relation to the strategy "s1" (high-performance home with no controlled ventilation/dehumidification).

Table 3. Risk Performance Evaluation Criteria

Performance Aspect	Performance Criteria	Performance Serviceability Limits
Durability (moisture related)	Limit excessive moisture accumulation f(exposure time, severity, & materials)	ANSI/ASHRAE Standard 160-2009
Health	Acceptable indoor air quality: fresh air for breathing & avoid excessive concentration of humidity & pollutants: Air changes per hour (ACH)	ASHRAE Standard 62.2-2010
Thermal Comfort	Satisfactory thermal indoor conditions for at least 80% of the occupants: Uniform conditions (i.e. no thermal asymmetries), no drafts, acceptable humidity levels, etc.	ANSI/ASHRAE Standard 55-2010

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Durability Risk Evaluation

In hot humid climate the main moisture loads come from high ambient humidity and absorbed wind-driven rain, as well as incidental rain penetration through interfaces (Lstiburek, et al., 1994). Some absorbed moisture is expected to dry towards the exterior. However, most is driven by the air conditioning and the sun towards the interior of the building (i.e. inward moisture flow). The stucco cladding and the masonry wall can absorb significant amounts of water when exposed to rain. Due to a high hygric buffering capacity and moisture tolerance, they are expected to store moisture and dry mainly by diffusion towards the interior. The risk for mold growth in strategy "s1" is higher compared to the current HFH "reference" HFH home, due to increased air tightness and higher latent loads.

Consequently, the inner wall layers in Figure 8 (b) should permit inward moisture drive to avoid moisture to be trapped in the wall. To mitigate this risk, in Figure 11, Scenario (ii), semi-permeable, moisture tolerant, extruded polystyrene insulation is specified. The inner layers (wood furring, gypsum board, and baseboard) are the more moisture sensitive, and also the more vulnerable to exceeding their moisture capacity because they receive the moisture from the outer layers while being cooled by the AC. Therefore, the risk of construction deterioration due to moisture, according to Scenarios (ii), (iii), and (iv), needs to be evaluated at the inner layers. Furthermore, based on the types of materials involved, the expected failure mechanism is biological, originated by mold.

Carmeliet et al. (Carmeliet, et al., 2009) describe two methods for moisture related durability assessment: the hygrothermal response method, and the damage response method. On the one hand, the hygrothermal response method is a mid-point approach that is based on the determination of hygrothermal indicators using hygrothermal models to be compared with critical values. Empirical models have been formulated that correlate hygrothermal indicators to damage growth regimes for several materials, as a function of time and exposure. On the other hand, the damage response method is an end-point approach that uses damage functions to relate changes in climatic conditions to changes in a specific performance parameter such as mold growth, decay, and corrosion. A damage end-point indicator (damage criterion) is then used to permit a more accurate prediction of service life. Table 4 illustrates examples of indicators used to assess moisture related durability.

Table 4. Sample Durability mid-point and end-point performance indicators

	Type 1 – Immediate	Type 2 - Cycling	Type 3 – Cumulative
Mid-point	• Critical degree of saturation for frost damage (S_{crit}) (Fagerlund, 1977)	• Temperature (t) cycles • Differential temperatures on components • Wet and dry cycles	• Critical cumulative exposure • Critical moisture content (MC_{cr}) • Critical relative humidity (RH_{cr})
End-point	• Degree of reduction in material properties • Extent of spalling or cracking of the material	• Degree of cracking, buckling, bond loss due to restrained movements • Wood expansion/contraction	• Mold index (M_{max}) • Mold growth rate (dM/dt) • Mass loss rate (%) • Concrete carbonation rate

Indicators types 2 and 3 are used to assess time-dependent deterioration. The critical cumulative exposure indicator combines cumulative time increments, in which the exposure exceeds a critical limit, and the severity of the exposure, which is based on a combination of relative humidity and temperature. MC_{cr} and RH_{cr} represent lowest material moisture content and surface humidity levels respectively before damage (e.g. mold growth) begins when exposed for a period of time (depending on the severity of the exposure). (Hukka, et al., 1999) developed an empirical model to correlate RH_{cr} with mold growth in wood as a function of

