Envelope and Systems Synergy for High Performance, Affordable Housing

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ABSTRACT

The Net Positive Studio is an interdisciplinary research and design effort in the College of Architecture, Planning, and Design at Kansas State University seeking to develop housing prototypes that are affordable, safe, high-quality, environmentally sensitive, and functional while demonstrating broad tenants of sustainability: energy and environmental conservation, economic tenability, and positive social and community impact.

In the Net Positive Studio's first iteration, the team partnered with the Mattie Rhodes Center, a community organization in Kansas City, to develop and build a single-family infill housing prototype, in a community known as Indian Mound, intended to be constructed for near $100/ft2 while achieving an EUI (energy use intensity) lower than 15 kBtu/ft2 per year. The project and the studio team are also participants in the current Solar Decathlon Build Challenge, sponsored by the U.S. Department of Energy.

In the design, a high-performance building envelope was integrated with a strategic approach to maximizing the efficiency of the home's environmental control systems. This paper elaborates in detail upon innovations in the building envelope and heating and cooling systems, describing how these systems work together. Using computational fluid dynamics simulation, the Indian Mound prototype's operation is compared to contemporary approaches to envelope and HVAC systems common in affordable housing. In summary, the project's design and the analyses presented in the paper show that critical improvements in envelope design can work in sync with modern HVAC technology, resulting in a solution that is both more affordable and better-performing than today's contemporary affordable housing solutions.

PROJECT BACKGROUND

Today, residential buildings are at the root of our society's energy crisis, consuming more than one fifth of all U.S. energy (EIA 2019), more energy than commercial and industrial buildings combined. At the same time, nearly half of Americans are over-burdened by housing costs (U.S. Census, 2013-17) and average annual household utility costs have climbed to nearly $2,000 (BLS 2019). Nearly half of American households earning less than $50,000 are overburdened by housing, yet for every inexpensive home built for $150,000, over 18 are built for over $350,000 (U.S. Census 2019). These statistics illustrate that the crisis in housing affordability is multidimensional: the U.S. housing market has an urgent need for lower cost and lower energy homes.

Unfortunately, poorly designed and poorly engineered *new* affordable housing has the potential to increase the energy cost burden of economically threatened households. Discussed later in the paper, owners of a recently constructed 'affordable' home were subjected to back-to-back wintertime heating bills that totaled $642.96. Utility bills of that magnitude cripple a family's economic stability, competing with mortgage payments, childcare, food costs, healthcare, and other critical expenses. On paper, the specs of the house and its heating and cooling systems seemed acceptable and ordinary. What happened?

Housing in the U.S. is driven by strongly held conventions and ordinary new housing doesn't receive the professional design and engineering oversight given to commercial buildings from start to finish. In the Indian Mound project presented here, a team of students working with their expert faculty advisors (co-authors on this paper) were able to start from scratch with the prototype home's design, keeping things simple while thoughtfully integrating the building's architectural design with the operation of its systems. While this paper will not elaborate on the full extent of the home's design and construction strategies, it will bring focus on decisions made by the student design team in the building's assemblies and form that enabled an innovative application of HVAC design. Together these decisions show how the Indian Mound house will leverage its simple approach to architectural form to maximize the performance of its systems, putting forward an improved model for thinking about how to integrate HVAC systems into affordable housing.

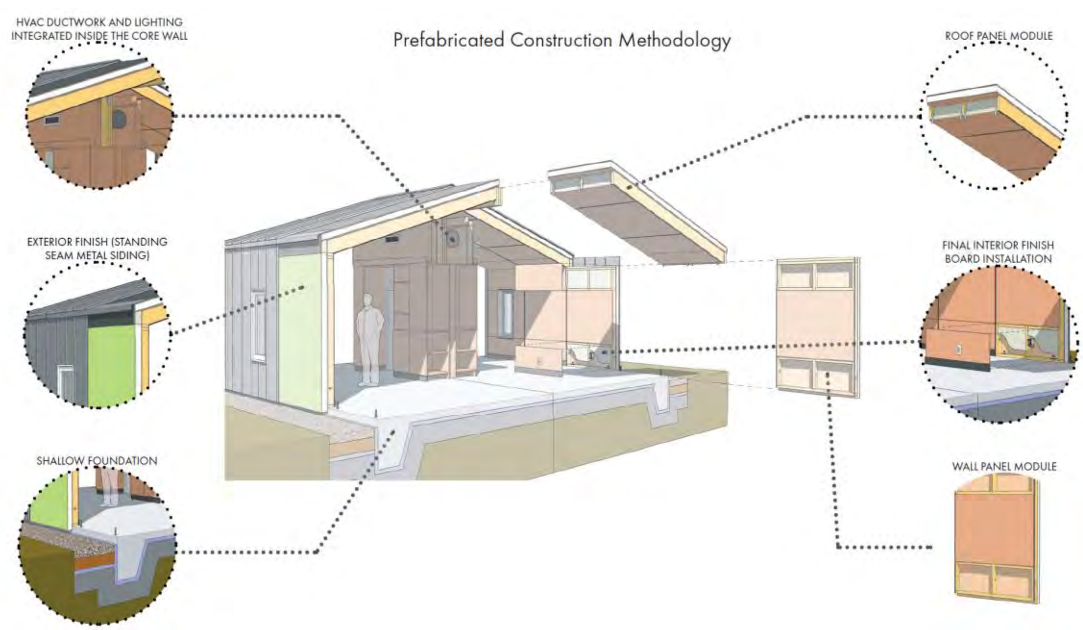

Figure 1: The cross-section of the Indian Mound prototype home exhibits its important features, working in synergy: a prefabricated envelope with robust levels of thermal control, a fully insulated slab coupled with the conditioned zone, and a central 'core wall' to contain essential building systems.

