70 Million Years of Building Thermal Envelope Experience: Building Science Lessons from the Honey Bee

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ABSTRACT

Technology transfer within the building industry can take many forms—from research reporting, to case studies, to classroom learning. Sometimes, we seek building science lessons from nature, hoping to apply the experience of time-proven systems to the construction and energy challenges we face today.

Honey bees (genus Apis) are highly eusocial insects that evolved during the Neolithic Age (approximately 70 million years ago). As such, Apis mellifera—the common Western honey bee—has been in the sustainable building science business for at least 20 million years (more than 10 million years longer than humans). Their nest construction, social structures, energy management, honey production, and crop pollination have been studied more than any other social insect. Evidence exists that humans have been harvesting honey and honeycomb as far back as 7000 B.C. and have been actively tending honey bee colonies since ca. 5000 B.C. So what building science lessons have we gleaned from honey bees?

This paper will address some of the building science lessons we continue to learn from the study of Apis mellifera. We will explore various aspects of structural design, energy conversion, indoor air quality, water management, thermal insulation, and ventilation that we might learn from the honey bee as a model system. First, we will briefly re-visit the well-studied structural characteristics of honeycomb, perhaps the best-studied example of building science that we have already applied from the study of the honey bee hive structure. Second, we will address key issues of temperature regulation within the hive, both through heating and cooling techniques. Third, we will outline specific mechanisms of maintaining colony health through the incorporation of certain building materials.

Lastly, we will reinforce several themes of sustainability—from energy and resource management, to planning for future growth, to new ways we might respond to resource depletion—in an effort to incorporate these lessons into the structures and communities we build.

INTRODUCTION

What Is a Honey Bee Colony?

To aid in describing some of the building science lessons we might learn from the honey bee, we must first provide a brief summary of their biology, colony make-up, social structure, and internal dynamics.

A standard colony of honey bees might contain between 20,000 to 60,000 individuals. Colonies typically consist of:

- A single queen bee—whose primary duty is laying eggs to produce new bees;
- A few hundred drones—male honey bees whose only job is to mate with a virgin queen from a foreign colony;
- Thousands of worker bees—sterile females that do all of the other tasks for the colony, including feeding young bee larvae, housekeeping duties, thermal regulation duties, guarding the hive, and foraging for food and other resources.

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The queen bee is a fertilized female whose health is paramount to the productivity of the colony. She typically lays 1000 to 2000 eggs per day (approximately twice her own body weight!). These numbers are necessary to maintain a sufficient colony population for its survival. Should anything happen to the queen, or her productivity starts to decline, the workers will produce a new queen that, upon emergence and mating, will claim the throne. A queen may live from 1 to 5 years, but is typically replaced after 2 years.

Male honey bees, or drones, do not perform any work in the hive, yet they are essential for colony reproduction. Drones have larger compound eyes so that they may more easily spot virgin queens on their mating flights. Males die during the act of mating, and thus drones only contribute their genetic material to the next generation. Drone bees generally last one season and are expelled from the hive prior to winter to maximize the available food (energy) stores for the worker bees needed for colony protection and thermal management.

Developing worker bees go through complete metamorphosis—from egg to larvae to pupae to adult—all in about three weeks. After emergence, the first half of an adult worker's life is spent inside the nest performing a variety of hive management and brood-related duties. The second half of a worker's life is spent primarily outside the hive, collecting either pollen, nectar, plant resins (to form a substance called propolis), or water. The life expectancy of the worker bee is generally 6 to 8 weeks.

The worker bees produce beeswax from which the honeycomb is produced. Wax is synthesized in special glands located on their abdomens, and the worker bees manufacture the wax combs during times of significant nectar availability. The wax is molded and formed into perfect hexagonal structures (combs) that serve as "nurseries" for developing brood or as "pantries" for food storage (honey and pollen). Several parallel combs provide the physical structure that supports the entire colony through all four seasons.

A single family of bees is called a "colony". The physical location of the colony is called a "hive". Since workers comprise the majority of a colony—and perform all of the work and nest construction—understanding their collective contributions is where we can learn the most about building science from the honey bee society. While this paper does not begin to address all of the self-regulating aspects of a honey bee colony and its hive environment (especially those associated with their social structure, division of labor, and colony reproduction), we will discuss specific mechanisms of building design, thermoregulation, and nest function that honey bee workers practice collectively.

