Improving Indian Beehives and Beekeeping

by

Jonathan E. Abbott

Submitted to the Department of Mechanical Engineering
in partial fulfillment of the requirements for the degree of

Master of Science in Mechanical Engineering

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

February 2016

Author . . . .
Department of Mechanical Engineering
January 15, 2016

Certified by . . . .
Alexander H. Slocum
Neil and Jane Pappalardo Professor of Mechanical Engineering
Thesis Supervisor

Accepted by . . . .
Professor Rohan Abeyaratne
Chairman, Department Committee on Graduate Theses

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Abstract

This thesis explores five beekeeping topics from a mechanical engineering perspective with findings that are relevant for both Indian and American beekeepers. First, hive weight scale mechanisms are quantitatively analyzed, yielding design improvements to improve accuracy. Second, designs of hive entrances are tested to promote traffic flow, assist ventilation, and exclude pests. Third, recommendations for Indian hive roofs and exteriors are given to keep hives cooler. Fourth, methods to bolster Indian hive standardization and manufacturing quality are suggested to promote larger, more productive colonies. Fifth, designs of hive management tools are prototyped to help encourage scientific beekeeping. This thesis concludes with further research topics and actionable improvements for Indian beehives and beekeeping.

Thesis Supervisor: Alexander H. Slocum
Title: Neil and Jane Pappalardo Professor of Mechanical Engineering

Acknowledgments

I would like to graciously thank my parents for their support and encouragement.

Thank you Debra and Alex Slocum for the inspiration, ideas, feedback, and beekeeping knowledge.

Much help for experimentation on US soil was provided by volunteer high school student Will Haering over summer 2014 and MIT undergraduate Oscar Guevara over summer 2015. Additionally, I would like to thank Noah Wilson-Rich from Best Bees in Boston and Dennis Setzer in South Carolina for providing hives to work with.

I also could not have done this without my friends in India. I would like to especially thank Dr. Vinod Beniwal from the All India Organic Farming Society in Hisar, Haryana. Thank you Dr. D. K. Sharma, Dr. R. K. Thakur, Mr. Ajay Saini, Dr. N. Nagaraja, Mr. Nalin Rai, Mr. Apoorva BV, Mr. Kumar, Mr. Sarajbhan, Mr. Chandiram, and Mr. Sandeep.

Thank you to the MIT Tata Center for Technology and Design and the MIT Department of Mechanical Engineering for providing funding.

For the bees and the Hands that created them...

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Chapter 1

Introduction to Thesis on Indian Beekeeping

Contents

1.1 Thesis Initial Motivation and Evolution

The initial motivation of this thesis was to prevent wasps from entering beehives. Wasps had attacked and destroyed multiple colonies on the apiary of Prof. Alex Slocum despite employing entrance reducers and wasp traps. Funding was received from the MIT Tata Center to stop the giant Asian hornets Indian beekeepers face.

As Fig. 1.1 highlights, my thesis evolved away from wasps to focus on a number of low-hanging fruit opportunities to help beekeepers. It was difficult to find overlap between a technical and appropriate scale solution to wasps. Additionally, visits to India showed that wasps were only challenges to Indian beekeepers in certain areas. What evolved was a focus on the design of hive entrances that might mitigate the wasp problem while tackling another challenge of hive ventilation. There noticeably

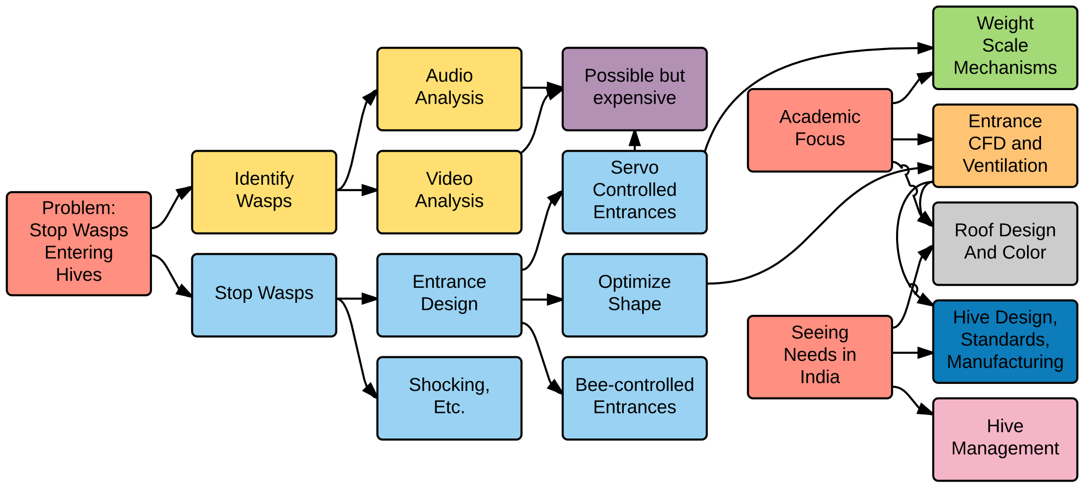


Fig. 1.1. Research evolution and topics. The research for this thesis started with the problem of how to tackle wasps in India. Visits to India showed wasps were only one of many problems and there were multiple problems with significant low-hanging fruit. Based on this insight and noting academic research gaps in hive fluid dynamics, the thesis evolved to focus on 1) weight scale mechanisms, 2) hive fluid dynamics, 3) design of roofs, 4) hive standardization, and 5) hive management.

existed a significant literature gap on beehive entrances, and hive ventilation was a challenge much more widespread.

Preparations for testing entrance ventilation led to an improved a set of recommendations for hive roofs to better shield the sun. Hive entrances also motivated fluid dynamics of the hive, and modeling Indian hives using CAD highlighted the need for improved hive standardization. Testing of hive designs led to a study of hive weight scale mechanisms. Lastly, visits to Indian showed that some of the largest gains could come from improved hive management. All of these topics became part of these thesis.

This thesis thus became a survey of topics on Indian beehives and beekeeping from the perspective of mechanical engineering. Since beekeeping is similar in many parts of the world, much of this thesis is relevant to beekeepers from all parts of the globe.

1.2 Meeting Indian Beekeepers

This thesis included three trips to India to directly meet with all of the key types of beekeeping stakeholders in India. These trips helped to understand and appreciate the context of Indian beekeeping, develop and test ideas within India, and provide ways to channel findings from this thesis to benefit the Indian beekeeping community.

The first trip in India was over August 2014. This trip included meeting with farmers in Chennai, researchers and a hive manufacturer in Bangalore, IITB students in Mumbai, a honey producer company in Dehradun, beekeeping researchers and beekeepers in Hisar, and ultimately the Central Bee Research and Training Institute in Pune. The second trip to India was over January 2015. This trip included meeting with researchers and beekeepers in Bangalore, the National Bee Board and the Project Coordinator for the All India Coordinated Research Project (AICRP) on Honey Bees and Pollinators in Delhi, bee researchers and producer companies in Ludhiana, and again researchers in Hisar. The third trip to India was over August 2015. This trip included meeting with the National Bee Board and AICRP Project Coordinator again in Delhi, beekeepers to do testing in Hisar, hive manufacturers and beekeeping instructors in Gangoh, and traditional beekeepers in Guptakashi. A map of the locations visited is shown in Fig. 1.2.

Meeting with beekeepers usually happened in their apiaries and always with an Indian researcher or host. Most of the beekeepers spoke some English, although often the researcher would translate much of the conversation. A notebook full of pictures and a box of physical prototypes was used to help discuss concepts as well as the actual apiary. Notes were taken in notebooks and pictures and video was taken where appropriate mainly focusing on hives.

The beekeepers and researchers were both colleagues and friends. From conversations over chai to stories on unpaved roads, the journey of meeting Indian beekeepers was deeply rooted in developing friendships.

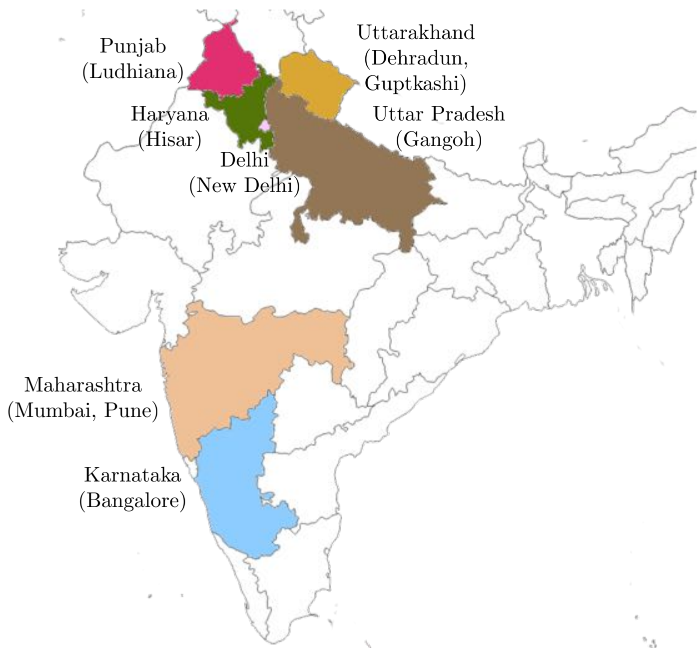


Fig. 1.2. Indian states and cities visited.

Chapter 2

An Introduction to Bees and Hives

Contents

2.1 Types of Bees

India has four main species of honey bees. There is the European honey bee Apis mellifera, the Asian honey bee Apis cerana, the giant honey bee Apis dorsata, and the dwarf honey bee Apis florea. While Apis mellifera and Apis cerana are domesticated and can live in human-built hives, Apis dorsata and Apis florea live in the wild in exposed hives. Fig. 2.1 shows all four types of these bees.

This thesis focuses on Apis mellifera and some on Apis cerana as these bees live in hive boxes and are the most common for commercial beekeeping practice. In addition, Apis mellifera is the honey bee used in the United States which allowed for comparable testing.

Apis mellifera and Apis cerana have a couple of important distinguishing factors relevant to this thesis. Apis mellifera is a larger bee with larger colonies that can

(a) Apis mellifera

(b) Apis cerana

(c) Apis dorsata

(d) Apis florea

Fig. 2.1. Four main types of Indian honeybees.

produce more honey than Apis cerana. Due to the differences in colony size, the hives for Apis cerana are built smaller. In the past, Apis mellifera has sometimes been susceptible to disease and other factors, and so the use of these bees varies by region. Another difference is that Apis cerana has evolved a defense again wasps [79, p. 85]. A cluster of Apis cerana bees can surround a wasp and then heat up just enough to kill the wasp without killing the bees. Apis mellifera does not have this ability and thus can be more susceptible to wasps. Continuing, Apis cerana does not collect propolis as Apis mellifera does. Propolis is a sappy substance from trees that the bees fill in hive cracks and gaps. Lastly, it is more difficult to migrate Apis cerana as it tends to swarm for smaller disturbances. As such, Indian migratory beekeepers are likely to be using Apis mellifera.

For more information on the differences between these two bees see [38, 69].

2.2 Types of Beehives

There are many hive designs and this thesis focuses primarily on the Langstroth hive. The Langstroth hive[1] has removable frames, and this allows beekeepers to individually inspect and remove frames. Honey can be harvested from specific frames and leftover wax after extraction can be placed back in the hive to allow wax reuse to expedite honey production. The Langstroth hive has boxes that can be stacked to expand the hive as the colony grows. Furthermore, the Langstroth hive is known for "bee space" where the spacing between frames is large enough that Apis mellifera bees tend to avoid adding propolis to fill gaps and small enough to avoid wax comb in-between the frames.

For these reasons the Langstroth hive is the default standard for much of the world. It is the most common hive in the US and for migratory beekeepers in India. Nonetheless, there exist variations in the number of frames, heights of boxes, and some other dimensions.

The Langstroth hive is not the only hive in India. Fig. 2.2 shows a mud hive,

[1] The Langstroth hive was designed in Massachusetts, US.

a log hive, and a wall hive. These hives were seen when visiting rural areas in the Himalayas.

Mud hive

Log hive

Wall hive (outside)

Wall hive (with cover)

Wall hive (cover removed)

Fig. 2.2. Other types of Indian hives.

One hive very uncommon in India is the top bar hive, which is popular in regions of Africa. The top bar hive is designed to be easy to manufacture. It consists of a box with an open top on which horizontal bars are placed. The bees build combs hanging from the horizontal bars. As the bees build all of the wax comb, the dimensions of the box and bars can have large tolerances. The reason for being uncommon in India may be because it is difficult to transport, known for producing less honey, and more difficult to extract honey with the uneven comb. Given the manufacturing capability within rural India, the top bar hive could potentially be very appropriate for beekeeping introduction to remote rural areas.

While rare or nonexistent in India, other types hives include warré hives and sun hives. The warré hive is known for having a quilt box on top that absorbs moisture to help colonies make it through cold, wet winters. The sun hive is related to the traditional skep hive but has removable frames. Many of these alternative hive designs focus on making hives similar to naturally found hives such as in hollowed tree logs. While this thesis focuses on Langstroth hives due to its Indian popularity and profitability, design improvements could come from these other less common hives.

2.3 Comparing US and Indian Hives

Although both the US and Indian beekeepers use Langstroth hives, the hives often have many differences. Fig. 2.3 shows a typical US hive and a typical Indian hive with the roof off.

Fig. 2.3. US vs. Indian Langstroth hives.

One of the key differences is that the US hive tends to have more supers (more boxes) than the Apis mellifera Indian hives, which usually is keptat a height of just one box.

Another difference is that the Indian Apis mellifera hive typically uses a burlap inner cover. The inner cover for the US hive is not visible, but it is made of wood and provides an upper entrance. The inner cover for the Indian hive does not provide an upper entrance but does allow air ventilation.

Other visible differences include the height of the individual boxes. The US hive shown just uses "mediums" but many beekeepers also use "deeps."

The stands are also different. Usually US stands are made to support a heavier hive than the stands for Indian beekeeping. Three common metal designs for the stands for Indian hives are shown in Fig. 2.4. Note that the folding type is especially convenient for migratory beekeepers. The folding and fixed types have specifications listed from the Bureau of Indian Standards [18, 19]. However, the folding stand shown lacks specified additional horizontal metal braces that stand about one quarter way from the base and this folding stand is built from flat strips and not pipe.

Folding type (standard)

Fixed type (standard)

A variation to limit bugs like ants and termites

Fig. 2.4. Indian hive stands.

Chapter 3

Beekeeping Context in India

Contents

3.1 Indian Beekeeping Stakeholders

Fig. 3.1 shows a graphic of Indian beekeeping stakeholders.

The beekeepers are both honey producers and pollinators, but unlike the US, the beekeepers do not get paid for pollinating farmer fields. This is partially due to the fact that farming plots are smaller in India, and so beekeepers may find it difficult to form such alliances with many farmers at one time. On occasion, beekeepers may pay to place hives near fields of nectar rich crops.

Indian beekeepers have a large interaction with the government groups that provide substantial subsidies (typically around 50% of the cost of the hive). The National

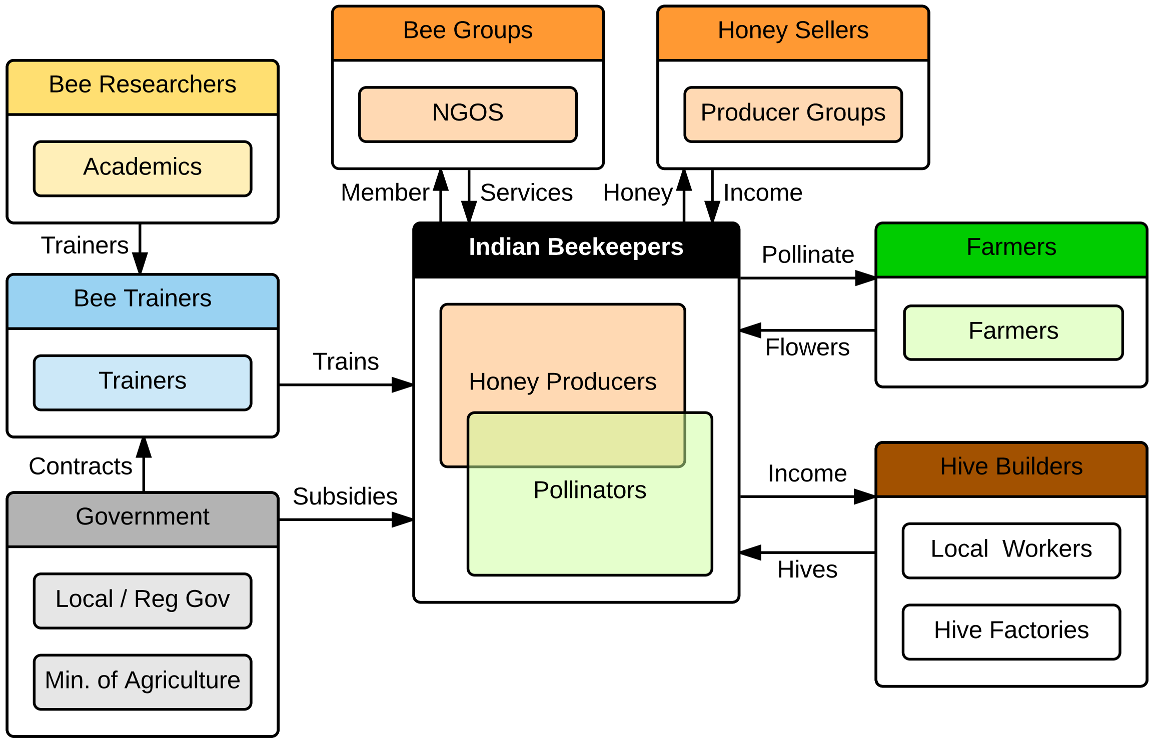


Fig. 3.1. Indian beekeeping stakeholders.

Bee Board (NBB) [26] under the Ministry of Agriculture is one of the main government bodies and there can be additional schemes run by local or regional governments. In addition there is the Khadi & Village Industries Commission (KVIC) under the Ministry of Micro, Small, and Medium Enterprises and KVIC works with the Central Bee Research and Training Institute in Pune. Government groups hire bee trainers that are often bee researchers from universities to teach aspects of beekeeping.

Bee researchers are incorporated under the Ministry of Agriculture and the research is often highly academic in nature. Training whether as classes or consultation is the main interaction with beekeepers.

The beekeepers can also be part of NGOs and producer groups. NGOs may provide a variety of services whether group meetings or other educational initiatives. The producer groups help to collectively bargain and provide a supply chain such that the honey can obtain a higher price.

The hive builders are either local wood workers or commercial sellers of hive equipment. The decision between using local wood workers or regional commercial sellers may impact the hive quality. Sometimes beekeepers will build their own hives.

3.2 To Bee or Not to Bee

The decision to become an Indian commercial beekeeper can be a high risk endeavor for any Indian farmer, but the risk may be worth it. Indian farming families traditionally subdivide farming land between sons, and this has resulted in smaller and smaller pieces of land held by individual farmers. Beekeeping, as it does not require land ownership, provides a way to increase earnings for these small scale farmers.

Furthermore, beekeeping also may require less work. A typical beekeeper may only visit the hives a few times a week, and so the beekeeper can have more time for other activities.

Despite the potential advantages for a higher income and less work, the occupation of beekeepers is generally not considered prestigious. It is sometimes considered an activity of "lower castes" [41, p. 42]. In the US, for comparison, the occupation of beekeeper is often looked upon with a more positive view, although recent challenges with colony collapse disorder and losses due to mites have made the occupation less profitable.

Beekeepers are not fully shielded from risk. Pests, diseases, theft, and other challenges can greatly affect the profitability of beekeeping. In addition, beekeeping with Apis mellifera often requires migrating during parts of the year.

When asked "What is your favorite part about beekeeping," one Indian beekeeper replied, "*I like getting stung.*" I asked, "You like getting stung?" He replied, "*I get stung when I extract honey, and that's when I get money.*"

3.3 What Keeps Indian Beehives Shorter?

While both US and many Indian beekeepers use the same bee species, Apis mellifera, US beekeepers usually super their hives and Indian beekeepers usually keep their hives limited to just one box except during the largest honeyflows. Larger hives

Fig. 3.2. Two box Indian Apis mellifera hive.

can potentially gain more honey per colony, survive longer periods of dearth, and better fend off some types of pests. It was desired to understand what explains and motivates the tendency for Indian Apis mellifera beekeepers to less frequently super their colonies.

One of the first reasons is likely the difference in climate. As India tends to be warmer and its winter is shorter, there is less of a need for a large honey reserve for the bees.

Another one of the factors responsible is manufacturing capability. Fig. 3.2 shows a supered Indian hive. Here the mud and nailed pieces of wood are used to secure the hive boxes together. There still exist gaps between the boxes. Moving this hive and ensuring that the boxes remain together during movement would be very challenging. For comparison, US hives are usually strapped together tightly when migrated and unintended gaps are very rare.

The gaps are due to the manufacturing process in which top and bottom hive surfaces are usually not perfectly level and the outer box dimensions of the hives may have a large variance. While the technique and tools needed for improving the tolerance of the hive edges is not necessarily out of reach, improvements in the manufacturing could command a higher price. Given the low resources for initial capital investments and higher inflation, it may not be as economical to obtain higher quality hives.

There are also advantages of smaller one box hives. One of the advantages is that smaller hives are inherently easier to lift and migrate. US commercial beekeepers often max out at two hive boxes to keep moving boxes realistic. Having one box means that except when migrating, no boxes need to be picked up. Another potential benefit is that having many smaller hives instead of a few large hives may minimize risk due to factors such as queen failure. Furthermore, as Indian bees are often collected from wild swarms, the monetary cost of starting an additional hive may be lower.

Another potential factor is that Indian beekeepers may prefer to cash in on the honey flow as soon as possible. Too much honey extraction may limit the hive growth from season to season.

Lastly, awareness and data may be lacking. After seeing US hives for comparison, one Indian beekeeper met had asked for insight as to what was the ideal time to add a super. Indian beekeepers may not recognize nor may it be known if having larger hives in India is more economical. This is something that requires further testing within India.

3.4 Indian Innovations

Indian beekeepers have developed and used many innovations. This sections hopes to highlight just a few of the innovations seen. Fig. 3.3 shows a number of such innovations.

Fig. 3.3a shows a very cost-effective way to apply mite treatments to hives. Using just a small piece of cotton and a small stalk, it is possible to make what typically would be an expensive application tool for hive treatments. This applicator design is purely organic and minimizes waste.

Fig. 3.3b shows a hive where a beekeeper added an extra frame to help give the bees more space and improve hive ventilation. This serves as a shim and minimizes extra hive components needed.

(a) Varroa mite treatment

(b) Using a frame as a spacer

(c) Inverting roofs to avoid bugs

(d) Water source

Fig. 3.3. Indian innovations.

Fig. 3.3c shows a roof flipped upside down. When asked why this was the case, the beekeeper explained that the flatter roofs make better contact with hive edges as the metal roof tends to be smoother. For this reason, it was easier to keep ants away from the beehives.

Fig. 3.3d shows a simple water source using locally available jute cloth. The cloth wicks up the water and provides a place for the bees to land. Providing a water source directly near the hives helps improve the colony. In addition, clay pots are known to cool water due to wicking and evaporation through the pot. In this way, the bees receive water cooler than the ambient environment.

There were many other Indian beekeeping innovations observed while in India. One example is the use of the jute cloth as an inner cover that provides more robustness to uneven surfaces. The jute cloth also can serve as a way to cool hives. Beekeepers can directly pour water on the jute cloth because it can hold and help slowly evaporate water. Another example is the variety of Indian hive stands. Section 2.3 described how India has a highly portable stand with minimal parts and a stand specifically designed to reduce the problem of ants and termites.

Throughout this thesis, Indian innovations are recognized and developments on their designs are recommended both for US and other Indian hives. This is the process of "reverse innovation" [36].

3.5 Indian Honey Production

Fig. 3.4 plots the number of Indian hives, Indian honey production, and Indian honey exports. Note that exports have become significant for the Indian market. The chart is set up such that the earnings per beehive is visible at slightly over $10 per hive per year. This seems low, but possibly reflects that many beekeepers in rural areas may personally consume their honey or sell their honey for lower rates than the national average.

Very rough estimates say that India has about 1 million bee colonies of Apis cerana and Apis mellifera in 40,000 towns that give at least part-time occupation to

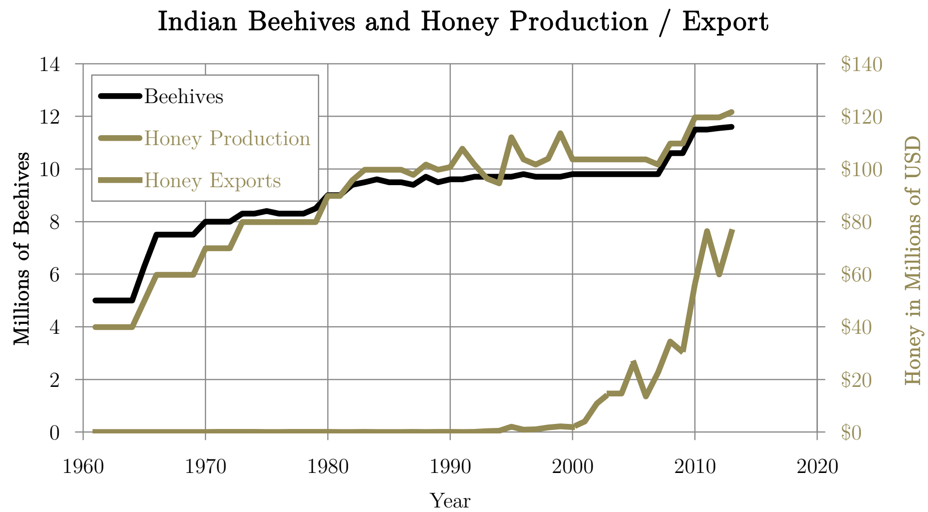


Fig. 3.4. Number of Indian beehives, honey production, and honey exports. The number of beehives in India has slowly grown, and production per beehive has only gradually risen to about 10 USD / beehive. The last decade has shown a sharp spike in honey exports. Notes that exports are in current USD whereas production is in constant 2004-2006 USD. 2013 current honey production was $155.05M. Data from the Food and Agricultural Organization of the United Nations (FAO) [31, 32].

a quarter million people [50]. These numbers are said not to be highly reliable. Of the 1.3 billion people in India [81], that means that about one in 5,000 Indians are beekeepers.

For comparison, the US in 2014 had 2.7 million honey producing colonies of beekeeper of 5 or more commercial hives that made 80.9 million kg of honey in 2014 at a value of $4.76 per kg [57]. Very rough estimates for the number of hobbyist beekeepers may be more than 200,000 [48] and somewhere between 1,600 large commercial migratory beekeepers [44] to roughly 10,000 commercial beekeepers with over 300 hives [48] and 30,000 commercial beekeepers with less than 300 hives. This means there is roughly 1 at-least-hobbyist beekeeper for every 1,500 people in America.

Chapter 4

Beehive Pests and Problems

Contents

Many books and resources are available to explain the array of pests and problems that beekeepers commonly face. For this reason, this chapter intends to briefly highlight some of the common pests and problems and draw particular attention to the challenges more unique for Indian beekeepers.

4.1 Pests

There are many pests that attack beehives both in the US and in India. Pests smaller in size include varroa mites, wasps, moths, ants, termites, beetles, and even other bees. Pests larger in size include birds and larger honey seeking mammals.

The pest perhaps responsible for the most harm in both the US and India is the varroa mite. The varroa mite is like a tick in that it feeds on the blood of bees. In this way, the mite can spread many viruses and diseases. Section 15.1 gives an overview of current methods to tackle mites. One of the new and more effective treatments used to treat mites is oxalic acid that gets vaporized inside the hive to kill the mites. This treatment is a cause for concern for Indian beekeepers because Indian hives are not as well sealed as US hives. This thesis predicts that as oxalic acid becomes a more common treatment among Indian beekeepers - likely over the next decade - Indian beekeepers will be more exposed to this chemical and this will lead to health problems.

This thesis was originally on how to stop wasps. Wasps are present in both the US and India, but US wasps tend to be smaller in size and be less frequently a problem. Wasps are a seasonal problem in India, primarily in hilly regions. Wasps can feed on dead or old bees [71, p.144], live bees, or fully take over a hive. The visits taken as part of this thesis did not see wasps attacking the hives visited. Nonetheless, Fig. 4.1 shows a response from an Indian beekeeper about wasps. “Shuttle bats” are like tennis rackets.

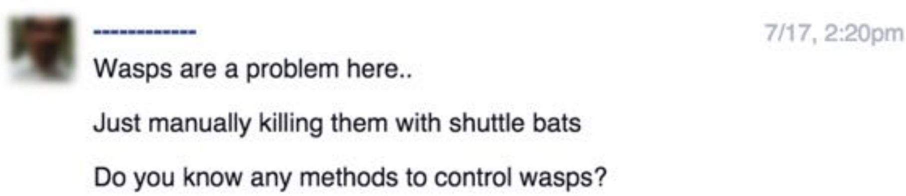


Fig. 4.1. Indian Facebook response about wasps.

The general solution to stop wasps is to reduce the entrance size or move the hive’s opening to stop the attack [71, p.144]. Tools such as robber screens or mesh are sometimes used to try to help limit attacks. One design to limit the opening size of the hive is given in [38] for which sheets of wood are horizontally spaced in front of the entrances. Traps are another option. One trap that appears to catch a lot of wasps is to simply use sticky paper [7]. After one wasp is caught more wasps are attracted and then get stuck. There also also other traps that work by making it easier to enter than to exit.

Ultimately, wasps can present a high risk for some Indian beekeepers and no complete solution has been found. One Indian bee researcher had pictures from an apiary where in just a few days, wasps came and destroyed all of the hives of an Indian beekeeper who was briefly away on travel.

Moths are another pest in both the US and India. The female moth lays eggs either inside or outside the hive [79, p.86], and then the larvae use and damage the comb. Good ventilation may help get bees to move around the hive more and thus decrease the presence of wax moths [28, p.131]. Indian beekeepers attempt to mitigate the problem of wasps by waiting to fill all of the frames in small hives.

Other small pests include beetles, ants, and termites. The small hive beetle, originally from Africa, got introduced to the United States in 1998 [71, p.139]. There are traps and other hives accessories made to help to stop these small beetles [71, p.139, 72]. Ants try to get in hives to eat the honey and take shield from outdoor weather [71, p.138]. Beekeepers can use cinnamon or boric acid with sugar to repel the ants from the base of the hive [71, p.138]. There are other techniques of putting the hive stand posts in cans filled with oil. Termites may attack hives to eat the wood.

Some weaker hives may be attacked by stronger hives, and this is called robbing. Reducing the entrance size, using robbing screens that divert the entrance, and making the stronger hive more vulnerable are all techniques used to minimize robbing.

Larger animals also cause challenges. One of the worst pests for Indian beekeepers is the bee-eater bird. The bee-eaters can greatly weaken hives. Bee-eaters are explored more in Section 16.5. Other larger animals include bears, mice, monkeys, and lizards. One reason for having hive stands is that it can expose the bellies of these predators to the bees [71, p.145]. Some beekeepers use fences or cages, but this can be expensive.

4.2 Disease

This thesis does delve into bee diseases, but it should be noted that disease has historically been responsible for widespread colony deaths in India. Carefully breeding more resistant bees is an important area of research to maintain strong genetics. As India does not commonly have formal queen rearing programs, distributing more hardy strains of bees can be difficult and the risk of outbreaks remains.

4.3 Foraging, Pesticides, and Colony Collapse Disorder

In the US a major problem for bees in monoculture, but in India the opposite may be more concerning. Commercial US bees often pollinate large one crop fields, and the lack of plant diversity can potentially put more stress on bees. In India, the farmer plots are very small, and so bees tend to obtain a larger foraging diversity.

However, with more farmer fields within range of the foraging bees, it becomes more difficult for beekeepers to avoid pesticides. Some of the Indian beekeepers in the roof experiment in Chapter 12 mentioned that their bees were hurt from pesticides used by cotton farmers. While a US commercial beekeeper may able to be able to coordinate pesticide use with one farmer, an Indian commercial beekeeper may find coordinating with many farmers more difficult.

The use of pesticides is well known to be harmful to bees, but the extent to which pesticides are responsible for bee death is less clear. This thesis generally avoids the topic of colony collapse disorder (CCD) that is marked by the mysterious and sudden disappearance of a colony's bees and was first noticed around 2007. Pesticides, especially the use of neonicotinoids, may be responsible for the hive deaths [40]. The use of pesticides is a complex political, economic, and scientific struggle among farmers, pesticide manufacturers, government agencies, and beekeepers.