HOUSING IN SECTION: PAST AND PRESENT ISSUES WITH BUILDING CLIMATE AND SYSTEMS

The quintessential American home is a homey living space, anchored by its cellar and topped off with an attic. The structural and material systems in use in today's typical construction are intertwined with the presence of basements, crawlspaces, and attics, which also happen to make building systems easy to resolve and locate. Yet these unconditioned spaces present a host of major environmental control troubles – both energy- and health-related. For one, the neatly organized thermal, air, vapor, and rain barrier systems in vertical walls are challenged to maintain continuity and their appropriate sequence when the vertical envelope transitions to basement and attic boundaries. Aside from draining heat from the home year-round, uninsulated and unconditioned basements introduce moisture to homes: moisture that, along with moisture from other indoor sources, must be vented out of the attic by intentional, uncontrolled, year-round infiltration of outdoor air. For modern, energy efficient buildings that are designed to be as 'tight' as possible, leaky, uncontrolled basements and attics are somewhat absurd. These spaces are also the last place one would want to put expensive and sensitive heating and cooling equipment and ductwork – yet this is what is commonly done.

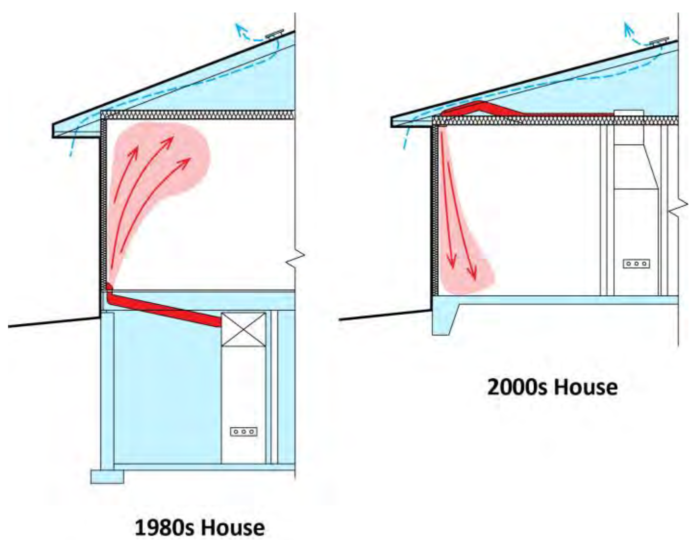

Figure 2. Two prolific ways of organizing conditioned, unconditioned, and HVAC systems: a house with a full basement, with HVAC equipment and distribution in the basement; and contemporary affordable housing, built on a slab with HVAC equipment on the occupied floor and distribution through the attic. These scenarios are introduced (respectively) as the 1980s and the 2000s house later in this paper.

In the post-war housing boom, when simplification and cost-efficiency in construction became a serious issue, basements and attics were quickly trimmed from the recipe for the midcentury home. Lofty, raftered attics beneath high-slope roofs were replaced with lower-slope, compact roofs with minimal framing. Basements were replaced by slabs-on-grade, or in milder climates, simple post foundations. In sum, resources were focused on the habitable living space: a basic approach persisting today in single family, affordable housing.

Modern homes on slabs, however, present challenges for the location of heating and cooling equipment and distribution systems. In such slab homes, the prevailing solution is to move the equipment to the living level and run forced air ductwork through the cramped, unconditioned, leaky attic where systems interfere with increasingly critical ceiling insulation. Recognition of the problems that ensue from this approach (see Lstiburek 2013) has yet to unseat conventional practices of locating ductwork in unconditioned attics.

Today, ductwork in homes is said to average a 20-40% loss of heating and cooling energy before it reaches living spaces as reported by the Department of Energy: a sobering statistic rooted not just in the location and installation quality of ductwork, but in its *configuration* for many houses. The uninsulated (or minimally insulated) building envelopes of the past dictated that heating and cooling should be supplied to the perimeter of the home to combat comfort problems at the weakest areas of the envelope, such as old drafty windows. For many houses, getting the ductwork to the perimeter involves little to no engineering or analysis, and the extra distance and air resistance that is introduced in doing so ensures, above all, that HVAC sizing should take no risks: it's better to 'go big' with furnaces and A/C installations. It is no surprise that over half of a typical U.S. household's energy is consumed by air conditioning and space heating according to the U.S. EIA. While the design of the building envelope has taken center stage in modern high-efficiency homes, the building design must also incorporate better approaches to air distribution in order to fully address energy conservation and indoor air quality goals. When compared to conventional approaches to HVAC integration, the Indian Mound prototype fully realizes the efficiency of new HVAC technology at the cutting edge of efficiency.

