International Journal of Sustainable Design

ISSN online: 1743-8292 - ISSN print: 1743-8284
https://www.inderscience.com/ijsdes

The Bee Brick: building habitat for solitary bees

Kate Christman, Rosalind Shaw, Laura Hodsdon

DOI: 10.1504/IJSDES.2022.10052860

Article History:

Received:	11 August 2020
Accepted:	16 February 2022
Published online:	25 January 2023

The Bee Brick: building habitat for solitary bees

Kate Christman*

Falmouth University,
Woodlane, Falmouth,
TR11 4RH, Cornwall, UK
Email: kate.christman@falmouth.ac.uk
*Corresponding author

Rosalind Shaw

University of Exeter,
Penryn Campus, Penryn TR10 9FE, Cornwall, UK
Email: r.shaw@exeter.ac.uk

Laura Hodsdon

Falmouth University,
Penryn Campus, Treliever Road,
Penryn TR10 9FE, Cornwall, UK
Falmouth University, UK
Email: laura.hodsdon@falmouth.ac.uk

Abstract: This article describes the process of designing the Bee Brick – a novel solution for integrating solitary bee habitats within buildings. Of the 250 species of bee in the UK, 90% are solitary bees of which 5% nest in cavities. Bees are key pollinators; this product provides nesting habitats for bees in suburban/urban communities. Existing bee nesting products tend to be ornamental and marketed by aesthetic considerations. Mainstream construction materials' primary function is to perform as structural components within the fabric of new buildings. These materials have been taken as a starting point to create habitat for bees displaced by the construction process. The Bee Brick provides a nesting site for solitary bees, adapting and rethinking how existing building components are used. Made using locally sourced recycled materials, it offers the dual function of being a construction material that also promotes biodiversity.

Keywords: design; sustainable design; product design; biomimicry; biodiversity; solitary bees; wildlife; nesting; construction.

Reference to this paper should be made as follows: Christman, K., Shaw, R. and Hodsdon, L. (2022) 'The Bee Brick: building habitat for solitary bees', *Int. J. Sustainable Design*, Vol. 4, Nos. 3/4, pp.285–304.

Biographical notes: Kate Christman is a Senior Lecturer at Falmouth University. She is a designer and educator. Her multidisciplinary work has been internationally recognised through awards, publications and exhibitions. She is the Co-Founder of Green&Blue, an award-winning B-Corporation. Green&Blue design and manufacture habitats for species displaced by urbanisation. Their products are sold internationally and can be found in developments across the UK. Her research is focused on sustainable design practices; adapting and rethinking how disciplines can work collaboratively to create environmental change. She has influenced policy, worked with government and cultural organisations and spoken widely at conferences and events.

Rosalind Shaw is an Impact Fellow at the Environment and Sustainability Institute, University of Exeter, specialising in conservation of species and habitats in human dominated environments, with a particular interest in plant-insect interactions. She has a BSc in Botany and Zoology from the University of Reading (2001) and PhD from the University of Aberdeen (2006) and has carried out ecological research in a variety of areas including mountains, farmland and urban green spaces.

Laura Hodsdon is a Senior Research Fellow at the Falmouth University. Her research focuses on social justice, using qualitative and quantitative social sciences methods across various disciplines and contexts. She has a BA from the University of York (2001) and PhD from the University of Leeds (2008), and has worked in policy roles at the University of Oxford before joining Falmouth University in 2018.

1 Biodiversity loss

Biodiversity loss has been highlighted as a key issue worldwide. It is important not only for its own sake, but also as the 'building block of our ecosystems' which "provide us with a wide range of goods and services that support our economic and social wellbeing [including] food, fresh water and clean air, but also less obvious services such as protection from natural disasters, regulation of our climate, and purification of our water or pollination of our crops" [DEFRA, (2015), p.8]. Within the context of this broader crisis of biodiversity, bees and other pollinators are widely acknowledged as playing a critical role in the maintenance of ecosystems, since "roughly 90% of the world's plant species are pollinated by animals, and the main animal pollinators in most ecosystems are bees" (Winfree, 2010). As well as their critical role within ecosystems, "bees are the main pollinators of agricultural crops, 75% of which benefit from animal pollination" (Winfree, 2010). Britain has more than 270 bee species, with some species declining (Biesmeijer, 2006; Powney et al., 2019; Senapathi et al., 2015) due to factors such as habitat loss, pesticide use and climate change (Vanbergen, 2013).