STRUCTURAL MATERIALS AND DESIGN

Honeycomb is one of the most studied structures in nature. As previously noted, comb is made from wax that is secreted by glands in the abdomens of worker bees (imagine us secreting our primary construction material from our stomachs!). The bees work this material into the perfect hexagonal form that is universally familiar (Figure 1). The hexagonal design minimizes the amount of building material while maximizing the storage capacity per unit area. Constructing circular, pentagonal, or octagonal cells leaves unused space between cells and therefore wastes construction material (Figure 2). Similarly, triangular and square cells have a greater total circumference area than hexagonal cells, which also requires more construction material per unit area. Moreover, the structural integrity of honeycomb is quite remarkable. A 832.5 cm^2 (129 in^2) section of comb, consisting of only 40 g (1.4 oz.) of beeswax, can hold 1.814 kg (4 lbs) of honey (von Frisch, 1974), an impressive strength-to-weight ratio. As such, the efficient use of the hexagonal honeycomb shape is copied in building designs across the planet. For example, the Space Shuttle has honeycomb wing designs that are strong, yet light in weight.

While the wax comb serves as the structural basis of the nest, it takes a substantial amount of energy to manufacture.

> Beeswax production is energetically expensive, however, requiring at least 6 g of sugar [in the form of honey] for every gram of wax synthesized… (Seeley 1995, Page 62).

Since wax is so energetically costly, bees do not build comb indiscriminately; they require both a significant surplus of nectar and a limited supply of empty honeycomb. When the existing comb is near full and plenty of nectar is available for honey production, worker bees will begin to synthesize additional wax. This process is highly regulated (Pratt, 2004) and governed by a "communal stomach". Workers regurgitate liquid food to each other through a process known as 'trophallaxis', so that food moves from satiated bees to hungry bees until all colony members reach an equilibrium point. Only when all workers become "too full", during a period of plentiful nectar and honeycomb congestion, will they initiate new comb construction. Thus reduced wax production is essential to minimize energy expenditure and optimize nest building.

Workers will also reuse the wax comb for different purposes, depending on colony need and time of the year. For example, the cells used to raise new drones are larger in size (since drones are about 50% larger than worker bees) and are spatially distinct within the nest (usually on the lower periphery). During the spring, this "drone comb" is used for rearing the queen's sons so that they may fly from the hive and mate with foreign queens. During the fall, however, drone rearing typically ceases and the drone comb is used for other purposes (such as food storage). These cells are effective honey pots, as they are larger and thus contain more food per unit area. Hence the reuse of wax comb is another means of maximizing nest efficiency.

Finally, bees engaged in comb building will notoriously recycle wax from different parts of the hive. Before bees can emerge from their cells, they must first cut through the wax capping that encases them. These cappings are usually the first wax to be incorporated into any new comb that is being built at the time. Moreover, wax that is not being used in one part

Figure 1 *New wax comb produced by the Worker bees.*

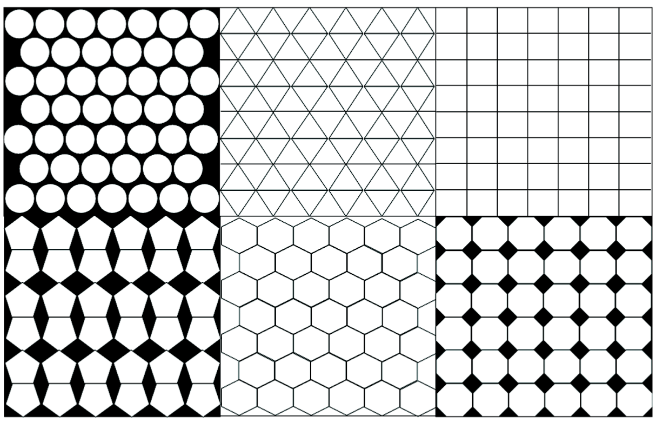

Figure 2 *Diagram of shapes and their spatial and material utilization efficacy.*

of the nest is often de-constructed in order to use the wax in another part of the nest. For example, when a colony prepares for the winter, they will often recycle empty comb from the central brood-nest area of the nest to bolster the peripheral food-storage areas of the nest.