Although this thesis does not focus on the challenge of pesticides, this thesis does try to limit other stresses. By limiting stresses due to ventilation, pests, sufficient food, and other factors, bees may be more robust to pesticide exposure.

Lastly, the electronic adjustable beehive entrance designs from this thesis may help provide a way to coordinate or intelligently restrict traffic flow when pesticides are applied.[1]

[1] I would like to acknowledge Dr. Noah Wilson Rich and also Mr. David Seaver for recognizing this potential use.

4.4 Other Beekeeping Challenges

Depending on the location in India, the knowledge of beekeeping can be very primitive. One Indian bee specialist explained that beekeepers have had problems where farmers, thinking the bees are stealing from their crops, attack beehives. With the great number of farmers with whom Indian beekeepers interact, challenges like this can be problematic.

Furthermore, theft of hives can occur - both in the US and India. Migratory beekeepers often live some distance from their hives.

Finally, while there are many groups that work to help educate and teach beekeepers, there is still a need for improved education among Indian beekeepers. The education and understanding of beekeeping can vary widely. With language differences, geographical separation, and limited telecommunications in some parts of India, there is much opportunity to improve Indian hive management.

Chapter 5

Hive Weight Scales

This is chapter contains a close copy of the submission of a paper originally titled "An Error Budget Analysis of Four Hive Weight Mechanisms." The focus of this chapter is most relevant for beekeepers with heavy bee boxes typically at least two deeps high where the whole hive cannot be easily be picked up whole by a beekeeper.

Contents

5.1 Abstract

Accurately measuring hive weights can help beekeepers track hive productivity, monitor potential swarming, assist wintering, and improve queen rearing. This paper provides an analysis of four hive weight mechanisms: direct measurement by load cell scales, a torque wrench and bracket, a leveraged pull design, and a top pull design. The accuracy of each is considered in the context of potential sources of error and other in-situ application effects. The direct measurement by load cell scales (within 2.5%) is the most accurate of these mechanisms and best for permanent measurement systems. The torque wrench and bracket (within 18%) requires user skill to mitigate imprecise or unrepeatable errors. The leveraged pull (within 5%) is most accurate portable mechanism if design improvements and practices described herein are implemented. The top pull mechanism (within 7.5%) avoids shims and bending over to take measurements, but does require wider and sturdier hive stands.

5.2 Introduction to Hive Weight Scales

Motivation Weight scales provide a quantitative means to monitor hive health and productivity. For beekeepers in colder climates, the weight can gauge how much honey can be harvested while leaving enough for the bees to consume during the winter [20]. Commercial beekeepers can track honey gain across different crops and fields, and bee breeders can identify more productive bee strains. Additionally, bee researchers can use hive weight as a quantitative metric in experiments [51]. Furthermore, there is a US initiative to weigh hives to track and monitor the effects of climate change [56]. Accurate and economical hive scales can thus greatly benefit the beekeeping community.

Prior Art Beekeepers have tried a variety of techniques to weigh hives and several designs have been commercialized. Some beekeepers have used digital bathroom scales that slide under hives [34]. Others have directly lifted hives with a pull force sensor [12]. One expired patent from 1977 used small levered prongs to get between boxes for which the stresses can then estimate the weight [10]. There exist a number of designs using four load cells in a short platform on which the hives rest. This style of design is commercially available but a wireless system can cost from \$250 [82] to over \$700 per hive [6]. Portable designs for weighing hives using four load cells also exist, but may require special hive stands [29]. Commercial designs also exist that use a torque wrench and bracket to slightly prop up a hive on one side to estimate the overall weight [63, 13]. There additionally exist a few designs that use 1D pull force sensors, cables, and pulleys to lift up a hive on one side [9, 33]. The wide array of previous designs suggests that no one design has met all the needs of all beekeepers. A better understanding of the accuracy of each weight mechanism is needed to help beekeepers select the most appropriate design.

Functional Requirements Hive scales should be able to measure between 13.6 kg (30 lbs) and 136 kg (300 lbs), although most hives do not pass 100 kg (220 lbs). To detect swarms, scales should ideally have at least ±0.45 kg (1 lb) precision as a swarm can be 1.4 kg (3 lbs). The accuracy needed to compare two hives is about 5% of the total weight. Some beekeepers want continuous readings for which the scale should remain in place, be water resistant, and typically be remotely powered. Portable scales that can be used across multiple hives should minimize disruption of bees from separating boxes, require no more than 222 N (50 lbs) user force, take less than 30 seconds per hive, and require minimal user math. Any scale design should also be compatible with hive equipment. While boxes are well standardized, baseboards and stands are more varied. Additionally, highly concentrated forces should be avoided that could detent or collapse hive equipment. Lastly, the scales should be in the price range of beekeepers. From discussions with beekeepers, scale cost should ideally be under \$50 depending on functionality. While all of these functional requirements are important, this paper will focus primarily on the accuracy of the weight measurement.

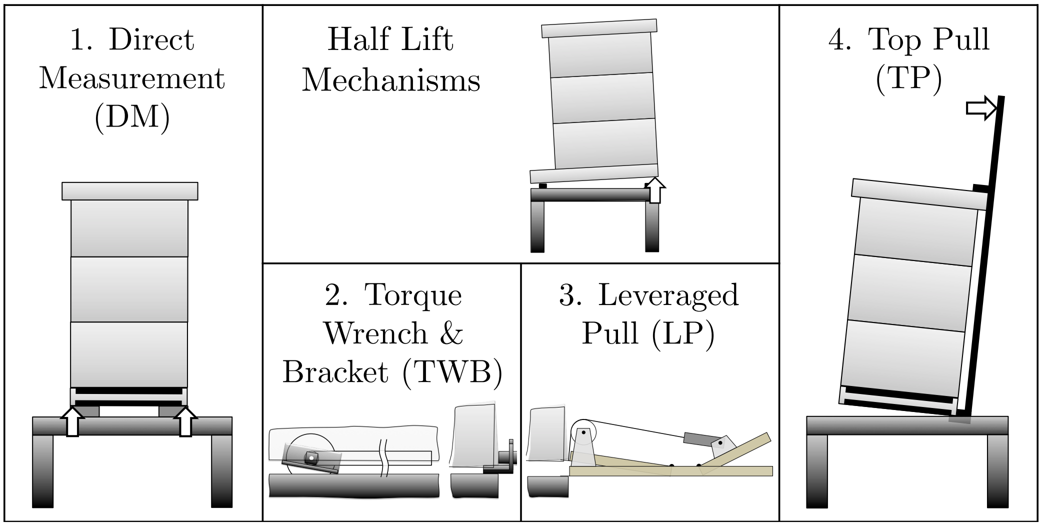


Fig. 5.1. The four hive weight scale mechanisms analyzed in this paper.

Overview This paper considers the accuracy and in-situ application effects of four hive weight mechanisms shown in Fig. 5.1 using the methodology given in Section 5.3. Section 5.4 gives a brief overview of (1) direct measurement (DM) using load cells that has the least error out of all mechanisms. Then the family of half lift designs where only one side of a hive is lifted is considered in Section 5.5.1 with two examples: (2) torque wrench and bracket (TWB) mechanisms in Section 5.5.2 and (3) a leveraged pull (LP) design in Section 5.5.3. Lastly (4), a top pull (TP) mechanism is analyzed in Section 5.6. Section 5.7 then summarizes the error ranges for all the mechanisms.

Symbol	Meaning
Δh	Distance from bracket midline to torque wrench
δ_{L}	Angle of lateral force F_{L}
$\delta_{\mathrm{L_{xz}}}$	Angle of lateral force F_{L} projected into xz-plane.
δ_{R}	Angle of lateral force F_{R}
ϵ	Dimensionless ratiometric error
ϵ_{arm}	Error from lever arm in LP
$\epsilon_{\mathrm{bracket}}$	Error from bracket when lifting hive
$\epsilon_{\mathrm{center}}$	Error from uncentered weight along hive
$\epsilon_{\mathrm{contact}}$	Error from hoisting hive slightly underneath
$\epsilon_{\mathrm{handle}}$	Error from handle in TWB

ϵ_{height}	Error from height measurement in TP
$\epsilon_{\text{incline}}$	Error from natural inclination
ϵ_{lift}	Error from extra lifting in half lift mechanisms
$\epsilon_{\text{oblique}}$	Error from oblique sensor in TP
ϵ_{pulley}	Error from pulley friction in LP
ϵ_{sensor}	Error from sensor tool
ϵ_{shim}	Error from improper shim placement
ϵ_{width}	Error from hive width measurement
η_{L}	Dimensionless hive height based on length
η_{W}	Dimensionless hive height based on width
γ	Rotation of bracket to lift hive
μ	Coefficients of friction
μ_{axle}	Friction between pulley and pulley axle
μ_{bracket}	Friction between bracket and hive or stand
ϕ	Natural hive inclination
ϕ_{F}	Natural stand inclination forward
ϕ_{L}	Natural stand inclination left
θ	Extra tilt due to lifting one end
θ_{F}	Extra tilt forward
θ_{L}	Extra tilt left
θ_{R}	Extra tilt right
Θ_{p}	Angle of wire around pulley
ζ	Dimensionless ratio used for ϵ_{pulley}
a	Horizontal distance of center of mass from front fulcrum
a_{W}	Horizontal distance of center of mass from left fulcrum
b	Height of center of mass from bottom board
c	Distance from contact to front of hive
d	Distance of contact under hive from hive edge
d_1	Distance of contact under hive from fulcrum
d_2	Distance of fulcrum to handle

F_{front}	Force on front of hive in half lift mechanisms
$F_{\text{g}_{\text{act}}}$	Weight of hive (actual)
$F_{\text{g}_{\text{clamp}}}$	Weight of clamp
$F_{\text{g}_{\text{est}}}$	Weight of hive (estimated)
F_{hand}	Vertical hand force on wrench
f_{hive}	Friction between hive and bracket in TWB
$f_{\text{hive}_{\text{x}}}$	Friction from hive along $\hat{x}$
$f_{\text{hive}_{\text{y}}}$	Friction from hive along $\hat{y}$
F_{hive}	Force from hive on lifting device
F_{L}	Lateral force left in top pull mechanisms
F_{pull}	Force pulled by sensor in LP
F_{R}	Lateral force right in top pull mechanisms
F_{side}	Vertical force from stand in half lift mechanisms
f_{stand}	Friction between stand and bracket in TWB
$f_{\text{stand}_{\text{x}}}$	Friction from stand along $\hat{x}$
$f_{\text{stand}_{\text{y}}}$	Friction from stand along $\hat{y}$
F_{stand}	Normal force on bracket
g	Acceleration due to gravity
H	Height where lateral force is applied
H_{act}	Height of lateral force (actual) in TP
H_{meas}	Height of lateral force (measured) in TP
l	Length of handle from center of bracket
l_{arm}	Length from hinge to wire in LP
L_{bottom}	Length of bottom board
L_{box}	Length of hive box
l_{contact}	Length from hinge to hive contact in LP
m	Mass of hive being weighed
$M_{\text{hand}_{\text{y}}}$	Hand moment on wrench about negative $\hat{y}$
$M_{\text{hand}_{\text{z}}}$	Hand moment on wrench about positive $\hat{z}$
m_{top}	Mass of top box

r_{hole}	Radius of pulley hole in LP
r_{pulley}	Radius of pulley in LP
t	Thickness of bracket
T_{act}	Torque in torque wrench (actual)
T_{meas}	Torque in torque wrench (measured)
w	Width of bracket
W	Width of hive
W_{act}	Width of hive (actual)
W_{meas}	Width of hive (measured)
$\hat{x}$	Unit vector left when facing hive front
$\hat{y}$	Unit vector forward perpendicular to gravity
$\hat{z}$	Unit vector up parallel with gravity

Table 5.1: Table of variables.

5.3 Methods

For each mechanism, a basic equation is provided that relates how the weight of the hive F_{gact} is estimated based on the output reading of the sensor device. There can be a conversion constant between the sensor reading and the estimated weight.

A more accurate equation is then developed using successive linear approximations that allows error sources to be considered independently. The following approximations are used with the assumption that the angle θ and error terms ϵ_1, ϵ_2, ... are each small and independent.

$$\text{Approximation 1: } \cos(\theta) \approx 1 \tag{5.1}$$

$$\text{Approximation 2: } \sin(\theta) \approx \theta \tag{5.2}$$

$$\text{Approximation 3: } \tfrac{1}{1-\epsilon_1} = 1 + \tfrac{\epsilon_1}{1-\epsilon_1} \approx 1 + \epsilon_1 \tag{5.3}$$

$$\text{Approximation 4: } (1+\epsilon_1)(1+\epsilon_2) = 1 + \epsilon_1 + \epsilon_2 + (\epsilon_1 \cdot \epsilon_2) \approx 1 + \epsilon_1 + \epsilon_2 \tag{5.4}$$

Note that Eq. (5.4) can be used recursively as in $(1+\epsilon_1)(1+\epsilon_2)(1+\epsilon_3) \approx 1+\epsilon_1+\epsilon_2+\epsilon_3$.

The error terms ϵ are random variables for which discussion will motivative bounds of minimum and maximum limits. The error distributions are generally not specified and may not be centered about zero. For this reason, the analysis aims to directly sum the minimum and maximum error bounds to get a full bound for the total error.

To motivate improved design, errors will categorized as repeatable (precise), unrepeatable (imprecise), or preventable. Repeatable errors will lead to the same measurement for the same hive for two consecutive measurements. Unrepeatable errors are especially troublesome because they can give different readings for the same hive. Preventable errors are errors that could be mainly eliminated using design improvements mentioned in this paper.

5.4 Direct Measurement by Four Load Cell Scales (DM)

Direct measurement by load cells gives a direct estimate of the weight of the hive in that $F_{\text{gest}} \approx F_{\text{gact}}$. However DM has two main error sources: error due to inclination $\epsilon_{\text{incline}}$ and error due to the sensor system ϵ_{sensor}. $\epsilon_{\text{incline}}$ is given as a cosine error as the scale ideally only measures forces perpendicular to its surface:

$$\epsilon_{\text{incline}} = \cos(\phi) - 1 \approx 0 \tag{5.5}$$

ϕ here is the total angle the hive is inclined. Most hives are tilted slightly forward in practice for drainage. Based on a small sampling of hives, $|\phi|$ is likely under 5°. In the near worst case of 5°, $\epsilon_{\text{incline}}$ is -0.38%.

For sensor accuracy, four load cell scales often can measure up to 136 kg (300 lbs) and are rated to be accurate to within .045 kg (.1 lbs) if they can be zeroed. Most hive scales put permanently in place lack the ability to be zeroed easily and thus are more susceptible to nonrandom temperature effects and gradual creep over time. Error ranges of sensors are typically reported as a percent of error of the maximum possible reading or as a percent of the measured value. Herein ϵ_{sensor} will be given as percent error from the actual value. For a non-zeroed sensor, ϵ_{sensor} will be considered to be within ±2%. Thus, the weight measurement equation for four load cell scales is given by

$$F_{\text{g}_{\text{est}}} = F_{\text{g}_{\text{act}}} \cdot (1 + \epsilon_{\text{incline}})(1 + \epsilon_{\text{sensor}}) \tag{5.6}$$

$$F_{\text{g}_{\text{est}}} \approx F_{\text{g}_{\text{act}}} \cdot (1 + \epsilon_{\text{incline}} + \epsilon_{\text{sensor}}) \tag{5.7}$$

5.5 Half Lift Mechanisms

A number of hive weight mechanisms lift just one end of a hive to obtain an estimate of the total hive weight. The main assumption is that the force of the hive F_{hive} on the measuring device is then approximately half of the weight of the hive $F_{\text{g}_{\text{act}}}$. While it takes more time, the accuracy is improved when averaging measurements from two opposite sides of the hive. Section 5.5.1 explores inherent errors of half lift mechanisms and benefits of taking an average from measuring opposite sides. Examples of half lift designs include torque wrench and bracket (TWB) designs where a small bracket is torqued underneath one end of the hive and leveraged pull (LP) designs that often use pulleys. Section 5.5.2 explores additional errors unique to TWB designs and Section 5.5.3 explores additional errors of a LP design.

5.5.1 Inherent Errors of Half Lift Mechanisms

Fig. 5.2 shows how a tilted hive with uncentered mass may not have F_{hive} exactly half of F_{g}. There is natural uneven placement of comb by bees and the rotational axis may be misplaced depending on shim placement. Most beekeepers tilt their hive slightly forward ϕ_{F} for drainage, and the lifting device can cause extra tilt θ_{L} or θ_{F} as the hive is propped up.

Effective use of a half lift device may require short shims to be compatible with most hives. The short shims are needed to 1) help the device easily get between the hive components and 2) prevent propolis from gluing the boxes together. Propolis is a

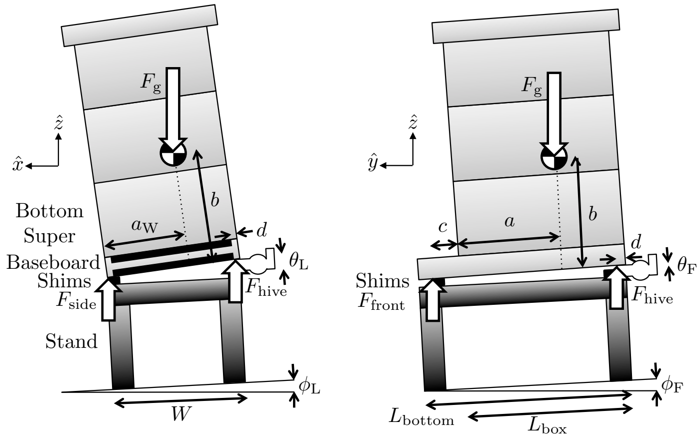


Fig. 5.2. A 2D free body diagram of the hive propped up between the stand and baseboard, measuring from the side or measuring from the back.

sticky substance collected by bees to fill small cracks. Propolis can be time-consuming to break and could otherwise affect the accuracy of the weight measurement. In Fig. 5.2 the shims are placed between the baseboard and hive stand because a gap between the bottom super and baseboard could let in cold winter drafts and small pests like ants.

Ultimately, the measured weight is sensitive to the placement of shims. Using a torque balance about the front shim for lifting from the back:

$$F_{\text{hive}}(c + L_{\text{box}} - d)\cos(\phi_{\text{F}} + \theta_{\text{F}}) = F_{\text{g}}((a + c)\cos(\phi_{\text{F}} + \theta_{\text{F}}) - b\sin(\phi_{\text{F}} + \theta_{\text{F}})) \quad (5.8)$$

Equation Eq. (5.8) can be approximated using the small angle sine and cosine and algebraic approximations given in Section 5.3.

$$\begin{aligned}
F_{\text{hive}} &\approx F_{\text{g}} \cdot \frac{a + c - b(\phi_f + \theta_f)}{c + L_{\text{box}} - d} \\
F_{\text{hive}} &\approx \tfrac{F_{\text{g}}}{2} \cdot \frac{\frac{2a}{L_{\text{box}}} + \frac{2c}{L_{\text{box}}} - \frac{2b}{L_{\text{box}}}(\phi_f + \theta_f)}{1 + \frac{c}{L_{\text{box}}} - \frac{d}{L_{\text{box}}}} \\
F_{\text{hive}} &\approx \tfrac{F_{\text{g}}}{2} \cdot \left(\frac{2a}{L_{\text{box}}} + \frac{c}{L_{\text{box}}} + \frac{d}{L_{\text{box}}} - \frac{2b}{L_{\text{box}}}(\phi_f + \theta_f)\right) \\
F_{\text{hive}} &\approx \tfrac{F_{\text{g}}}{2} \cdot (1 + \epsilon_{\text{center}} + \epsilon_{\text{shim}} + \epsilon_{\text{contact}} + \epsilon_{\text{incline}} + \epsilon_{\text{lift}})
\end{aligned} \quad (5.9)$$

Where it is defined (considering the corresponding case for lifting from the sides):

$$\epsilon_{\text{center}} \equiv \tfrac{2a}{L_{\text{box}}} - 1 \text{ or } \pm\left(\tfrac{2a_{\text{W}}}{W} - 1\right) \tag{5.10}$$

$$\epsilon_{\text{shim}} \equiv \tfrac{c}{L_{\text{box}}} \text{ or } \tfrac{c}{W} \tag{5.11}$$

$$\epsilon_{\text{contact}} \equiv \tfrac{d}{L_{\text{box}}} \text{ or } \tfrac{d}{W} \tag{5.12}$$

$$\eta_L \equiv \tfrac{2b}{L_{\text{box}}}, \eta_W \equiv \tfrac{2b}{W} \tag{5.13}$$

$$\epsilon_{\text{incline}} \equiv -\eta_{\text{L}} \cdot \phi_{\text{F}} \text{ or } \mp \eta_{\text{W}} \cdot \phi_{\text{L}} \tag{5.14}$$

$$\epsilon_{\text{lift}} \equiv -\eta_{\text{L}} \cdot \theta_{\text{F}}, -\eta_{\text{W}} \cdot \theta_{\text{L}}, \text{ or } -\eta_{\text{W}} \cdot \theta_{\text{R}} \tag{5.15}$$

It is possible to reduce some of the error from Eq. (5.9) by taking measurements from two opposite sides of the hive and taking the average. In practice this usually would be done by taking measurements from the left and right sides rather than the front and back as bees tend to become defensive when their flight path is blocked. If the average is taken, the errors ϵ_{center} due to uncentered mass and $\epsilon_{\text{incline}}$ due to ground inclination are eliminated to first order. The equation for measuring from both sides is then given by:

$$F_{\text{hive}} \approx \tfrac{F_{\text{g}}}{2} \cdot (1 + \epsilon_{\text{shim}} + \epsilon_{\text{contact}} + \epsilon_{\text{lift}}) \tag{5.16}$$

The errors of the different terms can be approximated. ϵ_{center} varies depending on the hive. In general, the weight is centered more lengthwise than along the width and smaller one box hives tend to be the least centered. A worst case partially filled one box hive measured $\epsilon_{\text{center}} \approx 14\%$ along the width but only $\approx$ -1.5% lengthwise. $|\epsilon_{\text{center}}|$ can be larger than 1.5% along the length. One partially filled deep frame from a different hive measured $|\epsilon_{\text{center}}| \approx 20\%$ lengthwise, but this would average closer to zero with other frames and the weight of the box. For future analysis, the typical bounds for ϵ_{center} will be $\pm 5\%$ for lengthwise measurements.

ϵ_{shim} for measuring from the back can be as much as 10% if no shims are used and the about 55.9 cm (22 inches) baseboard sticks out a typical 5.1 cm (2 inches). However, proper use assumes that shims are used to set the rotational axis flush with the edge of the hive boxes. ϵ_{shim} can thus range $\pm 1.3\%$ if the shims are assumed within 6.4 mm (quarter inch) of the correct location. For taking measurements from the left and right, ϵ_{shim} ranges from about -1.5% to 0% for a 10 frame langstroth hive with a width of 41.3 cm (16.25 inches). ϵ_{shim} for the sides cannot be above 0% as the axis of rotation cannot be beyond the edge of the box.

d ranges from 0 to 1.27 cm (.5 inches), so $\epsilon_{\text{contact}}$ ranges from 0% to 2.5% lengthwise and 0% to 3.1% along the width.

Natural hive inclination ϕ_{F} is typically less than 5° (0.087 rad) forward and 2° (0.035 rad) backward. η_{L} depends on the number of boxes. For a hive with two deep boxes 24.4 cm (9 5/8 inches) high, η_{L} is about one and η_{W} is 1.23. The error $\epsilon_{\text{incline}}$ could range from -8.7% to 3.5% for lifting from the back.

Lastly, error ϵ_{lift} due to θ_{F} can be estimated. Most hive lifting mechanisms only lift the hive at most 1.27 cm (.5 inches) at the hive edge - which is about 9.53 mm (3/8 inches) extra lift if the hive originally had 3.18 mm (eighth inch) shims. At this extra lift height, ϵ_{lift} ranges from -1.9% to 0% lengthwise and -2.8% to 0% left and right.

Fig. 5.3 shows the combined error bounds. The error bounds are reduced from -16.9% to 12.2% for lifting from the back to -4.4% to 3.1% for averaging side measurements.[1] The reduced error bounds are mainly due to the fact that ϵ_{center} and $\epsilon_{\text{incline}}$ are removed to first order when averaged from opposite sides. However, measuring twice requires more time and some mental calculation.

Lastly, while ϵ_{center}, ϵ_{shim}, and $\epsilon_{\text{incline}}$ tend to be repeatable, $\epsilon_{\text{contact}}$ and ϵ_{lift} can be sensitive to how the measurement is taken. Thus there exists up to about -1.9% to 2.5% vs. -2.8% to 3.1% unrepeatable error from back and sides respectively.

5.5.2 Torque Wrench and Bracket (TWB)

One half lift mechanism is a torque wrench attached to a short bracket that when twisted slightly props up the hive. As the hive is lifted on just one side, the bracket

[1] The errors bounds using the nonlinearized Eq. (5.8) give error bounds of -17.1% to 12.4% for lifting from the back and -4.5% to 3.2% averaging the sides.

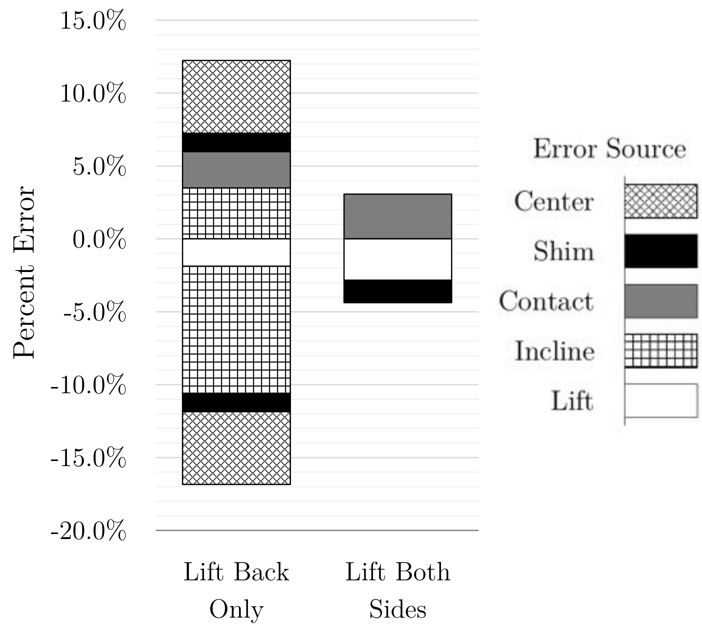


Fig. 5.3. Lifting mechanisms can be made more accurate by averaging measurements taken from both sides and averaging. Averaging removes to first order errors due to uncentered hive mass ϵ_{center} and the ground incline $\epsilon_{\text{incline}}$ (both shown patterned).

has to support about half the weight of the hive. This force F_{hive} multiplied by the length of the bracket approximates the torque measured in the torque wrench. Thus the following equation estimates the weight of the hive:

$$F_{\text{gest}} \approx T_{\text{meas}} \cdot \frac{2}{w} \tag{5.17}$$

Commercially available TWB designs include the Honey Hefter© [63],[64] and the Nectar Detector® [13]. The Honey Hefter uses a torque wrench with a bracket of 15.2 cm (half foot), and so by Eq. (5.17) the nominal torque in ft-lbs is multiplied by 4 to get the estimated hive weight in lbs. The Nectar Detector, shown in Fig. 5.4, uses a torque wrench with a 50.8 mm (two inch) bracket, and so the nominal torque in inch-lbs is the estimated hive weight in lbs. A metric TWB design could use a 10.2 cm (4.02 inch) bracket that requires multiplying by 2 to get the estimated hive mass in kg (using $g = 9.81$ m/s^2).

Eq. (5.17) can be improved to account for previously considered half lift errors and also potential errors due 1) bracket friction, 2) forces on the handle, and 3) error of

Fig. 5.4. One commercially available TWB design is the Nectar Detector. It has a 50.8 mm (2 inch) long right angle bracket mounted to a digital torque wrench.

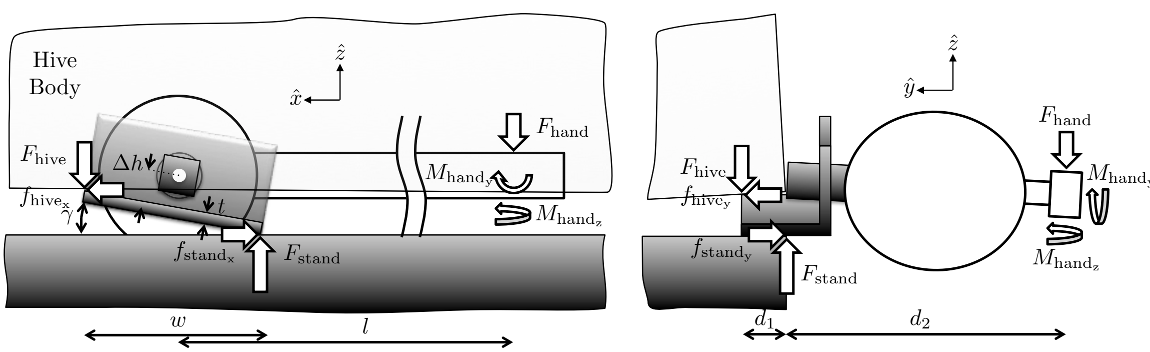


Fig. 5.5. Free body diagram of a TWB mechanism.

the torque wrench. Eq. (5.18) shows a linearized, first order error analysis considering all of these sources of error.

$$F_{g_{\text{est}}} \approx F_{g_{\text{act}}} \cdot (1 + \epsilon_{\text{center}} + \epsilon_{\text{shim}} + \epsilon_{\text{contact}} + \epsilon_{\text{incline}} + \epsilon_{\text{lift}} + \epsilon_{\text{bracket}} + \epsilon_{\text{handle}} + \epsilon_{\text{sensor}}) \tag{5.18}$$

The errors $\epsilon_{\text{bracket}}$ and ϵ_{handle} can be estimated, and it can be shown that they can constrain each other due to friction. Fig. 5.5 shows a TWB free body diagram. Important is that due to the location of the torque wrench axle, the vertical force on the handle affects the torque reading. A vertical force balance shows that unless F_{hand} is nonzero, the reaction force F_{stand} does not equal F_{hive}.

$$F_{\text{stand}} = F_{\text{hive}} + F_{\text{hand}} \tag{5.19}$$

To gauge the error ϵ_{handle} due to F_{hand} it is first useful to fully define the actual torque T_{act} about the torque wrench center. This process also shows the error $\epsilon_{\text{bracket}}$

due to friction and the angle of the bracket.

$$
\begin{aligned}
T_{\text{act}} = F_{\text{hive}} \cdot (\tfrac{w}{2}\cos\gamma - \tfrac{t}{2}\sin\gamma + \Delta h \sin\gamma) \\
+ F_{\text{stand}} \cdot (\tfrac{w}{2}\cos\gamma - \tfrac{t}{2}\sin\gamma - \Delta h \sin\gamma) \\
\pm f_{\text{hive}_\text{x}} \cdot (\tfrac{w}{2}\sin\gamma + \tfrac{t}{2}\cos\gamma - \Delta h \cos\gamma) \\
\pm f_{\text{stand}_\text{x}} \cdot (\tfrac{w}{2}\sin\gamma + \tfrac{t}{2}\cos\gamma + \Delta h \cos\gamma)
\end{aligned}
\tag{5.20}
$$

If there is no horizontal force applied on the torque wrench by the hand, $f_{\text{hive}} = f_{\text{stand}}$. If the hand pushes downward, then $F_{\text{hive}} \leq F_{\text{stand}}$, and so the frictional forces are limited by F_{hive} for a given coefficient of friction μ_{bracket}.

$$
\sqrt{f_{\text{hive}_\text{x}}^2 + f_{\text{hive}_\text{y}}^2} = |f_{\text{hive}}| \leq \mu_{\text{bracket}} \cdot F_{\text{hive}} \tag{5.21}
$$

$$
|f_{\text{hive}_\text{x}}| = |f_{\text{stand}_\text{x}}| \leq \mu_{\text{bracket}} \cdot F_{\text{hive}} \tag{5.22}
$$

Eq. (5.20) simplifies by using Eq. (5.19) and treating Eq. (5.22) as limiting equalities:

$$
\begin{aligned}
T_{\text{act}} &= F_{\text{hive}} \cdot (\tfrac{w}{2}\cos\gamma - \tfrac{t}{2}\sin\gamma + \Delta h \sin\gamma \pm \mu_{\text{bracket}} \cdot (w \sin\gamma + t\cos\gamma)) \\
&\quad + (F_{\text{hive}} + F_{\text{hand}})(\tfrac{w}{2}\cos\gamma - \tfrac{t}{2}\sin\gamma - \Delta h \sin\gamma) \\
T_{\text{act}} &= F_{\text{hive}} \cdot w\Big(\underbrace{\cos\gamma - \tfrac{t}{w}\sin\gamma \pm \mu_{\text{bracket}} \cdot (\sin\gamma + \tfrac{t}{w}\cos\gamma)}_{1+\epsilon_{\text{bracket}}} \\
&\quad + \underbrace{\tfrac{F_{\text{hand}}}{F_{\text{hive}}}(\tfrac{1}{2}\cos\gamma - \tfrac{t}{2w}\sin\gamma - \tfrac{\Delta h}{w}\sin\gamma)}_{\epsilon_{\text{handle}}}\Big)
\end{aligned}
\tag{5.23}
$$

Eq. (5.23) shows two error sources: 1) $\epsilon_{\text{bracket}}$ - the error from the projected width of the bracket and torque due to friction and 2) ϵ_{handle} - the error due to a net vertical force on the handle. Note that in practice, the human operator skill element required is the most difficult to model and control.