2 Biodiversity and sustainable building design

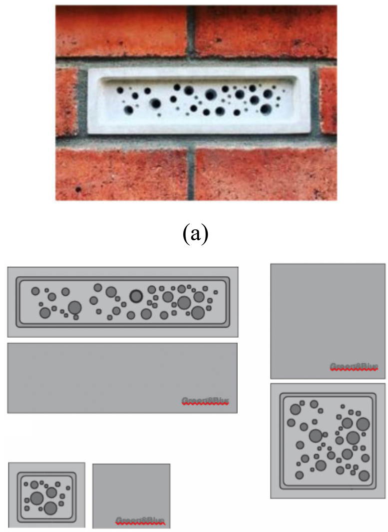
Urbanisation can have contrasting effects on different bee fauna, depending on their ecology and life history traits (Baldock et al., 2015; Cane et al., 2006; Senapathi et al., 2015). Bee species which appear to thrive in urban areas include cavity nesting bees; those able to use a wide range of floral resources (polylectic diet); and those with late emergence times (Ayers and Rehan, 2021). The value of urban green spaces for bees can vary substantially (Baldock et al., 2019). While cavity-nesting solitary bees in urban areas are not currently considered rare or at risk, whether their populations are limited by a lack of floral resources or nesting sites is unknown and they can potentially be used to raise awareness of, and increase habitats for, other bee species. Careful management of the housing strategy and subsequent delivery systems therefore has the potential to make a large difference to urban bee populations (English Nature, 2006). This is particularly important in light of the UK Government's plans for additional housing targets to deliver an average of 300,000 new homes a year (Homes England, 2018). As Winfree (2010, p.172) observes, 'bees' use of human-disturbed habitats, in combination with the ecosystem services they provide, may make them especially well suited to conservation planning that combines ecological and economic criteria, and includes both preserved and human-used habitats' and Baldock et al. (2015) found a larger number of bee species in urban areas than in rural farmland (but see Bates et al., 2011). A 2013 report commissioned by Friends of the Earth recommended that "government and local planning authorities [should] encourage developers to include bee-friendly habitat when carrying out developments" (Evans and Potts, 2013). It seemed logical, therefore, particularly given DEFRA's call for more integration across policy and practice, that the construction industry itself could contribute to safeguarding and enriching biodiversity. The design challenge was therefore to consider how to create nesting habitats for bees within buildings: this article outlines the research process towards a novel solution for integrating solitary bee habitats within sustainable building approaches.

3 UK bee fauna

Of the UK bee fauna, around 25 species are eusocial (including honeybees and most, but not all, bumblebees), around 73 are parasitic, and the remainder considered 'solitary' (Falk and Lewington, 2015). They exhibit a variety of life histories and ecological traits; however, the majority have an annual life cycle whereby adults emerge from nest sites in spring or summer (depending on species). Males generally emerge first (Danforth et al., 2019).