It is also important to note that wax comb can last a long time. As long as the temperature does not exceed the melting point of the beeswax (62ºC to 65ºC)(144ºF to 149ºF), it can last indefinitely. Samples of honeycomb have been found in old buildings and even ancient tombs. Thus the bees' constructions maximize longevity, as they are intended for many lifetimes of service.

If we look for examples of this in architecture we can see parallels in family dwellings in almost every society: Spanish hacienda styles, African underground villages, or homesteads of early settlers in the New World. These structures usually consist of a central structure built by the first family members, then add-ons to accommodate additional family and generational growth. Some of our most celebrated colonial homes show this pattern and durable construction techniques—some now over 300 years old. In other countries in Europe, Africa, and Asia, these same construction and durability patterns can be thousands of years old.

THERMAL MANAGEMENT

We generally build our homes and commercial buildings with the expectation that our building envelope will be somewhat resistant to the outdoor environment. Moreover, we rely on our HVAC systems to deliver conditions that provide human comfort—defined by certain temperature, humidity, and ventilation air boundaries. We have thermostats that can switch between a combination of heating, cooling, and ventilation to keep us comfortable.

Honey bees also highly regulate the temperature of their nests, and they do so with extraordinary precision.

> From late winter to early autumn, the annual period of brood rearing by honey bee colonies, the temperature in the broodnest region of each colony's hive is precisely regulated between 33ºC and 36ºC, averaging 34.5ºC and varying less than 1ºC across the day. This impressive temperature stability is accomplished through a set of mechanisms whereby colonies either heat or cool the broodnest, depending on the ambient temperature… (Seeley 1995, pg. 212)

For honey bees, thermal management of the hive is intimately linked to the welfare of the colony. The conditions for brood rearing encompass a fairly narrow band of temperature and humidity conditions—especially when compared to human comfort conditions. Colonies must raise brood successfully for almost the entire year to remain viable. Young bee larvae require specific temperature conditions, along with adequate food and water supplies, to grow into healthy pupae and adult honey bees. In order to regulate the temperature, honey bees have evolved numerous mechanisms to both increase and decrease hive temperature (Figure 3). Here we will cover, in turn, the heating and cooling processes that honey bees use for hive thermoregulation.

Winter Heating

As winter approaches, honey bees employ fairly sophisticated thermal management strategies to prepare the nest and protect the colony from freezing. An individual worker can sense changes in temperature to within 0.25ºC using temperature receptors located on its antennae. Foraging activities generally stop around 10ºC (50ºF) and honey bees have been know to survive the winter with outdoor temperatures as low as -29ºC (-20ºF). The outer edges of the honeycomb help to trap air and prevent convective looping within the cells, providing additional buffers between the thermally regulated area of the hive and the cold of winter. Lower ambient temperatures and diminishing floral resources prompt workers to drastically reduce brood rearing. Simultaneously, food (pollen and particularly honey) is stored up for the winter, creating a thermal mass to help regulate internal hive temperature. As the external temperature drops and a colony reduces the size of its brood nest, the bees reduce their core nest temperature from

