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DESIGN, TOPOLOGY OPTIMISATION AND ANALYSIS OF THREE-DIMENSIONAL PRINTED STINGLESS BEEHIVE BOX

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Abstract— Using a traditional wooden compartment to house a hive for stingless bees presents numerous challenges. Among these issues, one significant concern arises from the gradual decay of the enclosure structure due to temperature fluctuations, forming holes. The wooden compartment is vulnerable to pests that risking potential failure and producing mouldy beehives. Besides, beekeepers face challenges in harvesting honey due to the heavy weight of the compartment and inadequate cover used. The objective of the study was to design a new stingless beehive box using three-dimensional printing method with topologically optimised features to solve the aforesaid problems. This

Optimisation	involved the collection of primary and secondary data through methods such as observation, interviews, and the examination of journal articles. The study then progressed through a series of stages, including the conceptualisation of design ideas, the creation of three-dimensional models, prototype fabrication, numerical analysis, and thorough usability testing. Our results indicated that the proposed stingless hive box design is considered satisfactory, given the incorporation of attributes such as materials with minimal deterioration and increased resistance to pests, a lightweight and low-cost design, user-friendliness, and efficiency in the harvesting process of the honey due to its two-layer structure and improved cover, and appealing aesthetic design. To further enhance the functionality of the box for accommodating the stingless beehive, additional refinements may be warranted.

I. Introduction

Honey, a dense golden substance, is created when honeybees gather, transform, and store nectar and plant extracts in honeycombs for colony sustenance. It serves diverse purposes, such as regulating blood sugar, providing nutrients, aiding wound healing, soothing coughs, enhancing memory, and treating burns. Industries use honey in the production of health beverages, chocolates, cosmetics, and other goods. In Malaysia, various types of honey exist, with stingless bee (*kelulut*) honey being the most prevalent [1, 2]. The stingless bee colonies or also known as trigona species, typically inhabit hollow trees, with colony sizes varying from a few dozen to well over 100,000 bees. The bees construct their hives within hollow tree stumps or branches, where they store the collected nectar [3].

Stingless beehives are typically found on trees with a circumference of at least 30 inches, which have an inner cavity. These hives feature walls crafted from durable, smooth hardwoods like Balau, Resak, Cengal, Keruing, and similar varieties, with a minimum thickness of 2.5 cm. The hive dimensions can vary depending on the bee species and hive size, but a size of 20 x 10 x 10 cm is generally considered adequate.

To facilitate commercial honey extraction, there is a proposal to install boxes in orchards for easier access to hives [1]. The current hive boxes, typically made from dipterocarp wood, face issues in Malaysia's weather conditions. Moisture-related fungus growth due to temperature fluctuations is a common problem [4]. Additionally, pest infestations often result from the holes in the wooden compartments [5]. Based on a study by Tadesse *et al.* (2021), honey production faces significant hurdles, with key constraints identified as the absence of modern technology (92.5%), issues related to absconding (69.5%), challenges posed by pests and predators (46.8%), limited access to credit (28.3%), inadequate extension services (57.4%), a shortage of essential beekeeping equipment (45.2%), and colony mortality (38.05%) [6]. In the present scenario, bee colonies encounter diverse challenges, including climate change, pesticides, and alterations in land use, impacting their growth, reproduction, and overall sustainability [7]. The serious issue of bee colony losses results in not only diminished honey production and quality but also a decline in the pollination services crucial for ecosystem maintenance, posing greater challenges in preserving native plants. Beekeeping exposes individuals to various risks, including the challenges of heavy lifting, extensive manual material handling, twisting, and adopting awkward positions which are common features in agricultural activities. Local beekeepers, utilising traditional wooden compartments, demonstrated that numerous tasks involve awkward body positions, strain on the arms and hands, lifting weights beyond recommended limits, eye strain, and exposure to chemicals and bee stings [8].