The females lay eggs into a nest cavity and provision the cell with pollen and nectar for the larvae. The majority of solitary bee species nest in the ground; however, around 5% of solitary bee species and some wasps nest in pre-existing cavities in plant material such as hollow reeds, stems, and branches, and in holes created by wood-boring insects and woodpeckers (Falk and Lewington, 2015). In the UK this includes *Megachile* spp (particularly *Megachile centicularis*, *Megachile ligniseca*, and *Megachile willughbiella*), *Osmia* spp (particularly *Osmia bicornis*, *Osmia caerulescens* and *Osmia leaiana*), *Hylaeus* spp (particularly *Hylaeus communis*) and *Anthidium manicatum* (Falk and Lewington, 2015). The majority of these species are common and not of conservation concern (Falk and Lewington, 2015). Cavity-nesting bees will usually create a series of cells from vegetation (particularly *Megachile* spp), mud (*Osmia bicornis*), chewed up leaves (*Osmia* spp.) or compressed plant hairs (*Anthidium*) (Falk and Lewington, 2015) (Figure 2). The number of eggs laid and provisioned varies between species: with *Osmia bicornis* recorded producing an average of 15.6 nesting cells (Giejdasz et al., 2016), whereas one study of *Megachile centuicularis* recoded an average of only 5.4 nesting cells completed (Raw, 1988). In the UK and other northern climates, once the larvae have hatched and consumed the provisions, they then enter diapause, an extended period of suspended development. Dependent on species they may overwinter as last instar larvae, prepapae, pupae or adults, before emerging the following year (Danforth et al., 2019).

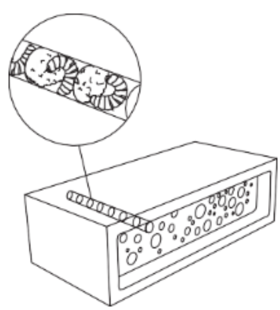
Figure 1 (a) Bee Brick in context (b) Bee Brick size variations (see online version for colours)



(a)

(b)

Figure 2 Solitary bee larvae illustration



4 Artificial nest habitat for cavity nesting bees

Artificial nesting habitat for solitary bees has been studied since the early 1900s and utilised since the 1950s, when use of some species for pollinating commercial crops was first considered (for summary see MacIvor, 2017). Dicks et al. (2010) reviewed 30 studies placing out nesting habitat for cavity-nesting solitary bees, and nests were observed in drilled holes in wood, reed stems, lengths of bamboo, paper tubes and plastic. Solitary bees produced for crop pollination have also used styrofoam nest containers (Mader, 2010a, 2010b). Significant research has gone into species such as *Megachile rotundata* and *Osmia* spp. that has been utilised as pollinators in commercial crops such as alfalfa, and apples and almonds, respectively (Mader, 2010a, 2010b). The impacts of design on the attractiveness of nesting habitat to bees; survival of eggs and larvae; sex ratio of bee populations and potential impacts on the parasitism and predation levels have been extensively studied (for a recent review see MacIvor, 2017).

Figure 3 (a) Large nest site, painted drilled holes in wood blocks with pine cones (b) Bent ply with bamboo reeds (c) Plastic and cardboard paper tubes (d) Suspended drilled wood and bamboo reeds (e) Painted wood with bamboo reeds and drilled wood, (f) Suspended wood with painted roof (g) Suspended wood, bamboo reeds (h) Painted wood with bamboo reeds and drilled wood (see online version for colours)

There has meanwhile been increasing interest in the use of solitary bee nesting habitat in urban and suburban areas by members of the public wishing to support wildlife in their garden. Solitary bees are ideally suited to live alongside people: they are non-swarming, do not produce honey, and do not live in colonies. As they have no honey stores to protect, encouraging them to nest in homes or the garden thus poses little threat to children or pets (Graham, 2015; O'Toole, 2001). Designs for solitary bee nesting habitats for use in gardens are already on the market (Kemp et al., 2009; Vanderhoff, 2018). Research across various markets to identify the basic characteristics found in solitary bee houses within the DIY sector, the garden retail sector, and online retailers revealed that nest boxes are made from a wide range of materials, and the designs vary enormously in size, material and colour (see Von Königslöw et al., 2019, Figure 3).

Designs aimed at urban and suburban gardens are often framed more as garden ‘ornaments’ than as integral parts of any responsible development. Indeed, existing products are often accompanied with little or no information to explain how to site them in the correct position, the importance of leaving them alone, or the species they cater for. Yet this new category of garden products set the status quo for ‘bug hotels’, and consequently misses the opportunity to inform customers of the importance of habitat for pollinators and the wider ecosystem. The research process towards the Bee Brick was therefore not only one of design, but one that required understanding of the life of solitary bees, and their natural behaviour and cycles.