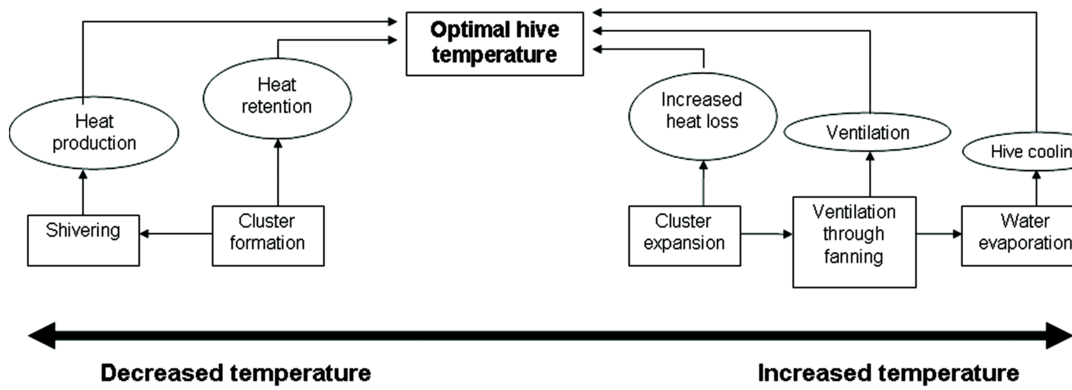

Figure 3 *Mechanisms of thermoregulation within a beehive.*

34ºC (93ºF) to approximately 18ºC (64ºF) (Seeley, 1985 pp.112). Research has shown that the total colony heat management is derived from a combination of both heat retention and heat production.

Honey bees can retain heat in two ways. First, they can retain heat over the long term by selecting a good nest site that is tightly sealed and enclosed. When founding a new nest in nature, a colony of bees will select an empty cavity (such as a hollowed tree) that is 15-80 L (0.5-2.8 ft^3) in volume with a bottom entrance of no more than 60 cm^2 (9.3 in^2). Larger entrances, or those located at the top of the cavity, will significantly increase heat loss for the colony during the winter. Sealing the cavity also plays a role in temperature management. While colonies require some ventilation year-round, they will use propolis—a sticky, wax-like resin from certain trees and plants—to seal up unwanted cracks and gaps in hive components. This sealing also helps with the overall defense of the hive by limiting possible openings for intruders as well as reduce the likelihood of unwanted air flow in winter. Propolis also serves to strengthen hive parts, acting like an elastic super glue holding pieces of the hive together. Propolis also has been found to have certain desirable antibacterial and antifungal properties thought to aid in overall colony hygiene, which will be discussed later in this paper.

Second, they can retain heat over the short term by "clustering", where adult members of the colony huddle close together to reduce the volume of air needing thermal management. This has a two-fold effect of reducing the surface area of bee bodies exposed to the cold air as well as creating a thermal mass of bees protecting the temperature of the remaining brood in the broodnest (usually right in the center of this mass of huddled bees). For simplicity, the surface area of a single bee can be approximated by cylinder of 2.0 cm^2 (0.3 in^2). By comparison, the surface area of a cluster of 15,000 bees is approximately 1,000 cm^2 (155 in^2), or 0.07 cm^2 (0.01 in^2) per bee (Seeley, 1985). Thus clustering has a profound effect on heat retention by drastically decreasing the surface area (and the subsequent heat loss) of each bee.

Interestingly, as the external temperature drops, the bees begin to cluster more tightly. As the external temperature drops from 18ºC (64ºF) (the temperature at which the bees begin to cluster) to -10ºC (14ºF) (the temperature at which the cluster reaches its maximum density), the total volume in the bee cluster decreases 5-fold. Increasing the density of the cluster further minimizes heat loss through convection by making it less porous and decreasing internal convection currents. Moreover, the outer shell of bees in the cluster, called the "mantle", serves as a blanket of insulation for the bees located in the inner core of the cluster, enabling them more room for movement. To maximize heat retention, bees in the mantle are often tightly oriented inward, and their overall heat conductance is approximately 0.10 W per kg per ºC, an impressively conservative number that is lower than reptiles and rivals that of furry mammals (Seeley, 1985).

As ambient temperatures drop below -10ºC (14ºF), heat retention is insufficient to keep the cluster warm. At this point, the adult bees begin to generate their own heat by consuming carbohydrates (in the form of honey) and exercising their powerful flight muscles while remaining clustered inside the hive. As such, the bees are their own central heating system. The rate of heat generation is proportional to the temperature difference between inside the hive and out. At their maximum, the flight muscles of a single bee can reach a maximum of 500 W/kg (776Btu/lb), over 25 times the energetic output of an Olympic rowing crew (Seeley, 1985)! Over the course of the winter, as bees die and the cluster size shrinks, younger bees take up the heat generation task, consuming honey, flexing their flight muscles, generating heat, and waiting for spring.

Our human ancestors used to employ some of these same strategies—reducing the volume of air needing heat by shutting off outer rooms, creating tempering buffers between the central heat source (usually a fireplace or wood stove) and the outside. Today, we build buffer zones, such as foyers and mud rooms, that help to reduce heat loss to the outside. Some HVAC systems are designed to allow for zoning and partial or complete shutdown of supply to minimally-tempered areas.