The potential ranges of $\epsilon_{\text{bracket}}$ are shown in Fig. 5.6 for different bracket coefficients of friction, thicknesses, and lengths. Importantly, $\epsilon_{\text{bracket}}$ is an unrepeatable error as it varies depending on the direction of f_{hive_x}. μ_{bracket} was measured as about

0.4 by placing a metal bracket on a tilted slab of smooth pine. For $\mu = .4$, $t = 3.18$ mm (0.125 inches), and $w = 5.08$ cm (2 inches), $\epsilon_{\text{bracket}}$ can potentially range from -13.0% to 7.0% for 1.27 cm (.5 inch) total elevation. Even lifting just enough to fit the 3.2 mm (eighth inch) bracket underneath the hive yields $\epsilon_{\text{bracket}} = \pm 2.5\%$. Decreasing μ_{bracket}, decreasing t, and increasing w can help reduce $\epsilon_{\text{bracket}}$.

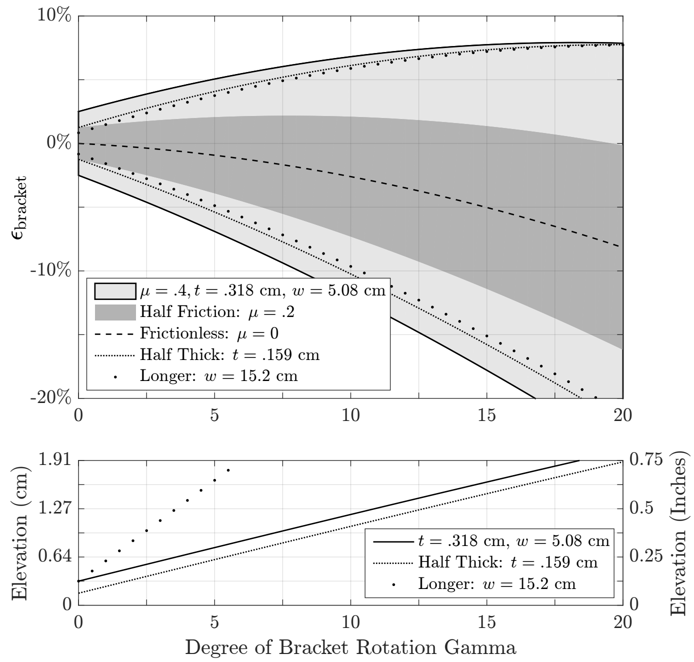


Fig. 5.6. Maximum ranges of $\epsilon_{\text{bracket}}$ with different coefficients of friction, thicknesses, and widths. Decreasing μ_{bracket}, decreasing t, and increasing w can limit $\epsilon_{\text{bracket}}$.

ϵ_{handle} from Eq. (5.23) can be further defined by isolating the ratio $\frac{F_{\text{hand}}}{F_{\text{hive}}}$. A torque balance in $\hat{y}$ about where the bracket touches the stand yields:

$$\begin{aligned} 0 = f_{\text{hive}_\text{x}} \cdot (t\cos\gamma + w\sin\gamma) + F_{\text{hive}} \cdot (-t\sin\gamma + w\cos\gamma) \\ - F_{\text{hand}} \cdot (l - \tfrac{w}{2}\cos\gamma + \tfrac{t}{2}\sin\gamma + \Delta h\sin\gamma) - M_{\text{hand}_\text{y}} \end{aligned} \tag{5.24}$$

Using Eq. (5.22) to replace f_{hive_x} and solving yields:

$$\frac{F_{\text{hand}}}{F_{\text{hive}}} = \frac{-t\sin\gamma + w\cos\gamma \pm \mu_{\text{bracket}}(t\cos\gamma + w\sin\gamma) - \frac{M_{\text{hand}_\text{y}}}{F_{\text{hive}}}}{l - \frac{w}{2}\cos\gamma + \frac{t}{2}\sin\gamma + \Delta h\sin\gamma} \tag{5.25}$$

If γ is very small, then ϵ_{handle} from Eq. (5.23) with Eq. (5.25) yields:

$$\epsilon_{\text{handle}} \approx \frac{w \pm t \cdot \mu_{\text{bracket}} - \frac{M_{\text{hand}_y}}{F_{\text{hive}}}}{l - \frac{w}{2}} \frac{1}{2} \tag{5.26}$$

Eq. (5.26) suggests that if no handle moment M_{hand_y} is applied, ϵ_{handle} could be as much as 20.5%. Fortunately, the current design encourages the user to apply at least some moment as the metal bracket rotates backward if too much downward force from F_{hand} is applied. This can be shown from Fig. 5.5 right. A torque balance (including friction) about the edge of the hive along $\hat{x}$ suggests that in order to avoid tipping:

$$\frac{d_1 + (t \cos\gamma + w \sin\gamma) \cdot \mu_{\text{bracket}}}{d_2} \geq \frac{F_{\text{hand}}}{F_{\text{hive}}} \tag{5.27}$$

Thus the maximum error due to ϵ_{handle} based on Eqs. (5.23) and (5.27) is given as:

$$|\epsilon_{\text{handle}}| \leq \frac{d_1 + (t \cos\gamma + w \sin\gamma) \cdot \mu_{\text{bracket}}}{d_2} \cdot \left(\tfrac{1}{2} \cos\gamma - \tfrac{t}{2w} \sin\gamma - \tfrac{\Delta h}{w} \sin\gamma\right) \tag{5.28}$$

For $d_1 = 1.27$ cm (.5 inches), $d_2 = 10.2$ cm (4 inches), $t = 3.18$ mm (.125 inches), and $\mu = .4$, Eq. (5.28) limits ϵ_{handle} at 6.9% for $\gamma = 0$

Since f_{hive_x} limits $\epsilon_{\text{bracket}}$ and f_{hive_y} limits ϵ_{handle}, the errors $\epsilon_{\text{bracket}}$ and ϵ_{handle} are not independent and limit each other. Coupling the equation for $\epsilon_{\text{bracket}}$ in Eq. (5.23) and the tipping constraint from Eq. (5.28) that limits ϵ_{handle}, it is possible to derive the maximum and minimum possible error ranges of these errors for different bracket angles γ.[2] Assuming M_{hand_y} and F_{hand} are nonnegative, $\epsilon_{\text{bracket}} + \epsilon_{\text{handle}}$ can range from:

- For $\gamma = 0$ $(-2.5\% + 0\%)$ to $(2.4\% + 6.4\%$, $\beta = 14.04 = -2.5\%$ to 8.8%
- For $\gamma = 10.87$ $(-13.0\% + 0\%)$ to $(6.8\% + 6.0\%$, $\beta = 12.51 = -13.0\%$ to 12.8%

[2] μ_{bracket} is replaced by $\mu_{\text{bracket}} \cdot \cos\beta$ in Eq. (5.23) and $\mu_{\text{bracket}} \cdot \sin\beta$ in Eq. (5.28) where β is an angle in the x-y plane that describes the direction of f_{hive}. β is optimized to maximize the sum of $\epsilon_{\text{bracket}}$ and ϵ_{handle} for any given bracket angle γ. M_{hand_z} is used to maintain a torque balance in $\hat{z}$ and no hand moment is assumed about the wrench in $\hat{x}$.

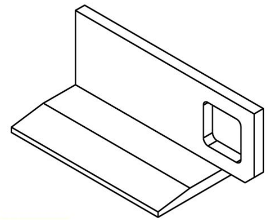


Fig. 5.7. An improved design of the bracket. This design centers the torque wrench over the fulcrum to essentially eliminate ϵ_{handle} and the front taper encourages contact at the edge of the hive to reduce $\epsilon_{\text{contact}}$.

Note that the total elevation is 12.7 mm (0.5 inches) when $\gamma = 10.87$ and this case will be used in the final analysis.

The last error considered here is ϵ_{sensor}. For the analysis here ϵ_{sensor} will be $\pm 2\%$ of the reading.

One way to greatly reduce ϵ_{handle} and $\epsilon_{\text{contact}}$ is with the design change shown in Fig. 5.7. By shifting the torque wrench axis to the lower pivot, F_{stand} and thus F_{hand} does not affect the measured torque for small bracket angles. If the torque wrench hole remains centered, a T-handle wrench is recommended that encourages the user to apply more of a pure torque and avoid a net vertical force component that would contribute to ϵ_{handle}.

Future analysis could consider deformation of the wood under concentrated loads and effects of holding the bracket non-level. Note that $\epsilon_{\text{contact}}$ can be very sensitive to the angle at which the bracket is held. If friction could be greatly reduced - perhaps by using a rolling element (e.g., needle bearings) - then using involute shapes on the opposing side could be beneficial to essentially eliminate $\epsilon_{\text{bracket}}$.

5.5.3 Leveraged Pull Mechanism

One design shown in Fig. 5.8 uses a lever to slightly lift one side of the hive [9]. The general equation is to multiply the scale's reading by two to get the weight:

$$F_{\text{gest}} \approx 2 \cdot F_{\text{pull}} \tag{5.29}$$

Eq. (5.29) also shows that the maximum weight measurable is twice that of the

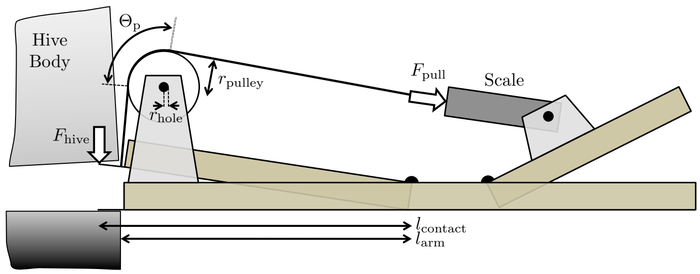


Fig. 5.8. Leveraged tilt and lift design with selected forces labelled. In this design the user can use a commercially available handheld luggage scale to help weigh the hive. A number of sources of error exist including the difference between l_{arm} and $l_{contact}$ and friction in the pulley.

scale. The most readily available and cheapest scales are luggage scales that are usually rated to 50 kg (110 lb). For these scales the hive can only be measured up to 100 kg (220 lb).

This general equation can be improved to account for other sources of error. As a half lift mechanism, there can exist ϵ_{center}, ϵ_{shim}, $\epsilon_{contact}$, $\epsilon_{incline}$, and ϵ_{lift}. Additionally there are the errors ϵ_{arm} due to F_{hive} applied away from the wire, ϵ_{pulley} due to friction in the pulley, and ϵ_{sensor}. A linearized equation accounting for these errors is

$$F_{g_{est}} \approx F_{g_{act}} \cdot (1 + \epsilon_{center} + \epsilon_{shim} + \epsilon_{contact} + \epsilon_{incline} + \epsilon_{lift} + \epsilon_{arm} + \epsilon_{pulley} + \epsilon_{sensor}) \tag{5.30}$$

ϵ_{arm} and ϵ_{pulley} can be further defined:

$$\epsilon_{arm} \equiv \frac{l_{contact}}{l_{arm}} - 1 \tag{5.31}$$

$$\epsilon_{pulley} \approx \pm \frac{r_{hole}}{r_{pulley}} \cdot \mu_{axle} \cdot \sqrt{2} \tag{5.32}$$

The derivation for ϵ_{arm} in Eq. (5.31) is from a torque balance about the hinge assuming vertical forces. If l_{arm} is 15.2 cm (6 inches) and $l_{contact}$ is 16.5 cm (6.5 inches), then $\epsilon_{arm} \approx 8.3\%$.

Eq. (5.32) for ϵ_{pulley} assumes that $\zeta \equiv \frac{r_{hole}^2 \mu_{axle}^2}{r_{pulley}^2 (1+\mu_{axle}^2)}$ is small. For wrapping around the pulley an angle Θ_p, a full derivation given in Appendix 5.A yields the following

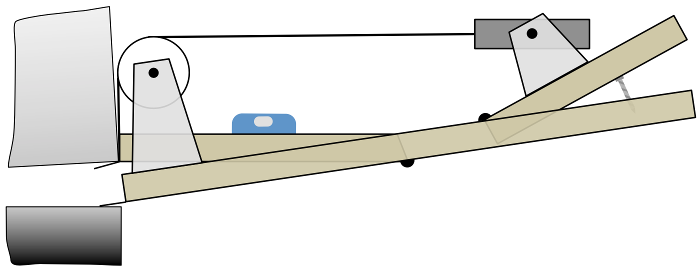


Fig. 5.9. Leveraged lift design with a number of subtle improvements. The upper lip that lifts the hive is angled slightly downward so the hive makes contact as close as possible to the wire. The hinge for the left arm has also been moved to the base. This hinge placement allows ignoring friction from the hive. Additionally a level is added to the upper arm as this is the arm that should be level during reading. A screw is added to increase repeatability.

for ϵ_{pulley}:

$$\epsilon_{\text{pulley}} = \frac{\zeta(1-\cos\Theta_{\text{p}}) \pm \sqrt{\zeta}\cdot\sqrt{2-2\cos\Theta_{\text{p}}+\zeta\cos^2\Theta_{\text{p}}-\zeta}}{1-\zeta} \tag{5.33}$$

Eq. (5.33) for $r_{\text{hole}} = 3.2$ mm (.125 inches), $r_{\text{pulley}} = 25.4$ mm (1 inch), $\mu_{\text{pulley}} = 0.2$, and $\Theta_{\text{p}} = 90$ $\epsilon_{\text{pulley}} \approx 3.5\%$ (also 3.5% by the approximate Eq. (5.32)). Note importantly that the friction can change direction if the hive is being raised or lowered, and so just the friction in the pulley can give about 7% change in the reading.

To mitigate ϵ_{arm}, the design can be modified to have a lip bent down as in Fig. 5.9. The bent down lip helps l_{arm} to be very close to l_{contact}. To mitigate ϵ_{pulley} bearings can be used.

Other sources of error can include the slight vertical misalignment of the device when applying forces, the slight misalignment of the pulley not pulling directly perpendicular to the arm, and the slight misalignment of scale as it may sag slightly due to gravity if not pivoted about its center. All of these scale with the cosine of the corresponding angle and thus tend to be small. $1-\cos(10 = 1.5\%$ and $1-\cos(5 = 0.38\%$. Another potential source of error is extra torque due to friction between the lip and the hive. The improved design shown in Fig. 5.9 tries to reduce these other error sources.

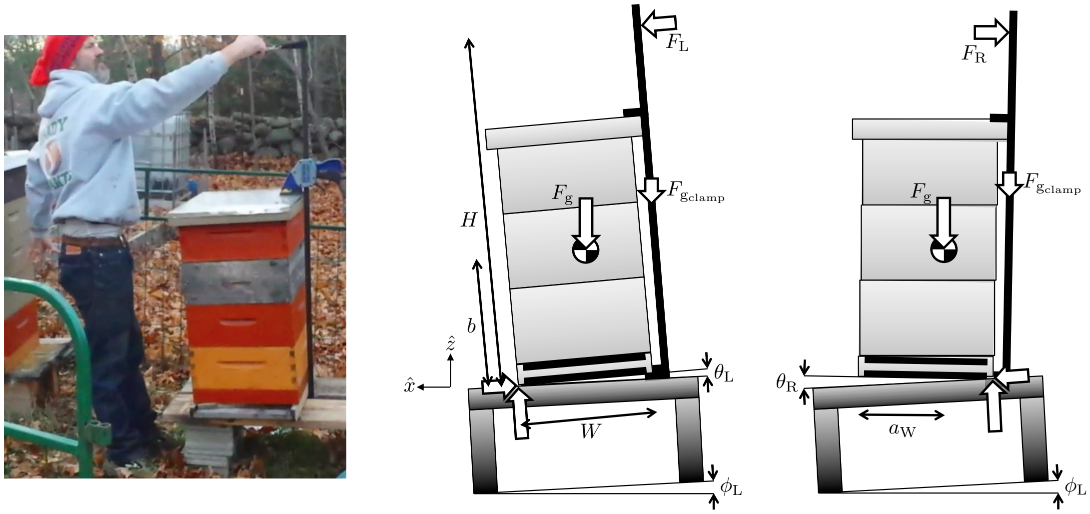


Fig. 5.10. Top pull mechanism with clamp to prevent box slipping.

5.6 Top Pull Mechanism (TP)

To reduce some of the inherent errors of half lift mechanisms, eliminate the need for shims, and avoid bending down by the beekeeper, presented here is a new hive weight measurement mechanism shown in Fig. 5.10.[3] This mechanism uses a lateral force applied at the top of the hive to slightly tilt the hive and then a torque balance relation is used to infer the hive weight. Accuracy is obtained by taking a measurement from each side of the hive and averaging the results.

Testing and analysis (given in Appendix 5.B) showed that to keep the hive boxes from separating, a clamp was typically necessary. The clamp also provided a way to secure the force sensor consistently at a known height H.

In practice, the TP mechanism works best with a hive stand this is significantly wider than the hive base to prevent the hive stand from rotating with the hive. Optionally the stand may have a gap to fit the clamp underneath the hive. Otherwise, it is okay to nudge the hive forward or backward on the hive stand to provide a slight overhang to clamp onto the base. The beekeeper must make sure that the hive stand and boxes can endure the concentrated forces from the clamp and that the hive stand will not move or give out when the hive is slightly tilted.

[3]Provisional patent pending.

The basic approximation for estimating the hive weight is:

$$F_{\text{gest}} \approx 2F_{\text{Lmeas}} \frac{H_{\text{meas}}}{W_{\text{meas}}} \tag{5.34}$$

Eq. (5.34) can be improved to account for errors due to uncentered mass, inclination, lift, measurement of the height and width, obliquely applying the lateral force, and the sensor. Note that ϵ_{shim} and $\epsilon_{\text{contact}}$ do not exist for the top pull mechanism with the assumption the flat stand is wider than the hive. New error terms are defined:

$$\epsilon_{\text{height}} \equiv \frac{H_{\text{meas}}}{H_{act}} - 1 \tag{5.35}$$

$$\epsilon_{\text{width}} \equiv 1 - \frac{W_{\text{meas}}}{W_{\text{act}}} \tag{5.36}$$

$$\epsilon_{\text{oblique}} \equiv \text{left: } \delta_{\text{L}}^2 - \frac{W_{\text{meas}}}{H_{\text{meas}}} \cdot \delta_{L_{xz}}, \text{ right: } \delta_{\text{R}}^2, \text{ avg: } \frac{1}{2}(\delta_{\text{L}}^2 + \delta_{\text{R}}^2 - \frac{W_{\text{meas}}}{H_{\text{meas}}} \cdot \delta_{L_{xz}}) \tag{5.37}$$

For the oblique error due to the lateral force, δ_{L} includes the angle out of the page whereas $\delta_{\text{L}_{\text{xz}}}$ is projected onto the x-z plane.

Lastly, the clamp adds a slight bit of extra weight. Fortunately, this can be subtracted from the measured weight. Designing the clamp such that its weight is an integer value can make the math for the beekeeper easier. The clamp can remain in place for both side measurements, saving time and reducing error due to the clamp's horizontal position. Other second order errors due to the weight of the clamp are considered small.

The final mostly linearized equations for the clamped TP mechanism as shown in

Fig. 5.10 are:

$$\text{Top Pull Left: } F_{g_{est}} \approx F_{g_{act}} \cdot (1 + \epsilon_{center} + \epsilon_{incline} + \epsilon_{lift} + \epsilon_{height} + \epsilon_{width} + \epsilon_{oblique} + \epsilon_{sensor}) + 2F_{g_{clamp}} \tag{5.38}$$

$$\text{Top Pull Right: } F_{g_{est}} \approx F_{g_{act}} \cdot (1 + \epsilon_{center} + \epsilon_{incline} + \epsilon_{lift} + \epsilon_{height} + \epsilon_{width} + \epsilon_{oblique} + \epsilon_{sensor}) \tag{5.39}$$

$$\text{Top Pull Avg: } F_{g_{est}} \approx F_{g_{act}} \cdot (1 + \epsilon_{lift} + \epsilon_{height} + \epsilon_{width} + \epsilon_{oblique} + \epsilon_{sensor}) + F_{g_{clamp}} \tag{5.40}$$

Taking the average of the measurements from each side of the hive cancels error due to ϵ_{center} and $\epsilon_{incline}$ and the weight of the clamp can be subtracted off.

The magnitude of the error terms can be evaluated. For 9.5 mm (3/8th inch) max total lift, ϵ_{lift} could range from -2.8% to 0%. If W_{meas} and H_{meas} are within 3.2 mm (.125 inches) of their actual value, $W = 41.3$ cm (16.25 inches), and $H = 1.03$ m (40.6 inches), then ϵ_{width} is bounded at ±0.8% and ϵ_{height} at ±0.3%. H can be intentionally set at 1.03 m (40.6 inches) so that H is 2.5 times W and thus $F_{g_{est}}$ is calculated as five times the lateral force. If it is assumed the maximum angle δ is 5%, $\epsilon_{oblique}$ can range from -1.4% to 2.5% for averaging from both sides. ϵ_{sensor} will again be approximated at ±2%.

The reading will be greatest when the hive just lifts off the ground, minimizing the effect of ϵ_{lift} and improving repeatability. ϵ_{width} and ϵ_{height} are also repeatable. $\epsilon_{oblique}$ could affect repeatability, but can be improved by providing a longer wire between the sensor and the clamp as well as a 90 reference off of the clamp.

5.7 Overall Comparison

Fig. 5.11 compares the maximum error ranges of four hive weight mechanisms: direct measurement by load cells (DM), torque wrench and bracket (TWB), leveraged pull (PM), and top pull (TP). DM has the lowest overall total error bounds: -2.4% to 2%. These error bounds are well within the functional requirement from Section 5.2

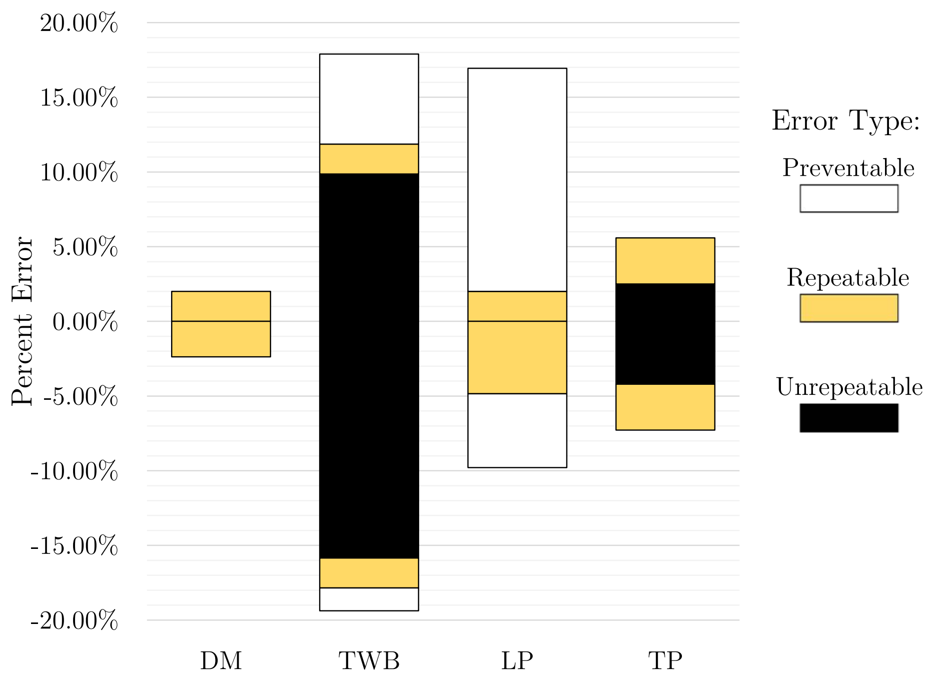


Fig. 5.11. The potential maximum errors for hive weight scale mechanisms. The TWB and LP mechanism include the half lift errors for averaging measurements from both sides.

of 5% accuracy. As ϵ_{sensor} is considered repeatable for all the mechanisms, DM only has repeatable errors, and thus can detect 1.4 kg (3 lb) swarms.

The two half lift mechanisms, TWB and LP, are both considered in Fig. 5.11 for taking measurements from both sides and averaging. Measuring from just the back would minimally affect repeatability, but the total error bounds would expand an additional -12.5% and +9.2%.

The TWB mechanism has the largest potential error bounds and most of the error is unrepeatable. Significant user skill is needed to mitigate the unrepeatable errors due to $\epsilon_{\text{contact}}$, ϵ_{lift}, and $\epsilon_{\text{bracket}}$ that together span about 25%. ϵ_{shim} and ϵ_{handle} are considered preventable. TWB is the smallest and thus most portable mechanism considered.

With design improvements the LP mechanism is the second most accurate weight mechanism with total error bounds of -4.8% to 2%. ϵ_{shim}, $\epsilon_{\text{contact}}$, ϵ_{arm}, and ϵ_{pulley} are all considered preventable. In addition, ϵ_{lift} is considered repeatable as a specific lift height is easy to repeat with the LP mechanism. As all of the non-preventable errors are repeatable, the LP mechanism could be precise enough to detect swarms. LP requires shims or slight hive modification but should be compatible with nearly all hives.

The TP mechanism has total error bounds of -7.3% to 5.6% with unrepeatable errors spanning 6.2%. User skill is needed to carefully limit $\epsilon_{\text{oblique}}$ and ϵ_{lift} that are considered unrepeatable. While TP avoids shims and bending over to take measurements, TP requires wider and sturdier platform hive stands to support lateral forces.

In summary, DM is best for permanent measurement systems. For portable measurement systems, LP is the best candidate followed by TP. LP, however, requires design improvements to achieve the desired accuracy and precision.

Acknowledgement

This work was sponsored by the MIT Tata Center for Technology and Design and the MIT Department of Mechanical Engineering.

Appendix

Contents

Appendix 5.A Efficiency of a Pulley Without Bearings

Pulleys tend to have some loses due to friction. Fig. 5.12 shows four forces: F_1, F_2, a normal force N, and a frictional force f. The pulley's inner hole and axle are assumed to have minimal deformation and different sizes such that they may have only one contact point.

It is desired to know the maximum possible ratio or efficiency $\frac{F_2}{F_1}$. The following

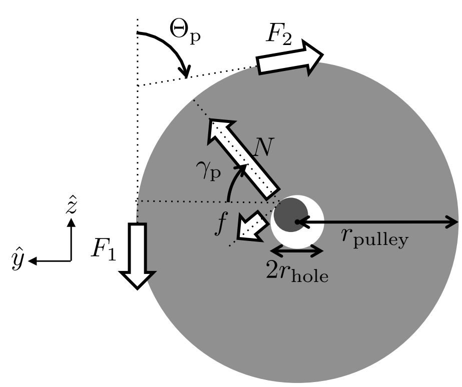


Fig. 5.12. A schematic of a pulley without bearings on a solid axle.

are known: r_{pulley}, r_{hole}, friction coefficient μ_{axle}, and Θ_{p}. If forces are engaged such that F_2 is increased gradually up to the limit of static friction, then the following are true for static equilibrium:

$$\text{Horizontal Forces: } f \sin\gamma_{\text{p}} + N\cos\gamma_{\text{p}} - F_2 \sin\Theta_{\text{p}} = 0 \tag{5.41}$$

$$\text{Vertical Forces: } -f\cos\gamma_{\text{p}} + N\sin\gamma_{\text{p}} + F_2\cos\Theta_{\text{p}} - F_1 = 0 \tag{5.42}$$

$$\text{Torque Balance: } F_2 \cdot r_{\text{pulley}} - F_1 \cdot r_{\text{pulley}} - f \cdot r_{\text{hole}} = 0 \tag{5.43}$$

$$\text{Friction: } f = \mu_{\text{axle}} \cdot N \tag{5.44}$$

Substituting Eq. (5.44) in Eqs. (5.41) and (5.42) yields:

$$N(\mu_{\text{axle}}\sin\gamma_{\text{p}} + \cos\gamma_{\text{p}}) = F_2\sin\Theta_{\text{p}} \tag{5.45}$$

$$N(-\mu_{\text{axle}}\cos\gamma_{\text{p}} + \sin\gamma_{\text{p}}) = -F_2\cos\Theta_{\text{p}} + F_1 \tag{5.46}$$

Squaring both sides of Eqs. (5.45) and (5.46) and adding yields:

$$N^2(\mu_{\text{axle}}^2\sin^2\gamma_{\text{p}} + 2\mu_{\text{axle}}\sin\gamma_{\text{p}}\cos\gamma_{\text{p}} + \cos^2\gamma_{\text{p}}) = F_2^2\sin^2\Theta_{\text{p}}$$

$$N^2(\mu_{\text{axle}}^2\cos^2\gamma_{\text{p}} - 2\mu_{\text{axle}}\sin\gamma_{\text{p}}\cos\gamma_{\text{p}} + \sin^2\gamma_{\text{p}}) = F_2^2\cos^2\Theta_{\text{p}} - 2F_2F_1\cos\Theta_{\text{p}} + F_1^2$$

$$N^2(\mu_{\text{axle}}^2 + 1) = F_2^2 - 2F_1F_2\cos\Theta_{\text{p}} + F_1^2 \tag{5.47}$$

Substituting Eq. (5.44) into Eq. (5.43) yields:

$$N = (F_2 - F_1)\frac{r_{\text{pulley}}}{r_{\text{hole}}\mu_{\text{axle}}} \tag{5.48}$$

Combining Eqs. (5.47) and (5.48) yields:

$$(F_2 - F_1)^2\frac{r_{\text{pulley}}^2(\mu_{\text{axle}}^2 + 1)}{r_{\text{hole}}^2\mu_{\text{axle}}^2} = F_2^2 - 2F_1F_2\cos\Theta_{\text{p}} + F_1^2 \tag{5.49}$$

Dividing by F_1^2 and using a new variable ζ for brevity:

$$\left(\frac{F_2}{F_1}-1\right)^2 = \underbrace{\left(\frac{r_{\text{hole}}^2\mu_{\text{axle}}^2}{r_{\text{pulley}}^2(\mu_{\text{axle}}^2+1)}\right)}_{\zeta}\left(\left(\frac{F_2}{F_1}\right)^2 - 2\frac{F_2}{F_1}\cos\Theta_{\text{p}}+1\right) \tag{5.50}$$

$$\left(\frac{F_2}{F_1}\right)^2(1-\zeta)+\frac{F_2}{F_1}(-2+2\zeta\cos\Theta_{\text{p}})+(1-\zeta)=0 \tag{5.51}$$

By the quadratic equation then:

$$\frac{F_2}{F_1} = \frac{2-2\zeta\cos\Theta_{\text{p}} \pm \sqrt{(-2+2\zeta\cos\Theta_{\text{p}})^2-4(1-\zeta)^2}}{2(1-\zeta)}$$

$$\frac{F_2}{F_1} = \frac{1-\zeta\cos\Theta_{\text{p}} \pm \sqrt{(-1+\zeta\cos\Theta_{\text{p}})^2-(1-\zeta)^2}}{1-\zeta}$$

$$\frac{F_2}{F_1} = \frac{1-\zeta\cos\Theta_{\text{p}} \pm \sqrt{1-2\zeta\cos\Theta_{\text{p}}+\zeta^2\cos^2\Theta_{\text{p}}-1+2\zeta-\zeta^2}}{1-\zeta}$$

$$\frac{F_2}{F_1} = \frac{1-\zeta\cos\Theta_{\text{p}} \pm \sqrt{\zeta}\sqrt{2-2\cos\Theta_{\text{p}}+\zeta\cos^2\Theta_{\text{p}}-\zeta}}{1-\zeta} \tag{5.52}$$

Eq. (5.52) gives the bounds of the ratio $\frac{F_2}{F_1}$. As a check, the inverse of Eq. (5.52) with opposite sign can be shown to give back Eq. (5.52).