In addition, such a ‘bottom up’ approach at the level of the individual householder seen in existing products has its value, albeit tempered by the lack of information for the buyer and no point of purchase display with relevant solitary bee facts. However, for impactful change to be enacted at the policy level and embedded in standard construction practice, it is clear that a more unobtrusive, integral, and widespread solution is required. The Bee Brick addresses this issue from a design standpoint since, from a habitat creation perspective, once Bee Bricks are installed in a build, by definition they cannot be taken away, nor will they downgrade over time as is common in wood or paper cells. The Brick also lends itself to a policy-driven solution, since it can be easily adopted by developers and planners, which means greater potential impact than piecemeal, non-integral solutions.

5 Purpose and functionality

The Bee Brick therefore aimed to create nesting habitat for cavity-nesting bees and wasps within sub/urban communities that was designed to be an integral part of the build, offering the dual function of being a construction material that also promotes biodiversity.

An underpinning approach was that it should be included in new build projects as a ‘fit and forget’ build component, and be able to sit alongside current green systems such as rainwater harvesting and sedum roofs (although the Brick can also be positioned free-standing in the garden). In common with these other green systems, Bee Bricks may require ongoing management, particularly to reduce parasite loads or fungus and mould within bricks. Alongside the practical and biological purpose, the design sensibility was to be shaped such that the brick could visually communicate its values in form as well as function, sitting alongside existing products as with aesthetic and scientific integrity.

6 Material selection

Bricks used within mainstream construction are versatile and sustainable. They are most typically made from clay using simple moulds; however, the limitations of production methods would not be suitable to produce the complex sealed cavities needed within the Bee Brick. Bricks are also commonly made from calcium silicate and concrete, which can be moulded into more complex shapes.

Figure 4 (a) Clay bricks (b) Production of clay bricks (c) Block (see online version for colours)

Previous research has demonstrated solitary bees using a wide range of nesting materials, but preferred nesting material has generally been more natural materials such as reed or wood (Gaston et al., 2005; MacIvor, 2017; Von Königslöw et al., 2019; Wilkaniec and Giejdasz, 2003). Based on observation of solitary bee houses and mainstream construction materials (and weighing them with commercial considerations) the requirements for the Bee Bricks were identified as the following:

1 It should have sufficient strength to be integrated within a build.

2 Longevity. The brick cannot downgrade over time.

3 The material used should be environmentally friendly.

4 The material used should be low-cost and recycled.

5 The new product design should be produced with few mechanical devices.

Building on these precepts and on existing studies, a variety of materials was explored. Some materials such as bamboo, reed and polystyrene were immediately excluded due to the criteria above as they do not have sufficient strength or longevity to be included into a brick.

6.1 Slip casting

Slip casting requires liquid clay or slip to be poured into dry plaster moulds. The moisture from the clay is absorbed into the plaster, leaving a coating of clay on the plaster mould; the excess slip is poured out of the mould, and the remaining clay left to harden before being removed from the mould for fettling, sponging and finishing of the final piece of clay before firing. To produce such a mould to meet the aims of this design would require pencil-like rods of plaster to form the cells or tubes: such a process would prove too difficult and costly, with a fragile end product.

6.2 Wood

Wood was considered as a possible material, since structural components used in builds such as beams were reviewed. Existing solitary bee houses tend to use cheap softwood houses coated in preservative or paint which would degrade over the lifetime of a building and does not consider the life cycle of solitary bees and the challenges over-wintering would bring. Dense hardwoods, conversely, could provide a better, more weather-resistant alternative. Trial pieces of American oak, English ash and more short-grained tropical woods like idigbo and mahogany were machined. Results were promising, but took too long to produce and would be costly to scale; in addition, they might only last marginally longer than treated softwood. There were also sustainability concerns: it seemed counter-productive to destroy trees that function as primary habitat for birds and insects, as well as the issue of importing tropical African hardwoods.