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exposure time and temperature. They introduced the concepts of mold index (M_{max}) to represent the extent of mold, and mold growth rate (dM/dt). Sedlbauer (Sedlbauer, 2001) developed a theoretical biohygrothermal model that describes the dependence of mold growth (mm/day) on surface temperature and relative humidity. Both damage models consider transient boundary conditions and intermediate drying of the fungus spores. (Krus, et al., 2010) found good correlation between these models. (Nofal, et al., 2006) coupled a hygrothermal modeling tool with Viitanen's damage model to analyze the damage on a wall as a function of indoor relative humidity and air-leakage in cold weather. For the case study the Type 3 mid-point indicator RH_{cr} is used to analyze the durability risk with strategy "s1".

The home indoor humidity conditions are calculated based on a full parameter calculation (method 3) in accordance with ANSI/ASHRAE Standard 160-2009, and evaluated according to the following criteria specified in the Standard:

In order to minimize problems associated with mold growth on the surfaces of components of building envelope assemblies, all of the following conditions shall be met:

a. *30-day running average surface RH < 80% when the 30-day running average surface temperature is between 5°C (41°F) and 40°C (104°F)*
b. *7-day running average surface RH < 98% when the 7-day running average surface temperature is between 5°C (41°F) and 40°C (104°F)*
c. *24-h running average surface RH < 100% when the 24-h running average surface temperature is between 5°C (41°F) and 40°C (104°F)*

In Figure 15 is clear that the above durability conditions are not satisfied by strategy "s1". The problem is exacerbated at higher temperatures. It can therefore be concluded that strategy "s1" without controlled ventilation and dedicated dehumidification is not viable.
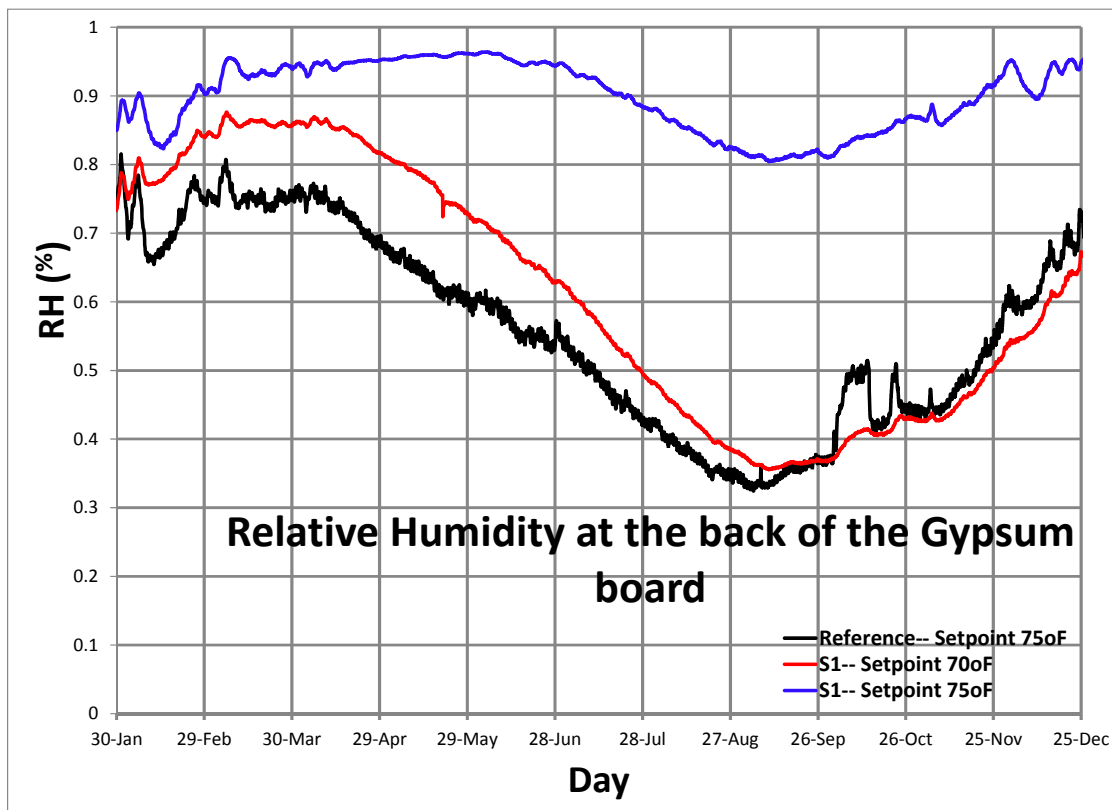