THE INDIAN MOUND PROTOTYPE

Aware of the issues tying together building systems with the building envelope, the Indian Mound prototype home was designed by its faculty and student team around a simple volumetric strategy. Emphasizing a wall and combined roof/ceiling assembly with similar construction, the prototype home was designed without an attic and utilized a panelization approach to prefabricate walls and roof/ceiling components. Lacking soffits and cantilevers, the home's envelope maintains ideal alignment of structural, air barrier, and water barrier systems from wall to roof. Outboard of the home's conventional wood frame and structural sheathing, three inches of XPS insulation and a combined air barrier and weather resistive barrier OSB system completes the package, which will be sealed with liquid flashing after assembly on site. Thermal resistance values for these assemblies are shown in Table 1. The frost-protected, reinforced edge foundation will also be continuously insulated.

Table 1: Thermal Resistance Values of Envelope

	Installed Insulation R-Value [h*ft2*°F/Btu]	Assembly R-Value [h*ft2*°F/Btu] [1]
Foundation Slab	R-10	-
Walls	R-14 + R-15 continuous	R-30.9 [2]
Windows	-	R-4.0 (U-0.25) [3]
Roof/Ceiling	R-31 + R –15 continuous	R-49.3 [2]

[1] Total assembly R-Value with air films
[2] Determined using area-weighted summation from ASHRAE Parallel Path method for cavity assemblies.
[3] Manufacturer rating using NFRC-certified testing methods

Overall, this approach to the home's structure and the envelope not only saved the extra expense of a separate ceiling structure, but it also avoids areas where the thermal, air, and moisture/rain barriers of wood framed houses usually have gaps and failures. More than just high R-Value construction, we expect this approach to the envelope will allow it to be more effectively sealed and will result in long term resilience.

While the scope of this paper cannot discuss the evolution of the home's design in detail, the students' intent in the floorplan and interior spaces was to split public and private areas of the homes while minimizing unassigned circulation area. This allowed the kitchen and eating areas of the home to be quite generous, despite the home's roughly 1000 ft2 footprint. In a further effort to maximize the benefit of prefabrication and reduce the amount of linear wall construction, the design team created a thickened "core wall" in the middle of the home that serves as both a partition between bedrooms and common areas, and a place for ample enclosed and open storage.

HVAC System and the Core Wall. Early in the development of the design, the opportunity to use the thickened core wall to locate HVAC systems emerged. Because of the relatively small heating and cooling loads of the house, the HVAC equipment and distribution systems could be housed in the upper volumes of this wall, freeing up floor area that would normally be dedicated to a mechanical room. Further, the configuration of the thickened, multifunctional core wall would allow equipment and distribution to remain entirely within the thermal control layers of the building, offering a direct and efficient pathway for conditioned and ventilation air that would eliminate losses to an unconditioned basement or attic.

With the air handling unit positioned on an equipment loft, a main supply duct was designed for center of the core wall as depicted in Fig. 3, below. Locating the equipment up off the floor minimizes duct runs which keeps costs down and fan power low. Equipment service access was not sacrificed for efficiency, with all serviceable parts accessible or replaceable from a large door, using a stepladder.

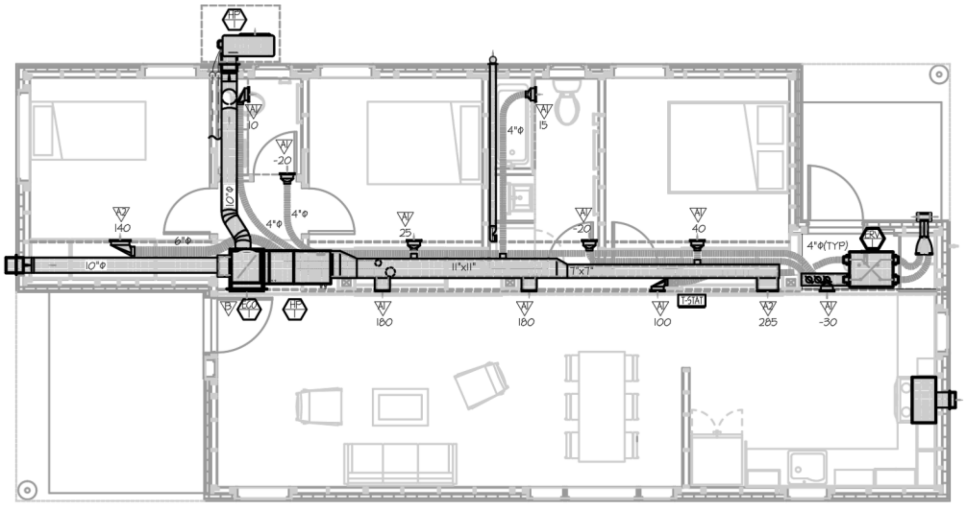

Figure 3. HVAC Floorplan of Indian Mound Affordable NetZero Home with HVAC unit in loft and ductwork centrally located.

The design also took advantage of a strategy gaining traction in many well-insulated, efficient homes where air distribution is consolidated in the core of the building, rather than at the perimeter (Burdick 2011). Supplying air to the building perimeter in this setting was a challenge addressed later in the paper.

A high-efficiency, mini-split, air-cooled heat pump system with central air handling unit was chosen for its mid-range cost and recognizable components. The cost is double the traditional furnace/ac system that is common to this market (retailing cost is $4,800 versus $2,700 respectively) but efficiencies can render a 10-year payback. Heat pumps have the additional benefit of heating without burning fossil fuels but must be carefully selected to operate through the cold winters of Kansas City. Additionally, the package utilizes a variable speed compressor for modulating cooling capacity in part-load. It also makes use of a "dry" control setting which can dehumidify when needed.