These winter heating techniques should sound familiar to any builder: air sealing to prevent unwanted heat loss; insulation against the cold; greater insulation density needed for colder temperatures; controlling the size of the conditioned space; efficient heat generation; good indoor air quality to promote occupant health. Thus while we have already incorporated these end results of honey bee building design, we may still glean certain structural lessons about the processes by which they are manifested.

Summer Cooling

Like most organisms, honey bees have a smaller range of heat tolerance above their optimum temperature (35ºC)(95ºF) than they do below. In fact, the upper limit for unaffected brood development and adult activity is between 38ºC and 39ºC (100ºF and 102ºF). Consequently, cooling the hive during the summer is of primary importance to the welfare of the colony. Nonetheless, recent thermal-imaging research by Human et. al. (2006) has shown that a colony can maintain broodnest temperatures at a near constant 35ºC (95ºF) while outdoor temperatures ranged from 3.7ºC (38ºF) to 30.7ºC (87ºF), and they can even do so indefinitely at ambient temperatures of 50ºC (122ºF)! A honey bee colony can achieve this extraordinary consistency primarily by active ventilation and evaporative cooling.

> When overheating threatens, the bees move farther apart on the combs and start to fan their wings, thereby cooling the hive interior through forced convection. If these measures prove inadequate, then they will spread water, especially within the broodnest, for evaporative cooling. Water is spread in small puddles in depressions on the capped cells containing pupae, as thin layers over the roofs of open cells containing eggs and larvae, or as hanging droplets in these cells. Water may also be rapidly evaporated through "tongue-lashing" whereby bees hang over brood cells and steadily extend their tongues back and forth. Each time a bee does this it expresses a drop of water from its mouth and pulls the droplet between mandibles and tongue into a thin film that has a large surface for evaporation. These various ways of using water for nest cooling can be referred to as "water spreading". (Seeley, 1995 pp. 212-213)

As previously stated, worker bees forage for four items necessary for hive survival: plant nectars (which are converted into honey), pollen (a protein source), propolis (a construction adhesive and sterilizer), and water. Water, either collected by itself or in the form of dilute nectar, plays a key role in summertime hive thermal management.

As outdoor temperatures rise beyond hive comfort desires, workers will ventilate hot air from the hive through active fanning. Bees throughout the hive will take up fanning positions to move air across the honey stores (to dry the water out of the honey) as well as to control brood nest temperatures. Bees will reposition themselves during these ventilation periods to dry out or cool specific areas of the hive. These ventilation paths move air across the hive as well as up through the hive.

Honey bees collect water for two reasons—thermoregulation of the brood nest and nutrition for immature bees. Worker bees will change jobs during periods of extremely hot weather in response to a need for additional water and hive cooling. As temperatures continue to rise, the colony will begin to increase water intake (usually by pollen foragers switching to water collection). They may take stored or just-collected water to spray in the hive as they fan, causing evaporation of the water and resultant hive cooling.

One final means of (passively) reducing hive temperature is by removing internal heat sources; that is, the adult bees themselves. Increased hive temperature will cause the adult workers to either move to less crowded regions of the nest, or even outside of the hive. Indeed, bees will often form a "beard" below the entrance of the hive, particularly when they do not have temporary access to a fresh water source (such as during the night) or when the ambient relative humidity is high (so that evaporative cooling is less effective).

Some have questioned whether the hive is also involved in direct humidity control, especially of the brood nest. Recent research by Human et. al. (2006) suggest that workers can only adjust broodnest humidity within less than optimal limits and note that the colony may try to maintain different humidity levels in different parts of the hive. In all cases, the measured relative humidity was controlled to between 20% and 50% while outdoor conditions varied from 20% to 60%.

Builders have long used similar evaporative cooling techniques, especially in hot, arid climates. Swamp coolers, evaporative fans, and other devices have evolved in our construction toolbox to help moderate indoor temperatures. However, we have yet to match the temperature stability of the bee hive when employing these strategies.