Topology optimisation allocates materials efficiently within a design area while adhering to constraints and loads [9]. Essentially, it is a method for shaping material distribution. A well-designed structure aims for even stress distribution within acceptable limits. Removing material from minimally stressed areas is feasible, achieving similar functionality with reduced mass in the final design [10].

Given the mentioned drawbacks of the current wooden hive compartments, it becomes essential to create a new compartment for stingless beehives. The primary emphasis of the present study is on enhancing functionality, ensuring bee accommodation and user safety, minimising harm to users, preserving honey quality, enhancing product durability and portability, and reducing pest intrusion.

II. Materials and Methods

A. User Needs Identification

Prior to proceeding with the design concepts for the hive box, it is imperative to establish user needs. This was accomplished through the implementation of two primary approaches which are observation and interview. To better comprehend the nuances of harvesting and managing the trigona honey, an observation session was carried out at a stingless bee honey production centre which is Bukit Wang Bioasli in Jitra, Kedah, Malaysia. An interview session was also conducted during the observation which included three participants and all of them are trigona honey entrepreneur. The questions encompassed subjects including their daily honey management routines, the characteristics of the harvested honey, their experiences with the beehive box, difficulties encountered in its handling, the risk of injuries during its use, and suggestions for improving the current beehive box design.

The interviewees reported challenges in relocating bee colonies from the current hive box. They highlighted pest infestations as a significant issue impacting honey quality. The existing hive enclosures were deemed inadequate in terms of material, ergonomics, weight, and safety, necessitating increased effort, and causing fatigue during extended operations. They proposed hive boxes that are lightweight, safe, ergonomic, and easy to use while maintaining optimal operational strength.

B. Product Design Specifications

Having reviewed all the data gathered from observation and interviews, the proposed beehive box design should meet the following specifications: 1) low degraded material; 2) lightweight material; 3) modular design; 4) adequate overall size; 5) adjustable or detachable beehive compartment; and 6) safe and ergonomic features. These criteria were then employed in a functional analysis conducted using a morphological chart. In this method, various functions associated with product specifications were suggested and subsequently discussed in a brainstorming session. This process led to the development of eight functional groups for the proposed design: beehive box design, material, pest prevention features, cover design, anti-slumping cover design, type of jointing, cover operating mechanism, and box attachment configuration. Each function was further elaborated into a minimum of three detailed ideas to explore multiple potential solutions. Combinations of ideas from each function were then integrated to generate four distinct design concepts, as illustrated in Figure 1.

To determine the best design concept, a comparative analysis was conducted using concept screening and concept scoring methods, evaluating various selection criteria. A selection matrix, based on user needs, was created for each concept. Additionally, all concepts underwent an additional evaluation to assess the need for revisions. Table 1 presents the data evaluation from the concept screening process for all proposed product concepts, with concept B and concept D chosen for further assessment.

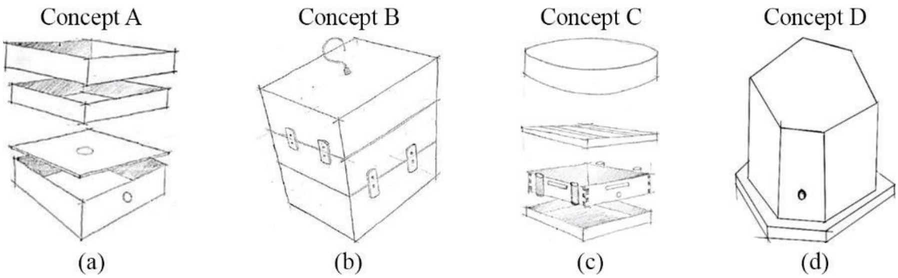

Figure 1: Four distinct design concepts for the proposed beehive box design

Table 1: Concept screening of all design concepts

No.	Selection Criteria	Concept A	Concept B	Concept C	Concept D	Competitor (Reference)
1	Low degraded and lightweight material	+	0	0	+	0
2	Safe and ergonomic	-	+	-	0	0
3	Affordable cost	-	-	0	+	0
4	Adjustable and detachable design	0	+	-	+	0
	Sum 0’s	1	1	2	1	4
	Sum –’s	2	1	2	0	0
	Sum +’s	1	2	0	3	0
	Net Score	-1	1	-2	3	0
	Rank	3	2	4	1	0
	Continue?	No	Yes	No	Yes	No

Concept B and concept D underwent comprehensive evaluation during the concept scoring phase to identify the most suitable design. Table 2 illustrates the concept scoring process for concept B and concept D. Notably, concept D achieved the highest total score when compared to concept B, leading to its selection as the final design for further development.