Using HVAC load calculation software at the Energy Star recommended design conditions of 1% cooling DB and 99% Htg DB (which are 94°F summer and 9°F winter in Kansas City, MO), peak cooling and heating load values were obtained, as shown in Table 2.

Table 2: HVAC Loads and Equipment Selection

	Loads	Capacity	Efficiency Rating
Heating	14,821 BTUH [1]	18,000 Btu/h at 9°F	13.6 HSPF
Cooling	18,611 BTUH [2]	27,000 Btu/h at 95°F [3]	18 SEER

[1] Using the CEC-DOE2 model
[2] Using RTS Heat Balance model
[3] The cooling capacity is more than needed but choosing the equipment to satisfy the heating load is the priority.

Heat pumps installed in Kansas City are often supplemented with electric or gas heat to handle the demand of extreme cold weather, particular with the loads from conventional construction. We did not want to complicate the system with supplemental heat and therefore selected equipment that could deliver the capacity needed at low ambient temperatures. Notably, the excellent building envelope design and coupled thermal mass in the home minimized equipment capacity selection in design, and these features should also reduce the impact of short term temperature extremes.

Whole-House Ventilation & Economizer. A commonly overlooked HVAC strategy in the affordable residential market is free-cooling using whole-house ventilation. While everyone knows you can save energy on temperate days by turning off the AC and throwing the windows open, homes in the 70s and 80s frequently used whole-house fans to accomplish the same effect. In both cases the occupant must be home and consciously decide to turn off the AC, open windows, and/or turn on the fan – and then perform the reverse when it is too warm or humid outside. Fresh air is not filtered, and moisture content of outside air is usually not considered. If ventilation could be accomplished automatically when conditions were favorable, the number of free cooling hours per year can be maximized for very little cost.

A residential economizer was therefore selected for this project with built-in controls that can interlock with the heat pump system to optimize the use of free cooling. Outdoor air temperature and humidity is monitored and compared with return air temperature and humidity. When the indoor cooling load can be satisfied with outside air, the economizer damper will automatically open and free cooling is achieved. Furthermore, the system is smart enough to allow the compressor to kick in during second-stage cooling and refrigerate outdoor air when it is cooler than return air, squeezing the last bit of free energy out of the system until the room is satisfied. In addition, the controls will allow occupants to program or manually increase thermostat setpoint to extend economizer usage when occupants are okay being a bit warmer or when they vacate the premises. Conversely, at the occupant's discretion after a warm day, the setpoint can be reduced at night to take full advantage of cool evening air to reset the building mass temperatures.

We believe that automating the whole house ventilation process and making the occupant a partner in their own energy savings by teaching them these techniques will result in significant free cooling over and above what the energy models predict. After the house is built and systems are running, we are interested in logging the economizer hours and comparing it to compressor run time and weather conditions to better understand the relationships.

Constant Ventilation. In order to deliver code-required ventilation, an energy recovery ventilator (ERV) with continuous operation was specified for the home – which saves energy by providing a heat and moisture exchange between exiting indoor air and entering fresh air. The ERV chosen for this house allows fine-tuning of fresh air and exhaust air quantities separately, allowing us to satisfy the code-minimum 20 cfm continuous exhaust per restroom, 25 cfm continuous exhaust from kitchen, and 45 cfm supply of outside air. The outside air values were set above code-minimum to create positive building pressurization which helps to minimize infiltration through building walls. Outside air is delivered directly to the main living quarters through a supply register on the wall. This fresh air is then naturally distributed throughout the house by the HVAC recirculating system.

The ERV system is an important component to mitigating humidity in the home, especially during the winter when it could pose a condensation risk in the home's insulation cavities (see Psychrometry Analysis, later in this paper).

Energy Analysis. Whole building energy analysis was conducted for the final design using EnergyPlus 8.4, with loads and utilization shown in Table 3 and graphically in Fig. 4. The resulting analysis shows a low Energy Use Intensity (EUI) of 14.3 kBtu/ft2 per year, which is approximately 1/3 of the regions typical residential EUI. Notably, energy analysis results from the whole building study were smaller than the worst hourly values used in sizing the systems. This is most likely attributable to the exposed concrete slab in the home, whose continuously insulated boundary keeps this relatively large mass in sync with the thermal conditions of the interior, tempering heat and cold swings.

Table 3: Whole Building Annual Energy Analysis Results

	Energy [1] [kWh]		**HVAC Loads [2] [KWh]**		**HVAC Fuel [3] [kWh]**		**Total Energy**	**PV Energy Prod.**
	lighting	equip	heat	cool	heat E	cool E		
Jan	71.55	178.22	391.08	4.45	218.48	0.84	**469.10**	286
Feb	64.63	160.97	305.42	18.70	170.62	3.54	**399.76**	314
Mar	71.55	178.22	98.61	44.56	55.09	8.44	**313.30**	417
April	69.24	172.47	3.60	70.15	2.01	13.29	**257.01**	443
May	71.55	178.22	0.22	111.04	0.12	21.03	**270.92**	470
June	69.24	172.47	0.00	365.36	0.00	69.20	**310.91**	479
July	71.55	178.22	0.00	474.39	0.00	89.85	**339.62**	509
Aug	71.55	178.22	0.00	450.81	0.00	85.38	**335.15**	464
Sept	69.24	172.47	0.00	303.22	0.00	57.43	**299.14**	431
Oct	71.55	178.22	3.94	92.04	2.20	17.43	**269.40**	361
Nov	69.24	172.47	119.16	36.57	66.57	6.93	**315.21**	299
Dec	71.55	178.22	348.33	7.65	194.60	1.45	**445.82**	249
Annual	842.48	2098.35	1270.36	1978.94	709.70	374.80	**4025.33**	4722

