ADDITIVE MANUFACTURING AS AN ENABLER OF ENVIRONMENTAL SOLUTIONS TO ADDRESS FOOD SECURITY

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Abstract. Pollinator decline is prevalent around the globe threatening food production, yields and the economic income of farmers. With reducing yields, land cultivation increases compromising natural habitats. Aligned with the UN Sustainable Development Goals of no poverty and zero hunger, the creation of artificial bumblebee nests enables a means to address habitat shortfalls. Considerations around preventing predator attacks, withstanding external environmental elements and creating a stable internal habitat were critical for success. Utilization of polymers with opacity and strength characteristics were important, whilst allowing for low volume prototype manufacturing methods (vacuum forming using additive manufactured formers). Subsequent design iterations utilised additive manufacturing as the primary production process, focusing on redistributed manufacture to enable rapid deployment in areas of crisis. Initial results from simulations and physical testing evidence the feasibility of the design in terms of strength, durability and environmental suitability. Deployment of six prototype units, with three artificially introduced bumblebee colonies, demonstrated a sustained natural reproduction cycle for a season. Subsequent deployment of empty units observed a successful wild queen habitation and sustained colony production over a season. Further field testing will ascertain how bumblebees utilise their nests long-term to drive future decisions on design and materials for environmental sustainability.

Keywords: Additive Manufacturing, redistributed manufacture, environmental solutions, crisis response, bio-inspired design.

1 Introduction

Aside from their intrinsic beauty, bumblebees are amongst the most ecologically and economically important of the many insects that pollinate our crops and wildflowers, ensuring secure food production [1, 2]. Ongoing mass declines threaten these key ecosystem service providers [3, 4] and bumblebees are suffering the most severe declines of all pollinators [5]. Although we have known for over 20 years that bumblebee populations are diminishing [3], declines are continuing despite efforts including Agri-

Environment Schemes (AES) and sustainable agriculture [6]. These continued reductions indicate the methods we have employed to support population growth are not sufficient to completely address pollinator decline [7].

Contemporary pollinator conservation has been focused on feeding bees by planting wildflowers [8], but bees do not subsist on food alone. Nest sites have largely been ignored by AES resulting in two significant implications for wild bees: critically limited understanding of what makes a good nest site [9, 10] and the reduction in availability of nest sites due to intensive agricultural land management [11]. To address this shortfall and increase nest sites for bees, two distinct strategies can be employed: create wild habitats or install artificial nest boxes. The latter offers an immediate response for areas in pollinator crisis and has the potential to address the food security concerns of the future. However, despite rapid advances in materials science and manufacturing technology [12], bumblebee nest box design has not developed since the 1980s. Commercially available bee nests for horticulture are currently cardboard or ceramic-construction, which presents numerous limitations for use outdoors including lack of weather resistance and vulnerability to predators.

2 Materials and Methods

Limited prior studies concerning the development of artificial bumblebee nests make it challenging to definitively specify the requirements for optimum conditions. Nest site choice is predicated on many factors, most of which are poorly understood [9], yet dark and enclosed spaces are a consistent recurring theme. Most of the more common species of ground nesting bumblebee prefer dry, dark cavities and nests can turn up in a variety of unexpected places such as abandoned rodent holes, under garden sheds and in compost heaps [13, 14]. However, contemporary boxes used for commercial colonies are translucent, allowing ingress of natural light. Utilization of opaque material to limit light ingress was therefore promoted as a requirement of the nest design, limiting light ingress to reduce any light induced stress. Strength requirements are governed by deployment location and proximity to predators or curious animals. Typical deployment locations may be shared with small ruminants such as goats, therefore there was a requirement to withstand accidental force applied from a misplaced hoof. Additionally, a secure fastening and installation method was essential to prevent predators such as badgers, that have been known to destroy artificial nest boxes to access honey. The optimum internal cavity size can be approximated utilizing data on the average Bombus terrestris nest size and analysis of opportunistic nest sites such as upturned plant pots. A domed cavity with diameter 200mm and height 125mm was designed to best fulfil the volumetric requirement. Additional requirements included subterranean access to the nest as is typical for Bombus terrestris, management of faecal matter to reduce pathogens, environmental resistance over a prolonged deployment period ($n \geq 2$ years) and camera access port for assessing occupation status.