Table 2: Concept scoring data for concept B and concept D

No.	Parameter		Concept B		Concept D	
	Selection Criteria	Weightage (%)	Rating	Score (%)	Rating	Score (%)
1	Low degraded and lightweight material	0.4	3	1.2	4	1.6
2	Safe and ergonomic	0.15	3	0.45	4	0.6
3	Affordable cost	0.1	3	0.3	4	0.4
4	Adjustable and detachable design	0.35	3	1.05	4	1.4
	Total Score	1.0	3.0		4.0	
	Rank		2		1	
	Develop?		No		Yes	

C. Three-Dimensional Modelling, Topology Optimisation and Prototype Fabrication

A three-dimensional (3-D) model of the selected design was created using computer-aided design (CAD) software, specifically SolidWorks. The model was built utilising various modelling features within the software, including revolved, extruded cut, extruded, mirrored, and shell features. Figure 2 (a) depicts the 3-D model of the beehive box design. Then, topology optimisation was performed using related tools in ANSYS software to construct an improved design that targeted to decrease volume and structural strain energy while maintaining the strength.

The optimisation process was executed using linear static analysis as solver through design and material domain definitions. The linear static analysis aims to calculate the mechanical stress value of a given design space, Ω, discretising it into a set of small subspaces, *N*. The overall equilibrium equation is shown in Equation (1).

$$[K]\{u\} = \{F^a\} \tag{1}$$

where:

$\left[K\right]=\sum_{m=1}^{N}\left[K_e\right]=$ total stiffness matrix; $\left\{u\right\}=$ nodal displacement vector; $N=$ number of elements; $\left[K_e\right]=$ element stiffness matrix; and $\left\{F^a\right\}=$total applied load vector.

The stress is related to the strain as shown in Equation (2).

$$\{\sigma\} = [D]\{\varepsilon^{el}\} \tag{2}$$

where
$\left\{\sigma\right\}=\left[\sigma_x \quad \sigma_y \quad \sigma_z \quad \sigma_{xy} \quad \sigma_{yz} \quad \sigma_{xz}\right]^T=$ stress vector; $\left[D\right]=$ elastic stiffness matrix; $\left\{\varepsilon^{el}\right\}=\left[B\right]\left\{u\right\}=$ elastic strain vector; and $\left[B\right]=$ strain-displacement matrix.

To conduct the topology optimisation analysis, the geometry was transformed into a 3-D finite element model utilising a ten-node solid tetrahedral element with three degrees of freedom. The model comprised a total of 28,448 nodes and 16,118 elements. Adopting 3-D finite element analysis (FEA) provides a more accurate representation of complex structural behaviours by considering 3-D effects, offering a comprehensive understanding of deformations and stresses. This surpasses the limitations of two-dimensional (2-D) FEA, enabling a more realistic simulation that accounts for spatial variations and enhances the precision of engineering analyses.

Applying a 100-N vertical force directed perpendicular to the bottom cover of the box, with fixed constraints on the bottom surfaces, and using acrylonitrile butadiene styrene (ABS) as the main material with the elastic modulus of 2.5 GPa [11] and Poisson's ratio of 0.35, resulted in the attainment of a favourable material distribution as shown in Figure 2 (b).