[1] Lighting loads assumed an all-LED house with optimum use of daylight. All occupied rooms achieve an average daylight factor greater than 3%. Equipment loads include electric point-of-use, tankless water heating.
[2] Loads included occupancy of 4 people and constant ventilation rate of 0.2 ACH, accounting for the ventilation rate of systems and their efficiency ratings.
[3] Fuel utilization for space heating and cooling used efficiency factors noted in Table 1. A final heating COP of 1.79 was used, derated from the manufacturer's HSPF shown in Table 1 according to climate factors.

In summary, the home is expected to achieve very low energy consumption values. In comparison to the EUIs exhibited by passive houses, the Indian Mound house's envelope and systems have been optimized to make net-zero performance affordable and relatively easy to implement using an array of available technology. The small building volume, rigorous envelope design, and coupled thermal mass also work together to make the high efficiency HVAC systems more promising and less risky in the mixed climate of Kansas City.

Indian Mound HVAC Design: Introducing the "Supply Casting" Concept

Air Distribution. As previously noted, a benefit of locating the HVAC system central to the space is the ability to minimize duct runs and omit elbows to minimize material cost and fan static pressure losses. Another improvement on the duct system was the use of a rigid-phenolic duct system instead of traditional sheet metal. The duct has a self-contained vapor barrier and insulation layer which helps maintain conditioned air temperatures and eliminates any danger of sweating. Installation is aided by its light weight and has inherently tight construction. Runs between segments can be longer than sheet metal duct which reduces the number of joints, all resulting in even lower leakage.

Displacement Ventilation Considered in a Residential Context. Locating supply and return grilles 10-feet high on the wall creates the risk of inadequate mixing and short-circuiting of supply air in the upper strata of the space. Supplying air down to the occupied space therefore became a high priority in the HVAC design. Traditional air distribution systems often introduce conditioned air into a space from ceiling diffusers or floor registers at a high velocity with the intent of fully mixing with the room air to achieve a uniform room air temperature throughout. In this type of system, simply known as "mixing", impurities are diluted to a large degree, but not carried away very efficiently.

The size and shape of this building suggested a ventilation strategy often used in large structures, but rarely seen in residential construction known as displacement ventilation (DV). This design strategy typically features the delivery of supply air down by the floor from large perforated supply diffusers and returning up high. Since DV can have as much as a 21% energy-saving potential over traditional air distribution systems in commercial applications (Goetzler et al., 2017) and produces better indoor air quality than traditional mixing systems (Chen, Q., Glicksman, L., Yuan, X., Hu, S., Hu, Y., and Yang, X., 1999), we were curious if DV could be used as an energy-saving strategy for this house. Displacement ventilation typically delivers low velocity, 65°F supply air to gently fill the lower portion of the room with fresh conditioned air while allowing the upper portion of the room to stratify at higher temperatures. This saves significant energy because only the occupied zone of air in the lower six feet must be conditioned while air in the higher portions of the room may be allowed to drift to warmer. The 65°F supply air temperature takes less energy to generate than 55°F supply air thereby increasing the number of available free cooling hours in the typical year.

Integrating large DV diffusers by the floor was not practical for this project, however, but the high warm ceilings still made DV appealing. Recent experiments using "confluent jet ventilation" by British and Swedish researchers (Cho, Awbi, & Karimipanah, 2008), supplied high-velocity air from the ceiling in an air-curtain down a wall. Once reaching the floor, the airstream slowed down and started behaving like DV. Fig. 4, below, compares traditional air distribution methods with displacement ventilation and confluent jet displacement.

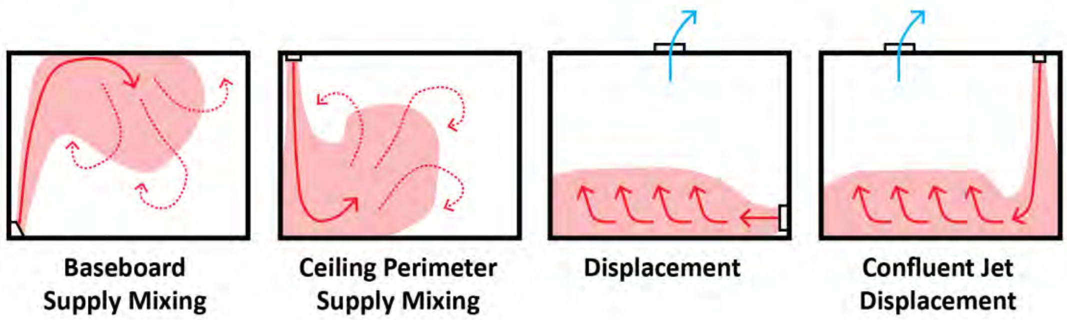

Figure 4. Comparison of traditional residential air distribution strategies.