The design of the artificial nest box consisted of an upper dome and a lower base, sandwiching a gasket at the adjoining rim to prevent water ingress, held together with retainer clips. The base was designed to support a raised perforated platform, allowing faecal matter to collect away from the wax cells of the bumblebee nest, and with an opening for a subterranean entrance tube. A flat disc depression added to the dome component allowed the addition of a housing for data capturing electronics (Fig. 1). Acrylonitrile butadiene styrene (ABS) offered a balance of opacity, formability and strength, for the batch production of six prototype units via vacuum forming.

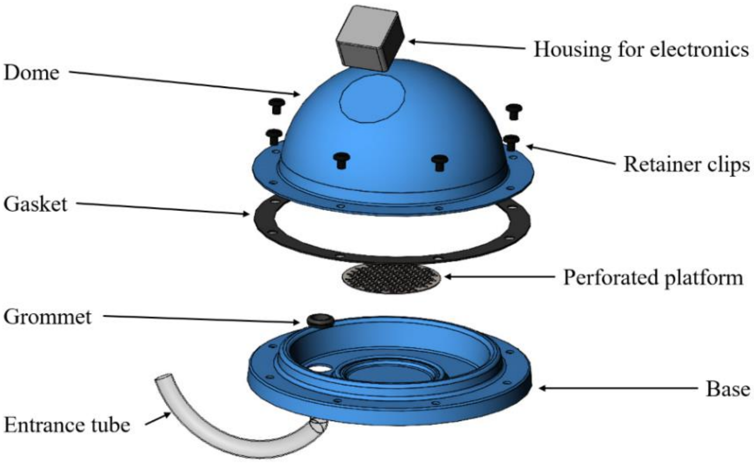

Fig. 1. Exploded view of artificial nest box design

To determine the thickness of material required, the draw ratio (D) was calculated using the surface area (SA) and footprint (F) of each component (Equation 1; Table 1). Draw ratio is defined as the proportion by which the material thickness will reduce during the forming process.

$$D = SA/F \tag{1}$$

Table 1. Component surface area, footprint and calculated draw ratio.

Component	Surface Area	Footprint	Draw Ratio
Dome	1000cm^2	615cm^2	1.62
Base	1032cm^2	615cm^2	1.68

Therefore, if the desired thickness of the final components is 2mm, a sheet of 3.36mm thickness is required. 3.5mm ABS sheet was therefore chosen as the closest standard size to ensure the final wall thickness remained greater than 2mm.

Stress analysis was undertaken on the upper dome of the nest box, to determine whether it would withstand the accidental load from an adult male goat. Given an adult male goat typically weighs no more than 90kg and assuming that the shape of the dome prevents the total weight of the goat to be applied, a value of 60kg was chosen as the worst-case load scenario (half a 95-percentile male goat = 45kg plus a safety factor (SF) of 1.33). 2mm thickness ABS was specified and the load was applied over a circular area of 30mm diameter at the top of the dome. The lower surface of the rim was fixed for the purpose of the analysis, given when deployed it would be attached to the base component of the nest box which in turn would be sunk into the ground.

With a load of 600N applied, a maximum stress of 42.2MPa and deflection of 1.74mm (Fig. 2) was predicted. ABS has a yield strength of 48MPa [15] however, given that the load scenario is possible but unlikely during the early testing phase, the value of 42.2MPa was considered sufficient.