For $\Theta_{\text{p}} = 90$ nd small ζ (meaning a large difference in radii and low μ_{axle}), Eq. (5.52) reduces to:

$$\frac{F_2}{F_1} \approx 1 \pm \sqrt{\zeta}\sqrt{2} \approx 1 \pm \frac{r_{\text{hole}}\mu_{\text{axle}}}{r_{\text{pulley}}}\sqrt{2} \tag{5.53}$$

If ϵ_{pulley} is defined as $\frac{F_2}{F_1}-1$, then Eq. (5.52) and Eq. (5.53) yield Eq. (5.33) and Eq. (5.32).

Appendix 5.B Top Pull Method Without Clamp

Fig. 5.13 shows a top pull mechanism where additional vertical forces F_1 and F_2 are used to try to keep the top box from sliding or independently rotating when lateral forces F_{L} or F_{R} are applied. Ideally propolis would secure the boxes together, but

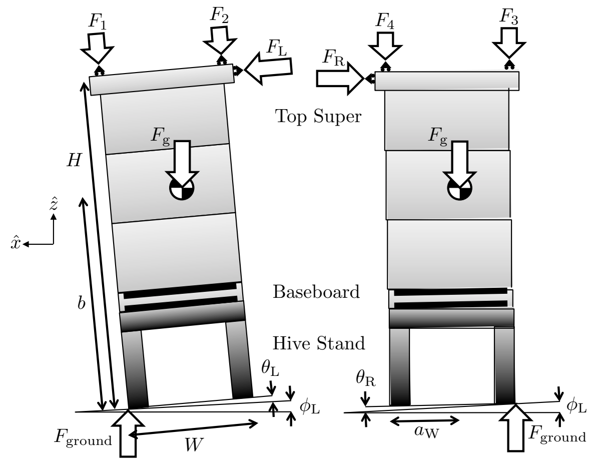


Fig. 5.13. This top pull mechanism tries to use vertically applied forces F_1 and F_2 to keep the hive boxes together when a lateral force F_L or F_R is applied.

initial testing showed the propolis often broke and large vertical forces were needed to keep the hive boxes together. The needed magnitude of these vertical forces can be estimated. For centered honey and minimal inclination, there are four constraints that must be satisfied:

$$\text{Sufficient Torque: } F_L = \frac{1}{H}(F_2 \cdot W + m \cdot g \cdot \frac{W}{2}) \tag{5.54}$$

$$\text{No Slipping (Top Box): } F_L \leq \mu_{box}(F_1 + F_2 + m_{top} \cdot g) \tag{5.55}$$

$$\text{No Rotating (Top Box): } F_L \leq \frac{1}{H_{top}}(F_2 \cdot W + m_{top} \cdot g \cdot \frac{W}{2}) \tag{5.56}$$

$$\text{No Slipping (Ground) [usu. inactive]: } F_L \leq \mu_{ground}(F_1 + F_2 + F_g) \tag{5.57}$$

Using Eqs. (5.54) to (5.56), it is possible to get a feel for if F_1 and F_2 are needed to keep the boxes from separating. Fig. 5.14 shows the values of F_1 and F_2 needed to prevent slipping and rotating for different coefficients of friction. In lab, μ_{box} was about .38 for static friction and .24 for kinetic friction. For safety reasons, the boxes should not separate even for kinetic friction. For $\mu_{box} = .25$, Fig. 5.14 shows F_1 needs to be almost 900 N (202 lbs). As the needed force F_1 is so large, it is only safe to require other methods such as straps, latches, or a clamp to keep the boxes together.

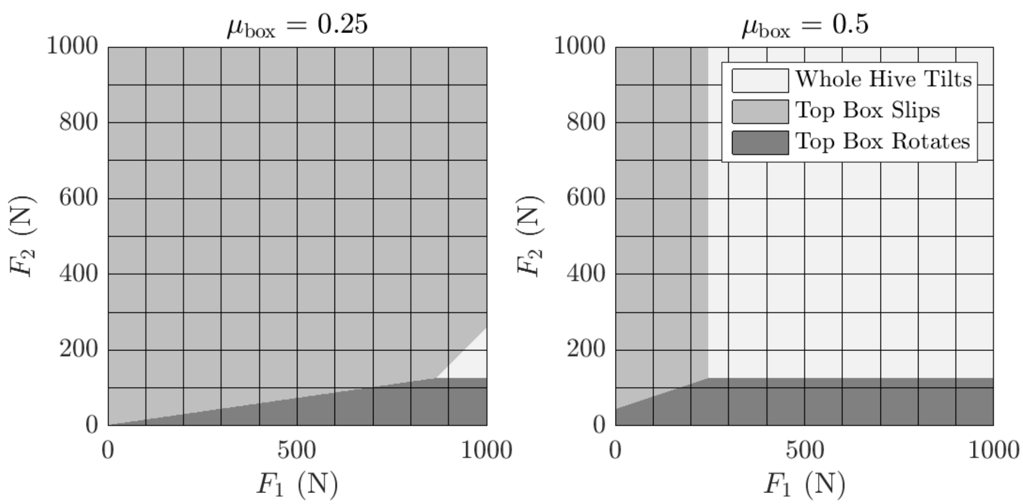


Fig. 5.14. Unclamped hives may have the top box slip or tilt. These plots show the top forces F_1 and F_2 needed to prevent the boxes from separating for an unclamped unpropolised hive with constant density, a mass of 100 kg (220 lbs), a width of 41.3 cm (16.25 inches), a total height of 82.6 cm (32.5 inches), and a top box height of 20.6 cm (8.125 inches).

Chapter 6

Hive Ventilation

Contents

Hive ventilation is a "buzz word" among beekeepers. Beekeepers know that ventilation affects how bees maintain the internal temperatures of hives. In addition, it is generally agreed upon that if it is easier for bees to maintain their ideal inside hive temperature, then the bees can devote more effort to making honey. This chapter briefly explains 1) the key ways in which bees thermoregulate their hives, 2) why there is a limit to which bees can cool hives, and 3) what makes for good hive ventilation for hot and humid regions.

6.1 Ways Bees Can Thermoregulate Their Hives

It is well known that bees work to keep the brood chamber somewhere between 33°C and 36°C [42]. This is important for brood development and should be maintained regardless of outside conditions. In addition, ideally the humidity should stay about 75-85% relative humidity [2], although sometimes other humidities may be better to prevent mold [28, p. 24] or chilling effects in winter.

Bees employ a number of mechanisms to help thermoregulate their hives. Bees can affect the thermodynamics of a hive by:

- Gathering water that can be evaporated [79]
- Fanning to increase air flow or help evaporate water [79, p. 85]
- Vibrating or changing behavior to change heat generation [79, p. 85]
- Bearding or leaving the hive to help decrease heat generation in the hive
- Changing the inside density of the bees [58]
- Foraging for nectar high in water content
- Capping honey cells that otherwise would assist in evaporation
- Sealing or expanding hive openings
- Heat shielding where bees absorb localized heat and then move to release it [70]
- Building and filling comb
- Limiting air exchange until external conditions improve

Many of these mechanisms require extra work on the part of bees and may add additional stress. For this reason, beekeepers have done a number of things to try to help their hives. This includes:

- Changing the entrance sizes
- Adding or removing entrance openings
- Uses entrances with mesh openings
- Adding a water source nearby
- Using a screened bottom board

- Adding insulation or extra layers around a hive
- Placing hives in sunny or shady locations

Many of the topics in this thesis such as entrances and hive roofs are motivated by determining what are the best things beekeepers can do to a hive to promote better hive ventilation and ultimately help bees.

6.2 The Limit to Cooling Hives

Despite the many mechanisms to affect hive temperature, bees have a thermodynamic limit to which they can cool hives. This is important because it makes proper beekeeper actions even more important, especially for hot and humid regions in much of India.

The mechanisms to promote the thermoregulation of hives can be reduced to the following four heat energy sources or transfers:

- Changing internal heat generation
- Changing water evaporation: phase change
- Changing heat exchange through the air: mass transfer with inside convection
- Changing heat exchange through the walls: conduction to the outside of the hive

These four sources / transfers are shown in Figs. 6.1 to 6.3 which are adapted from [78] made by Israel Urieli and released under an Attribution-Noncommercial-Share Alike 3.0 United States license.

The system is a control volume of the air inside of the hive with an effective single average or characteristic temperature. The arrow for heat generation is directed rightward, representing adding thermal energy. The arrow for evaporation is diagonally up left along the lines of constant enthalpy. Evaporation is limited as only so much water can be added to air before the air is saturated at 100% relative humidity. For this reason, the arrow is drawn only as far as the 100% relative humidity line. The heat (and mass) exchange with the outside through air is shown with an arrow from the inside conditions to the outside conditions. The heat transfer through conduction through the hive exterior is lastly shown either to the left or to the right from the inside conditions to the exterior temperature. The arrows represent the "direction" of sources, sinks, or transfers of the heat energy. The arrow lengths represent the maximum change for a small mass element and not the actual magnitude of heat or moisture transfer. For static conditions, the sources, sinks, and transfers must balance in sensible heat energy (horizontally) as well as water content (vertically).

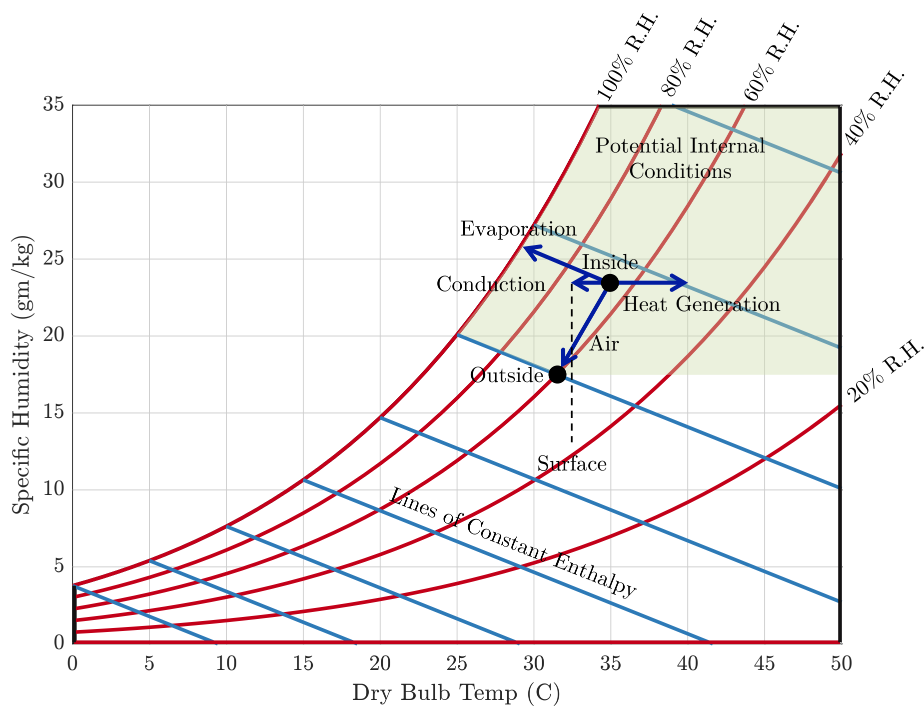


Fig. 6.1. Psychrometric chart: cool conditions.

Fig. 6.1 shows how on cool days with low humidity, the exchange of air with the outside can be beneficial and heat generation is tolerable to maintain the ideal temperature and humidity. Here, the surface temperature is shown as slightly cooler than the inside hive temperature and so heat exchange through the hive walls tends to cool the hive. The need for hive evaporation is minimal. There is a wide range of potential internal conditions for the hive and the hive can adapt as desired.

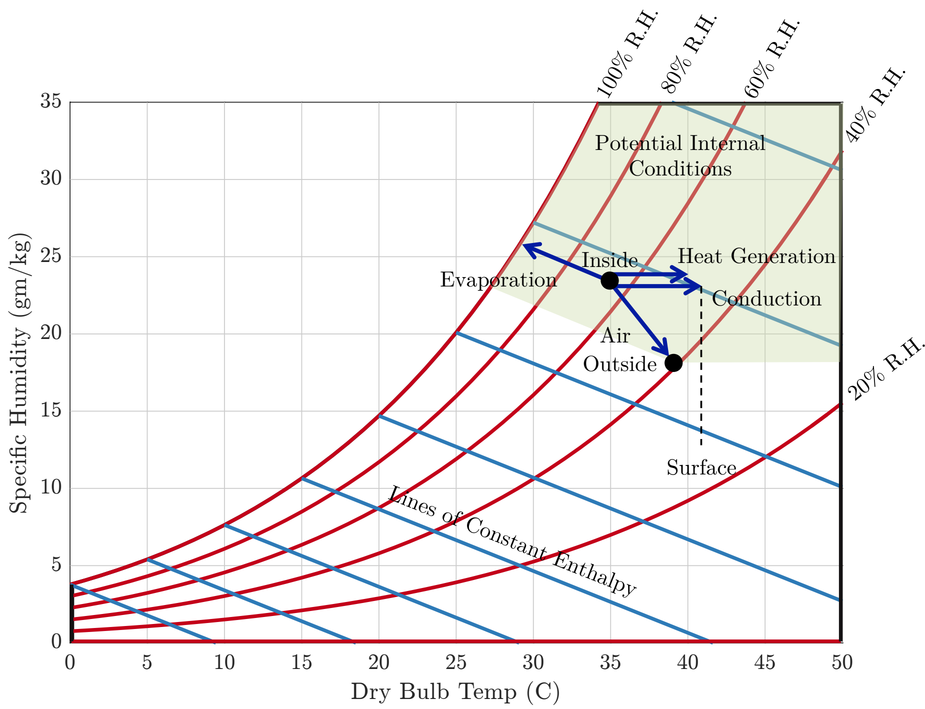


Fig. 6.2. Psychrometric chart: warm conditions.

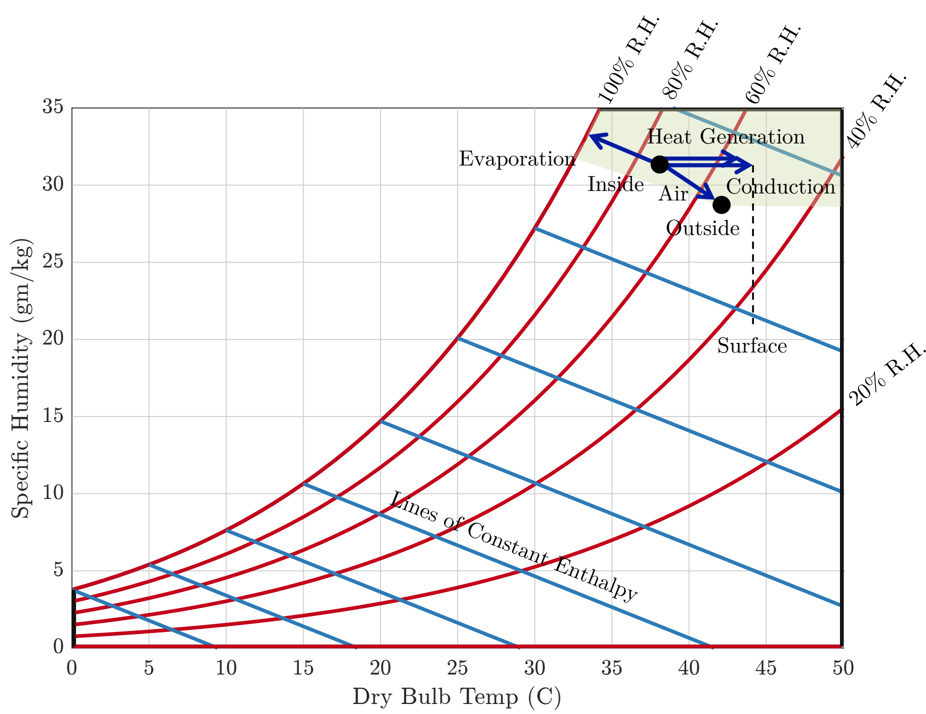


Fig. 6.3. Psychrometric chart: hot conditions.

Fig. 6.2 shows how on warmer days, evaporation is very important to keep the hive cool. In this case, heat generation should be minimized and the conduction through the hive exterior is detrimental to keeping the hive cool. The range of potential internal conditions for the hive is reduced.

Fig. 6.3 shows a hot and humid day for which the heat generation and conduction must be kept to an absolute minimum. The rate of evaporation must be high as well as the exchange of air with the outside to balance the water content and the internal heat generation. As shown, the temperature and humidity are above the optimal levels.

Note that the bees have a limit to how much the temperature can decrease due to water evaporation. Water cannot be evaporated past 100% humidity. To evaporate more water, which is an endothermic process, air exchange with the outside has to happen. This explains why good ventilation - even with slightly hotter air - is often associated with helping to cool hives.

The challenge is that good ventilation and great evaporation may not be enough to keep the hive conditions cool. Evaporation cannot move the hive down and to the left of the diagonal lines of constant enthalpy.[1] In summary, there is a thermodynamic limit to how much bees can cool the hive with evaporation.

6.3 Good Hive Ventilation for Hot and Humid Regions

Based on the psychrometric chart and modeling in Section 6.2, what characterizes good hive ventilation on hot and humid days is having the ability to evaporate water and recycle air easily with the outside.[2] In addition, conduction through the hive

[1] The exception to this is if a hive had a heat exchanger with the outside such that the incoming stream of air was pre-cooled but maintained the external specific humidity. With a perfect heat exchanger, the combined effects of evaporation and air exchange could move the internal conditions of the hive directly to the left, limited again by the 100% relative humidity mark. This is similar to indirect evaporative coolers.

[2] The circulation of carbon dioxide is not considered here as usually temperature is a larger concern.

body must be limited. For the regions of India that are hot and humid, this means the hive should have entrances designed to allow sufficient air flow, have water sources nearby, and minimize the hive surface temperature.

Chapter 7

Overview of Existing Hive Entrances

The design of entrances was motivated by improving hive ventilation as well as assisting traffic flow and defending against pests. The first step was to do a survey of existing hive entrances.

7.1 Types of Common Bottom Entrances

Contents

7.1.1 The Wood Block and Varieties

For a Langstroth beehive, there is typically a wide entrance opening at the base of the hive. Beekeepers often insert into this opening slot an "entrance reducer" that is designed to limit the size of the entrance. The Indian Standard for beehives calls this an "entrance rod." [17] In practice, the entrance reducer can take many different forms, but very often it is simply a block of wood with openings. Figure 7.1 shows the typical entrance reducer found in practice.

Fig. 7.1. Common basic wooden entrance reducer. By rotating the entrance reducer by 90° it is possible to obtain a different entrance size, and it also possible to remove the entrance reducer for the full size entrance.

In India, in addition to the design in Figure 7.1, it is common to have a larger block that rests in front of the bottom slot. Although the larger block design may require a bit more wood, it requires less precision in manufacturing. Figure 7.2 shows the larger entrance reducer. Robustness to manufacturing error can be important. For instance, Figure 7.3 shows an example of poor craftsmanship for which the larger entrance was too long for the hive.

The inset block entrance reducer and the bigger block entrance are both mentioned in India's BIS standard for beehives.

7.1.2 Slider

There are also slider entrances that allow for a more continuous range of sizes. Figure 7.4 shows a slider entrance that can be used to set the width of the entrance.

Fig. 7.2. Big block entrance reducer. This entrance reducer found in India has very high tolerances for all of its dimensions.

Fig. 7.3. Entrance reducer too long. This entrance reducer was poorly manufactured for this hive as it is too long to fit. Inset entrance reducers like this require more robust manufacturing to properly work than the bigger entrance reducers that simply fit in front.

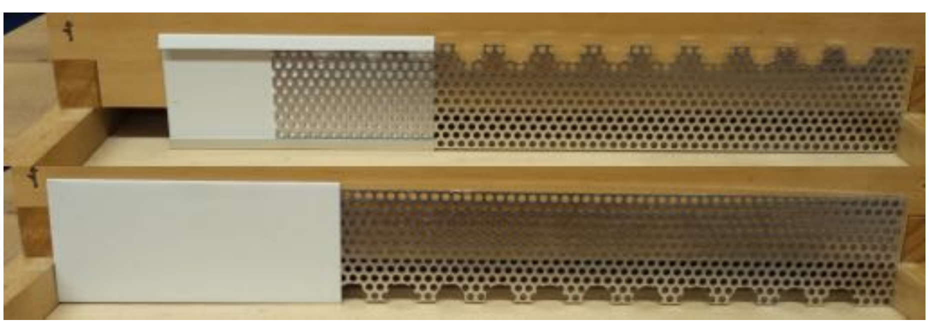


Fig. 7.4. Slider entrance reducer. This entrance reducer made by Betterbee is designed to allow beekeepers to slide the entrance open to the appropriate size as in the top picture, or leave it roughly fully open as in the bottom picture. The mesh is designed to let airflow through and the metal is sharp to prevent mice from entering. In practice this could be secured by pushpins or screws.

7.1.3 Holes

One design of the hive entrance employs simple holes, often in either plastic or metal. Using plastic or metal prevents animals such as mice from eating away the material and then gaining entry. Figure 7.5 shows an example of this type of entrance. Some beekeepers will just use hardwire mesh.

Fig. 7.5. Entrance reducer with holes. This entrance reducer employs holes designed to especially prevent the entry of mice. The material that this entrance reducer is made with cannot be eaten away by mice and thus mice cannot enter [5].

7.1.4 Fill

In India it is possible to find entrances that have been reduced by filling the hole with organic material such as a mixture of cow dung and sand. Beekeepers can also use corks, grass, small sticks. For these entrances, the entrance size is generally "fixed" and then other material is added as filler. Figure 7.6 shows an example of a filled entrance in India.

Filled entrances may have a few advantages over other entrance designs. One of their main advantages is that they require little cost in manufacturing as the basic entrance is a fixed size. Additionally, the filled material allows the entrance to have a continuous range of sizes rather than discrete options. Furthermore, the filled material may also be slightly adjustable by the bees. One beekeeper talked about using paper and letting the bees eat the paper to find an optimal entrance size [62].

Fig. 7.6. Indian Filled Entrance. This entrance has a fixed wood size, but the beekeeper uses a mixture of cow dung and sand to reduce the entrance size to be more appropriate for the bees. Also seen in this pictures is a metal piece that could lock bees in the hive for during transport but allow some ventilation. Additionally, the small stick protruding from the entrance is for giving medical treatment; the stick is attached to a cotton ball that has been medicated. Altogether, this entrance is a cost saving adjustable entrance.

7.2 Special and Unique Entrances

7.2.1 Queen Excluders

Beekeepers will use queen excluders over the front entrance when the hive is just established or there is a large chance of swarming. When the hive is just established, there is a chance the queen may want to relocate the colony. A queen may want to swarm if the food supply in the local area is low, the hive temperature is too high, the population is too large for the size of the hive, or if the hive has been overrun by pests. Whatever the case, the beekeepers will add queen excluders that have holes or slots big enough for the passage of the worker bees, but are small enough that the larger queens cannot go through. Potentially queen excluders can also be used to stop some wasps [17]. Figure 7.7 shows a queen excluder being used.

Fig. 7.7. Queen excluder. This entrance reducer from India simply has smaller slots to prevent the larger queen bee from getting out.

7.2.2 Robber Screens

When beekeepers notice robbing - or when bees from other colonies attack a weak colony - the beekeepers may employ robber screens. Robber screens are unique in that they purposely reroute the entrance to a hive to help trick the invaders of how to enter while the bees who belong to the hive hypothetically will figure out how to use the modified entrance. Robber screens are highly varied. Some beekeepers recommend just adding a wet towel over the front of the hive, diverting the bees out through the sides. Other beekeepers have special made entrances such as the one in Figure 7.8.

Fig. 7.8. Robber screen. This robber screen made by Betterbee is designed to confuse invaders who should not figure out that the only entrance is hidden to the top left. The bottom metal gate would be closed. The invaders should stay in front of the hive crawling around on the mesh until they give up.

7.2.3 Bee Escapes

Another special entrance is the design of bee escapes. Bee escapes allow the bees to only move in one direction. This can be useful for getting bees out of a super chamber such that then it is easier to harvest the honey. Bee escapes come in different forms usually by using angled walls that effectively point the way out with a large exit width but a small entrance width. Figure 7.9 conceptualizes what a bee escape looks like.

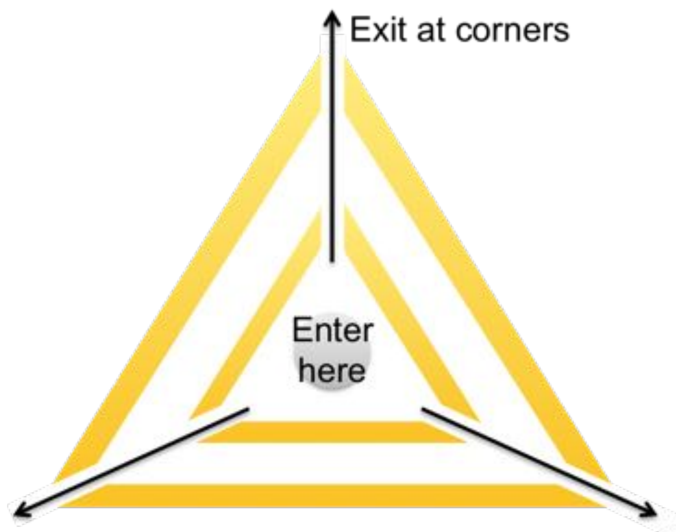


Fig. 7.9. Bee escape diagram. This diagram shows how bee enter at the inlet (the grey circle) and then they tend to leave at the corners of the triangle as this is the easiest motion for them to take. The openings at the corners make it much harder to go in the reverse direction.

7.2.4 Bumblebee Entrance

Potentially there could be entrances that bees could manually adjust. One previous way of doing this has been done for bumblebees that resembles a flap door [16]. The door hangs down across the entrance such that normally the entrance is shut. At the base there is a small lip that the bumblebee knows they can use to prop the door open. Figure 7.10 shows this design. Although this may work for bumblebees, honeybees are much smaller and many more in number. For this reason, this entrance may not be as practical for basic honeybees.

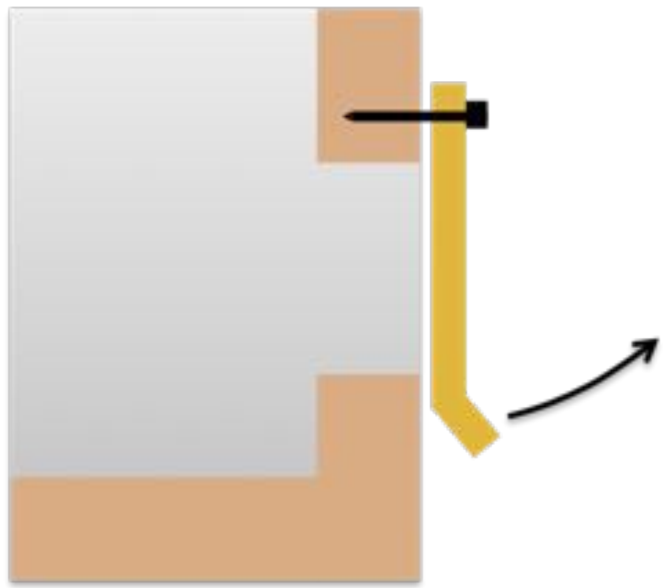


Fig. 7.10. Bumblebee flap entrance. This diagram shows a flap that hangs in front of the entrance hole. A bumblebee can figure out how to use the lip at the bottom to open the flap from the outside. In practice the flap could be clear.

7.2.5 Patents and Patent Applications

No patent is known to the author that defines a mechanical entrance reducer that automatically adjusts the size of the entrance reducer. However, personal conversation with one beekeeping inventor has suggested that mechanical devices have been used for controlling traffic flow [1], likely for use in experimentation by bee scientists. The adjusting entrances from this thesis, especially based on continuously updating the optimal entrance size, appears novel for the field, especially for implementation in practice.

There are a few patents for entrances and other hive ventilation accessories. US3200419 A (1965) is a patent application for which moving the hive along the bottom board changes the entrance size [74]. In US7632167, the front entrance included small groves in which small hive beetles can be trapped (2009) [77]. US5575703 (1996) is a solar powered system with a fan and temperature sensor designed to thermoregulate the hive [76]. US4074378 (1978) uses a small wind tunnel like device that looks like two funnels in a T-connector pipe that goes into the hive to help increase circulation in the hive [75].

For future reference, the US classifications at the time of this publication was:

449 Bee Culture

- **499.21** Passage
  - **499.22** Queen/drone control means
  - **499.23** One-way passage
  - **499.24** Adjustable
    - **499.25** Entrance

7.2.6 Pollen Traps

Pollen traps usually have round holes. However, the shape of a bee with pollen is not round, but oval shaped in cross-section. Designing entrances to use round holes is likely less ideal than oval holes if the goal is not to collect pollen. Figure 7.11 shows how a bee carries pollen on its legs and it can shift the pollen underneath to become more circular if needed.

Fig. 7.11. Shape of Bee Carrying Pollen. The left shows the bee in its more normal state with its legs carrying pollen out to its sides. The right shows the bee with its legs moved underneath to make the bee more circular.

Chapter 8

Adjustable Hive Entrances

Contents

The earliest entrance prototypes focused on ways to adjust the entrance size. The goal was to emulate the traditional entrance reducer in the overall form, but modify the entrance size to help bees defend themselves against pests. Considered were bee controlled entrances, electronic entrances, and manually controlled entrances.

8.1 Bee Controlled Entrances

8.1.1 Flap Entrance

One of the first bee controlled entrances was a design where clear flaps could be pushed open, but might present a slight challenge for other pests. This was modeled after the bumblebee entrance discussed in Section 7.2.4. This prototype shown in Fig. 8.1 is an entrance with clear flaps.

Fig. 8.1. First flap entrance prototype. This design used a simple secured flap entrance with the hope of allowing the bees to push their way out.

This entrance greatly restricted traffic flow as the bees were not able to push the flaps open. Qualitatively it was taken that at least one of the following was true:

1. The bees may not have been not strong enough to open the flap.
2. The bees may not have had the time to learn how to open the flap.
3. The bees may have found the flap uncomfortable.

Perhaps if the flaps were angled more horizontal rather than vertical, less bending would have been required and the bees could have pushed themselves through. However, a later model made in India with locally sourced materials and longer, easier-to-open flaps also had trouble with getting bees to push through the flaps.

8.1.2 Rotating Door Entrance

Another initial prototype was to use rotating doors. It was desired to know if bees could learn to open and close the entrance. This was briefly tested as shown in Fig. 8.2.

Fig. 8.2. Bee controlled door rotating entrance. This design used clear plastic doors that could be pushed open but could also lock to the outside. Two doors were clear and one was colored black. The bees opened the doors and on occasion seemed to accidentally close them.

The bees did manage to open both the clear and black doors. The bees did on occasion shut the doors, but it appeared this was largely by accident and not by any intention. On multiple occasions the bees tried to squeeze through the gap created between the door and the door stop. The slight differences in rotational resistance appeared to have a large effect on utilization by the bees. The design would unlikely be robust to propolis, which would be a problem for Apis millifera, but not for Apis cerana.

It was not fully answered if at least some bees could eventually learn to purposely open and shut the door and if they would activate this tool in the presence of a pest.

8.2 Electronic Adjustable Hive Entrances

8.2.1 Butterfly Entrance Design

Next was considered having a door that could be electronically sized.