6.3 Plastic

Plastic was rejected early in the materials process. As it is non-permeable, there were concerns that too much moisture could form within the cavity. In addition, because of the complexity of tooling required to create a shape containing narrow tubes, using plastic would be very expensive, entailing huge risks in producing an injection-moulded product.

6.4 Concrete

Cast concrete, conversely, had a number of the material properties required for the Bee Brick to function in its intended manner. It is permeable and already used by some species of solitary bee: whilst many species of solitary bee nest in individual holes in the ground, some nest in walls, mortar joints, soft bricks, stones and cob. It is strong and clearly appropriate for use in construction, and is also inexpensive to produce, designed to be used outside year-round, and straightforward to mould into complex shapes.

Given the qualities described above, concrete was thus selected as an appropriate material to pursue. However, given the requirement for the material to be low-cost and environmentally friendly, alternative waste materials were explored. Cornwall has an abundance of high-grade granite waste material, a by-product of aggregate processing in the china clay industry. 95% of what is removed from a china clay pit is waste material, but is processed into granite aggregates and granite sand. Using an iterative approach, mix designs were trialled that combined cement with sand and aggregates in different ratios. Too little aggregate made the mix weak, while too much made it difficult to work with, although far more robust. Plasticiser water reducer was added to the concrete to reduce the amount of water required to make a fluid mix, which reduced the drying time of the concrete. Plymouth University’s heavy structures lab conducted compression testing and thermal testing on the mix design to establish its suitability as a cast construction material.

The final mix comprised 75% waste material from the Cornish china clay industry, and the remainder granite aggregate and cementitious material as a binding agent.

7 Design

Each Bee Brick provides 18 cavities for solitary bees to lay their eggs, each of which is moulded part-way into the brick, ensuring bees cannot enter the building the brick is installed in.

When designing the structure, the nesting requirements of solitary bees had to be considered and balanced with the structural requirements of the brick as a whole. Initial sketches were made to explore the basic aesthetic of the habitat, inspired by the natural patterns and cavities within walls, crumbling buildings, exposed mud and sand banks commonly inhabited by solitary bees, and using various hole sizes and pattern exploration as starting points [Figures 5(a)–5(f)].

Figure 5 (a)–(b) The red mason bee in mortar and brick work of old buildings (c) Nest cavities in mud bank (d) Sand bank cavities (e) Exposed mud bank (f) Nest cavities in wall (see online version for colours)

7.1 Number of cavities

The manufacturing process developed at the start of the Bee Brick project meant there were limitations on the number of cavities that could be produced in each brick. The cycle of concrete casting, curing and demoulding concrete made from granite aggregates wears moulds and tools quickly, due to its abrasive qualities. A balance had to be struck between the number of cavities for bees and damaged, difficult-to-repair moulds. The number of cavities was also constrained by the need to maintain the Brick's structural integrity.

While the Bee Brick is classified as a non-structural component (as are windows, air bricks and extractor ducts), too many holes would compromise the structural integrity of the Brick, while too few would decrease available habitat. Trials concluded that 18 was the optimum number of cavities.

8 Fascia design

The fascias were inspired by the natural patterns and cavities within walls, crumbling buildings, exposed mud and sand banks commonly inhabited by solitary bees.