Figure 15. Relative humidity at the back of the gypsum board

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Health Risk Evaluation

Traditional and most newly built affordable homes in hot-humid US climates rely on infiltration to provide ventilation, which results in poor indoor air quality in high-performance, air-tight homes. ASHRAE 62.2-2010 specifies controlled mechanical ventilation with the dual purpose of providing acceptable indoor air quality for air-tight homes and improving energy efficiency for leaky ones.

As indicated in Figure 7, there is a premium to pay in terms of annualized costs and energy savings when installing these systems (s2) in an already air-tight home (s1). However, the premium is small compared to the likely price to pay due to poor health consequences from a lack of fresh air. Due to a lack of actual data, the natural ventilation rate through infiltration, for "s1" was calculated from pressurization tests using the simple Sherman and Grimsrud model (AHF, 2009). Table 5 compares the calculated rate with the ASHRAE 62.2 specification.

Table 5. Infiltration-based ventilation versus Standard

Case	cfm	ACH
Infiltration-based ventilation	18 (Sherman & Grimsrud)	0.12
ASHRAE 62.2-2010	45	0.31

Obviously, the estimated ventilation rate is much lower than the one required by the ASHRAE Standard 62.2-2010. The difference between the two values is so high that even considering the uncertainties involved in the simplified model and in the occupancy, the probability of meeting the standard is very low. Furthermore, given the high occupant densities expected in affordable homes, the air quality should be expected to be even poorer.

Comfort Risk Evaluation

At this point, it is clear that strategy "s1" does not meet durability and health requirements, and therefore is not viable. However, thermal comfort is evaluated using Fanger's PMV-PPD model for completeness in demonstrating the proposed methodology. Table 6 summarizes the results.

Table 6. Fanger's PMV-PPD model thermal comfort results

Season	Winter	Summer	Winter	Summer
Temperature	70°F	70°F	75°F	75°F
Relative humidity	80%	40%	95%	85%
Clothing	1 clo	0.5 clo	1 clo	0.5 clo
PMV	-0.42	-2,43	0.79	-0.5
PPD	8.76	91.87	18.31	10.24
Thermal sensation	Neutral	Cold	Slightly warm	Neutral

From Table 6, it is apparent for both setpoint temperatures occupants can achieve comfort simply by wearing more indoor clothing in the summer or taking some clothing off in the winter.

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Another possibility is having different thermostat settings for the summer and winter seasons. However, it is clear that thermal comfort is not a concern under AC operation.

4 Discussion and Further Work

The proposed methodology and the case study demonstrate that performance and risk can be evaluated systematically under the constraints of affordable housing. However, further work is required in the following areas:

- Obtaining statistical data on the characteristics of the families that live in these homes, including composition, size, and habits.
- Obtaining long-term indoor environment and durability monitoring data.
- Surveying the general comfort and health perception of home occupants.
- Obtaining reliable data on performance, operating conditions, and maintenance requirements of high-performance technologies to be potentially used in affordable homes.
- Producing reliable climate data tailored for health, comfort, and durability evaluations.
- Provided that statistical data is available on the home operating and its boundary conditions, as well as on maintenance, a formal probabilistic risk methodology can be implemented to increase the degree of confidence in planning and designing high-performance affordable homes.