The first design used rotating flaps and was called the "Butterfly Design" as it looked like a butterfly value. The prototype for this is shown in Fig. 8.3. This

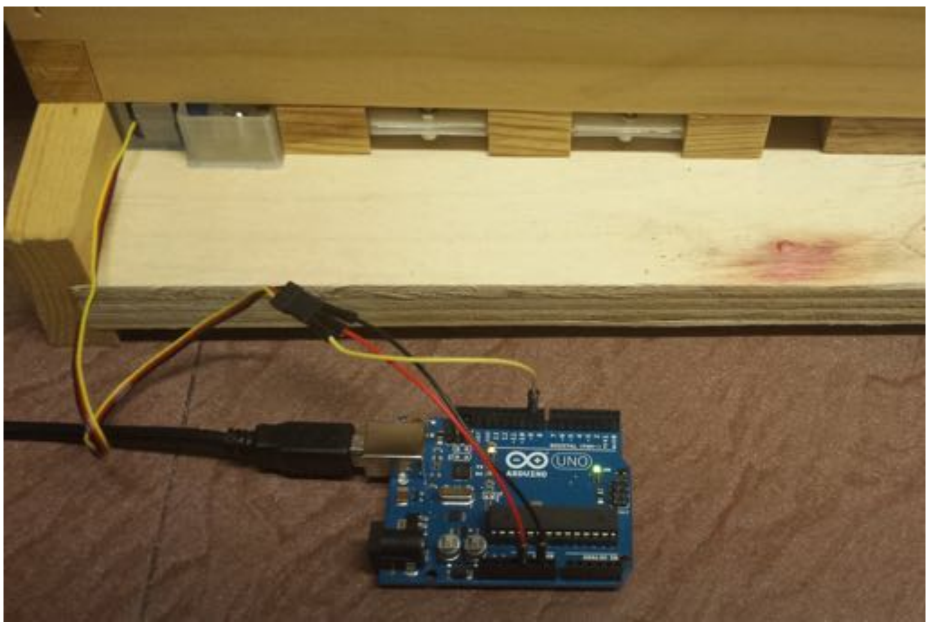


Fig. 8.3. Butterfly value entrance prototype. An Arduino was connected to a servo laid in a 3d printed case. A shaft connected to 3d printed gates was secured to the servo. The slight gap to the right remains open to prevent fully trapping bees outside of the hive.

prototype was tested on a hive as shown in Fig. 8.4. This prototype showed that having an entrance that slowly rotated (tested at about 20 and 10 degrees per second) seemed to prevent bees from getting squished. In addition, this design was also robust in that if any bee were ever trapped under the entrances, the entire beam and doors could move slightly vertically.

Fig. 8.4. Butterfly valve prototype testing. It was found that bees would not get stuck under the entrance if the entrance moved slowly enough. The above pictures show the entrance in the open state, during closing, and while closed. Note that the bees use both the upper and lower part of the entrance.

8.2.2 Helical Entrance Designs

It was desired to have a continuous range of entrance opening sizes. To utilize a simple noncontinous rotary servo and get a continuous linear range in the width of the opening, a helical design was considered. The design was modeled in SolidWorks and then 3D printed. The first helical prototype is shown in Fig. 8.5.

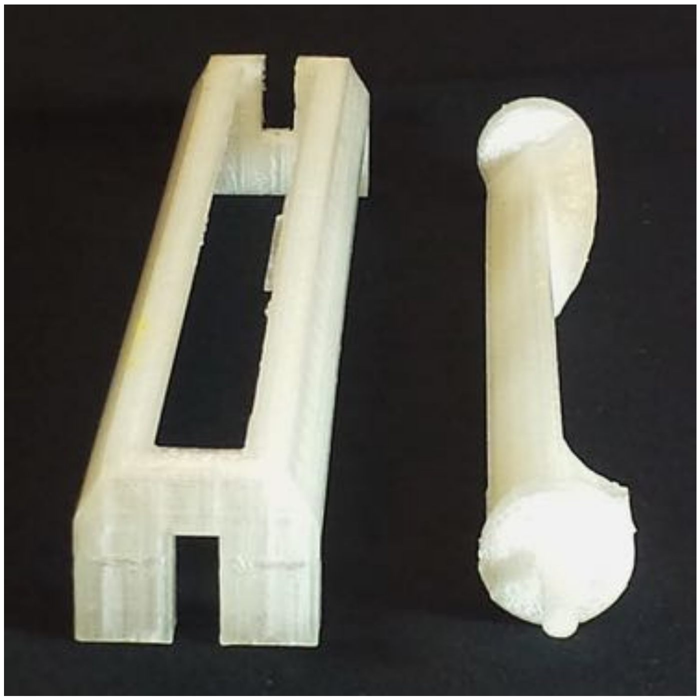


Fig. 8.5. First helical prototype entrance.

The helical prototype included two components: the helical shaft and then a top part. The top part helps to block the opening when the helix rotates 180°. The design was made such that if the entrance were rotated too far, the bees could still get though by crawling over the helix. This would prevent any accidental full blocking of the entrance.

After being printed it was noticed that the second 90° of rotation did little to extend the effective width of the opening as only the corner edges were lifted. Notice the helix in Fig. 8.5 only goes 180°. To make the limited 180° of rotation lead to a larger range of width, a second helical entrance was printed as shown in Fig. 8.6 where the helix was swept 270° of which only 180° was useable by the servo.

Fig. 8.6. Second helical prototype entrance.

Testing as shown in Fig. 8.7 was done in South Carolina. Propolis was not visible on the entrance components after about two days left on the hive. Testing did suggest a few improvements. One was that the heavy weight of the hive and possible unevenness of the baseboard or bottom box could be problematic for a long entrance. It might be useful to have some supporting mechanism in the middle to prevent the entrance pieces from colliding. In addition, a small chamfer or fillet on the inner helix part rotor could minimize any scraping due to bending or other external material.

8.3 Manually Controlled Entrances

Due to the cost associated with electronic components, it was desired to make a manually adjustable entrances, especially for India. Traditional block entrance reducers tend to be difficult to adjust as they require propping the hive up to remove and rotate them. To solve this problem two methods of manually controlled entrances were made.

Fig. 8.7. Second helical prototype entrance in use.

The first manually controlled entrance is shown in Fig. 8.8. This design uses a wedged block with a handle protrusion for gripping. A beekeeper can quickly grasp the protrusion, remove the slider, and press the slider into a more ideal location. In this design both the entrance reducer and the slidable block were wedged to improve tolerance to variance in hive dimensions.

Fig. 8.8. Manual wedged slidable entrance.

While this design was ergonomic, the design was not especially easy to make. The rabbet (meaning groove) and wedged surfaces could be mass produced, but would take longer to make than a traditional entrance reducer. Furthermore, this was only compatible with hives entrances that already had a wide slot opening. As many Indian hives had fixed entrances to begin with, a second option was explored where one or two pieces of wood each with a nail can be slid in front of a larger fixed opening. This is shown in Fig. 8.9. A similar variant could be simply using a heavy square object such as a brick.

Discussion with beekeepers to potentially try such entrances on their hives revealed

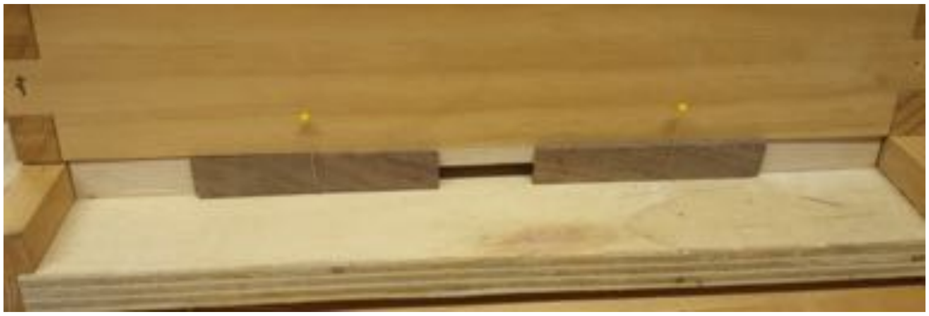


Fig. 8.9. Manual slidable entrance block.

that Indian migratory beekeepers often live a good distance from their hives. For this reason, the potential benefits of a manually adjustable entrance would be less.

Chapter 9

Entrance Traffic Flow

Contents

This chapter looks at how the entrances to hives impact bee movement and if bees have a preference for different entrances. Testing was done with a number of quickly prototyped designs that generally tried to test just one or two variables. While not all of the tests were conclusive, most of the tests offered substantiated qualitative insights.

9.1 How to Measure Entrance Traffic and Preference

There are a number methods by which one can measure bee traffic flow and entrance preference. These are given in Table 9.1.

Table 9.1: Methods to measure bee traffic and entrance preference

Method	Discussion
Qualitative Observance	Qualitatively observing the bee's reception to an entrance design is a quick way to evaluate an entrance. It may not be as rigorous as the following other methods, but it can be useful for rapidly testing new designs.
Mechanical Means	Past researchers have made small tunnels to count bees that pass through narrow tunnels [25]. While highly accurate, the tunnels limit the form factor of the entrances.
Computer Vision	Computer vision could potentially allow analyzing a lot of data with the flexibility of using nearly any entrance. It is unlikely to be as accurate as mechanical means.
A/B Preference	In this method, bees selectively choose one opening over another. This provides quick quantitative results. A more lengthy experiment can use of bee swarms to choose between hives with different entrance styles [67].
Eating the Entrance	This method is used to quantitatively determine what size entrance the bees perceive as optimal. It generally measures the maximum desired size.

Testing entrances is nontrivial. First, the ideal size of an entrance is hive dependent and can change depending on the time of day. For this reason, the entrance testing aimed to answer specific questions in as brief as time as possible. Moreover, bees tend to follow previous scent patterns and must each reorient themselves if an entrance is substantially changed. A few experiments done may have also increased bee traffic in part due to curious or concerned bees. Lastly, hive ventilation may be very sensitive to the entrance. Bee traffic can be impacted by bees fanning at the entrance or bees rushing out to reduce heat generation in the hives.

9.2 Preference of Tunnel Size and Length

One test looked at the diameter of holes the bees would fit through and also if they minded being in a closed area. This was done by drilling a series of holes in wood of different thicknesses as shown in Figure 9.1. It was clear from the testing that bees preferred larger holes and that they also preferred shorter tunnels. Some of the worker bees without pollen would go through the about 7/32 inch diameter hole (third smallest). These may have been younger bees. The short tunnels (left half) had a thickness of .26 inches and the longer tunnels were .47 inches. While a more smooth material such as plastic or acrylic would be needed to more accurately measure precise diameters for bees, it was evident that the bees tended to select the biggest and shortest of entrances.

Fig. 9.1. Testing different entrances sizes and tunnel lengths. The holes to the left were shorter than the holes to the right.

9.3 Effect of V-shaped Entrances

One thought was that it might be possible to avoid backups by directing bees using V-shaped entrances as shown in Fig. 9.2. It was expected that bees would tend to enter towards the left and exit towards the right as the width of the entrance is widest.

Almost 10 minutes of footage was analyzed. This was tested on a US hive in Boston. This hive was very small and the bees were very uncentered (mainly off to the right when facing the hive). The results are shown in Fig. 9.3. A chi-squared test says that the entrance side and probability of entering or exiting were not independent ($p<0.01$).

It may however be that the tendency to leave in higher proportion from the right and enter from the left was due to bees simply choosing the nearest opening. Bees leaving the hive had their nearest exit as the right. Incoming bees if landing more randomly on the baseboard could find the nearest opening to the left. Needed was a more centered hive or testing also with the entrances swapped.

Fig. 9.2. V-shaped entrances to direct traffic.

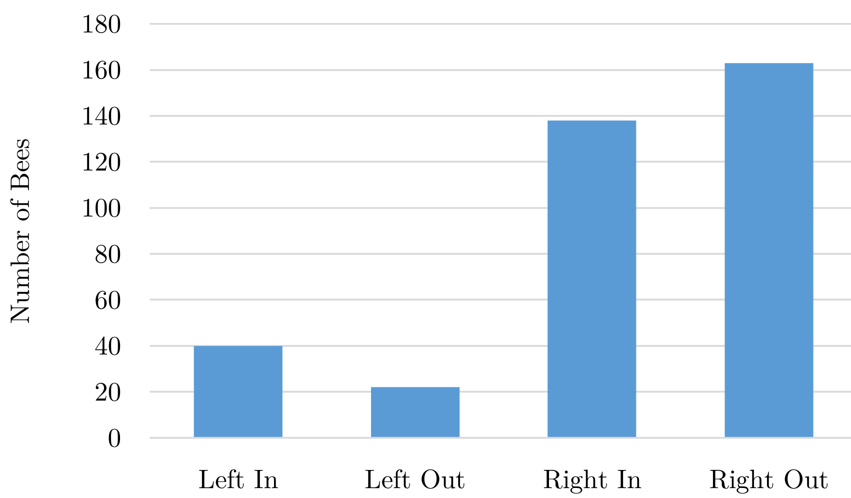


Fig. 9.3. V-shaped entrances results.

9.4 Effect of Entrance Width

It was desired to know what the effect of width is on the traffic flow of the bees. To test this a special entrance reducer was made that allowed the width of the entrance to be modified. Images from the experiment are shown in Fig. 9.4. The hive tested in Boston on July 11, 2015 was a deep box with one recently added medium super (mostly empty). This particular hive had no upper opening. The bees fanning is very noticeable and tended to cause traffic congestion, especially when the entrance was small.

Due to the heat and sunlight, the camera used (a Samsung Galaxy S4) kept overheating. As such there were a series of short clips taken.[1] At some points it was necessarily to move the camera to the shade for a few minutes before resuming footage. The timing of the footage is shown in Fig. 9.5. The needed time to cool down drew out the duration of the experiment. This makes it more difficult to compare traffic from the largest to smallest entrances. It is known that the number of bees entering and exiting a hive can change over time [21].

The footage was counted by playing the recordings at a reduced rate. The average bees per minute is shown in Fig. 9.6. The accuracy of the average bees per minute is greatest for the smaller entrances.

Due to the prolonged experiment duration, it is not possible to conclude that a smaller entrance decreases traffic. However, a number of observations were made that are of qualitative significance.

One important observation is that making the entrance smaller may cause ventilation problems before causing traffic flow problems. Fanning increased long before the bees faced major congestion. In addition, fanning - especially right in the entrance way - ended up blocking the bees entering and exiting. Blocked bees typically pushed through, colliding with the fanning bees. This surely decreases the effectiveness of the fanning bees. Given the hot conditions and the lack of an upper entrance, problems with ventilation may take a smaller entrance before they arise in other hives. For hot climates, entrances should probably focus on ventilation over traffic flow.

Another observation is that any change in the entrance size tends to briefly promote movement by bees.

It was also observed that there was a slight tendency for bees to consecutively follow each other. Fig. 9.7 shows the distribution of consequentially entering or exiting

[1] The initial temperature at 4:05 PM measured 45.8° C with 16.7% humidity, but the anemometer used (a La Crosse EA-3010U) tended to gradually rise with incident sunlight. 4:30 measured 41.4° C and 5:40 ended with 41.1° C.

Fig. 9.4. Entrance width traffic testing.

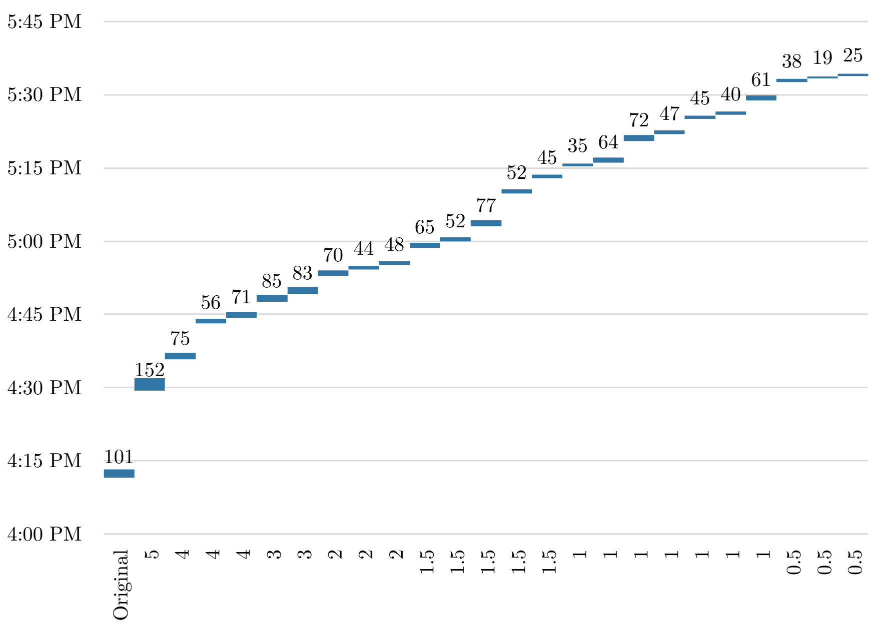


Fig. 9.5. Time taken for entrance width testing. The values above bars represent the duration in seconds.

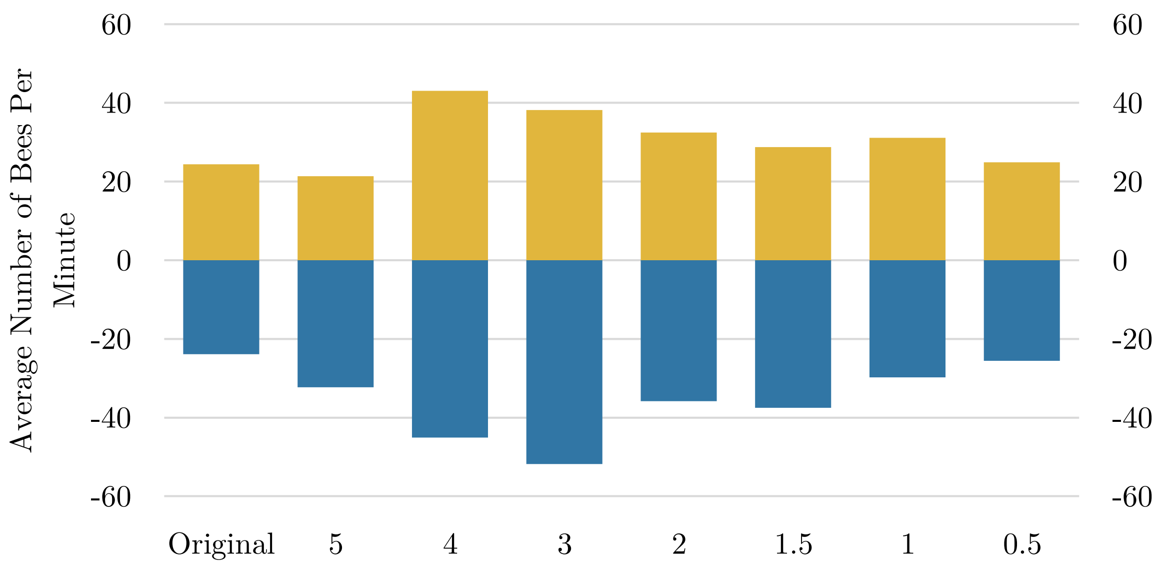


Fig. 9.6. Effect of entrance width on traffic. Bees coming into the hive are positive and bees leaving the hive are negative.

bees going the same direction. For instance, if 5 bees exited in a row and the next bee entered, a 5 would be recorded. The probability of a given number x of consecutive bees before a switch in direction is given by:

$$p(x) = p^x \cdot (1 - p) + (1 - p)^x \cdot p \tag{9.1}$$

If the likelihood of entering or exiting the hive were equal, then the distribution should follow the solid black line in Fig. 9.7. If the probability were 5/8 (for either entering or exiting), then the distribution would follow the dashed black line (which is by Eq. (9.1) a sum of two geometric distributions).

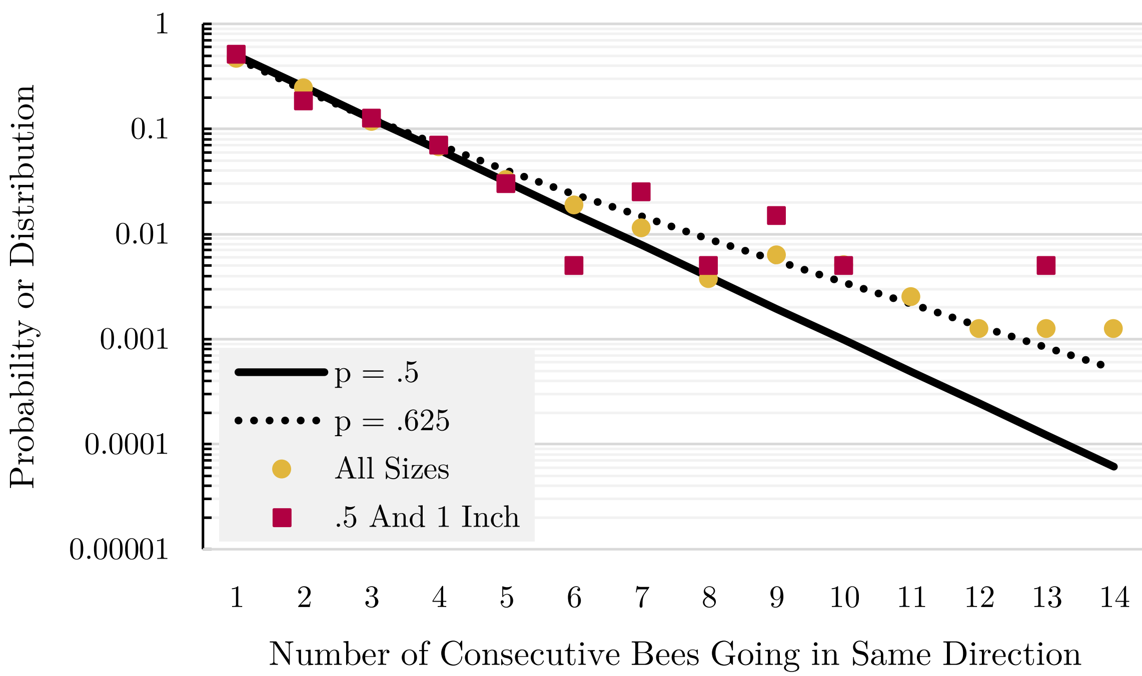


Fig. 9.7. Pattern of entering and exiting bees. Points with zero occurrences not plotted.

However, a quick check on the typical proportion of bees exiting shown in Fig. 9.8 suggests that instead, there were very few instances where the probability of exiting or entering bees exceeded 5/8. This preliminary data suggests that instead bees may exhibit a slight tendency to follow each other, especially when clustered. As one bee moves out, others follow and vice versa.

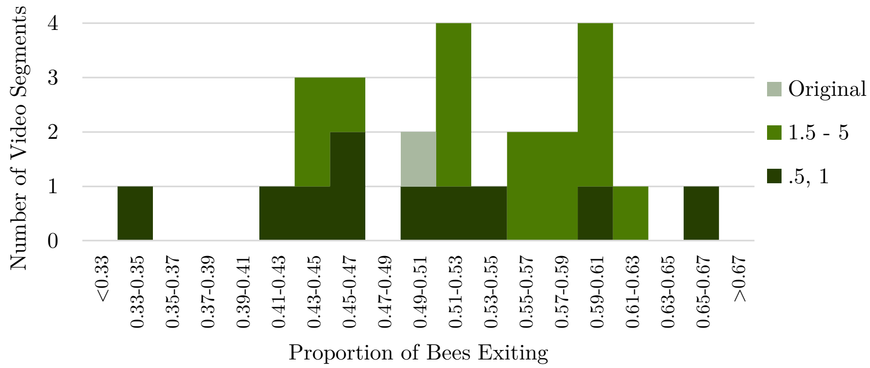


Fig. 9.8. Proportion of bees exiting. The longer videos with wider entrances were closer to .5, but the probability was generally centered around .53.

9.5 Entrance Height Preference

One test was conducted in which alternating height tunnels were employed to study the effect on entrance height on traffic. The entrance reducer is shown in Fig. 9.9. The entrance reducer had 16 rectangular tunnels alternating a half inch and a quarter inch tall, all a half inch wide and three-fourths inch deep, and spaced a quarter inch apart. The entrance reducer was made by joining multiple eighth inch laser cut pieces of plywood.

Fig. 9.9. Entrance reducer for height traffic test.

The entrance reducer was put in place for over 24 hours in advance to allow the bees to adapt to the new the entrance that had a sappy aroma after being cut. The test was conducted between 6 and 7 PM on July 31, 2015 at Best Bees in Boston for a 3 deep Langstroth hive. The outside temperature was about 27.1°C. While about 30 minutes of footage was taken of the bees moving in and out of hive, only 5 minutes is analyzed as counting bees was time-consuming. Fig. 9.10 shows the bees and entrance reducer in place.

Fig. 9.10. Height traffic test.

A small script was written in Matlab to allow keystrokes to be recorded. Recorded was if a bee entered or exited each entrance (numbered 1-16 left to right) and if the bee entered crawling on the bottom, the right side, the top, or the left side. It was observed that a portion of the bees entered and exited the hive upside down. To minimize observation error in counting the bees, the playback rate was slowed and recording was limited to between 2 and 4 entrances at a time. Fig. 9.11 shows the number of bees in 5 minutes that entered and exited the hive in each tunnel.

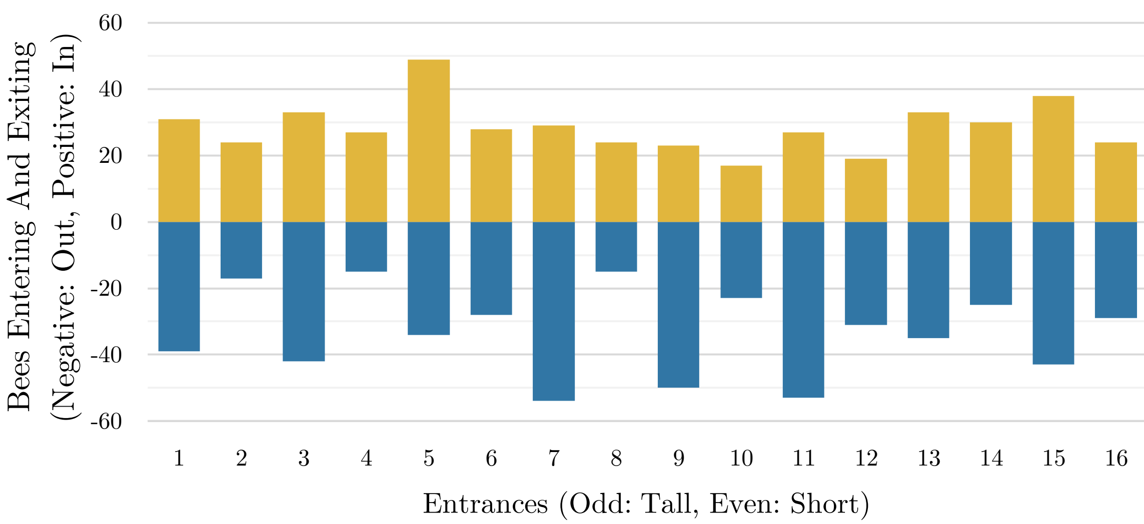


Fig. 9.11. Height traffic test bee counts. The bee counts were over 5 minutes.

Fig. 9.12 shows the grouped ranges counts for tall and short entrances. A chi-squared test of combined in and out traffic gives $p < 0.001$. This means that traffic flow was not independent of entrance heights for the hive conditions tested. In general it is possible to say that bees exhibit some preference for taller entrances when given a choice.

A second chi-squared test run of this data to measure if exiting and entering is independent of entrance height gives p about 0.01. Taller entrances are slightly more attractive to bees exiting the hive, and entrance size matters less to bees entering the hive.

This finding could be explained by a variety of potential reasons. First taller entrances shine more natural light inside the otherwise dark hive. Second, bees climbing down the inside front wall are closest to the taller (or higher) entrances. Lastly, bees that have landed on the baseboard to enter the hive tend to have equal distance to the entrances regardless of height, barring congestion due to other bees.

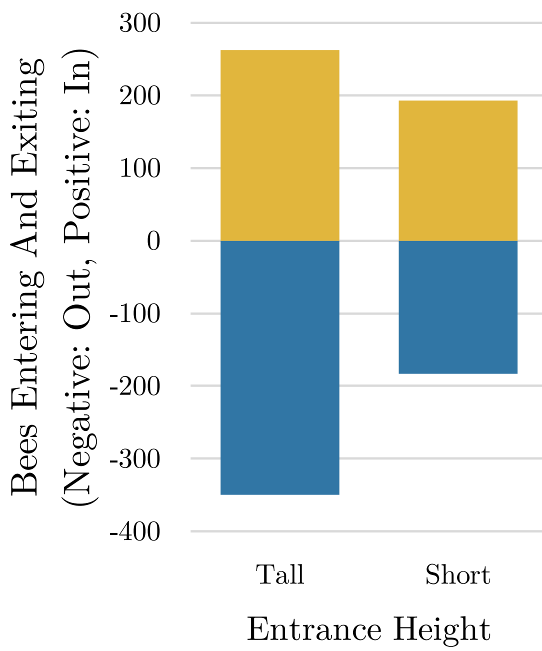


Fig. 9.12. Height traffic test bee counts grouped. The bee counts were over 5 minutes.

Lastly it was looked at which surfaces the bees used to enter and exit the hive. Fig. 9.13 shows the percent of bees that entered and exited on the top, sides, and base of the tunnels. It was observed that bees leaving the hive tended to have a slightly greater preference for using the top and sides than for bees entering (not independent: $p < 0.01$). Additionally, the taller entrances encouraged more climbing on the top and sides than on the bottom board (not independent: $p < 0.001$).

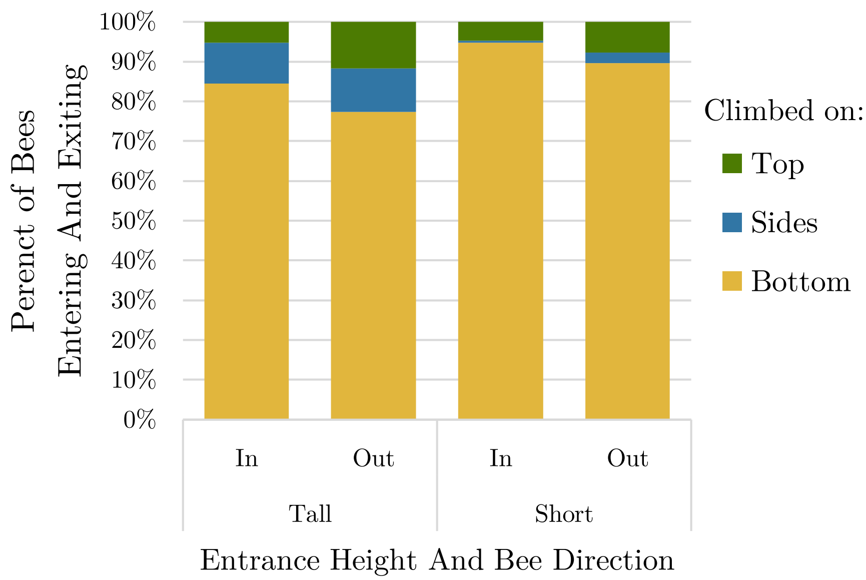


Fig. 9.13. Height traffic test: surface climbed on. Exiting bees and bees in taller entrances climbed on the sides and top surfaces more often.

Ultimately, this section has showed that bees have a slight preference for taller entrances when given the choice of shorter and taller entrances, and this is especially true when leaving the hive. This insight could be used to mitigate traffic congestion by more orderly directing bees to leave more from certain openings than others. Preventing the congestion right in the entrance could also help improve ventilation for the same fixed size entrance.

9.6 What Size Entrance Do Bees Want

A South Indian beekeeper mentioned during a phone conversation of his innovation to place crushed paper in the entrance to beehives to allow the bees to eat out the entrance to be the optimal size [61]. This inspired a quick method to estimate ideal entrances sizes for different hives.

A first test was done in the US using a custom entrance reducer to secure and hold the paper. The entrance reducer with quarter-inch graph paper is shown in Fig. 9.14. The width was 10 5/8 inches with a height of 5/8 inches. This test was done on a 3 deep Langstroth hive at Best Bees in Boston on August 1 to 2, 2015.

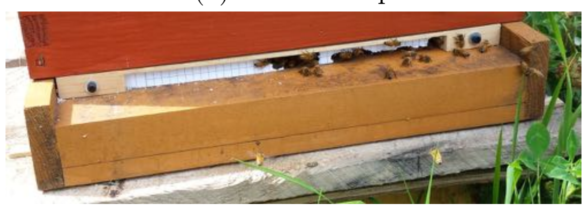
Fig. 9.14. Paper entrance test: large hive. Grid paper was inserted in an entrance to let the bees choose their optimal entrance for a 3 box Langstroth hive.

Fig. 9.15 shows that the bees in just 24 hours had eaten practically all of the paper. This suggests that for the given conditions, the optimal size of the entrance is at least as big as this area eaten away.