Supply Casting: A New Approach. Making the most of the shape of our house, we imagined using the confluent jet strategy, but instead of aiming the supply air straight down, we would aim high-velocity air jets across the sloped ceiling like an angler casting a line across a river, efficiently planting a lure among far-away fish. Several point-source supply registers, as noted in Fig. 4, would deliver air in parallel streams against the perimeter of the space. If enough energy (both supply temperature and velocity) is preserved in this configuration, the supply air could cascade into the occupied zone with the required heating and cooling.

The Coanda effect would assist the airstream by keeping it close to the ceiling as it travels down the outside walls to the floor. This keeps high-velocity air away from the occupied zone as it hugs the surfaces while transporting the supply air to its destination. After reaching the floor, it would then behave like DV, tempering the occupied zone and carrying impurities up and out as illustrated in Fig. 6, below.

This Supply Casting air distribution pattern solves a notorious weakness of DV which is heating. Low-velocity warm air from DV diffusers tends to rise quickly from buoyancy and return to the air handling unit before mixing with the room. Most DV systems therefore require costly supplemental perimeter heating. The high-velocity air pattern, we hypothesized, would overcome the buoyancy effect of the warm supply air and carry it all the way to the floor. This theory would later be tested in a computational fluid dynamics (CFD) analysis discussed later in this paper.

By designing for an HVAC system inside the high-performance building envelope, incorporating a residential economizer for whole-house ventilation, and letting the building shape and ceiling slope inspire a new kind of airflow pattern all working together, we felt available resources were effectively optimized to achieve an affordable high-performance home.

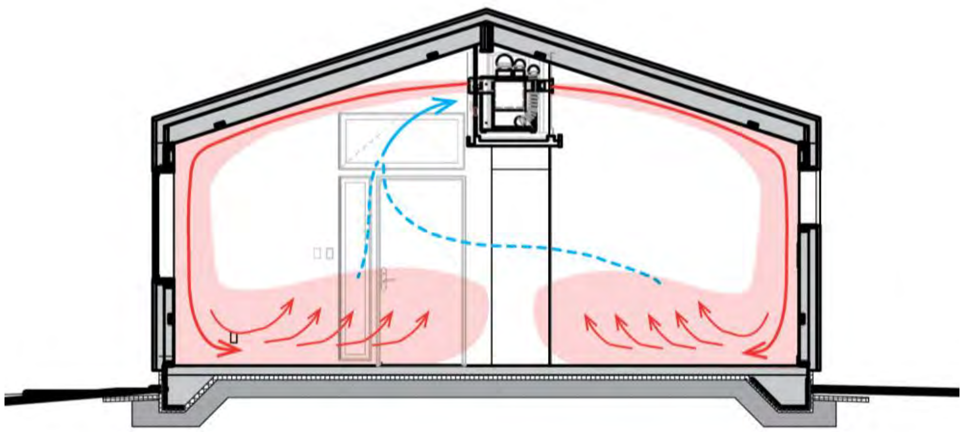

Figure 5: Building Section of Indian Mound Affordable NetZero Prototype Home with proposed "supply casting" airflow pattern

ANALYSIS: SUPPLY CASTING IN THE INDIAN MOUND HOME COMPARED WITH TWO CONVENTIONAL LOW-COST HOUSING APPROACHES

As a mixed climate, Kansas City exhibits winter and summer environmental concerns, though winter heating fuel used is typically much greater in magnitude than cooling for residences. As discussed earlier, heating output was more critical than cooling output in sizing the heat pump, and the performance of air source heat pumps in the region is still met with some skepticism. Given the relatively modest temperature output from our heat pump, would the combined outlet velocity and temperature at diffusers provide enough energy to maintain comfort on a cold day, given the anticipated temperatures in the room?

Computational Fluid Dynamics simulation was used to evaluate the heating and mixing hypothesis in a typical room in the home, using designed outlet temperatures and velocities along with thermal boundary conditions of the air volume. Boundary conditions were derived from the temperature gradient through the assembly for the design temperatures and given the assembly's layer R-values, resulting in the approximate surface temperature that would interface with the air film. Initial conditions of each simulation were set at 68°F for the interior air volume. The results of the simulations show how, given a steady state condition, the incoming air flow and temperature would mix with and raise the occupied zone temperature.

Two Comparison Houses Introduced. For the purposes of this paper, two comparison cases – referred to as the 1980s house and the 2000s house, illustrated in Fig. 7, were introduced into the analysis and simulated using the same CFD methods. The 1980s house is the home of a co-author, constructed with typical insulation for the period and featuring a full basement and attic, with steel ductwork and perimeter distribution from below, and featuring a substantial propane-fired furnace. In the comparison, this home represents a still-common strategy for residential construction and environmental control: oversize your heating and cooling source in order to produce robust outlet temperatures to the perimeter, compensating for a relatively weak thermal envelope.

The other home – the 2000s house – was a home built by regional affordable housing program, whose occupants were experiencing extremely high wintertime utility bills: approaching $400 during cold months. Though a relatively new home, it was built outside a code jurisdiction and had R-11 insulated walls lacking continuous insulation, no perimeter insulation for the slab-on-grade foundations, and had blown-in attic insulation that was installed with great difficulty (and poor results) due to low-slope trusses and voluminous, untrimmed flex-ducts in the attic. The energy consumption problems for the home were only multiplied with the installation of an undersized air-source heat pump that frequently resorted to its backup resistance coil to supply heat. The heat pump's tepid output was also a source of complaints from the owners. On a cold day the house just didn't feel like it was being heated and the furnace ran constantly.