Overall, the proposed design comprises a top cover, an acrylic plate, a beehive compartment, a bottom cover, and a hinge set. The dimensions are 285 mm in width, and 210 mm in height. The 3-D model files were properly saved in appropriate format in the SolidWorks. A thorough examination of the files was conducted before creating the initial product mock-up for the initial functional assessment. The process then advanced to prototype manufacturing using both 3-D printing and metalworking works. The 3-D printing method allows for intricate designs that optimise ventilation and space efficiency, promoting a healthier environment for the bees. Additionally, it enables cost-effective customization, adapting to specific hive requirements with ease. Figure 2 (c) shows the completed prototype.

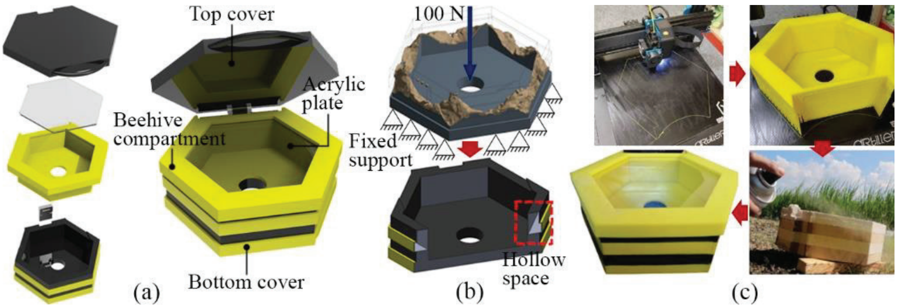

Figure 2: (a) Three-dimensional model of the design (b) Topologically optimized design to reduce weight and cost (c) Prototype fabrication processes

D. Usability Testing

The operational and functional aspects of the finished prototype were put to the test. The evaluation was carried out at the Bukit Wang Bioasli stingless bee honey production center in Jitra, Kedah, Malaysia.

III. Results and Discussion

A. Computational Analysis Results

The outcomes from the 3-D linear static Finite Element Analysis (FEA) in topology optimisation were displayed in terms of the highest magnitude and the dispersion of equivalent von Mises stress within the bottom cover (critical part). Visual representation of stress pattern in the model were achieved through spectrum colouring scale, with red indicating the most critical areas and blue signifying the least critical regions. Based on the results, the model subjected to topological optimisation showed a reduced maximum stress level, measuring 257.66 MPa, in contrast to the model lacking topology optimisation, which registered a higher value of 266.83 MPa. The difference in percentage was only approximately 3.5%. Figure 3 illustrates that the critical stress zone was located at the entrance hole's edge on the bottom cover for both optimised and non-optimised designs. The areas covering the vertical wall of the bottom cover experienced minimal stress levels (blue). The reason why the non-optimised design yielded a higher stress value compared to the optimised one may be attributed to the greater volume of the structure, which subsequently enhances its ability to withstand the applied load. In contrast, the optimised model's reduced volume has led to a more even distribution of stress within the structure. Chen *et al.* (2022) previously explored bi-material structures and similarly noted a decrease in the maximum stress value within the optimised model [12]. When subjected to a three-point-bending test, the stress concentration in the joints exhibited a significant decrease compared to traditional flat and zigzag joints, resulting in a notable 120% to 143% improvement in flexural strength compared to the zigzag joint [12].

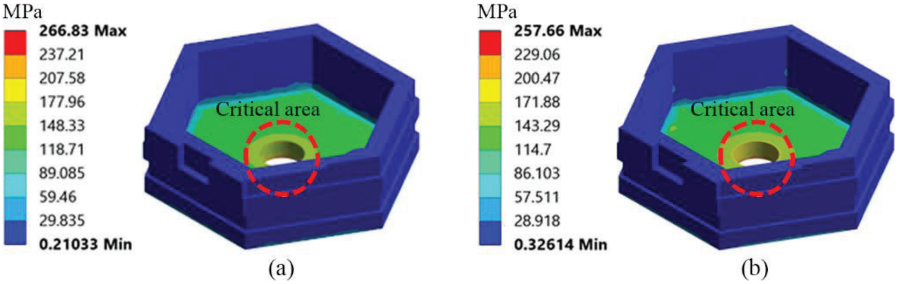

Figure 3: Color contour plot of equivalent von Mises stress within the bottom cover for (a) non-optimised and (b) optimised designs

In both designs, the maximum stress levels were notably below the yield strength of ABS, which stands at 50 MPa. The non-optimised and optimised designs exhibited stress levels approximately 5.34 and 5.15 times lower than the threshold, respectively. Overall, the topologically optimised model displayed approximately a 5% improvement in structural strength compared to its non-optimised counterpart.