Fig. 9.15. Paper entrance test: large hive results. After about 24 hours, the bees had eaten nearly all of the paper entrance.

A second US test was done on August 7th, 2015 at the farm of Debra and Alex Slocum for a smaller hive. The hive had 3 medium boxes, weighed about 56 lbs as measured by a Nectar Detector® from two sides and taking an average. The initial hive entrances is shown in Fig. 9.16a. Images of after 3 and 18 hours are shown in Figs. 9.16b and 9.16c and show that the eating away of the paper nearly reaches its characteristic value in less than 24 hours. In this slightly smaller hive, the bees did not eat away all of the paper.

(a) Initial setup



(b) After 3 hours

(c) After 26 hours

Fig. 9.16. Paper entrance test: medium hive results.

This test was similarly repeated in India with three 1 box Langstroth hives with different strengths. The testing was done in Haryana, India on August 19th, 2015. The hives each with 9 frames were selected by the beekeeper. Hive 12 was the weakest hive weighing 21.05 lbs. Hive 78 was a stronger hive weighing 24.18 lbs (frames had likely been swapped or recently added between the 6th and 14th with another hive to help it get grow). Hive 86 was considered strongest by the beekeeper and weighed 22.92 lbs. These weights had been taken on August 14th. Hive 12 is shown in Fig. 9.17. Notice that the hive roof is shifted back to increase ventilation through the jute cloth, and there exists a middle screen hole for extra ventilation.

Fig. 9.17. Paper entrance test setup in India. Notice the entrance was only about a quarter inch wide by a half inch tall. This hive and the other two others had a fixed entrance size opening approximately centered behind the graph paper that was taped on.

Fig. 9.18 shows the hives and a close up of their entrances after about 18 hours.

One important conclusion from this section is that the hive entrances of many of the Indian hives are likely smaller than the ideal size for boxes for two deeps high. To support double deep Langstroth hives, a new larger standard entrance will likely be beneficial. However, the entrance size - especially for smaller hives - should be kept to a small size.

9.7 Untested Entrances

Not every entrance that got built got tried on a hive. Fig. 9.19 shows two entrances that did not get to be tested. The top entrance was built to test if having a stacked entrance could improve traffic flow for the same width opening. The bottom entrance was to study the effect of fillets on traffic flow and traverse time.

(a) Weakest hive (b) Medium strength hive (c) Strongest hive

Fig. 9.18. Paper entrance Indian tests results. Stronger hives desire larger entrances.

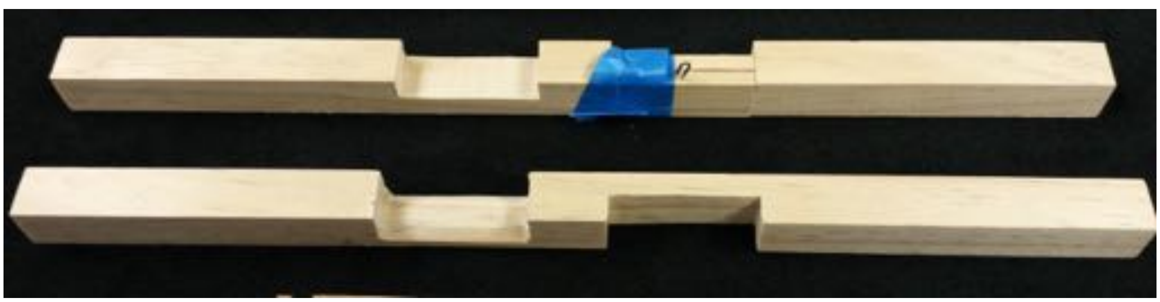


Fig. 9.19. Two untested entrances.

Chapter 10

Electrical Shocking Entrances

Contents

One way to help defend again wasps could to be shock them. This chapter explores some of the testing done to test the potential effectiveness of this approach.

10.1 Quickly Prototyping Shocking Wasps

To quickly prototype the effect of shocking a wasp, a purchased bug zapper was connected to two metal strips separated by a small distance. The purchased bug zapper was labeled as "Dynazap®." The setup is shown in Figure 10.1.

In a few minutes after placing the two terminals, a yellowjacket landed on the hive's landing board. After a quick brawl, it crossed over the two strips, after which the bug zapper button was pressed to begin the shocking. The shocking lasted approximately 7 seconds - far more than was likely needed. The result is shown in Figure 10.2. Ultimately the wasp was killed as well as about 14 bees. This presumably caused an

Fig. 10.1. Setup for prototyping a high voltage shocking method against wasps.

alarm pheromone to be released which summoned a great many of the bees inside the hive to rush out.

About two minutes prior to the wasp being shocked, 3 bees had been individually zapped. The initial shocking of these single bees summoned very few other bees. It took about 40 seconds for a fellow bee to tend to one of the injured ones. It was only after the wasp and 14 other bees were zapped together that the bees all rushed out. This suggests that the feedback reaction to respond to a pest problem may require a great danger before a full response.

10.2 Shocking Only Pests

Beekeepers may be reluctant to have many bees die in the process of stopping pests such as wasps. For this reason, other solutions were considered as to how to make shocking less lethal to bees.

One thing that could reduce bee carnage would be to make the maximum shocking duration shorter. The shocking of the yellowjacket in Section 10.1 could have likely been effective with a shorter shocking duration than 7 seconds.

Fig. 10.2. Hive voltage shocking result. These images are taken from a video. The images are -4, 0, 10, 20, 30, and 40 seconds after the shock took place (arranged down then across). The shock lasted about 7 seconds effectively killing the wasp and about 14 bees. Notice that this caused a large surge of bees out of the entrance.

In addition, it may be possible to use lower voltages. While bug zappers can produce voltages as high as two thousand volts, bees are known to feel shocks as low as a half volt [65]. According to [65], roughly 60% of the bees they tested showed a instinctive stinger response to voltages of just 1 volt and 2 volts showed a response in roughly 80% of the bees. If bees can feel shocks at these low voltages, it may be that wasps could also sense - and dislike - such low voltages.

Unlike US yellowjackets, many of the wasps in India are considerably longer than bees. For this reason, it becomes more practical to separate the terminals by a greater than one bee length. Bearding on the landing board could still connect the terminals, but a moderately low voltage could prevent bee death from occurring. For reference, [66] discussed nonlethal venom collectors between 10 and 25 volts.

While tests were ready to do both in India and the US over the summer and fall of 2015, wasps were not present when testing would have been possible at the hives available. Some footage of the response of bees to low voltages is shown in Fig. 10.3. Bees definitely showed a response to shocks and tended to move to avoid crossing the terminals, but not all bees seemed to "learn" to avoid crossing the terminals.

Fig. 10.3. Low voltage shocking of bees.

10.3 Low Voltage Shocking Robber Screens

One of the ideas that came out of this was that it may be possible to use low voltage shocking terminals to prevent robbing. The terminals could be placed either on the outside of a robber screen, be the screen, or simple rest on the landing board. This was not tested as no major instances of robbing were evident on the hives used.

Chapter 11

Beehive Fluid Dynamics

Contents

Modeling the fluid dynamics of a beehive can give important insight into how air moves around and inside a hive. This chapter considers external flows around a beehive. The results from the computational fluid dynamics (CFD) motivate design improvements for US and Indian hives.

11.1 Air Flow Around Hive

As an introduction to using computational fluid dynamics, it seemed most appropriate to start modeling a hive by simply considering the air flow around the outside. It was hoped that the outside air flow could lay the foundation for what parameters to test inside the hive and give other useful insight.

11.1.1 CFD Setup

The first step was to model the beehive in CAD. It was decided to use a double deep standard US Langstroth hive. These dimensions approximately match the dimensions of the standard Indian Langstroth hive for Apis mellifera. The hive as rendered is shown in Fig. 11.1.

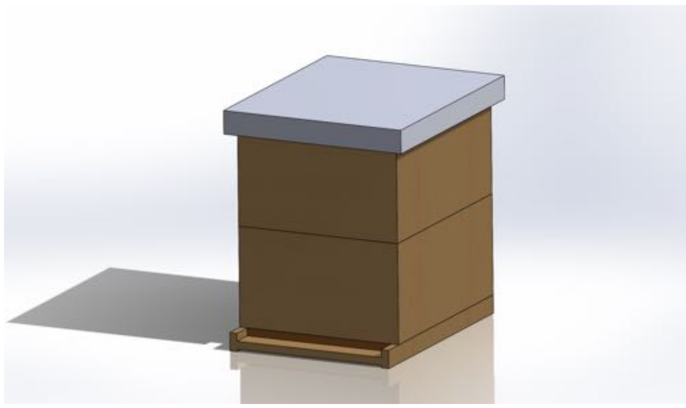


Fig. 11.1. Rendering of double deep hive used in CFD.

The next step was to model basic airflow over the outer surface of the beehive. For the modeling Ansys Fluent R16.0 was used. It was desired to closely detail the airflow around the front entrance. For this reason, the meshing used a fine mesh near the hive surface. To speed up the calculation, there were multiple bounding boxes that allowed the tetrahedral cells to be smoothly transition to larger sizes away from the hive. A 2D projection of the bounding boxes is shown in Fig. 11.2.

A view of the final mesh is shown in Fig. 11.3. It should be noted that initially a courser mesh was tried, and it was found that there were not enough cell layers within the boundary layer. The simulation used "enhanced wall treatment" instead of "standard wall functions" to improve the estimation of the heat transfer coefficient. While standard wall functions require just one cell layer to approximate air flow and heat transfer in the boundary layer, enhanced wall treatment requires multiple cells layers in the boundary layer.

The law of the wall suggests that the viscous sublayer ends at about $y^+ \approx 10$. y^+

Fig. 11.2. Bounding boxes used in mesh generation.

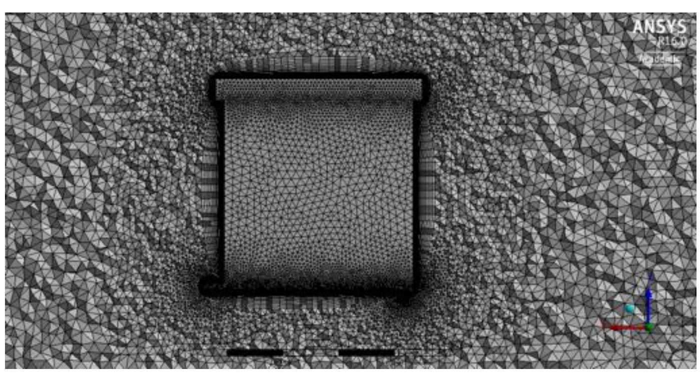


Fig. 11.3. CFD mesh.

is defined as:

$$y^+ = y\frac{\sqrt{\tau_s/\rho}}{\nu} \tag{11.1}$$

where τ_s is the sheer stress, ρ is the density of air (1.225 kg/m^3), and ν is the dynamic viscosity of air ($1.461 * 10^{-5}$ m^2/s). τ_s ranges from .001 to .05 Pa over the surface of the hive for the front flow case, and so the viscous sublayer depth ranged from 5 mm to .7 mm over the hive in initial testing. As such, the fine mesh had a first layer size of .25 mm.

The air velocity at a distance was chosen to be 1 m/s as that is a realistic speed for air. The surface of the hive was chosen to be a constant temperature of 1°C greater than the incoming air. While the surface of a beehive in practice would not necessarily be uniform, the constant one degree temperature difference would help in approximating the heat transfer coefficient h over the hive without modeling internal flows.

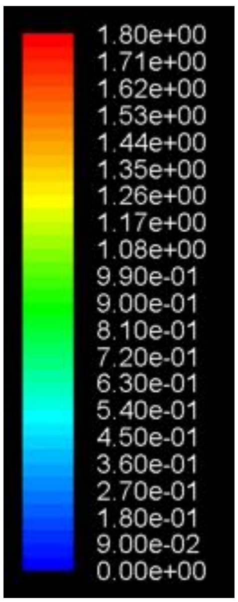
The CFD model used was a realizable k-ϵ model. To speed up computation, a first order upwind scheme was used for 100 iterations and then a second order upwind scheme was used until the result settled. While the front and side flow settled, the diagonal flow showed some cyclic instability, suggesting that this case could be improved if later modeled as a transient flow.

The simulation was run for front flow, side flow, and diagonal flow.

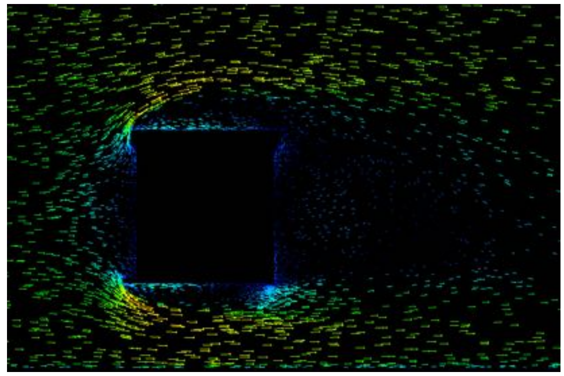
11.1.2 CFD Results and Analysis

Air at 1 m/s was blown directly onto the hive as shown in Fig. 11.4. Fig. 11.4 highlighted that even at 1 m/s the air separates from the hive body and does not reattach. This changed the way I decided to model air flow over the top of the hive. Originally, I had hoped to analytically estimate the heat transfer coefficient over the top of the hive as simply air over a flat plane. The flat plane model would thus be invalid for most typical wind speeds. Instead, more appropriate was to use heat transfer results directly from CFD results as shown in Fig. 11.5.

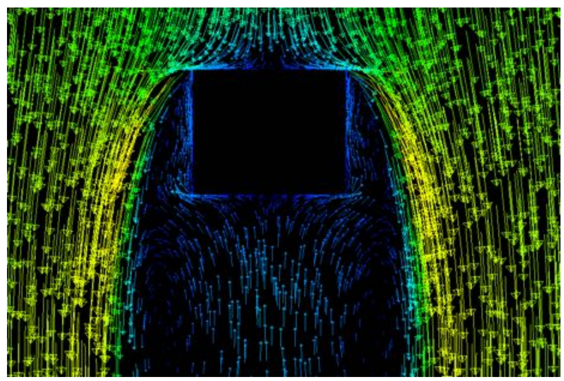
Fig. 11.5 importantly showed that the heat transfer coefficient was very nonuni-



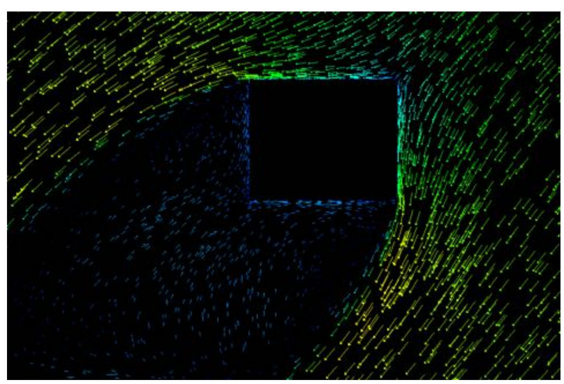
Colored by velocity magnitude (m/s)



Front flow



Side flow



Diagonal flow

Fig. 11.4. Flow over hive exterior.

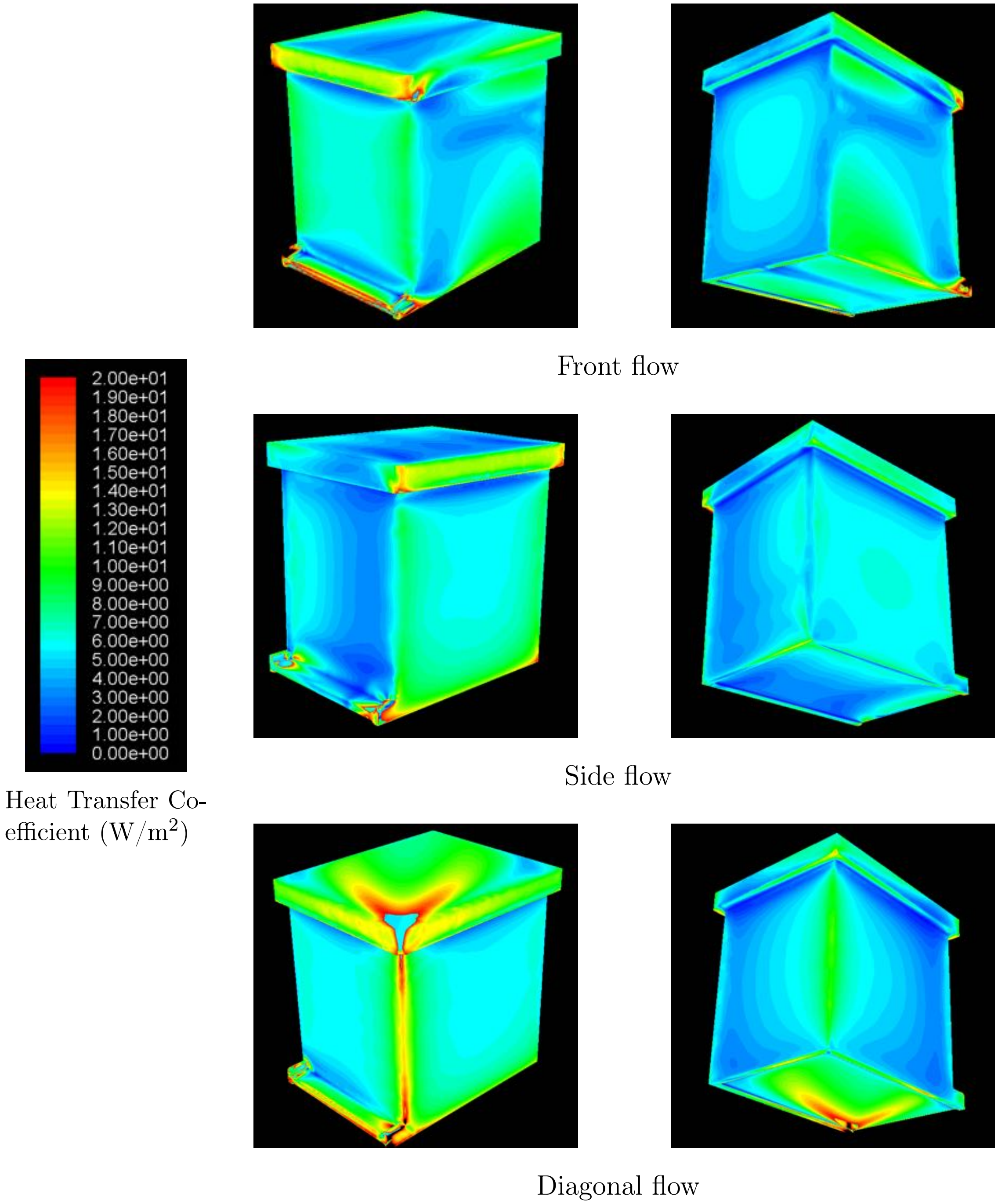


Fig. 11.5. Heat transfer coefficient of hive exterior. For 1 m/s wind for constant surface temperature. Surfaces with the heat transfer coefficient above 20 W/m^2 are not shown.

form over the surface of the hive. In general, the heat transfer coefficient was highest at the edges of the hive. In practice, the heat would have the most resistance passing through the corners of the hive and the front because the edges are the furtherest from the center of the hive and the internal heat generated would have to pass through the most hive body to get to the corners. This led to the conclusion that heat from incident sunlight that hit the hive would get wicked away faster on the edges and corners of the hive than on the faces.

Part of the external CFD analysis was also to motivate how to model internal fluid dynamics inside a hive. Fig. 11.6 shows the external pressure on the surface of the beehive. Essentially the airflow stops on the front surface of the hive, and thus the front surface of the hive has the greatest pressure. This is expected by the Bernoulli equation given in Eq. (11.2). $\frac{1}{2}\rho v^2 = 0.5 * 1.225(1^2) = 0.6125$ Pa vs a maximum of 0.686 Pa for front flow. The closeness of the pressures improves confidence in the model.[1]

$$\tfrac{1}{2}\rho v_1^2 + \rho g h_1 + P_1 = \tfrac{1}{2}\rho v_2^2 + \rho g h_2 + P_2 \tag{11.2}$$

The external pressures give insight on how air moves inside a hive for different external wind conditions. For front flow, the consistent and high pressure along the front of the hive and fairly consistent and low pressure along the back of the hive give qualitatively important insight into the internal fluid dynamics of the hive for different entrance arrangements. If there is a lower front entrance and a top front entrance, then the internal flow is likely powered most by buoyancy and flows powered by fanning bees. However, if there is a lower front entrance and a top rear entrance, then the internal flow is potentially powered more by external flows than by buoyancy.

Indian hives that use a burlap inner cover that fits loosely effectively have both a top front and back entrance. This would make the external wind effect the flow inside the hive. The ventilation of the hive could then be very sensitive to wind speed.

[1]Note that some of the extra pressure found could be caused by the outlet at the back having zero pressure and the hive causes some extra resistance.

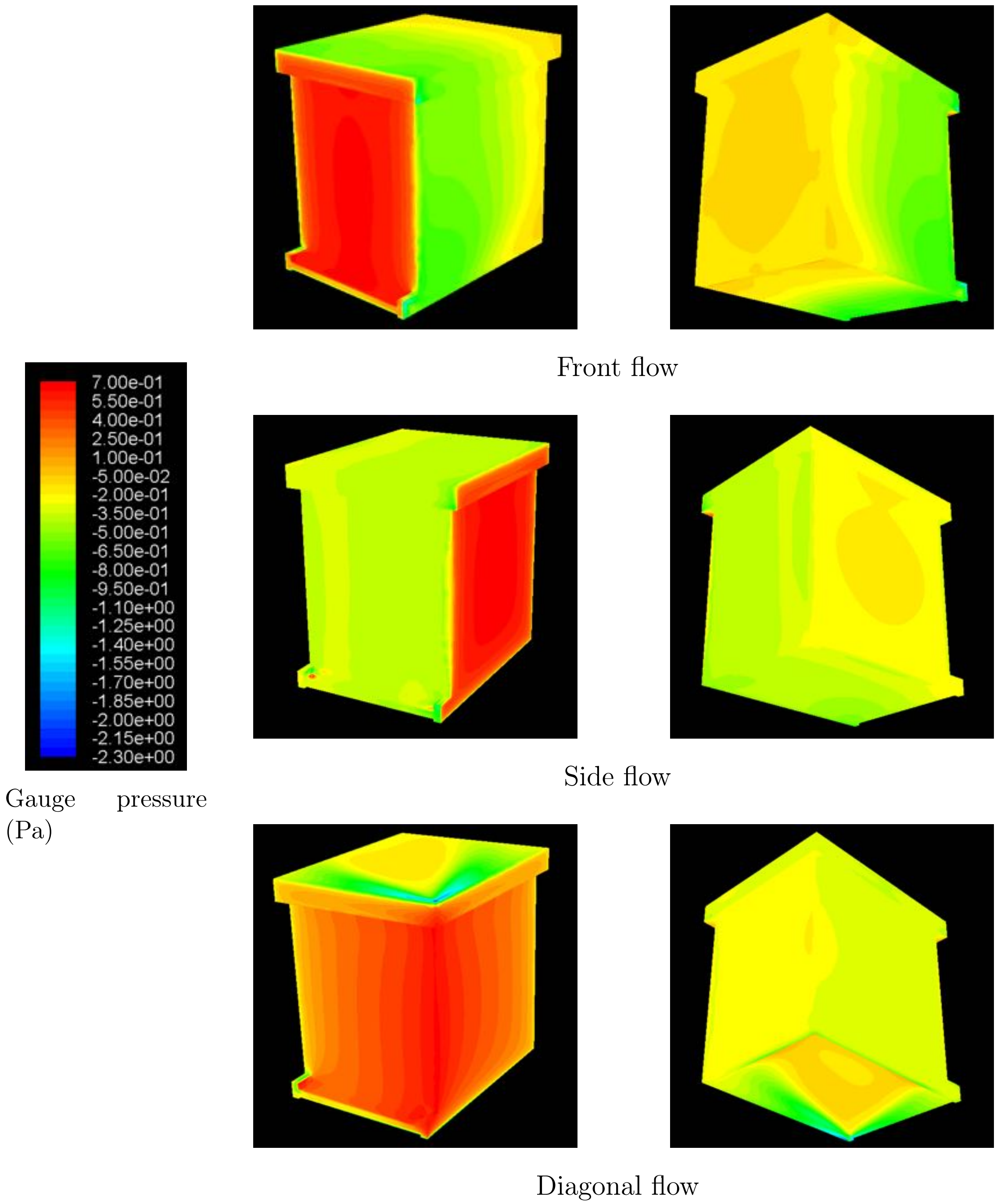


Fig. 11.6. Pressure on hive exterior.

11.2 Indian Application for Painting Hives

In India, it was noticed that many Apis cerana hives are painted dark colors. The Bureau of Indian Standards (BIS) explicitly requests that beehives be painted "white, blue, yellow, green or grey." No details in the standard explain the rational for these explicit colors [17]. The problem is that dark colors tend to absorb more sunlight, heating up the hive. Given the hot conditions the hives face, thermodynamics would suggest painting the hives white.

Sources within India gave different explanations for the dark colors. One of the explanations was that different levels of government giving subsidies for the hives request specific colors of beehives for branding purposes. Another potential reason for the dark colors is that the colors may be directly requested from beekeepers for aesthetics.

The fluid dynamics done in this chapter suggested a way to maintain the color diversity of Indian hives while minimizing the extra heat absorption from dark colors. Fig. 11.5 had shown that the heat transfer coefficient was greatest on the edges and corners of the hive, and thus heat would get wicked away from the hive surface most in these locations. Thus it is possible to paint the edges and corners of beehives nearly any color with minimal thermodynamic effects. Fig. 11.7 depicts how the edges and corners of a hive could be painted.

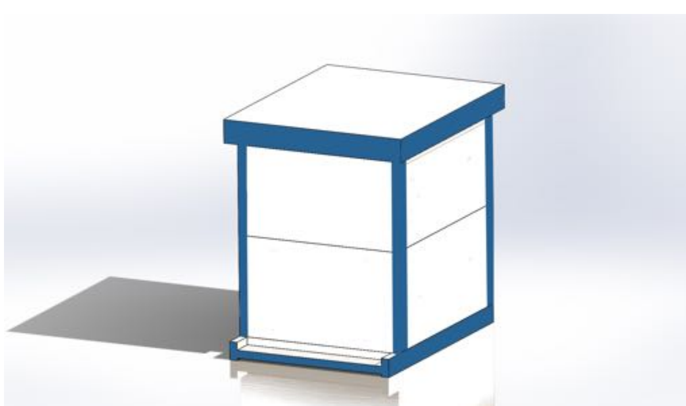


Fig. 11.7. Painting colored hive edges with white faces.

In discussion with beekeepers it was released that the Fig. 11.7 was potentially confusing as it appeared that all of the edges had to be painted. For this reason, the Fig. 11.8 was drafted where just the front strip of the hive is colored. Painting the hive with just the front strip nonwhite is simplest and would most reduce extra heat absorbed from the sun. In addition, having the front strip different colors for each hive may help bees to more quickly identify their hive. Fig. 11.8 (using any color desired for the front strip) is what this thesis recommends for Indian hives in warm climates.

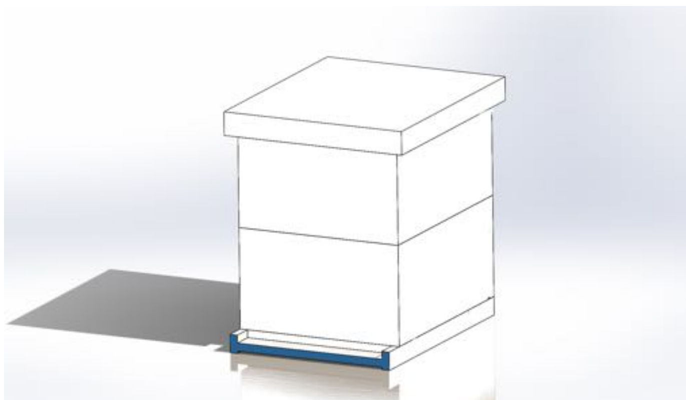


Fig. 11.8. Recommended method of painting hive edges and faces.

Chapter 12

Indian Hive Roofs

Contents

This chapter describes a test intended to measure the effect of shade that led to finding multiple improvements to Indian hive roofs and important insight into Indian beekeeping.

12.1 Motivation

Many Indian hives are placed in full sun. The sunlight causes the bees to have to work harder to keep the hive cool on warm days. Ideally hives in hot climates would be moved into shaded environments.

However getting all the hives under natural shade is not always an easy process. When moving hives, beekeepers have to prioritize multiple factors including availability of flowers and water, distance from a beekeeper's home and other apiary sites, and availability of space. Since migratory beekeepers often move bees at night to keep the hives cooler during relocation, it can be challenging to place hives precisely in a predetermined ideal location. In addition, beekeepers with many hives may underestimate the needed space required for all of their hives, and thus some hives may be moved to less suitable locations. As hives should not be moved short distances under about two miles and renting trucks costs money, once hives are placed, they tend to remain in a fixed location. For these reasons, Indian beehives may be placed in sunny locations that make it harder for the bees to keep the hive cool. Fig. 12.1 shows some Indian hives in the sun.

Fig. 12.1. Indian hives in the sun.

One approach to limit direct sunlight for hives already in a sunny location is to provide some form of artificial shade. Shade could be made by tents or various roof coverings. It was hoped to analyze and quantify the effect of having some form of radiation shielding from the sun.

12.2 Initial Experimental Setup

An experiment was designed where hives could have an extra sheet metal roof elevated about one inch off the hive top cover and extending one inch beyond the top cover. The ultimate goal was to determine how much having this slight extra shade would boost the hive's productivity. Hive productivity would be measured through weight gain over time.

Weight gain of hives can be influenced by many hive dependent factors such as the state of the queen, presence of disease and pests, and overall genetics. Thus to more accurately show the effect of extra shade, it was hoped to control for other hive dependent factors by alternating whether an individual hive received an elevated roof each week. By measuring the relative weight gain with and without extra shade for the same hive, the extra shade might show a statistically significant effect. Fig. 12.2 shows the original plan for alternate treatments.

Shade Test	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week
Week days:	Jun 1 - Jun 7	Jun 8 - Jun 14	Jun 15 - Jun 21	Jun 22 - Jun 28	Jun 29 - Jul 5	Jul 6 - Jul 12	Jul 13 - Jul 19	Jul 20 - Jul 26	Jul 27 - A
Measure weight:	Jun 1	Jun 8	Jun 15	Jun 22	Jun 29	Jul 6	Jul 13	Jul 20	Jul 27
Instructions:	Shaded	Not Shaded	- Number all hives with a marker. - Measure the weight of each hive (in kg) every Monday around the same time of day. - Every week (Monday - Sunday), shaded boxes get the extra metal sheet elevated and other boxes get just the metal sheet. All else is the same.						
General Notes - Medical treatment - Feed bees - Other problems - Migrated - Added supers, etc.	Ex: Fed all bees.								
Hive 1	35.1								
Hive 2	22.4								
Hive 3	40.8								
Hive 4	36.2								

Fig. 12.2. Google Sheets initial testing spreadsheet.

Pictures of the hive roofs showed that many of the roofs were quite dirty and not very reflective. To prevent measuring the effect of a new shiny additional elevated roof vs. a dirty top cover, the experiment was set up such that a "non-elevated roof" would place a layer of sheet metal directly on the old roof. Assuming good contact, the reflectance of the top surface would be same and it was expected that with good contact the additional metal layer would add minimal resistance for the non-elevated roofs.

Three beekeepers, each in Haryana, were found through the NGO All India Organic Farmers Society. Dr. Vinod Beniwal conducted the experimentation. To have sufficient data for the effect size anticipated, each beekeeper would use 100 hives for the experiment. At any time 50 hives would have elevated roofs and 50 hives would have non-elevated roofs.

12.3 Working Through Challenges

Overall the experiment was faithfully conducted to the best extent possible with much care and hard work. The goal was to do the experiment specifically in India to get the most representative data. Throughout the experiment, the challenges in conducting the experiment gave great insight into beekeeping in India.

The first challenge was setting up the experiment. Recruiting and training beekeepers required travel to communicate in person, and the beekeepers chosen happened to be located in opposite directions about one hour from the NGO. Procuring materials in India, especially the professional grade weight scales, could not be simply ordered online. Testing began in late June / early July 2015 when there was not a honeyflow.