Figures 4A and 4B illustrate the general similarities between the temperature and environmental management techniques employed for human dwellings and honey bee colonies. In both cases the occupants face the same set of environmental forces (sun, wind, rain, etc.) and seek to thermoregulate to manage comfort. Issues of available energy resources, energy storage, fresh air availability, pollutant liberation, humidity control and temperature control exist for both organisms.

THE HEALTHY HIVE/HOME

The survival of a colony is significantly dependent upon cleanliness and hygienic behavior. In fact, a specific form of hygienic behavior (uncapping and removing diseased brood) is a readily quantifiable trait that is often selected for in genetic breeding programs. Hive hygiene in a general sense, however, may take many forms—from general housekeeping duties (such as removing dead bees) to cleaning out used cells of honeycomb for future use in egg laying or for pollen and honey stores.

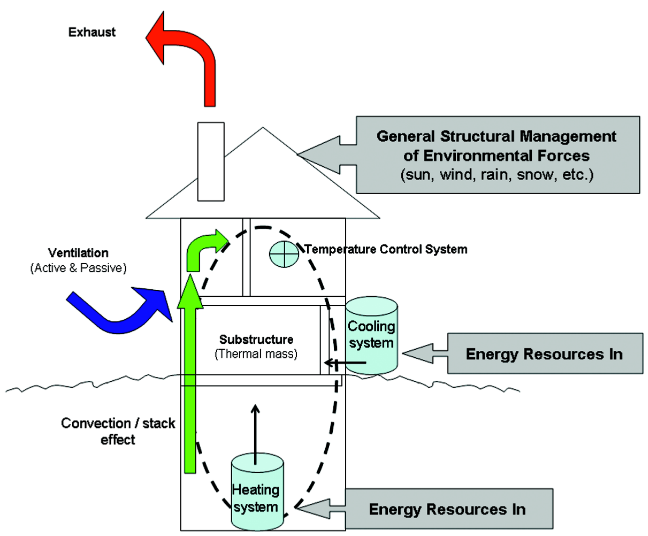

Figure 4a *General temperature and environmental management dynamics in human buildings.*

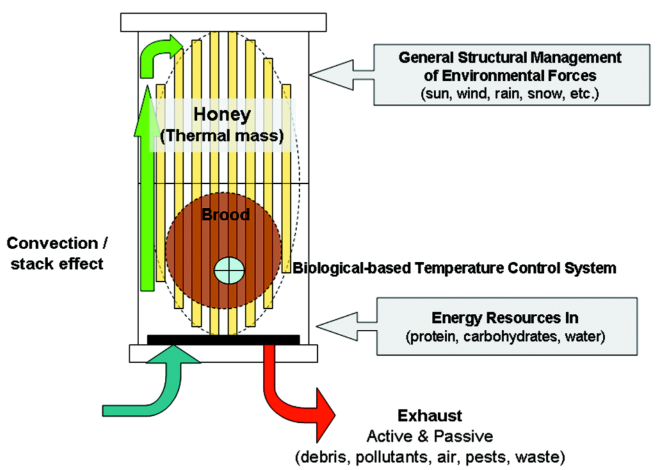

Figure 4b *General temperature and environmental management dynamics in human buildings.*

Hygienic behavior generally refers to the rate at which bees remove unwanted items from the hive that otherwise might put the colony health at risk. Some bees have been shown to identify certain risks and take preventative action. For example, studies have shown disease-laden larvae and pest-carrying pupae being removed from their cells before emergence and expelled from the hive, reducing the likelihood of spreading viral and bacterial vectors within the colony.

Honey itself is a key part of the hive health. Honey, by definition, has less than 18.6% moisture content, which is so low that it prevents the formation of yeasts and other potentially harmful microbes from growing in it. Consequently, ripened honey is immune to fermentation and spoilage, ensuring the bees have access to a healthy food supply and hive environment. Because honey is naturally anti-bacterial, it has long been used by many cultures as a wound dressing.

As previously mentioned, propolis also plays a role in hive hygiene due to its antibacterial and anti-fungal properties. Not only is it used to seal against unwanted air flows and intruders, it also is used to prevent the spread of contaminants and pests. For example, mice that have found their way into hives seeking winter warmth have been found in the spring fully encased in propolis – effectively mummified. This mummification protects the colony from the decomposition of the dead mouse. Colonies have been found with "pest corrals" where propolized areas are used to trap small hive beetles, an emerging scourge of the honey bee. Some honey bees have been known to coat the entire surface of their hives with a thin coating of propolis. Research is still underway to better understand and quantify the specific hygienic contributions from such actions.