B. Usability Testing Results

The completed prototype of the beehive box was tested to assess its functionality and effectiveness. Regarding the operation of the product, it follows a straightforward and simple process. Initially, a wooden stump accommodating a group of stingless bees of appropriate size was prepared, with the wood stump being cut until the bees' eggs become visible. Subsequently, the bottom surface of the bottom cover was glued and securely attached to the top surface of the wooden stump. The box is then left undisturbed for a 2-week period to allow the stingless bees within the wooden stump to generate propolis and subsequently create honey cups inside the hive compartment of the box. After this 2-week interval, the top cover can be opened, the hive compartment lifted from the bottom cover, and the acrylic plate gently removed from the hive compartment to detach the honey cups for the purpose of harvesting. The honey produced within these cups can then be collected as shown in Figure 4.

This new hive box design offers several advantages. Firstly, no pests were found inside the hive compartment that could potentially impact the honey cups and propolis. This could be attributed to the nature of ABS, which is uninviting and unattractive to pests, thus preventing them from entering the compartment. Secondly, unlike wood compartments where honey cups are typically firmly attached to the hive compartment, in this design, the honey cups are not rigidly affixed due to the presence of acrylic plate. This feature simplifies the harvesting process. Additionally, the hive box is user-friendly, making it easy to handle, install, and transport to different locations during the harvesting process.

In contrast, the suggested hive box achieves a significant reduction of approximately 50% in mass or material usage compared to the conventional wooden compartment, all while maintaining optimal strength. The commercial product typically weighs around 2.1 kg, which is comparatively heavier than our innovation, which weighs just about 1 kg. Regarding cost, the optimised design (~MYR 300) has the potential to reduce the expenses by approximately 40% when compared to the cost of the traditional beehive box (~MYR 500).

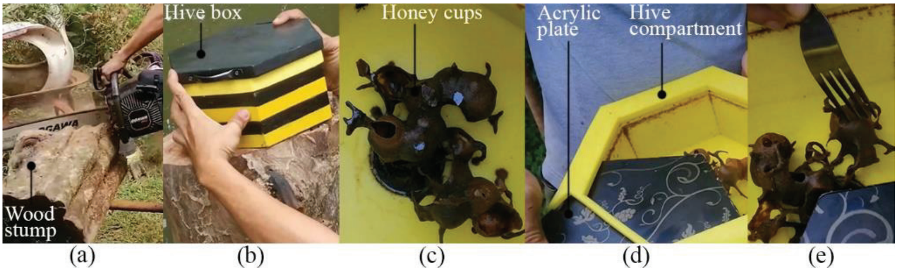

Figure 4: (a) Cutting the wood stump (b) Placing the hive box on top of the wood stump (c) Honey cups inside the compartment (d) Sliding out the acrylic plate (e) Pitting the honey cup for harvesting purpose

IV. Conclusion

It is evident that the proposed beehive box design has yielded satisfactory outcomes. The stress within the optimised design structure falls within acceptable limit (with 3.5% lower stress level than the original model), demonstrating its ability to withstand the applied load. The enhanced operational mechanism of the hive box, with its emphasis on reducing material degradation, pest attack, weight (50% lighter) and cost (40% lower), safety enhancements, and ergonomic features, serves to mitigate or even prevent unfavourable situations. As a result, this innovative beehive box design is poised to address the shortcomings of existing wood compartment effectively. In future endeavours, it may be essential to explore advanced materials for improved durability and investigate sustainable design approaches in alignment with environmental considerations. Furthermore, a promising avenue for future research involves integrating machine learning algorithms to dynamically adapt beehive structures based on evolving bee behaviours and environmental conditions.