Shortly into the experiment some of the metal roofs on the hives were found to have been taken for their recycling value. Due to the risk of additional theft, the roofs were then nailed in and had to stay in only one position for the duration of the experiment. Not alternating the roofs makes it much more difficult to show a statistically significant difference in hive productivity.

Recordings were also taken conventionally by paper and later entered into Excel. While the Google Sheets app would have automatically synced and logged data entry times, the learning curve for such technology is nontrivial and would have required in person instruction. Some extra data was also recorded. Often the temperature and humidity measurement was taken directly above each hive with the time.

To ensure tests were done correctly, the NGO traveled to the beekeepers to help with all weight measurements. As requested, pictures were taken and two representative and cropped photos taken are shown in Fig. 12.3. Fig. 12.3a shows a hive with the roof elevated and Fig. 12.3b shows a roof that is touching.

(a) Roof elevated (b) Roof touching

Fig. 12.3. Roof test photos.

The pictures revealed that the majority of the hives already had natural shade. In addition, it was noticed visiting in August 2015 that the hives with non-elevated roofs typically did not make good contact with the metal top cover. The wood and manufacturing technique of the top covers made it so that roofs tended to be bumpy. From a thermal resistance perspective, any air gap between the two metal sheets could greatly increase the thermal resistance. The natural shade and air gaps could have decreased the effect size.

The data revealed that some of the hives showed large weight fluctuations. What happened and was found out during the site visit was that the beekeepers oscassionally switched frames between the hives. This will be discussed more in the analysis section.

12.4 Analysis

12.4.1 Overall Weight Patterns

It was noticed that multiple hive boxes showed odd changes in the weight. Figure Fig. 12.4 shows the weights of all of the boxes from one week to the next. The third beekeeper had only gone for three weeks toward the end of the experiment.

Many things can be recognized from the weekly weights. First, only the second beekeeper ended up adding an extra super to the hives. This is noticeable by the uncharacteristically large weight gains in week 4-5 and week 5-6. In addition, beekeeper 1 had a few hives that have appeared to have essentially died, as they had very minimal weight.

One interesting pattern is for beekeeper 1 in the week 3-4. The fact that many of the weights reached a fixed upper bound suggests that perhaps frames were added in the hive. The beekeepers explained they would wait to add all of the frames to hives to prevent bugs from getting into unused comb.

When talking with the beekeepers, it was also discovered that they would occasionally swap frames between the boxes. This could have also increased the variation in the changes in the hive weights.

12.4.2 Bearding

To provide an additional quantitative measure besides weight gain, the hives were viewed in the evening when there was a significant amount of bearding. It was the case that bearding was most evident in the evening when roofs on top would be expected to have minimal effect as the sun is not overheard.

Nonetheless, the surface area covered by the bees was estimated by sight for the first beekeeper in one apiary location with 55 hives. The area was estimated as a percent of the front of the hive. After the bearding was visually estimated for each hive, the roof was raised and the number of frames was counted. The data in **??** shows a positive correlation between the number of frames in the hive and the amount of

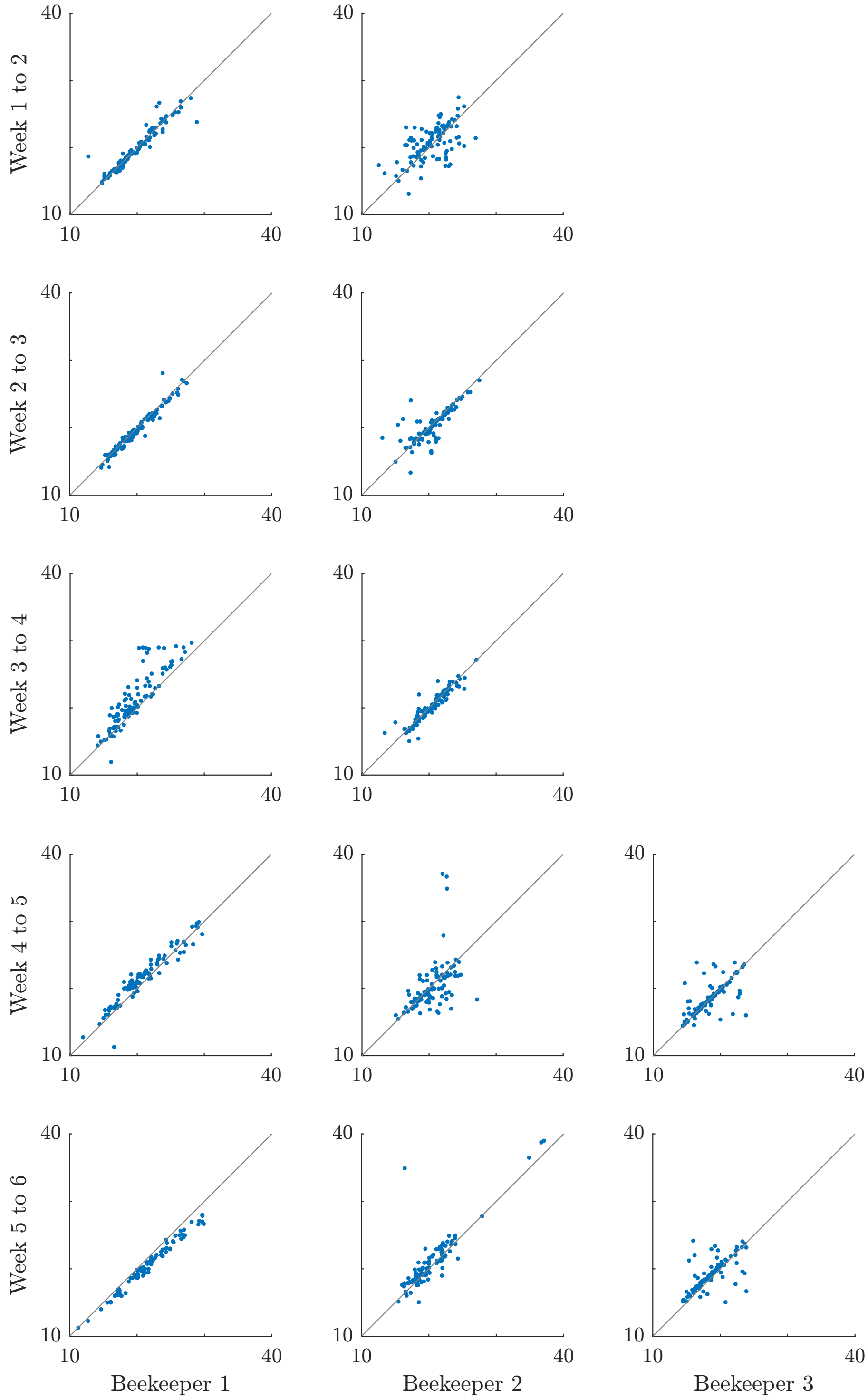


Fig. 12.4. Weekly weight changes. Measured in kg.

bearding.

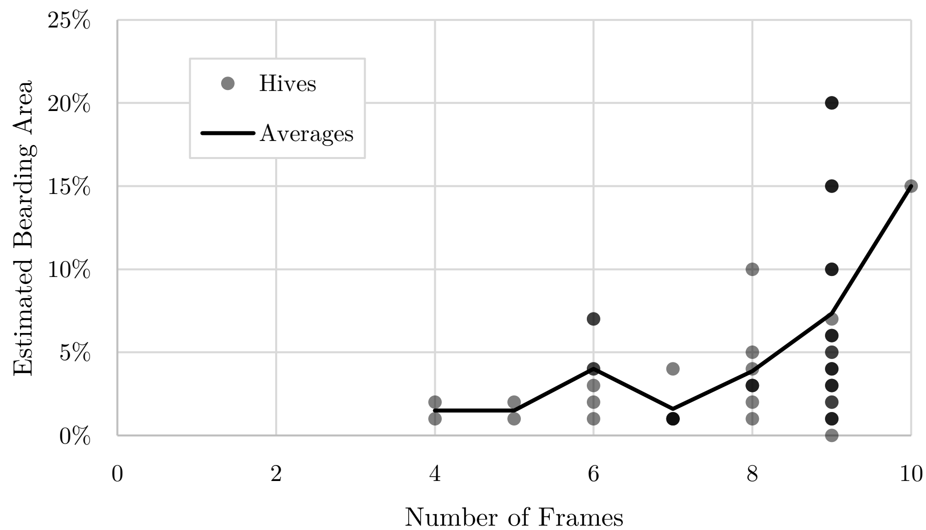


Fig. 12.5. Bearding of hives vs. number of frames. Dots are slightly transparent to convey multiple points.

The data shows a spike for hives filled with all of the frames. (Note the beekeeper often preferred to only use up to 9 frames.) This spike in bearding suggests that many of the 9 frame hives were ready for an additional super, which the beekeeper had not yet provided.

12.4.3 Roof Gaps

One of the unique findings that came from doing this experiment was that there may be a unintentional benefit from the manufacturing technique used in the beehive roofs. Fig. 12.6 shows the underside of one of the roofs. Note that the roof panels were quite warped. One of the results of this is that much of the roof has a slight air gap between the metal and the wood and this can help insulate the hive.

This slight air gap could also be very beneficial for hives in developed countries. Using materials such as small wood chips, rubber offsets, various meshes, or standard insulation, the metal surface could be slightly offset from direct contact with the wood underneath.

Fig. 12.6. Warped boards make air gap.

12.4.4 Other Covers

While no significant differences were shown for the hives tested in the shade, hives in the sun might show an improvement with an elevated roof.

Having an extra layer above the top cover has been used in the past, and a few examples were identified. For instance, Fig. 12.7 shows a custom built Warré hive outer cover where there is an extra gap for air to pass through.

Fig. 12.7. Warré roof with air gap.

In addition, some Indian beekeepers used organic plant material or cloth to improve the insulation of the top. These examples are shown in Fig. 12.8.

Fig. 12.8. Indian roof coverings.

12.4.5 Roof Color

From procuring the supplies for the extra metal roof, it was found that most Indian roofs are made of galvanized iron. In the US beehive roofs are often made from aluminum which is more reflective but more expensive. One way to use the cheaper galvanized iron but make the hive more reflective is to paint the roof white. Fig. 12.9 shows 9 sheets of galvanized iron where three were unpainted, three were painted blue, and three were painted white. The hives were placed in full sun. The testing took place on September 2nd, 2015 around midday in Hisar.

The differences in temperature between the roofs could easily be identified by the human hand. Fig. 12.10 shows temperatures recorded for each of the roofs. The ambient temperature was around 39°C. The wind speed varied from 0.9 m/s to 2.4 m/s.

The white roofs averaged 50.2°C, the blue 55.8°C, and the plain 56.8°C. A two-sided T-test confirmed that the white roofs were significantly different than the blue and plain roofs (each $p<0.01$). The 6.6°C temperature difference between the unpainted roofs and the white roofs strongly supports that beehive roofs for hot regions in India should be painted white - or at least a much lighter color.

Fig. 12.9. Painted roof testing.

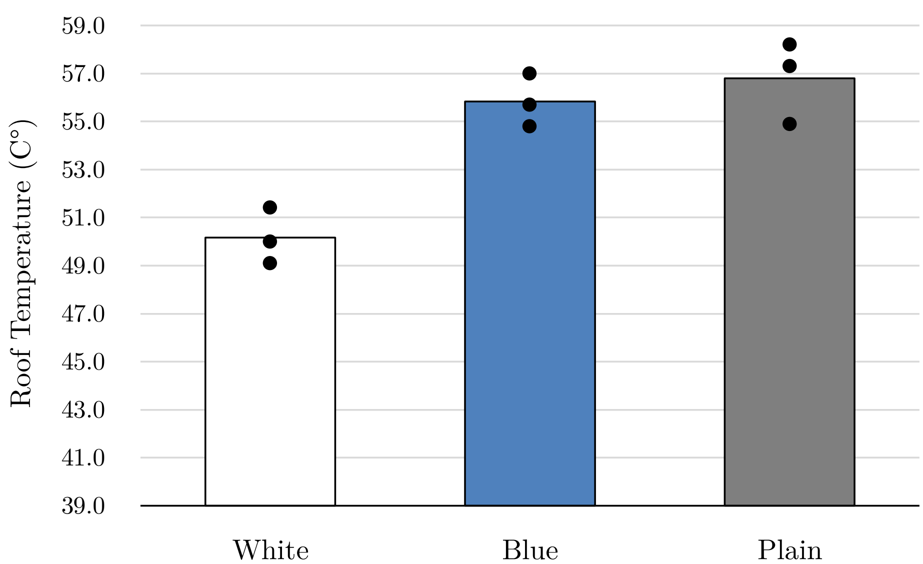


Fig. 12.10. Roof temperatures for different colors. Bars depict the averages and dots depict individual surface measurements. 39°C was the approximate ambient temperature.

12.5 Design of Additional Roofs

The extra metal roof was not a very suitable option for the beekeepers. The edges and corners were sharp and unless nailed in the roofs tended to blow off the hive during the hottest weather. The extra inch overhang on the edges made stacking boxes for migration difficult, although this problem could be avoided if the roof could be made the same size as the top cover. To try to make more optimal alternative roof designs, a few different roof designs were made.

The first alternative roof design was to use bamboo. Local bamboo suppliers in Hisar created a bamboo roof from split bamboo lengths as shown in Fig. 12.11.

Fig. 12.11. Bamboo roof.

The makers of the bamboo roof charged 350 INR (about $5.25 USD) and said for more than 50 roofs, they would reduce the cost to 200 INR (about $3 USD) each.

A second design was considered using tent material. This design is shown in Fig. 12.12. This design only uses nails or staples on the side of the top cover which avoids making holes in the top sheet metal. In addition the design is robust to set up because the sticks can be pushed to the left and right to keep the fabric taut. This material cost for this design was about 10 INR or $0.15 USD.

Fig. 12.12. Tent roof.

12.6 Another Benefit From This Experiment

This experiment initiated the formulation of beekeepers in an organized manner who otherwise were scattered, independent, and without a formal network. Now NABARD (Nation Bank for Agriculture and Rural Development) has chosen an NGO whose president is Mr. Vinod Beniwal for proper training of beekeepers/farmers who will be the stakeholders/shareholders of the company. This company will have one thousand beekeepers. This company will deal in good beekeeping practice, the production and processing of honey, grading, branding, certification, packaging, marketing, and exporting.

Chapter 13

Indian Hive Standards

Contents

This chapter discusses the present state of standardization for Indian beehives with a focus on the current Indian Bureau of Standards *India Standard Beehives - Specification (Fourth Revision)*. This chapter suggests the following:

- There are certain specifications for beehives that matter more than others and some rigid specifications for beehives may inhibit beneficial improvements or price-appropriate options of beehives.

- The current standard for beehive is complex, has conflicting specifications, and is difficult to access. This challenge renders the document nearly impossible to use for proper enforcement of standards or as a guide.

- Ultimately, a careful and considerate plan is needed for improving the standardization of hives. Multiple plans are presented and discussed.

Much effort has been made to provide objective feedback about the standard without saying exact specifications (which would be against Indian law). For this reason, it is encouraged that anyone seeking the exact standard refer to an official copy that can be purchased from the Bureau of Indian Standards.

13.1 What Matters in Standardization

There are benefits of having and following a common set of beehive standards. Here are a few of the most important benefits:

- Interchangeable parts
  - Reuse components such as frames in different bee boxes
  - Make sure beehive boxes are stackable
  - Increase manufacturing competition, lowering hive prices
  - Encourage development of more sophisticated equipment, such as honey extraction tools
- Improve craftsmanship
  - Give recommendations for better manufacturing processes, such as better joint techniques or materials
  - Be able to stop poor practices that could hurt productivity or sales
  - Incorporate best scientific practice
  - Ensure subsidies are well-spent
- Empower beekeepers, hive manufactures, and other stakeholders
  - Ensure quality equipment
  - Increase awareness of best practices

Some specifications, however, are more important than others. Table 13.1 lists a number of hive parts, each with a few specifications grouped by relative importance.

Table 13.1: Specifications and Their Relative Importance

Part	**More Important**	**Less Important**
Frames	Length, depth, and "bee" spacing Inside size for starter comb	Actual frame design How to secure premade comb
Boxes	Inside lengths and common widths	Thickness of the boxes
Entrances	Have a way to be adjustable	Specific design or sizes
Roofs	Cover in metal	Size overhang
Joints	Avoid simple butt joints	Specific joint used

In addition, some specifications ironically may inhibit the creativity and functionality of beehives, and this could be the case if the standard did not allow other features or practical variations. Table 13.2 lists a number of features that may be found in beehives that could improve their quality or desirability while often requiring a higher cost. The actual needs for these sometimes costly beehive features ultimately depends on the regional needs of the beekeeper, balancing functionality with cost.

Lastly, there are cases for which specifications could potentially hurt beekeepers. Here are a few examples:

- Overly strict or unrealistic specifications could render the creation of fully-compliant hives unrealistic for available tools, skills, or stock.
- Unneeded additional features could substantially raise the price that beekeepers and governments would have to pay.
- Substantial changes to the specifications or increases in enforcement could be difficult in the short-term for beekeepers and hive manufacturers.

In summary, different aspects of beehives matter more for standardization, and intelligent variation across beehives could benefit beekeepers depending on their needs.

Table 13.2: Beneficial Variations in Beehive Boxes

Feature or Design	Complexity	Initial Cost	Impact
Screened bottom board	Medium	Medium	Reduces varroa, improves ventilation
Sloped bottom board	Medium	Medium	Prevents water buildup
Higher quality wood	Low	High	Improves durability
Thicker box sides	Low	Medium	Improves durability
Better joints (finger)	High	Medium	Improves durability
Topbar Frames	Easier	Saves money	Cannot migrate, less honey, less disease
Jute cloth on top of hive	Easy	Similar	Improves ventilation
Different paint styles	Easy	Similar	Artistic and may improve cooling
Simpler frame design	Easy	Saves money	Almost as sturdy
Handles	Easy	Varies	Artistic and may help migration
Top ventilation holes	Low	Low	May improve ventilation
Different number of frames	N/A	N/A	(In)compatibility for stacking, easier to lift

13.2 Comments on the Current Standard

In general, the current standard for Indian beehives (the fourth revision) is complex with many specifications, some of which conflict. The complexity and conflicts make it difficult to define a precise standard, and accessing the standard may be difficult.

Part of the complexity has to do with designing beehives for three different bees found in India: Apis cerana cerana, Apis cerana indica, and Apis mellifera. Each of these bees are slightly different sizes and can benefit from different spacing between frames. Additionally, the standard allows different numbers of frames as well as different hive sizes. In total, there are 16 official variations of sizes for the beehives just between the bees, different spacings, and number of frames.

Moreover, there are a few discrepancies within the standard. Table 13.3 lists some of these discrepancies.

A close inspection of the text suggests part of the history of the development of

Table 13.3: Some Discrepancies in Current Hive Standard

Specification	Discrepancy
Wall Thickness	In 6.5.1, the thickness of walls is defined, but the tables that list inner and outer dimensions for beeboxes give conflicting dimensions by up to 5 mm (>3/16 in).
Entrance Design	In 6.1.1, the entrance is specified to only have one centered opening of a specified size. The referenced Figure 1A however shows two openings that require rotation of the entrance rod by 90 degrees, and Figure 2 shows another style of entrance with two openings with an oversized entrance rod that must be flipped 180 degrees to change between two sizes.
Frame Orientation	The forward suggests the fourth revision is designed to have frames aligned with the length of the hive, but Figure 1B and 1C show frames orientated along the width.

the standard. Many of the dimensions, nearly all specified in mm, are very close to common inch measurements. It it is thus probable that the dimensions were taken (potentially directly) from hives made using imperial units. Although this is not necessarily a problem, it gives part of the explanation for some of the discrepancies in sizing as well as explanation for the uneven dimensions from some of the tables. The text tries to rectify the availability of common wood stock - sometimes in metric sizing, but this does not match the tables that largely correspond to imperial sizing.

The many official variations of the hives may reflect the desire of each region in India to be in compliance with the standard, but no one region in India wants to modify their current designs. Thus, the standard provides many acceptable variations with no stated preference for any design.

Lastly, the current standard is only accessible to few individuals. Here are a few limitations that decrease the standard's accessibility to hive manufacturers and common beekeepers:

- The current standard costs money to purchase. As of June 2015, the price is 340 INR from within India.

- Further, the standard is primarily accessible with an online internet connection from a computer or as a physical copy that must be ordered and may take time to arrive.

- Lastly, the standard is in English, with much technical text. With the conflicting specifications, the standard can be difficult to read and interpret.

13.3 Exploring Different Routes to Improve Standardization

This section presents a variety of different routes for improving the standardization of beehives with potential benefits and drawbacks of each approach.

Table 13.4: Potential Routes to Improve Hive Standard

Route	**Action**	**Political Feasibility**	**Impact**
Do Nothing	Keep the status quo	Easy	None
BIS Standard	Modify text to allow more varieties	Fairly easy	Minimal
	Simplify text and drawings	Medium	Medium
	Limit the official varieties	Very difficult	Large
Fines / Subsidies	Crack down on nonstandard hives	Difficult	Large
	Different subsidies based on quality	Medium	Medium
Information	Publicly available quality guide	Easy	Medium
	Vendor and price listing	Medium	Medium
	Build-your-own guide	Medium	Large

13.3.1 The Status Quo

The easiest political option is probably to maintain the status quo. The status quo has a largely unenforceable standard. This may appear favorable to individual hive manufacturers that often receive a substantial portion of their income from government subsidies, and to some beekeepers who may not want to change their hives' design.

From a personal limited but hopefully representative survey of beekeepers, hive manufacturers, and beekeeping media, it is possible to say that

1. A substantial number of hives used do not conform to the standards.

2. There are also two groups of people for whom the BIS standard does not target well. These two groups are:

    (a) Beekeepers who desire to make their own equipment.

    (b) Beekeepers and even hive manufacturers who are in secluded rural parts of India.

There are many beekeepers who desire to make their own equipment largely to save money. These beekeepers with limited knowledge and tools may try to make boxes for themselves. Unfortunately, these boxes can be far from the standard. Sticking with the status quo will continue the creation of boxes far from the standard.

The beekeepers who are very secluded in rural parts of India may not have the tools needed to make the more complex joinery requested by the official standard. Maintaining the status quo will continue their creation of boxes far from the standard.

13.3.2 Options and Challenges to Modify the BIS Standard

The BIS standard could be modified to officially accept a wider array of boxes while improving both compliance and use of the standard. In effect:

- There could be an explicitly stated larger tolerance on dimensions that matter less, such as wall thickness.

- The dimensions and features that do matter, such as inner box dimensions, would then take more focus.

- Preferable dimensions or features could be mentioned as a way to encourage better practices.

These easy to implement changes would make it easier to test compliance while focusing on what matters most.

Another change could be to greatly simplify the requirements and provide more drawings. Here are two simplifications that would help make compliance with the standards much easier with minimal detriment to the quality of the hives:

- The standard currently requires a sloping bottom board. This requirement is not common among most beehives, is exceptionally difficult to make, and can be replaced by simply tilting the beehives forward. It might be useful to state that sloping bottom boards are preferred and also allow a substitution of a screened bottom board.
- The standard currently does not allow butt joints, but butt joints are the easiest to make, and perhaps could be mentioned as a less preferable, but tolerable option. There is also an easy-to-make variation of the finger joint that uses only 1 "finger" on each board such that it can be made by nearly any wood saw.

The standard would benefit from digitally made exploded assemblies that reduce the text wherever possible. This exploded drawing could help to show the rabbets, details of the frames, and other features such as base board variations that would help increase readability and compliance.

It would also be useful to require large numbers to be painted or clearly marked on the outside of the beehives to help encourage more scientific beekeeping practices.

Additionally, it may be possible to reduce the number of official designs from 16 to a more reasonable 7 (4, 8, and 10 frames for the Apis cerana cerana / Apis cerana indica and 10 frames for Apis mellifera). This may need time for the transition in practice, and perhaps a recommended design could be put forward with a 5 year date for which the other designs would be phased out. Admittedly this could be politically difficult.

13.3.3 Using Fines and Subsidies

To tackle the problem of noncompliance both from official hive manufacturers and beekeepers, the enforcement of the standards could be intensified. This may be exceptionally difficult. It may work better to first modify the conflicts in the current standard before resorting to fines.

A potential easier approach is to modify the subsidy scheme to reward better joinery techniques, wood quality, or conformance to specific standards, tested tolerances, or other features. This is currently partially done by reimbursing a fixed percentage of the overall cost, but a different subsidy scheme with either increasing reimbursement rates or fixed allotments for better features might help.

13.3.4 Creating an Open Guide

Here are presented three creative ways to substantially improve the standardization of beehives that might be politically easier to accomplish.

A Hive Quality Guide Written for the Beekeepers

Beekeepers want the best for themselves, so it may be beneficial to provide a guide for them to evaluate the quality of the hives and adherence to hive standards.

The guide could take the form of an online form and/or a paper copy that could be distributed to beekeepers. The contents of the guide could include the following:

- The typical types of wood and their expected lifetime
- The variations of joints and their expected lifetime
- The top 3 measurements to confirm: the inner length, width, and height of the boxes
- Elements of good manufacturing such as no cracks, no warping, painted (preferably light colored)
- Additional features such as screened bottom boards and their benefits
- Whom to contact if hives might not be appropriate

A paper copy could also include a to-scale ruler with the most important dimensions such that the beekeepers themselves could evaluate how well the hives meet the standard.

Vendor and Price Listing

One way to save money overall while increasing the conformance to standards is to list hive manufactures with their stated prices online. By listing the vendors and their prices this could help beekeepers to find the most reasonable price. It might be possible to state a few variations for each hive manufacturers (joinery, different types of wood). Ideally, the hive manufactures would have a way to update their prices online. This site might also list if the hive manufacturers are BIS certified.

This website could also include where to find subsidies currently offered.

A Hive Manufacturing Guide Written for Hive Manufacturers

Part of the challenge of the building Indian beehives is that there is a lack of knowledge sharing about how to create good quality beehives. For this reason, a simplified guide that conforms to the most BIS standards could be made. The guide could:

- State the basic recommended dimensions for beehives
- Show pictures of the assembled beehive and each component
- Describe useful techniques for how to make each component

The guide could be provided to all hive manufacturers at no cost for best implementation. Additionally, it may be useful to have the guide freely online. This would additionally help beekeepers that currently make their own hives better conform to the standard.

In addition, it may be useful to make and provide metal patterns for cutting hive components that could more easily be used both for making hive parts and checking compliance.

Chapter 14

Improving Hive Management

Contents

This chapter describes designs of accessories to beehives to help beekeepers record and track hive health to promote more scientific beekeeping.

14.1 Motivation

Proper hive management may be the single most critical aspect to improving beekeeping. Proper hive management is about making good choices on how to take care of a hive. Good choices require proper identification of pests, diseases, and problems and then taking appropriate actions. One of the critical parts to proper hive management is remembering which hives need help and tracking progress over time.

Easily remembering the health and progress of a hive has many potential benefits. It is often possible to skip or more lightly inspect a hive that has been known to be doing well. More judicious inspections not only save time for the beekeeper, but it also helps to minimize disturbance to the bees.

At present, there is no standard way to remembering the status and progress of hives in both the US or India. US beekeepers have used techniques such as arranging bricks on the roofs in set patterns. [43] One beekeeper in discussion online noted using wax pens that can write information on the top of hives. Usually queen bees are dotted on their backs in colors to mark their age. This requires finding the queen in the hive to recall this information. One of the beekeepers in India mentioned placing a rock on the hives that were sick as an indicator. This is a very appropriate-scale solution to flagging hives that are sick. However, in over 100 hives, only two had rocks and many of the hives were in poor condition. It was clear this potentially useful method was not fully utilized.

Some US beekeepers use dedicated cell phone apps to record detailed information about each of their hives. Examples of this include HiveTracks [39], Beekeeping Hive Manager by Colmena [22], Beesness Hive Manager [11], B-Ware [68], and Beetight [46]. These apps all aim to allow the user to record significant amounts of information. Most of the apps are underdeveloped and unfortunately recording data is time-consuming. Some of the apps are not free and usually use of the app requires not wearing gloves when adding in the information. There may exist other apps in other Indian languages, but most of these apps findable in English had a limited subset of languages supported. Most of the beekeepers I met in India did not have smartphones yet. Smartphone apps may not be the most appropriate means to assist Indian beekeepers improve hive management.

Additionally, none of the standard commercial beekeepers I met in India kept regular written records of hive inspections. At least one Indian beekeeper mentioned keeping records of total honey harvests and prices. Of beekeepers met, only Indian hives used for research included records of hive inspections. Many of the Indian hives additionally lacked numbers that might help identifing one hive from another.

The lack of a widespread hive management system suggests that no solution has been made that is sufficiently convenient and beneficial, especially for Indian beekeepers. It might be that a small investment in creating a convenient method to record and read the status and progress of hives could lead to substantial increases in honey productivity. Section 14.2 highlights a number of design concepts to help record the health of hives.

14.2 Designs

One of the first design concepts shown in Figure 14.1 was to explore if being given a dedicated notebook might motivate the beekeepers to keep track of the hive information. Rather than replicate other hive management sheets (ex: [53]) that list a whole page of factors, this design focused on the most basic parameters to record: the heath of the bees, queen, and honey. Additionally there is a place to keep basic notes needed and star hives that should receive additional attention.

A small book with the hive management design was printed in English. This was presented to Indian beekeepers to see their initial reaction. The notebook did not excite the beekeepers, even after explanation of what the notebook was and how it could be used. There may be beekeepers who would use and benefit from such a notebook, but the limited subset of beekeepers suggested it is unlikely to be adopted widely and regularly used consistently.

The first design of a management device to be located on the hive is shown in Figure 14.2. The concept was that an injection molded device could be fixed to the hives and allow an easy-to-read record of each hive's previous condition. It was designed to track bee population (important for preventing swarming), honey production (exciting for the beekeeper), queen laying (important to know if the queen should be replaced), and pests and diseases. The paper designs overlayed on the plastic were to determine if the beekeepers understood all of the symbols and allow quick modification.

In general, the beekeepers did not immediately understand all of the symbols - especially for the various pests. The slider design also tended to get stuck and was hard to move without being tedious. This prototype showed that creating universal symbols was going to be difficult both in terms of recognition and requiring a good resolution for reading properly. A new design was needed that was more robust to grit that would be faster to use.

Instructions

Record the health of your hives

1) Number all of your hives
2) During each inspection take important notes

A star means an action is needed

Here is an example:

Date: *1-9-15*	Notes: *Warm and sunny*			
Hive	Honey	Brood	Problems, Treatments, Notes	Star
1	*Good*	*Good*		
2	*Low*	*None*	*No queen*	★
3	*Good*	*Full*	*Should split hive or add super*	★
4	*Good*	*Good*		
5	*Good*	*Low*	*Varroa high, should treat*	★
6	*Low*	*Low*	*Gave sugar water*	
7	*Good*	*Good*		

Date:	Notes:			
Hive	Honey	Brood	Problems, Treatments, Notes	Star

Fig. 14.1. Beekeeping notebook. One option explored was if beekeepers might benefit from being given a notebook that would make it easier to maintain hive information.

Fig. 14.2. Hive management slider. It was attempted to explore how to make a method of keeping track of relevant information on the hive itself. The first prototype used paper to allow for easy switching and new designs. The sliders were not robust however to grit and could easily get stuck. A similar cadded and 3d printed version of this demonstrated that it required high resolution to make out and interpret the design.

One of the design concepts, suggested by Prof. Alex Slocum, was an abacus design. This design is shown in Figure 14.3. It was never built as it was hoped to reduce the manufacturing complexity of the design.

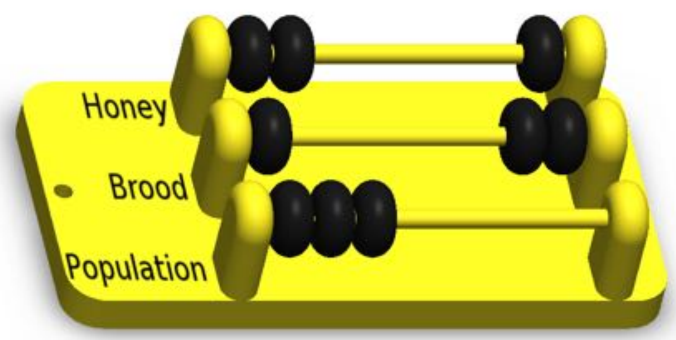


Fig. 14.3. Hive management abacus.