For simplicity, the case study assessed performance only under tight AC operation. However, analyses involving natural ventilation, at least for certain periods of the year, possibly coupled with ceiling fans are promising for energy and sustainability. However, other issues related to affordable homes, such as decreased security from opening windows, may render those analyses useless.

5 Conclusions

This paper presented a performance-risk methodology for the design of high-performance affordable homes. The methodology defines a systematic approach to treat performance and risk involved in designing affordable homes under new operating conditions. A case study on affordable homes in hot-humid climate demonstrated the use of methodology. Further work is required to obtain relevant statistical data on the indoor and outdoor boundary conditions, as well as the performance, operating conditions, and maintenance requirements of potential high-performance technologies to be used.

6 References

AHF ASHRAE Handboof of Fundamentals [Book]. - [s.l.] : ASHRAE, 2009.
Alfano A Thermal Environment Assessment Reliability Using Temperature-Humidity Indices [Journal]. - [s.l.] : J-STAGE, Advance Publication, Industrial Health, 2010.
ANNEX-55 Reliability of Energy Efficient Building Retrofitting - Probability Assessment of Performance & Cost (RAP-RETRO) [Online]. - IEA Energy Conservation in Buildings and Community Systems, 2011. - 08 2011. - http://www.ecbcs.org/annexes/annex55.htm.
BA Building America Best Practices Series // Handbook for Improving New Home Efficiency, Comfort, and Durability in the Hot and Humid Climate. - [s.l.] : U.S. DOE Building Technologies Program - Building America, 2004. - Vol. 1.
Bass J Personal communication. - [s.l.] : Former Director of Constructions of HFH Greater Miami, 2010.

[1] British Columbia Institute of Technology (BCIT), Building Science, Burnaby, BC, Canada
[2] Florida International University, Department of Civil and Env. Engineering, Miami, Florida

Carmeliet J and Derome D Stochastic Design Merhod to Determine the Moisture Buffering of Walls [Conference] // 12th Canadian Conference of Building Science and Technology. - Montreal, QC : National Building Envelope Council of Canada, 2009.

Carmeliet J, Roels S and Bomberg M Towards the Development of Methods for Assessment of Moisture Originated Damage [Book Section] // Moisture Control in Buildings: Key Factor in Mold Prevention, 2nd Ed. / book auth. Trechsel H and Bomberg M. - West Conshohocken, PA : ASTM International, 2009.

Crawley D [et al.] EnergyPlus Energy Simulation Program [Journal]. - [s.l.] : ASHRAE Journal, 2000. - Vol. 42. - pp. 49-56.

CSA Guidelines for the Development of Limits States Design [Report]. - Rexdale, ON : Canadian Standards Association Special Publication, CSA S408, 1981.

Deru M and Torcellini P Performance Metrics Research Project - Final Report [Report]. - Golden, CO : U.S. National Renewable Energy Laboratory (NREL), 2005.

DOE2 Building Energy Use and Cost Analysis Software [Online]. - James J. Hirsh and Associates, LBNL, 2011. - http://doe2.com/.

DOE-2.2 Overview of DOE 2.2 [Report]. - Berkeley, CA : Laurence Berkeley National Laboratory and James J. Hirsh and Associates, 1998.

EnergyGauge Energy and Economic Analysis Software [Online]. - Florida Solar Energy Center, 2011. - 08 2011. - http://www.energygauge.com/.

EnergyStar Energy Star Qualified Homes HERS Index Target Procedure, for National Program Requirements Ver. 3.0 [Report]. - [s.l.] : U.S. EPA, 2010.

EPA Energy Star program [Online]. - US Environmental Protection Agency (EPA), 2011. - 08 2011. - http://www.energystar.gov/.

EPA ENERGY STAR Residential Water Heaters: Final Criteria Analysis [Report]. - [s.l.] : EPA, 2008.

Fagerlund G The Crtitical Degree of Saturation Method for Assessing the Freeze-Thaw Resistance of Concrete [Journal]. - [s.l.] : Materials and Structures, 1977. - 10 : Vol. 58. - pp. 217-30.