Drawing on principles of biomimicry as a sustainable design strategy (Benyus, 1997; Fecheyr-Lippens et al., 2015; Rossin, 2010; Volstad and Boks, 2012) this approach meant that the design was underpinned by nature both aesthetically and practically. Aesthetic considerations led to the decision, based on the initial habitat study, to lay out the cavities in a non-uniform pattern rather than a uniform pattern such as an air brick or ducting grill. In this way the Brick would communicate something that had natural qualities, echoing the bees' natural habitat as closely as possible. The sizes of the cavities vary, some with recessed openings, some without, to create a more organic feel, and circular indents added amongst the cavities to add further detail to the natural aesthetic. Nesting cavity diameters had to accommodate the exact body size of each bee, since "bees select cavities that match their own body width to ensure the brood, cells fit tightly and reduce pathways for parasites to access brood deeper in the nest" [MacIvor, (2017), p.313]. Existing products' diameters range from 2 mm–3 mm to 25 mm (MacIvor, 2017), but in this case 5 mm–7 mm was chosen to encourage cavity nesting bees common in towns: mason bees (*Osmia* spp.) and leaf cutter bees (*Megachile* spp.). Varying the cavity size was therefore a solution both to the aesthetic imperative for a natural feel, and to accommodating as many bee species as possible.

Figure 6 (a)–(b) Pattern formation within sand bank (c)–(d) Coastal bank nest cavities pattern formation (e)–(f) Exposed mud bank pattern formation (see online version for colours)

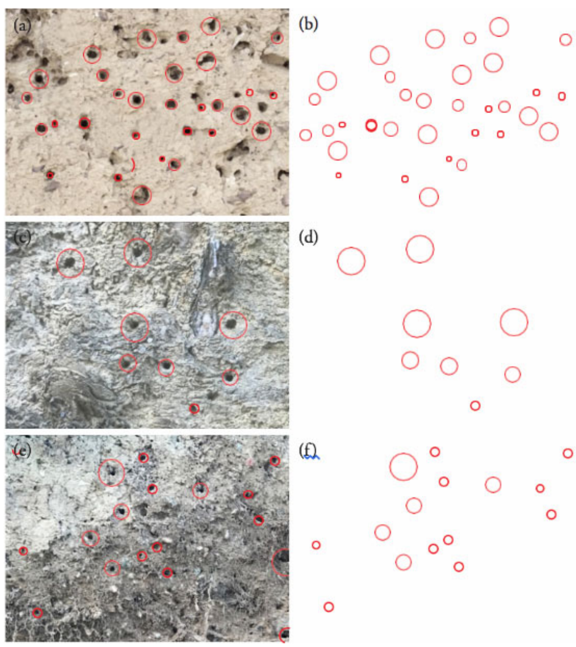
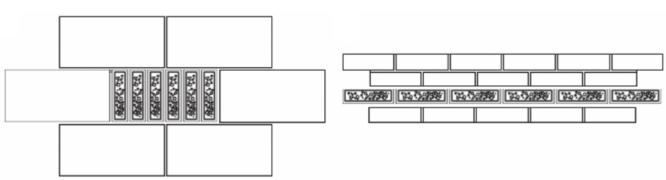
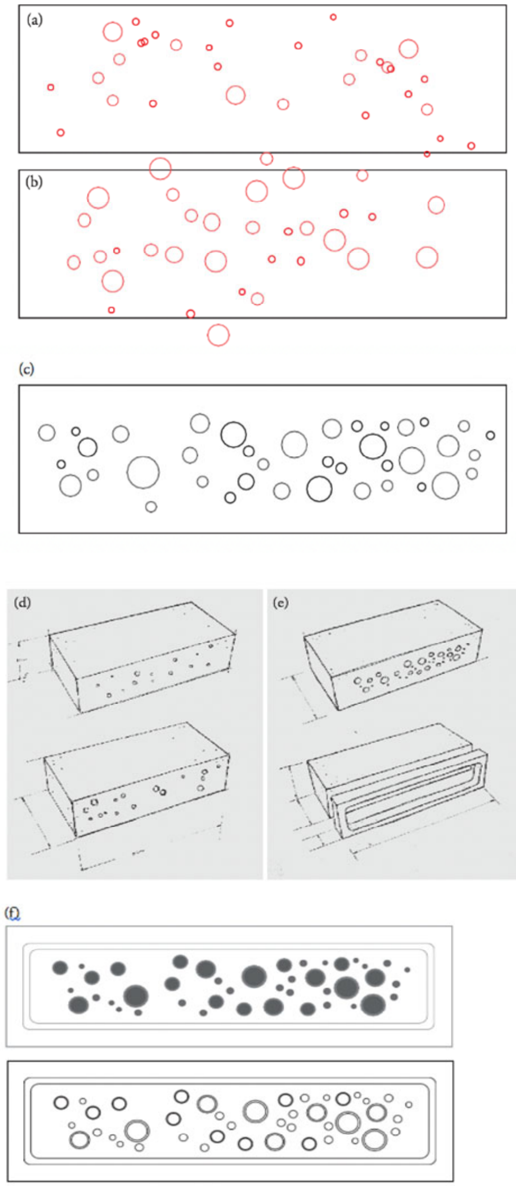