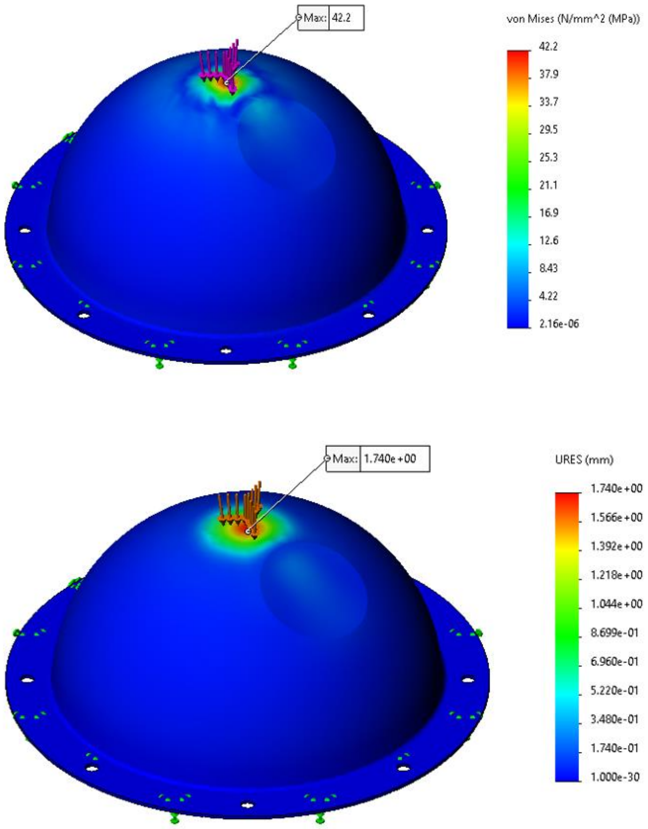

Fig. 2. VonMises stress analysis of dome component (top image). Displacement analysis of dome component (bottom image).

Traditionally, vacuum forming tools are manufactured from a variety of materials using subtractive processes for original designs and forming processes for replication of existing designs. However, additive manufacturing (AM) offers an alternative method of tool production enabling rapid manufacture and the potential for redistributed manufacture (RDM). The equipment to produce AM tooling, specifically material extrusion (MEx), is both more accessible and more economical compared with subtractive manufacturing methods, such as milling or turning on a lathe, and therefore offered an efficient means of developing the prototype nest boxes.

The formers were designed with draft angles between 5°≥30° and included equally spaced (18.6mm-22mm centre to centre distance) through holes of diameter 1.5mm at the point of gradient change from a horizontal surface. Draft and correctly placed through-holes ensure part definition and successful release from the moulded component post-forming. Male formers were designed to ensure compatibility with the vacuum former available (Formech 300XQ), with the design including compensation for shrinkage of the components post-forming.

Initial formers (Fig. 3) were built on a Builder Extreme 2000 Pro using white ABS filament, 40% infill, 2.5mm wall thickness and a 0.2mm layer height. Additional surface finishing with abrasive paper reduced the typically ridged surface that MEx produces. Subsequent designs were manufactured in two halves on an Ultimaker 3 before being bonded together, demonstrating the feasibility of using a more accessible 3d printer.

Fig. 3. From left to right: Base and dome being manufactured on the Builder Extreme 2000 Pro; Final base component former; Final dome component with MEx halves bonded together

Sealing gaskets were cut from 1.5mm thick rubber sponge sheet, perforated disks were waterjet cut from 1.5mm perforated stainless steel sheet, entrance tubes were formed into a curved tunnel and drainage holes added, and formed ABS components were manually finished using standard workshop manual/hand tools before being assembled into complete prototype units.

Fig. 4. From left to right: Digging holes for nest box base and entrance hole deployment; Installed nest box base and entrance hole; Complete installation with domed top attached.

Six units were deployed at a field-testing site in Lancaster (UK) in May 2021, with the base and entrance tube sunk into the ground before attaching the top half of the assembly (Fig. 4). Captively bred Bombus terrestris colonies were placed in three of the six nest boxes, along with environmental data loggers (temperature, dew point and humidity) inside all occupied boxes and a single control data logger situated externally. The nest boxes remained deployed until September 2022.

3 Results and Discussion

3.1 Nest Box Suitability

The colonies were observed from May 2021 through to their natural senescence in September. World first video data (Fig. 5) captured the natural life operations of bumblebee nests, including: wax cell production, production of food stores, egg laying by the queen, hatching of imago adult bees from pupal cells, the successful lifecycle of the nest through to gyne (virgin queens) production and absconding during the senescence period.