So honey bees protect their food stores, keep their home clean, and use antibacterial and antifungal treatments to protect the occupants.

STRUCTURAL LESSONS

Incorporate Hygienic Materials Into Building Designs

While it is impossible to mandate the cleanliness of building occupants, there are perhaps some lessons from the honey bee model that can be used in building science. In particular, honey bees have demonstrated to us the value of using building materials that are inherently clean and reduce the likelihood of disease (such as propolis).

In the building industry we try to employ preventative techniques to promote healthy homes and buildings. For example, employing good water management techniques as a means of reducing the risk of mold growth protects building materials and occupants alike. Similarly we have designed various types of filtrations systems to catch potential air borne contaminants before they circulate through the buildings. We have even developed active air cleaning systems that use ultraviolet light and other means to reduce bacterial and viral exposure of the occupants. We often recommend the regular cleanout of fresh air intakes to promote improved building health. As people have become more chemically sensitive, we have also developed construction techniques that limit the use of known potential contaminants.

Reduce…Reuse…Recycle

Green building has gained prominence as supplies of construction materials have become less available and clientele groups have placed a greater emphasis on eco-friendly and sustainable building practices. Honey bees have been employing sustainable nest construction for millions of years; they minimize the amount of wax they build by only manufacturing what they need and when they need it, they utilize the wax combs for different purposes and reuse the same cells for different things depending on colony need, and they recycle used wax in the construction of new comb before they synthesize more.

Architects, developers, city planners, and builders are rapidly moving to employ various green building techniques – from using more eco-friendly materials to minimizing construction waste with optimized framing and sheathing techniques, to planning for deconstruction. Civic leaders across the nation are looking for ways of reusing existing buildings and infrastructure to help reduce the energy and cost impacts of city growth objectives. The National Council of Mayors was among the first organizations of civic leaders to publicly embrace specific building efficiency and green building objectives as part of an overall goal to reduce greenhouse gas emissions.

Home builders and urban planners are investigating new ways of building to minimize commute distances and maximize space utilization. Sarah Susanka and other noted architects have published a variety of books and treatises on "building smaller" as part of these local, national and global movements. How far do we have to travel for our foods? How far do our foods have to travel to get to us? What are the energy implications of these travels? City planners are now looking at the energy implications of past community designs where people must access their cars to get to needed, life-sustaining resources, and beginning to suggest new community designs and approaches that are more resource efficient.

Communities are trying to decide what to do with existing building infrastructure that is now at or near the end of its useful life. Should the buildings be torn down, even though they may be structurally sound? What reuse opportunities exist? What are the energy and job and economic implications of reuse, versus abandonment, destruction and new construction?

Honey bees have been known to reuse the homes vacated by other bees. Stories abound of bees living in hollow trees and walls of houses. When looking for new real estate, honey bees will gladly occupy an older property and will add on to it as necessary to fulfill their food storage and brood-rearing needs.

Many of the green building techniques we are currently considering (or are already employing) are lessons we are relearning from our grandfathers or from nature. For example, the "green roof" efforts around the country emulate the earthen and subterranean construction techniques used by our ancestors to reduce summer heat gain and provide passive cooling. Water cisterns are becoming increasingly popular (again), especially with the growing concerns over the quality of our municipal water supplies and the aging of our water delivery infrastructure. And there is an ever-growing interest in reclaiming and re-using deconstructed building materials – rather than put them in landfills.

Durability is an oft-overlooked component of truly sustainable construction. The beeswax honeycomb is an incredibly durable and strong material that can last centuries. How many of the buildings we are building today can we similarly characterize as lasting centuries? Truly sustainable construction must not only be energy efficient – it must last.

Figure 5A shows a close-up of the honeycomb structure in which brood is raised and in which hive nutrients (honey, pollen, water) are stored. Figure 5B shows a photo of hive parts essentially glued together by the natural anti-bacterial and anti-fungal plant secretion propolis.