Fairey P Building Energy Efficiency: Keeping an Eye on the Prize // PowerPoint presentation. - Orlando, FL : Florida Solar Energy Center, 2007.

FGBC Florida Green Home Certification Standard Ver. 7 [Report]. - Tallahassee, FL : Florida Green Building Coalition, 2011.

FSEC Low Cost Interior Duct Systems for High Performance Homes in Hot Climates [Report]. - Cocoa, FL : Florida Solar Energy Center, 2010.

FSEC Potential for Energy Efficiency and Renewable Energy Savings to Impact Florida's Projected Energy Use in 2014 [Report]. - Cocoa, FL : Florida Solar Energy Center, 2006.

Hukka A and Viitanen A A Mathematical Model of Mold Growth on Wooden Material [Journal] // Wood Science and Technology. - [s.l.] : Springer-Verlag, 1999. - Vol. 3. - pp. 475-485.

Krus M, Seidler M and Sedlbauer K Comparative Evaluation of the Prediction of two Established Mould Growth Models [Conference] // Buildings XI. - Clearwater, FL : ASHRAE, 2010.

LBL DOE-2 User Guide, Ver 2.1, Report LBL-8689 Rev. 2 [Report]. - Berkeley, CA : Laurence Berkely Laboratory and Los Alamos National Laboratory, 1980.

Lstiburek J and Carmody J Moisture Control Handbook: Principles and Practices for Residential and Small Commercial Buildings [Book]. - [s.l.] : John Wiley & Sons, Inc, 1994.

Modarres M, Kamiskiy M and Krivtsov V Reliability Engineering and Risk Analysis - A Practical Approach [Book]. - New York : Marcel Dekker Inc., 1999.

Nofal M and Kumaran M Durability Assessments of Wood-Frame Constructions Using the Concept of Damage Functions [Report]. - Ottawa : NRCC, 2006.

[1] British Columbia Institute of Technology (BCIT), Building Science, Burnaby, BC, Canada
[2] Florida International University, Department of Civil and Env. Engineering, Miami, Florida

NREL BEopt Software for Building Energy Optimization: Features and Capabilities [Report]. - [s.l.] : U.S. DOE Building America - Building Technologies Program, 2006.

Pietrzyk K Probabilistic Modeling of Air Infiltration and Heat Loss in Low-Rise Buildings [Book]. - Goteborg, Sweden : Chalmers University of Technology, 2000.

RESNET RESNET: Residential Energy Services Network [Online]. - Residential Energy Services Network, 2011. - 08 2011. - http://www.resnet.us/.

Sedlbauer K Prediction of mould fungus formation on the surface of and inside components [Report]. - [s.l.] : Fraunhofer Institute for Building Physics, 2001.

Tariku F, Kumaran K and Fazio P Determination of Indoor Humidity Profile Using a Whole-Building Hygrothermal Model [Journal] : International Journal of Building Simulation, Springer, 2011. - 1 : Vol. 4.

TRNSYS Transient System Simulation Tool [Online]. - TESS, 2011. - 08 2011. - http://www.trnsys.com/.

US-DOE Builders Challenge Program [Online]. - US-DOE Building Technologies Program, 2011b. - 2011. - http://www1.eere.energy.gov/buildings/challenge/about.html.

US-DOE Building America Program [Online]. - U.S. Department of Energy, 2011a. - 08 2011. - http://www1.eere.energy.gov/buildings/building_america/.

US-DOE EnergyPlus Energy Simulation Software [Online]. - U.S. DOE Building Technologies Program, 2011c. - 08 2011. - http://apps1.eere.energy.gov/buildings/energyplus/.

Viitanen H Factors Affecting the Development of Mould and Brown Rot Decay in Wooden Material and Wooden Structures [Report]. - Uppsala : Department of Forest Products, The Swedish University of Agricultural Sciences, 1996.

[1] British Columbia Institute of Technology (BCIT), Building Science, Burnaby, BC, Canada

[2] Florida International University, Department of Civil and Env. Engineering, Miami, Florida