CFD Results: Supply Casting Versus Conventional Approaches. Results of the CFD simulations are summarized in Fig. 8. The 1980s house, despite the relatively poor performance of its envelope, mixes heated air effectively in the occupied zone, exhibiting temperatures well above the initial conditions in the simulation. This appears a result of the high output temperatures from the propane furnace, and as this heat is delivered from the baseboard level, some combination of buoyancy and residual momentum moves it through the room to the return, despite some hot spots. The 2000s house yields a very different picture of heat dissipation and mixing. Low temperature heat arrives at the perimeter from the ceiling, where it quickly loses energy when it encounters the cold, uninsulated slab. In this relatively large room, the incoming heat reserves little energy for raising the temperature of the zone, and the resultant room temperatures are much lower than the 1980s house. Moreover, incoming air in the 2000s house spends a great deal more time meandering in the room – an average of 40 minutes as predicted by the CFD particle traces.

The two comparison houses use perimeter heat distribution, yielding modest inlet velocities. However, the 1980s house overcomes inefficiencies in distribution with extra heat capacity. Having lived in the house for some time, the author attests that this is the same case for the cooling months. The subpar flex duct installation in the 2000s house, combined with the cool interior slab temperatures, creates a distribution challenge that an air source heat pump – even with a more appropriate model – would have trouble serving.

In contrast to the two cases, the Indian Mound home's simulations yield a very different result. Higher outlet velocities and a well-insulated envelope preserve a considerable amount of heating energy, even though the air supply is originating from the middle of the home. By the time this heated air reaches the interior room, it is still carrying a significant and balanced amount of heat through the occupied zone. While the air has slowed down below the thresholds of immediate perception, important in avoiding the feeling of drafts, the conditioned air reaches the air return efficiently.

The sum of these results show that even with the modest heat outlet temperatures from the air source heat pump, the strategy of Supply Casting provides similar or better comfort than that provided from an oversized, fossil-fuel heated furnace of the past.

Consolidated ductwork into a compact form within the conditioned volume is also key to this strategy, as it maximizes heating/cooling energy delivered into the space as well as velocity.

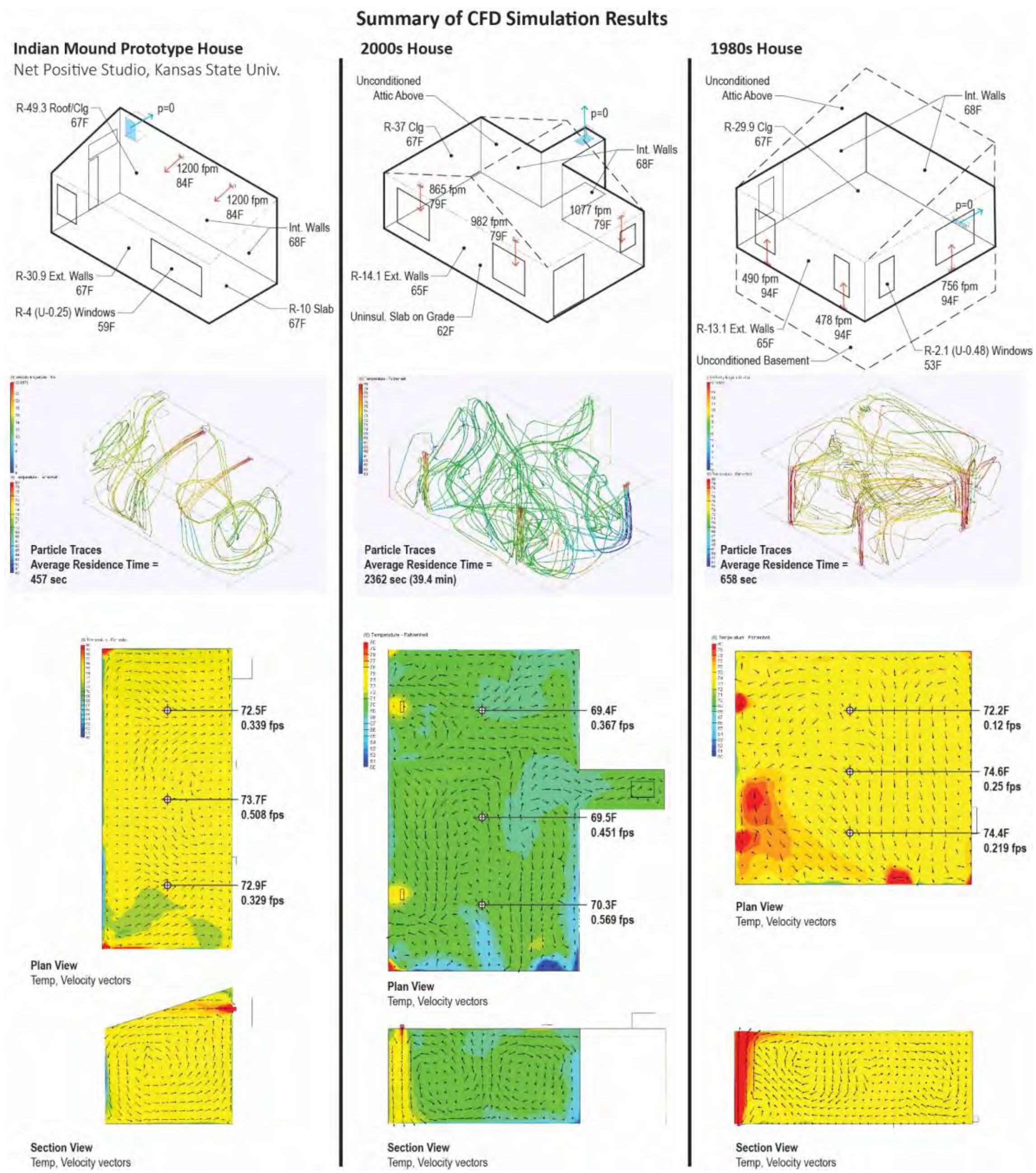

Figure 6. A summary of CFD simulation results is shown above, along with the boundary condition inputs for temperature and the general zone geometry. The outlet velocity and temperatures for the 1980s and 2000s house were measured in-situ.