Decentralized Control

Perhaps the greatest lesson that we can learn from honey bee nest construction is how it is regulated. Specifically, all of the tasks performed within a hive are done collectively and additively, such that no one individual has complete knowledge of the colony's needs or controls the activities of others. Rather, each individual worker assesses what needs to be done in her immediate vicinity and responds to the external and internal stimuli with an appropriate response. This is known as decentralized control (Seeley, 1995), and it has many benefits for internal hive regulation compared to centralized control like a thermostat (Figure 6).

One of the greatest benefits of decentralized control is that it is much more responsive to perturbations in environmental conditions. This may be accomplished because such a system is not reliant on one single, central system to detect and react to environmental changes but rather on multiple, redundant components of a global system. In honey bee colonies, for example, each individual adult serves as a redundant unit for both sensory input (e.g., increase in temperature) and behavioral output (e.g., cooling the hive through fanning). Collectively, the actions of all individuals help to modulate the environment so that it quickly returns to the optimal after a perturbation. While such a system is highly reactive and greatly reduces the variation within a structure, it may be more inefficient and costly (because of redundancy).

Perhaps one possible application of employing decentralized control in building science is to rely less on single "thermostat" systems but rather on multiplicative, integrated systems.

In residential buildings we often employ one thermostat to "drive" the environmental conditions of the whole house. Some larger homes are "zoned" to allow some degree of local control. In previous eras, we designed buildings based on space use objectives and local climate. Bedrooms were typically placed on the north side of the building, needing less heat in winter and buffering the heated portions of the building from the dominant winds. Kitchens were often placed to the east to have ready access to early light before the work day (read "food cultivation and harvesting") began. There was some degree of planning that acted as a surrogate for active control.

As we developed the ability to control the space conditions with a switch, we soon abandoned climate-responsive construction plans (like orientation) and opted for centrally-controlled systems with a thermostat.

Figure 5a *Close-up of honeycomb structure.*

Figure 5b *Close-up of hive parts adhered using propilis.*

Centralized control	Decentralized control
Little input	Substantial input
Efficient but highly variable	Inefficient but highly consistent
Localized with few components	Global with many components
Non-redundant units	Redundant units
Slow response and feedback	Immediate response and feedback
Single sensory probe and generator	Multiple sensory probes and generators

Figure 6 *A comparison of centralized and decentralized control systems.*

Building scientists today are looking at ways to (again) minimize the loads to which a building must respond. Better thermal enclosures (better insulations, windows, air sealing, etc.) all enable much better overall building environmental control.

Decentralized controls do exist in our building industry. But without good attention to the thermal enclosure's performance, they can result in greater energy use. Consider the commercial building where the occupants are demanding simultaneous heating and cooling. The morning sunrise has already helped to temper the eastern offices while those on the west side of the building perimeter may still be requiring heating to fend off the cold surface temperatures remaining from the night before. Again, a much more efficient building skin would reduce the temperature variations from surface to surface and orientation to orientation – enabling greater overall building environmental control (and less overall energy use).

Some examples of successful decentralized control strategies in buildings include photo sensors to reduce lighting loads in unoccupied spaces, task lighting for local illumination control, operable windows for passive ventilation and fresh air availability, among others.

CONCLUSION

We have long built our homes and commercial buildings in response to nature. Nature is a pretty good teacher – especially if survival is an objective. However, with abundant resources and seemingly limitless available energy we could theoretically ignore many of nature's lessons.

Now, we are re-evaluating the assumptions of abundant resources and limitless energy supply. We are reconsidering food production, supply and delivery. We are re-examining existing building infrastructure and materials – looking for ways to reuse and recycle. We may also be well advised to re-examine some of the proven, durable and sustainable systems in nature.

Honey bees may offer some significant insight into our notions of sustainability. They may help us to reconsider some of our current building and community planning practices. From the efficient use of building materials, to energy resource management, to decentralized control strategies, to the use of hygienic building materials and systems, to active and passive ventilation and temperature control – honey bees have developed a proven building science. They have over 60 million years more experience at sustainability than we do. Perhaps we should consider their lessons more closely as we seek to achieve new levels of energy efficiency, durability, indoor environmental health and truly sustainable building design.

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