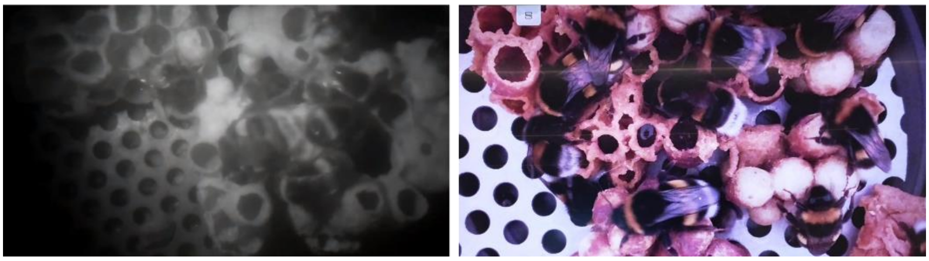

Fig. 5. Left: Infra-Red (IR) camera capture from inside the artificial nest box. Right: Colour camera capture from inside a translucent AM iteration of the artificial nest box.

Subsequent observation of a cleaned and empty nest box in March 2022 witnessed wild queen recruitment resulting in successful colony production, however further research is required to ascertain whether the queen was truly wild or returning having been born in the nest box the previous year. Nevertheless, demonstration of recruitment of this type gives confidence in the suitability of the nest box for use in areas of natural habitat decline or destruction. Further field testing will ascertain how bumblebees utilise their nests long-term to drive future decisions on design and materials for environmental sustainability.

3.2 Environmental Data

Data loggers captured temperature, dew point and humidity data within and outside of the nest boxes during habitation. Typical data captured (Fig. 6) illustrated that internal temperature fluctuates in line with outside measurements, albeit with elevated peaks likely due to thermal absorption from the nest box materials. It is anticipated that this is akin to fluctuations experienced by the ground nesting bumblebee in natural habitats, although this is likely dependent on nest location above or below ground. Dew point inside the artificial nest box can be seen to fluctuate with that outside, but peaks again appear elevated, influenced by both temperature and humidity. Humidity inside the nest box fluctuates to an extent, however there are periods where it remains high despite the outside humidity dropping. Further analysis of the results suggests this correlates with a period of rainfall in combination with lower day-time temperatures and therefore less fluctuation in internal nest box temperature. Fungal and bacterial parasites will grow rapidly in high humidity conditions and are well known as a threat to bumblebee nests, leading to colony mortality [16].

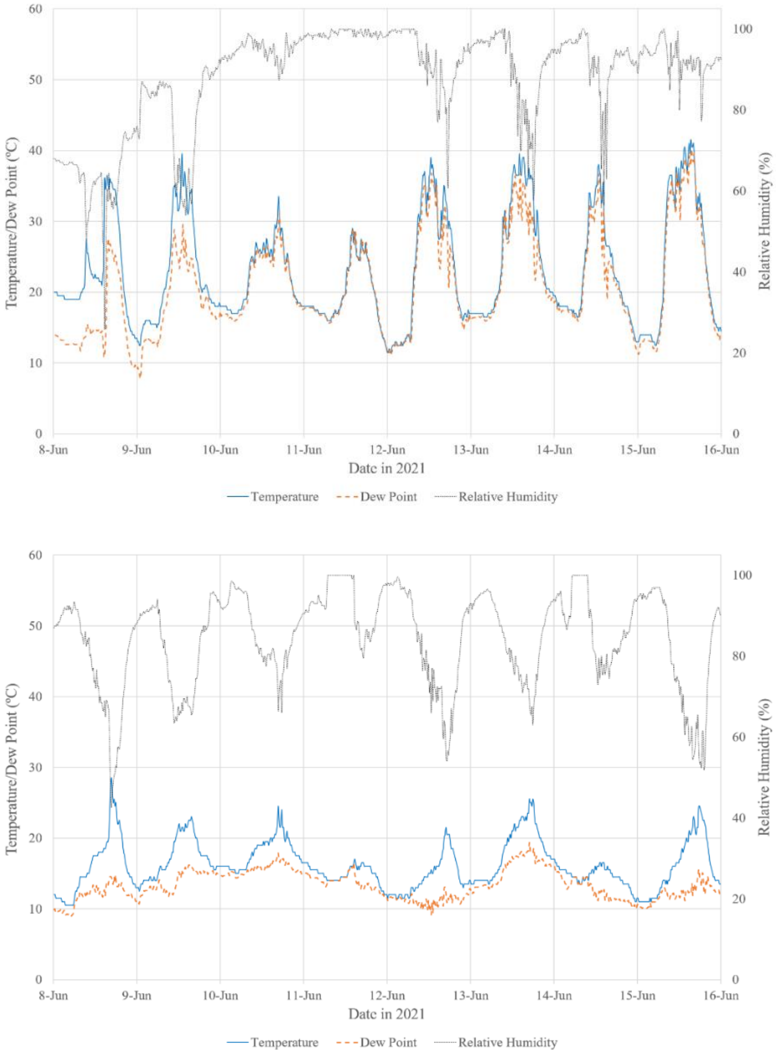

Fig. 6. Environmental data internal (top image) and external (bottom image) to the nest boxes