V. Acknowledgments

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VI. References

[1] M. Z. Mustafa, N. S. Yaacob, and S. A. Sulaiman, "Reinventing the Honey Industry: Opportunities of the Stingless Bee," (in eng), *The Malaysian journal of medical sciences : MJMS,* vol. 25, no. 4, pp. 1-5, Jul 2018, doi: 10.21315/mjms2018.25.4.1.

[2] W. J. Ng, N. W. Sit, P. A. Ooi, K. Y. Ee, and T. M. Lim, "Botanical Origin Differentiation of Malaysian Stingless Bee Honey Produced by Heterotrigona itama and Geniotrigona thoracica Using Chemometrics," (in eng), *Molecules (Basel, Switzerland),* vol. 26, no. 24, Dec 16 2021, doi: 10.3390/molecules26247628.

[3] M. Kieliszek *et al.*, "Recent advances and opportunities related to the use of bee products in food processing," *Food Science & Nutrition,* vol. 11, no. 8, pp. 4372-4397, 2023/08/01 2023, doi: https://doi.org/10.1002/fsn3.3411.

[4] S. Dedesko and J. A. Siegel, "Moisture parameters and fungal communities associated with gypsum drywall in buildings," *Microbiome,* vol. 3, no. 1, p. 71, 2015/12/08 2015, doi: 10.1186/s40168-015-0137-y.

[5] W. Ebling, "Chapter 5 Part 1 - Wood-Destroying Insects and Fungi," in *Urban Entomology*, 2002, pp. 128-167.

[6] B. Tadesse, Y. Tilahun, W. Woyamo, M. Bayu, and Z. Adimasu, "Factors influencing organic honey production level and marketing: evidence from southwest Ethiopia," *Heliyon,* vol. 7, no. 9, p. e07975, 2021/09/01/ 2021, doi: https://doi.org/10.1016/j.heliyon.2021.e07975.

[7] M. C. Robustillo, C. J. Pérez, and M. I. Parra, "Predicting internal conditions of beehives using precision beekeeping," *Biosystems Engineering,* vol. 221, pp. 19-29, 2022/09/01/ 2022, doi:

https://doi.org/10.1016/j.biosystemseng.2022.06.006.

[8] D. I. Fels, A. Blackler, D. Cook, and M. Foth, "Ergonomics in apiculture: A case study based on inspecting movable frame hives for healthy bee activities," *Heliyon,* vol. 5, no. 7, p. e01973, 2019/07/01/ 2019, doi: https://doi.org/10.1016/j.heliyon.2019.e01973.

[9] Y. Gupta *et al.*, "Design of dental implant using design of experiment and topology optimization: A finite element analysis study," (in eng), *Proceedings of the Institution of Mechanical Engineers. Part H, Journal of engineering in medicine,* vol. 235, no. 2, pp. 157-166, Feb 2021, doi: 10.1177/0954411920967146.

[10] K. Zhang, G. Cheng, and L. Xu, "Topology optimization considering overhang constraint in additive manufacturing," *Computers & Structures,* vol. 212, pp. 86-100, 2019/02/01/ 2019, doi: https://doi.org/10.1016/j.compstruc.2018.10.011.

[11] S. Residori, S. Dul, A. Pegoretti, L. Fambri, and N. M. Pugno, "Three Dimensional Printing of Multiscale Carbon Fiber-Reinforced Polymer Composites Containing Graphene or Carbon Nanotubes," *Nanomaterials*, vol. 12, no. 12*,* doi: 10.3390/nano12122064.

[12] X. Chen, Q. Yang, L. Qu, Y. Wang, F. Wang, and D. Li, "Stress-concentration reduction and mechanical performance improvement of Cf/SiC composite-to-superalloy joints by using topology optimization," *Materials & Design,* vol. 216, p. 110537, 2022/04/01/ 2022, doi: https://doi.org/10.1016/j.matdes.2022.110537.