The next design was a peg and hole design shown in Figure 14.4. A hexagon inspired design was laser cut that only tracked two variables: queen health and bee health. One way of increasing the manufacturing rate of this device would be to use a painted stencil. A stencil was created using a waterjet and the design was quickly marked on a longer piece of wood that would double as a hive handle. The peg-in-hole design required a lot of precision for the diameters. A tapered design was used for the pegs, but this required significant machining and would not be practical on a large scale. The creative aspect of building the hive management device into the hive handle was something that got further attention.

Fig. 14.4. Peg and hole design. This design for improving hive management started with a hexagon inspired flat plate that could easily be placed on the hive. The concept was to make it easy to place the small pegs in an easy-to-understand design. Recognizing that for replication, the words and symbols needed to be made faster, a stencil was made and a longer piece of wood that could also serve as a hive handle was created.

Figures 14.5 and 14.6 show a final design where the hive handle has vertical holes (with small drainage holes) that can fit a wide variety of pegs. The design used paint colors rather than symbols to communicate the status of hives. Beekeepers shown this design were excited and suggested that it would be possible to mark the queen and bee simple as 1 and 2 and that they would remember what these two variables meant. This would allow them to innovate to mean other things as needed. The pegs could be replaced easily from simple twigs. Potentially different colors of pegs could also be used to represent other things such as feeding, specific treatments, etc. The beekeepers said they would be willing to pay about 10 INR per hive for this extra feature on hives.

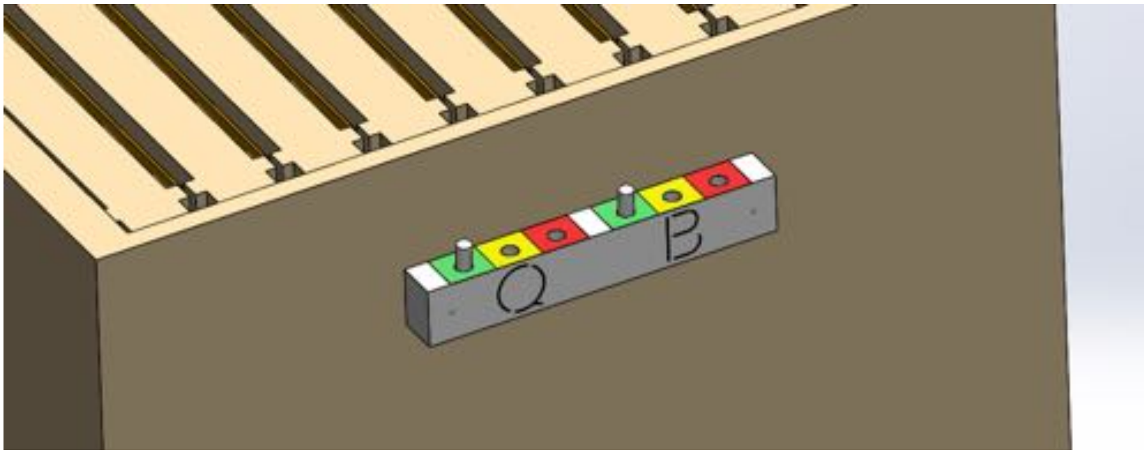


Fig. 14.5. Hive management handle. This was a concept sketch for a handle for which the pegs sit vertical and thus the peg diameter is more robust to size variations.

10 INR more per hive was also something that excited one hive manufacturer. The design takes a small bit of drilling and painting, but it does not require significant extra wood than would already be used for the hive. This appropriate-scale solution could also be sponsored by groups attempting to improve beekeeping in highly cost-effective ways.

One last option to be considered that is an injection molded dial that could be sit on the baseboard front extension. This was a design inspired by seeing one dial system used on a high-end plastic beehive [24]. The injection molded dials could come in a variety of colors to help bees more quickly find their hives to improve hive productivity. The injection molded dials require less labor to directly make, but may not be as environmentally friendly.

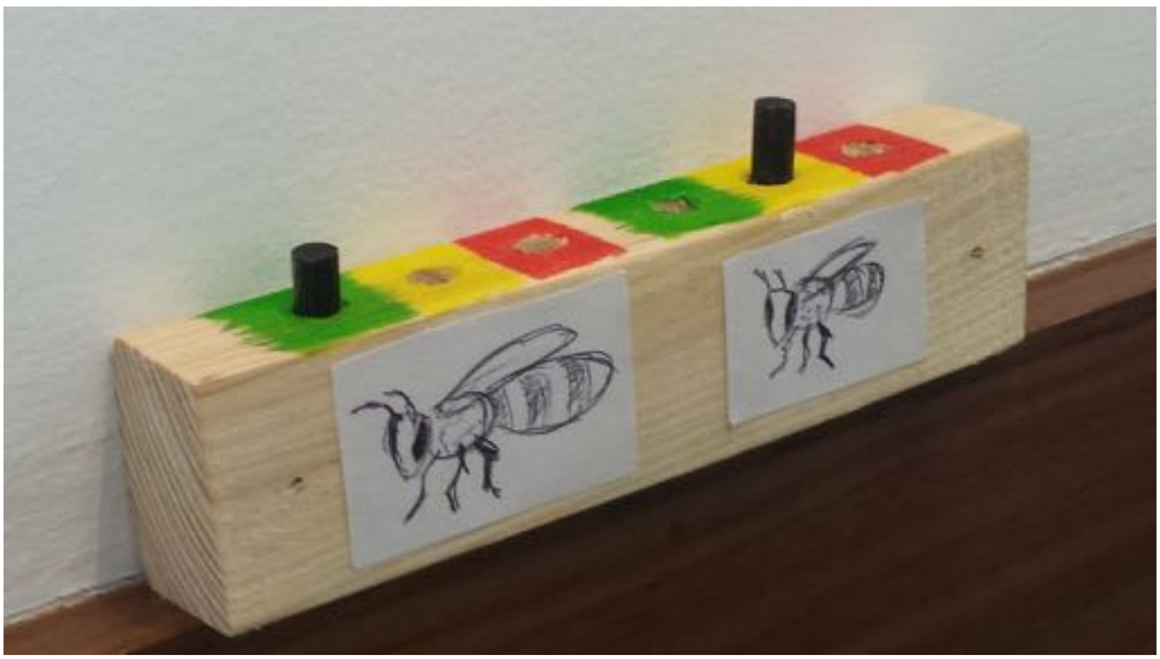


Fig. 14.6. Final hive management handle. Talking with beekeepers revealed that simple twigs could be used for the pegs.

Chapter 15

Other Topics Explored

Contents

This chapter discusses a few other areas of this research. A quick unsuccessful prototype for minimizing varroa was made, a new entrance reducer was design, and a supply chain problem leading to honey crystallization was identified.

15.1 Varroa Mites

Varroa mites are one of the most pressing problems facing modern beekeepers [52] in both the US and India [35]. There have been a number of approaches to reduce varroa mites including better breeding, chemical treatments, killing/removing infested comb, and adding powdered sugar to increase grooming behavior. This section briefly describes some of these techniques and then describes a prototype made to deposit powdered sugar on the backs of bees as they pass though the entrance. The prototype did not work as the bees tended to eat the sugar, blocking the entrance; however similar designs with other powdered substances may be useful for counter varroa.

15.1.1 Current Approaches to Limit Varroa

One approach to limit varroa mites is to breed bees that are more "hygienic" [14] or are better at "grooming." Hygienic bees remove larvae from capped cells that are diseased or highly invested with varroa. Similarly, some bees exhibit good grooming behavior for which they are inclined to be persistent at removing mites off their backs [37]. Classifying and breeding such bees is an area of active research and practice.

Other approaches are to use chemical treatments that cause more damage to the mites than the bees. Chemical treatments include fluvalinate (Apistan), coumaphos (CheckMite), amitra (Apivar), thymol (Apiguard), and formic acid (Mite-Away Quick Strips) [45]. Additionally, oxalic acid is starting to be used by beekeepers in US, but it can be toxic to beekeepers if used improperly. Contacts in India mentioned that US import law does not allow traces of oxalic acid in honey. There have been other techniques tried including various oils [37] and even (tested in India) cow urine [73].

Another approach is a commercially available special frame of drone comb. As the varroa mites prefer to lay their eggs in the drone comb, the beekeepers can apply an electrical voltage through the comb by connecting a battery and generating heat [55]. The drone bee larvae die in the process, but drones are not considered as important to the beekeepers.

Another approach is to sprinkle powdered sugar on the bees in the hive. This is often used as part of integrated pest management for beekeepers who want to avoid using chemicals on their bees. As the bees lick each other clean they are inclined to remove the varroa mites from each other's backs. The sugar may also make it hard for the varroa mites to hold onto the bees. The sugaring technique is reported as limited in its overall effectiveness [59], but it does help and can be used as an additional treatment.

There are a few approaches that have tried to use the hive entrance. One patent application from 2014 proposes using cameras and lasers to burn varroa mites as bees enter and exit the hive [3]. The entrance has been also getting attention as a way to apply chemicals to treat mites. One group has been developing a means to dispense chemicals as bees pass through their entrance which uses concentration gradients to drive consistent doses of treatments [49]. This could potentially limit mites from using robber bees as a way to travel between hives.

None of these approaches fully stop mites, but they all can help to mitigate the problem. Thus there are opportunities for developing additional treatment methods.

15.1.2 Sugar Depositing Entrance Prototype

A prototype was made to deposit sugar on the bees as they entered and exited the hive. The prototype was a design in which powdered sugar could fit in an easy-to-fill box with tunnels that have a screened ceiling. As the bees pass through the tunnel, the hair on their backs dislodges the powdered sugar. Figure 15.1 shows the 3D printed prototype.

Fig. 15.1. Sugar depositing entrance prototype to counter varroa. This prototype was 3D printed and then filled with powdered sugar on top of a screen layer. The design was to have the hairs of bee backs dislodge the sugar that would coat bee backs, encouraging localized grooming. The grooming can help bees remove the varroa mites from each other. In practice the box would have a lid.

Varroa mites tend to stay most on the backs of drones, and so this approach appeared attractive as the drones have a higher height than the queen and the workers. Potentially this entrance design could help focus depositing the sugar more effectively on the drones.

This prototype was tested on hives as shown in Figure 15.3. It was observed that the bees learned there was sugar available and the bees began to block the entrance as they appeared to be consuming the sugar. The prototype also showed that the deposit of sugar was also sensitive to the height of the screen from the baseboard. A better design would keep the screen flat rather than bent and pressed in. Slight curvature of the screen may have limited the contact area.

Fig. 15.2. Testing of the Varroa Prototype showed that the sugar could be localized on the backs of the bees. Sugar did land on the backs of the bees with some on the wings. Over time less sugar was noticeable on the wings of the bees.

To confirm the prototype was working the height was lowered until sugar was visible on the backs of the worker bees. It was observed that less sugar was deposited over time as the sugar became increasingly settled. Figure 15.4 shows how the sugar at the end was stuck such that it was harder to dislodge just by hairs on the backs of the more common worker bees.

This simple prototype and test did not arrive at an effective solution for treating varroa mites. Nonetheless, this concept and design may be useful for inspiring future products to treat mites.

Future researchers may want to consider similar techniques used to coating the backs of bees with chalk dust used by some researchers to track bees. Less attractive substances may be able to change the smell of drone bees likely to be carrying mites. It has been researched that one of the reasons why varroa mites are able to coexist with the bees is that their smell matches that of the bees [54, 23]. It has also been shown that particular compounds inhibit the varroa mites from distinguishing between nurse and forager bees [30]. There may exist a scented powder or liquid that could rub off

Fig. 15.3. Bees backed up at entrance. This was expected as the bees needed to relearn the entrance. However, it also appears there were bees in the entrance eating the sugar and thus blocking the exit path.

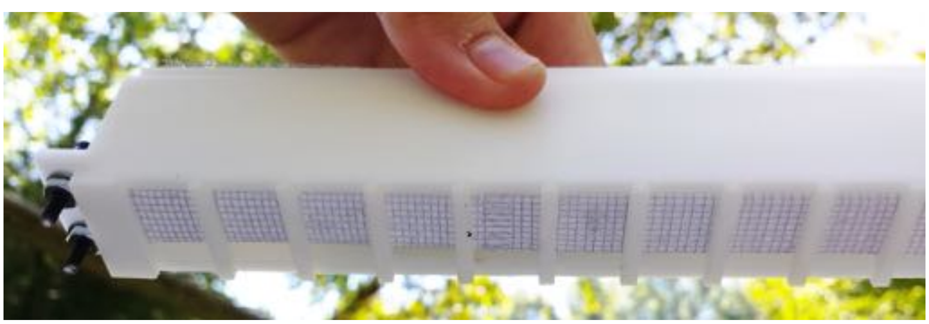


Fig. 15.4. Sugar depositing prototype not dispensing. The sugar in the prototype tended to get stuck over time such that less sugar was getting deposited on the bees.

onto the drone bees to encourage other bees to check them. Lastly, improvements to this design might be to make the sugar get dispensed more easily. Multiple layers or screen with larger holes may help the sugar to be deposited more evenly. Having the bees consume sugar at the entrance may also not be harmful if the rate is slow enough to not encourage robbing.

15.2 Hex Reducer

It was observed that the static hive entrance was limited in changing the size of the entrance to only two sizes (or three if one were to fully remove the entrance). This is a great limitation because a hive could benefit from a more continuous range of sizes. Thus a concept was devised that allowed an entrance reducer whose cross section was hexagonal instead of square. This design allows for three difference sizes instead of just two. This is shown in Figure 15.5. Figure 15.6 shows how the openings must be cut no more than halfway through the block of wood.

Fig. 15.5. The Hex Reducer. This design of an entrance reducer uses a hexagon for the cross-section. This hexagonal shape allows three unique sizes to be made instead of two, improving the functionality of the entrance reducer. Additionally, its iconic shape can make it attractive to beekeepers.

15.3 Preventing Honey Crystallization

During the third trip to India in August and September 2015 a visit was made to Dehradun, Uttarakhand and Guptkashi, Uttarakhand. In Dehradun met was Devb-

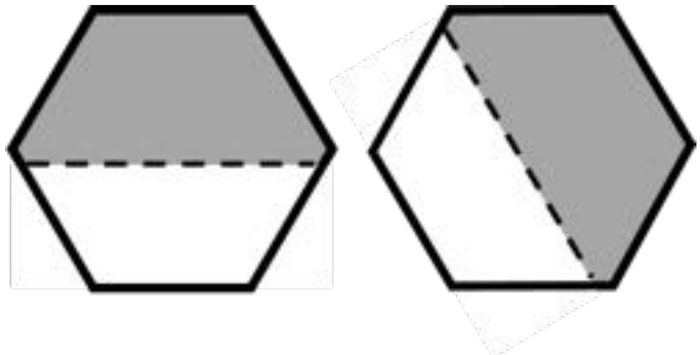


Fig. 15.6. The Hex Reducer Design. The openings cut through the entrance should be at most halfway through to make sure that there is no small opening when tilted.

humi Natural Products Producers Co. Ltd. [27]. The plan was to visit Devbhumi for one day and then the next day travel about 10 hours through the Himalayas to the beekeepers around Guptkashi under the direction of the NGO Appropriate Technology India (ATI) [4]. The beekeepers far in the Himalayas are trained by ATI, and Devbhumi provides a means to sell the honey to a larger market. Figure 15.7 shows a cropped map of the mountainous road through the Himalayas.

Fig. 15.7. Open Street Map: Dehradun to Guptkashi. The processing plant was in Dehradun (left marker) and the honey was collected near Guptkashi (right marker). The arduous 10 hour drive is very mountainous. During rainy seasons the road is often inaccessible. ©OpenStreetMap contributors [60].

In discussion with Devbhumi in Dehradun, it was discussed that one challenge faced is honey crystallization.

Devbhumi had a honey processing and storage facility in Dehradun. However, the honey was being collected in Guptkashi. Due to the long drive, cost of transport, and the natural tendency for the beekeeper to harvest at slightly different times, harvested honey wait in Guptkashi to be brought to Dehradun. This waiting period could be as much as 1 month.

The crystallization problem Devbhumi faced could be mitigated through a fairly simple logistical change: move the processing plant up the mountains and improve the storage facility in Guptkashi. If the processing could be maintained at a consistent quality and the storage facility could be kept warm even during winter, the honey crystallization could slow down.

It is possible that Devbhumi's honey crystallization problem due to logistics is not unique. Since the early effects of crystallization are not visible to the human eye, many beekeepers may not realize how even temporarily storing the honey in the cold and being left unprocessed is beginning crystallization even if not visible. If beekeepers can attest their honey has undergone less crystallization, the market price can be raised.

Chapter 16

Further Research Topics

Contents

One of the goals of thesis was to identify future research topics and opportunities that would benefit beekeepers. This chapter highlights a set of unknowns and compiled research topics that could use more exploration.

16.1 Finding Best Foraging Spots in India

One challenge Indian beekeepers face is suitably migrating hives, which may happen two to four times a year. Part of this challenge is finding the optimal location to place hives. This research project would be to develop a way to 1) analyze the satellite imagery and 2) design an interface for beekeepers to find potentially more suitable locations.

Moving hives can be formidable for new beekeepers unaware of good locations as well as experienced beekeepers who have a lot of hives to manage. The optimal location:

- Needs flowers in bloom
- Avoids crops such as cotton that are likely to be sprayed with pesticides
- Is nearby to a clean water source
- Is shady if warm, sunny if cold
- Has clear space for all the hives or hives can be close together
- Avoids placing on private property without permission
- Avoids locations with bee eating birds in dusty locations
- Avoids locations of high wasp presence
- Avoids flower types during colder seasons that lead to honey that crystalizes faster
- Nearby to farmers that understand that bees help and do not hurt crops
- Nearby to farmers that practice minimal pesticide and herbicide practices
- Close to the home or desired residence of the beekeepers
- Minimizes travel distance from the previous location

Many of these criteria for optimal locations could be assisted by analyzing satellite imagery. Computer vision technology could determine what flowers are being grown and will flower in specific regions. Some of this criteria could be assisted by connecting beekeepers with registered farmers via phone calls. Additional aspects of this project may be linking beekeepers to improve knowledge sharing, assist with moving, and/or improve collective bargaining.

Farmers or farming groups that desire to have bees pollinate their crops may also want to have the ability to post or advertise locations nears their fields.

16.2 Improving Hygienic Behavior to Counter Varroa Mites and Resist Birds

Varroa mites have become one of the greatest problems facing modern beekeepers. It may be possible to develop a method to deposit sugar, scented powder, or liquids on the backs of bees where varroa mites tend to burrow. The sugar or scents may promote grooming and lead to higher mite resistance. Extending the insight gained from the prototype explained in Section 15.1, it may be possible to develop a mechanism to coat the backs of bees. The coating may be sugar that is typically used anyway for feeding. Scents could be used to detect the present of varroa mites.

It has also been shown that certain compounds could inhibit mites from distinguishing between nurse and forager bees. [30]. Thus developing the mechanism to distribute the compounds, especially in less toxic, lower quantities may benefit the bees.

Additionally, careful selection of the coating may deter birds from eating bees in a localized area. If a coating could be applied to bees that is unpalatable, this may deter birds from eating the bees. A solution of this sort would be immensely beneficial to the beekeepers in locations in India and Asia that currently have no adequate solution for countering bee eating birds. There are many substances that birds should avoid [8].

16.3 Improving Top-Bar Hives So Comb Breaks Less

One of the key advantages of Langstroth style frames is that they provide extra support for the wax comb such that it is less likely to break as the beekeeper picks it up. Langstroth hives require more precision to build than top-bar hives that are popular in Africa. Good top-bar beekeepers have to careful never hold the comb sideways during inspections as the comb could break off.

One potential way to decrease the likelihood of comb breaking off would be to make the wood top bars more rough to help the bees attach the wax better. This concept was discussed in a forum [15], but it could be empirically tested and modeled. Other beekeepers have tried ways to add side supports [80]. It would be useful to quantify the likelihood of breaking for any one of these methods.

16.4 Varroa Mite Infestation Image Recognition

Treating varroa mites requires proper treatments and knowing when to treat. While much research has gone into developing effective treatments, less has been done to help identify when to treat. Beekeepers may do routine treatments or try to estimate the varroa infestation to determine if and when treatments would be best. Measuring the level of infestation is usually done in the US with a sticky board dropping, an alcohol wash which kills a few hundred bees, or with sugar dusting which is less accurate. Neither of these identification methods is fast nor free. It would be highly beneficial to develop image recognition technology that could accurate estimate the percentage of bees with mites on their backs from images of brood frames. A sample frame of Indian bees is shown in Fig. 16.1. The varroa mites in this pictures hard to see, but can be found if zoomed on a digital copy. One varroa mite is circled.

This software would be helpful for both US and Indian beekeepers. The technology could be distributed through smartphone applications.

Fig. 16.1. Frame of bees to spot varroa.

16.5 Limiting Bee-Eaters

Many Indian beekeepers mentioned that they would wish they could eliminate the problem of bee-eaters. Bee-eaters are birds that pick off bees usually in the air. These birds can be especially troublesome and may force a beekeeper to migrate. Ultimately, there does not exist an effective solution for bee-eaters.

With limited research time and minimal ability to do testing, tacking the problem of bee-eaters was generally avoided. However, the following Fig. 16.2 shows a basic system diagram of the relationship between bee-eaters and honey bees. This diagram was used to highlight where technology might be useful in avoiding birds in my communication with Indian beekeepers.

Future research on this topic may want to look at encouraging migration of birds in the case of airports. In addition, Apis dorsata can combat the bee-eaters by clusters together and attacking from multiple colonies against the birds [47]. Placing Apis mellifera or Apis cerana colonies near Apis dorsata colonies may provide some natural protection and/or a secondary food source.

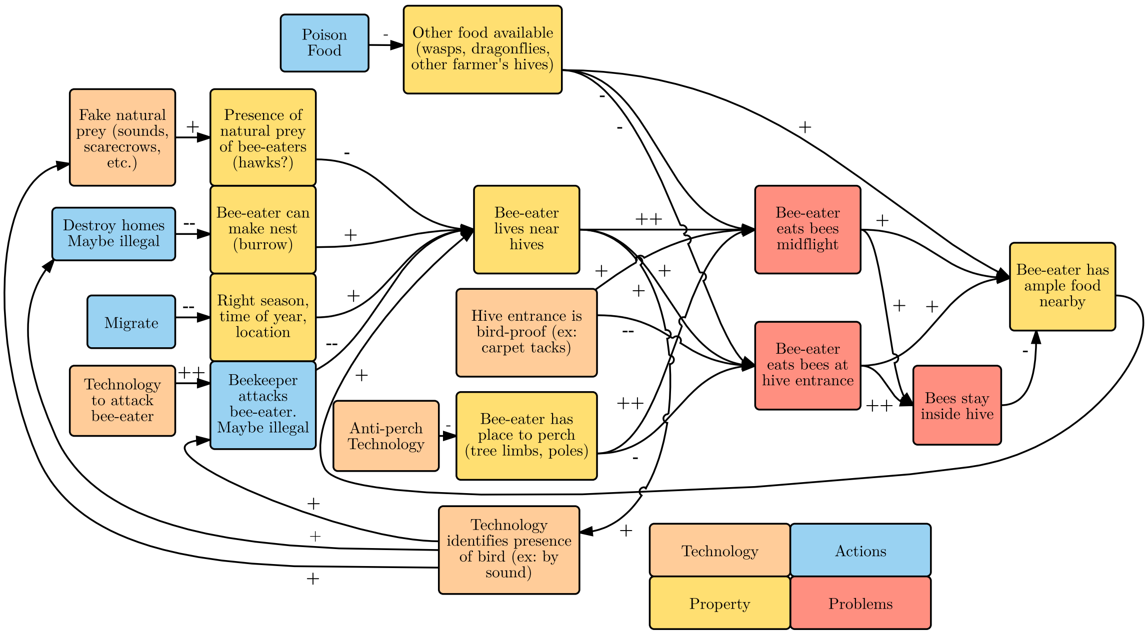


Fig. 16.2. System diagram of bee-eater relationship with bees.

16.6 More Traffic Tests

As queen gates and mesh can be desired to prevent swarming and certain larger pests, a remaining question is if they limit traffic flow and if they are undesired by bees. One quick way to do this test is to laser cut a hardwire mesh replica out of a thin sheet of soft wood and see over time what the bees eat away. Pertinent questions to answer are:

- Does the presence of a queen gate or mesh limit traffic flow?
- Does the presence of a queen gate of mesh limit the effectiveness of fanning?
- If enough openings are provided, is traffic flow limited?

If many smaller openings are provided it may be possible to significantly reduce the impact of larger wasps in India and other predators that could otherwise fully decimate a hive. Even if the wasps could potentially eat some of the bees in flight, wasp presence around hives may decrease for hives wasps cannot enter.

16.7 Improved Honey Extractor

One problem of current honey extractors is that they tend to be severely unbalanced. It can take two people to remove honey from combs: one person to help spin the frames and another to keep the extractor in place. Most beekeepers do not have a surface onto which they can bolt an extractor. This is related to an unbalanced rotor problem. A sample extractor with this problem is shown in Fig. 16.3.

Fig. 16.3. Honey extractor.

Chapter 17

Conclusion

This thesis ultimately explored five keys areas relevant for Indian and American beekeepers. First four hive weight scales mechanisms were evaluated to determine their accuracy. The analysis found that a leveraged pull design with the improvements identified was most promising for a portable hive weight scale mechanism for large hives.

Second, designs of many hive entrances were created and tested to help optimize hives entrances to promote traffic flow, assist ventilation, and exclude pests. It was explained how there is a thermodynamic limit to how much bees can cool hives and so improving hive ventilation and minimizing heat incoming from the hive exterior is needed. Testing of hive entrances showed that ventilation was a problem long before traffic flow became a serious issue. In focusing on hive ventilation, entrance testing in India showed that the standard fixed entrance size was not large enough for full one box colonies and double deep boxes would require an even larger entrance size. Fluid dynamics also motivated a new paint design for Apis cerana hives in which the exterior should be painted all white to minimize heat absorbed from the sun, but the front bottom board extrusion may be painted any color desired without causing overheating.

Third, Indian hive roof experiments led to the conclusion that the galvanized iron roofs should be painted white to minimize the surface temperature. The roof testing identified that hives may unintentionally benefit from having a slight air gap between the metal and wood layers. A few new designs for how to provide localized shade for hives in the sun were created, although it was most recommended to keep hives under full shade in hot and humid areas.

Fourth, these recommendations and others were suggested for improving the Indian hive standards. It was noticed that the Indian hive standards could benefit from focusing on a few key goals: helping boxes to stack, allowing less variations in hive size, and ensuring that frames fit. Other specifications could be relaxed for maximum impact. Communicating the standards in an easy-to-read format for both hive manufacturers and beekeepers is encouraged.

Lastly, designs of hive managements tools were explored to help record and track hive progress to promote scientific beekeeping.

Ultimately, this thesis has identified, tested, and recommended a number of improvements for Indian beehives and beekeeping. It is hoped that beekeepers, bee researchers, beekeeping trainers, hive manufactures, and political officials will heed and further develop these recommendations to benefit the Indian beekeeping community.

Appendix A

Planning

A.1 Planning of Thesis Work

This appendix provides a glimpse of the planning that went into this thesis.

The first major planning started in February 2015 after returning from India and taking a short course called Project Engineering at MIT. The planning consisted of simple sticky notes of all of the chunks of work desired to complete over the course of the spring semester. It was hoped to make a variety of entrances in preparation for summer testing. At the end of the semester, items completed were crossed off as shown in Fig. A.1. In general, few of the original planned tasks were completed, but some CFD progress was made in a numerical fluid mechanics class (2.29).

The main reason for the delay was caused by trying to get legal permission to work with Indian beekeeping researchers. Research project proposals were written and sent off, but it was not fully understood until late summer how much legal agreement documentation (∼100 pages) was needed to collaborate. The timeline for scrutiny and legal approval by MIT would have likely taken 6 months to a year. There was unfortunately no informal collaboration option.

To make sure there would be Indian beekeepers to work with, a collaboration was established with an NGO, the All Indian Organic Farming Society. This collaboration also took time to set up and the experimental plan went through multiple iterations

Fig. A.1. Original planned schedule: spring 2015. Items crossed off had been completed by end of mid-May.

before it suitably met the needs of the beekeepers. Experimentation ended up starting in late June.

Fig. A.2 shows the planned events for the summer and what had been finished by mid-September. Only a portion of these tasks were completed.

Another hurdle was getting enough hives to work with on US soil. Plan A was to get hives on MIT's campus through the MIT Beekeeper's Club. Ironically, after getting full approval for on campus bees from MIT Environmental Health and Safety and MIT Facilities in the spring, there turned out to be an MIT staff member allergic to bees who worried about them being placed outside their building. Due to this concern, the approval process for getting hives to MIT's campus switched hands to the Division of Student Life. Collaboration with the Division of Student Life led to a new agreed location midsummer, but then it was determined that construction planned for the fall of 2015 would make it inhospitable to bees. Ultimately the hives were moved far off campus to a location about 1 hour drive away from campus. Trips to these hives were reserved mainly for other students curious about beekeeping, and

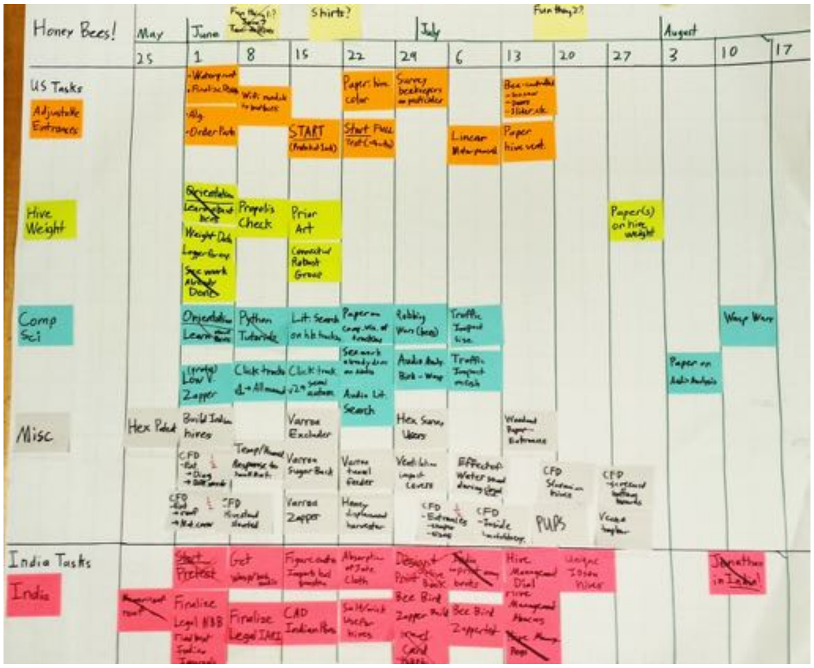


Fig. A.2. Original planned schedule: summer 2015. Items crossed off had been completed mid-September.

so testing at this location was minimal.

Plan B was to use hives at Best Bees in Boston who had graciously allowed use of their hives. However, only about two hives were available at any time and the sporadic movement / swapping of hives meant that experiments needed to be brief and not long-term. Plan C was to use the hives of Debra and Alex Slocum located in New Hampshire. Plan B and C allowed some US experiments to happen, but it was generally limited to short experiments that could be done in one day.

To make the summer more productive there was undergraduate help with hive weighing and computer vision. Managing these projects took time and both projects ended in a partially finished state at the end of the semester. Despite defining accomplishable milestones, it would have been helpful to arrange the project such that earlier milestones would be more immediately useful.

After returning back from India, there was only a month where bees would stay active. A few last experiments were possible in the bit of time that remained warm. Fig. A.3 shows the list of potential tasks. Four presentations were given. No classes were taken to allow more time for writing this thesis. Much time was spent on work on the weight mechanisms as it was something that could be analyzed and tested even without bees active. Ultimately this thesis was written.

Fig. A.3. Fall 2015 tasks. Items crossed off had been completed by end of December 2015

A.2 Recommendations for Future TATA Project Planning

- Working through industry, academia, or nonprofits each have their benefits and drawbacks. Starting your thesis in partnership with the intended distribution channel is likely best. Make sure the incentives align.
- Typically have multiple contacts available for collaboration.
- Always have a backup plan. Preferably have backups to the backup.
- Carefully allot time needed for setting up collaborations and political delays.
- Getting extra help from undergraduates can potentially be helpful. Make sure to recruit for undergraduates early and frame the project in a way where short milestones - even early ones - can directly benefit the project.
- Combining thesis work with projects for classes can be a great win-win.

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