Figure 7 (a) Bricks within block walls (b) Bee Bricks in brick wall



(a) (b)

Figure 8 (a), (b) and (c) Pattern exploration inspired by observations in Figure 6, (d) First sketches of brick, (e) Sketch of brick with weather shield, (f) Final design fascia including weather shield (see online version for colours)



Similar considerations were required when specifying cavity length. In existing products this tends to average around 150 mm, but ranges up to 200 mm–300 mm. Research has indicated that the optimum cavity length is likely to be 150 mm or greater (MacIvor, 2017). Shorter cavities may lead to a change in sex ratio of populations, as male eggs tend to be laid in the cells closes to the end of the cavity (Danforth et al., 2019), although this also varies with environmental conditions, (e.g., Petersen and Roitberg 2006), and for *Osmia bicornis* appears to be less important than tube diameter (Seidelman et al. 2016.).

Clearly, again, the functionality of the brick design meant that there were other considerations to take into account. The brick was to conform to standard UK brick dimensions 215 mm × 105 mm × 65 mm so that it could be used in the broadest spectrum of build methods [Figures 7(a), 7(b)]. A cavity length of 80mm was therefore specified.

Initial sketches explore the basic aesthetic of the habitat followed by technical drawings and ergonomic studies exploring a recessed fascia which would provide protection from the elements [Figures 8(a)–8(f)].

Figure 9 (a)–(g) Frog exploration, size, shape, (h) First sketches of frog, (i) Sketch of frog recess, (j) Sketch with logo in position, (k) Final illustration for frog (see online version for colours)

Another consideration in designing the external surface was the ‘frog’. Bricks can be solid, or they can have holes perforated through them to reduce the amount of material used. Alternatively, they may have an indentation on one or two surfaces, commonly called a ‘frog’. The frog reduces the amount of material used to form the brick, makes it easier to remove from the form, and gives the completed wall better shear resistance. The size, depth, pattern and shape of the frog can vary enormously. It is also used to brand the bricks and often can carry the manufacturer’s mark or logo.

Figure 10 (a) MDF brick frog trial to establish depth of cut for bond strength (b) MDF brick fascia prototype to establish depth of fascia frame (c) Silicone fascia impression trial (d) Fascia impression tool (e) Prototype tool with frog impression and embossed Bee Brick text (f) Production tool (g) machining fascia depth (see online version for colours)

Once the aesthetic had been determined, further sketches and detailed drawings were used to construct the prototypes. Various scale models of the brick were developed using different methods and materials. Early models were made out of medium-density fibreboard, cut out by hand and glued together. Further models established the depth of the frog [Figure 10(a)], the depth of the fascia frame [Figure 10(b)], the fascia design [Figure 10(c)] and more detailed prototypes established the positioning of the frog [Figure 10(e)].

9 Colour

The colour and pattern was another key consideration: not only for aesthetic purposes, but because patterning and colouration of the area around the nest box entrance can improve nest recognition when multiple suitable cavities are available (Fauria and Campan, 1998; Fauria et al., 2004; Guédot et al., 2009). Making high quality white concrete from granite aggregate and white cement allows pigment to be added to the mix – an advantage when designing a product made to fit unobtrusively into builds that use a variety of brick colours. A range was designed that incorporated appropriate brick colours (red – a commonly used colour brick in UK housing stock; yellow – reflecting yellow clay bricks found in parts of the UK and white – reflecting rendered concrete).