The Importance of an ERV System: Pyschrometric Analysis. Designing for the Kansas City environment is challenging because the presence of both extreme cold winters and hot, humid summers. Improperly designed HVAC systems have been known to exacerbate indoor relative humidity rather than lower it. Condensation is a particular risk for the prototype due to its unventilated roof panels and low permeability of its exterior insulation and metal cladding. Given the presence of the ERV system, analysis was conducted to examine if the interior air in the winter would be dry enough to encourage inward drying and prevent moisture migration into cavities.

The first step in this process was to predict typical condensing surface temperatures, using average wintertime temperatures and the thermal resistance of assembly layers. Following the method described by Lstiburek (2001), for a median January outdoor temperature of 26°F, the condensing surface temperature at the underside of the roof deck would be 40°F – indicating the interior of the home would have to remain below 35% RH in the coldest months in order to prevent condensation. Next, a psychrometric analysis on the house in both heating mode and cooling mode was done to confirm humidity levels could be kept under control during all seasons. In the winter, we noted convergence on a room setpoint of 70°F, 20% RH. More importantly, the indoor dewpoint was seen to follow the outdoor dewpoint temperature and therefore always be lower than the indoor building envelope surface temperatures. This is significant to prevent condensation and ensure inward drying and vapor pressure. In the summer, we derived a steady-state room setpoint of 75°F, 52.5% RH, which is an acceptable indoor condition. Operating an ERV at a steady state serves as the overriding humidity control mechanism that keeps the indoor air moisture at bay.

CONCLUSION

In an effort to conserve energy in today's homes, modern equipment such as heat pumps and ERVs are increasingly common in homes. While it is important to engineer these systems properly, the exercise in design shouldn't stop merely in the specification of systems. The Indian Mound prototype home, designed and constructed in part at Kansas State University, shows the possibilities of what can be achieved in a small, modest home when investment has been made in bolstering the environmental performance of the envelope, while also taking advantage of architectural attributes of the design to distribute heating and cooling in the simplest possible approach.

Comparisons made in the paper, however, show the consequences of changing the status quo of oversized heating and cooling equipment, and to some extent relying on infiltration and attic ventilation for drying the home's climate. If the envelope isn't improved and the materials, assemblies, windows, and other elements kept in synchrony, a new house can actually perform much worse than an old house. Nowhere is this truer than in affordable housing, where decisions must be balanced between long term energy savings and first costs. As a truly integrated project, the Indian Mound prototype home has made use of design, engineering, and building expertise throughout its process and we hope that this effort will demonstrate that it is possible to succeed – and excel – in energy performance even in an ultra-affordable home.

References

Burdick, A. (2011) ed. In Building Technologies Program, *Advanced strategy guideline: Air distribution basics and duct design*. National Renewable Energy Laboratory (U.S.). doi:10.2172/10.1397

Chen, Q., Glicksman, L., Yuan, X., Hu, S., Hu, Y., and Yang, X. (1999). "Performance evaluation and development of design guidelines for displacement ventilation." *Final report for ASHRAE RP949*; Massachusetts Institute of Technology, Cambridge.

Cho, Y., Awbi, H. B., & Karimipanah, T. (2008). "Theoretical and experimental investigation of wall confluent jets ventilation and comparison with wall displacement ventilation." *Building and Environment*, 43(6), 1091-1100. doi:10.1016/j.buildenv.2007.02.006

Goetzler, W., Shandross, R., Young, J., Petritchenko, O., Ringo, D., & McClive, S. (2017). "Energy savings potential and RD&D opportunities for commercial building HVAC systems." United States: doi:10.2172/1419622 Retrieved from https://www.osti.gov/servlets/purl/1419622

International code council. (2015). International Residential Code. Country Club Hills, IL: ICC

Janbakhsh, S., & Moshfegh, B. (2014). "Experimental investigation of a ventilation system based on wall confluent jets." *Building and Environment*, 80, 18.

Joe Lstiburek (2001) "Unvented Roof Systems." Somerville, MA: Building Science Press.

Joe Lstiburek (2013) "Duct Dynasty." Somerville, MA: Building Science Press.

Peña Malo, J. J., & Panjkov Zafra-Polo, I. (2013). Analysis of three ventilation systems in an office: Mixing, displacement and confluent jet ventilation system.: Analysis of temperature gradient, tracer gas and thermal comfort

Risto, K., Arsen, M., Elisabeth, M., Panu, M., & Nielsen Peter, V. (2017). References REHVA.

U.S. Energy Information Administration. (2018). Residential energy consumption survey (recs). Retrieved from https://www.eia.gov/consumption/residential/index.php