The current design has a single entrance hole to allow access and ventilation. Video data captured bees fanning the entrance tube with their wings to promote air circulation, however this was not sufficient to reduce humidity effectively. Therefore, the use of AM processes which result in naturally porous structures (e.g. from scaffold production in MEx processes or the process of powder bed sintering) may well benefit this application [17]. In addition, incorporating learning from the natural world, such as the passive ventilation methods employed in termite nests, may provide a solution to providing environmentally balanced structures that remain weather resistant. The application of computational fluid dynamics (CFD) to future designs will give key insights into the effectiveness of these more organic structures in optimising air flow and internal humidity regulation. Consideration around geographical location of deployment further highlights the need for active management of humidity but also challenges how effective temperature and dew point management is currently and whether deployment in a location with a temperate climate has masked any potential shortcomings.

3.3 Structural Integrity

There was no evidence of tampering from predators or accidental damage from larger animals. However, the location selected for the initial field trials was a managed site with little threat from anything other than curious wild mammals. Effective design strategies to reduce the likelihood of sustained force being applied to the artificial nest box will reduce the requirement for excessive structural strength, but geographical location and associated fauna may dictate the minimum level of structural integrity required. Designing to ensure misplaced hooves glance off the nest box, rather than allow force to be applied, will reduce the force requirements substantially. RDM, where data files are sent electronically to enable production at multiple locations, will allow the freedom to select the most appropriate design for the deployment location demonstrating lean and sustainable principles [18]. For example, in areas with little or no expected damage from ruminants, strength requirements are minimal and therefore the design can be optimised to use less material. Conversely, in areas where accidental load is more likely, additional structural elements can be included to ensure the nest boxes' longevity.

3.4 Future Design and Manufacture

The production of six vacuum formed prototype nest boxes was labour intensive and prone to errors. With elevated production rates, employing automated manufacturing techniques becomes more feasible, enhancing quality and efficiency. However, with increased quantity, distribution logistics will become more prevalent, especially if the artificial nest box is intended for use in areas of crisis that may be a substantial distance from the place of manufacture. AM offers access to RDM to enable production at the point of need, reducing the time and cost associated with distributing products and enabling a more agile response.

Subsequent research has resulted in the replication of the existing nest box design dome utilising MEx with ABS filament. The manufactured dome was initially used solely for demonstrations of the research, in which livestream video was broadcast from within the nest box utilising a Raspberry Pi camera module. Latterly, the unit has been coated in black paint primer and deployed outdoors, where initial observational data suggests that it performs adequately. Further research is required to ascertain the comparative performance against the earlier vacuum formed version, both in terms of internal environment and strength. Whilst AM offers more design freedom and opportunity to address the current environmental limitations, strength performance is typically less favourable with polymer MEx structures [19].

Drawing on inspiration from stalactites and termite nests, exploration of internal condensing stalactite structures that deposit moisture into a reservoir is an area of imminent research. It is anticipated that these structures will also provide additional strength to the dome akin to a vaulted ceiling, thus exploiting the advantages of design for additive manufacture (DfAM) fully.

4 Conclusions

The research has demonstrated the success of the artificial bumblebee nest box in both the sustainment of colonies throughout the natural cycle and through wild queen recruitment. Issues around humidity control and prototype production methods have been identified as being detrimental to future success. The application of DfAM principles in conjunction with strategies to create a homeostatic environment within the nest boxes will advance the current research unit into a functional product that can be utilised around the globe. Striving to remove geographical barriers via RDM will enable use in areas where pollinator decline is hampering crop production, increasing farming yields to prevent both hunger (directly) and poverty via loss of income. The importance of this alignment to the UN Sustainable Development Goals of zero hunger and no poverty cannot be understated.

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