Figure 11 (a) Production colour trial chips (b) Wet paper pigment trial and resulting bricks (c) Cast concrete colour trials (d) Batch casting colour trials for consistency (see online version for colours)

10 Prototype analysis

Initial trials of the Bee Bricks were conducted in Cornwall across two main sites in April 2019. Five prototype bricks were retrofitted within a wall [Figure 12(a)] and 35 were positioned within a designated test area [Figure 12(d)]. Test bricks varied in colour and size, and were placed at different heights [Figure 12(e)]. Cavity-nesting bees were observed nesting in the prototype bricks which gave the confidence for a further trial to be carried out: [Figure 12(f)] when observed in September 2020 126 cells out of 591 were capped by materials characteristic of solitary bees [Figure (g)].

Further studies were undertaken in partnership with the Environment and Sustainability Institute (ESI), University of Exeter, testing the impact of height and colour on occupancy of bricks (Shaw et al., 2021). The trial of bricks was carried out in urban domestic gardens and rural large public gardens to assess their occupancy in a range of habitats.

While overall occupancy of bricks was low (1.3% and 2.8% over the two years of the study), they compared well to drilled wooden control bricks installed at the same sites (1.1% and 0.7% over the two years of study; Shaw et al. 2021). The study indicated that cavity-nesting bees were found in bricks of all colours and on both urban and more rural sites. Cavities in bricks were capped with mud (likely *Osmia bicornis* or potentially cavity-nesting wasps such as *Trypoxylon figulus*, *Euodynerus* spp, *Microdynerus* spp; Osorio-Canadas et al., 2018), masticated leaf (likely *Osmia* spp) and cut leaves (likely *Megachile* spp.).

Figure 12 (a) Retro-fit charcoal prototype Bee Brick analysis,(b) Leaf-cutter bee nesting in charcoal prototype (c) Retro-fit red Bee Brick analysis (d) Test site Green&Blue, Cornwall (e) Red mason bee nesting in prototype, Green&Blue Cornwall, (f) Occupied cells charcoal prototype and (g) Occupied cells close up (see online version for colours)

Figure 13 (a) Heligan, Cornwall (b) The Eden Project, Cornwall (c) Enys gardens, Cornwall (d) Studies in the domestic garden (e) Red mason bee nesting in prototype, Talley, Wales and (f) Filled cavities in prototype, Talley, Wales (see online version for colours)

11 Final design

The final colourways were selected not only to blend with existing brickwork and rendered surfaces [Figures 14(a), 14(b), 14(c)], but also as a design feature to create contrast and interest within a build [Figures 14(e), 14(f)]. Bespoke colour options were also developed to provide a 'Bee Brick colour match' service based on the needs of the build project [Figure 14(g)].

Figure 14 (a) White Bee Brick range (b) White Bee Brick in rendered wall (c) Bee Brick in block wall (d) Red mason bee on Bee Brick (e) White brick feature in red brick wall (e) Yellow Bee Brick feature in charcoal wall and (g) Final range plus colour match service (see online version for colours)

12 Installation and implementation

Following the early field trials and studies conducted by the University of Exeter, a range of installation and implementation guidelines were recommended. Bee Bricks can be installed above ground in external walls, in boundary walls, and used within landscaping.

They should be installed in direct sunlight, ideally with the fascia facing south or south-east. Bee-friendly plants should ideally be planted nearby to ensure a sufficient food supply. The bricks should be positioned at least 0.75 metres from the ground, with no upward limit. They can be built into course work using a mortar mix as a main build component in place of a standard brick or block. Once installed, occupancy can be observed by the number of capped holes and if evidence of high numbers of pollen mites, fungus or mould is observed (no emergence of bees in spring); management such as cleaning cells post bee emergence should be considered.

13 Uptake and influence

The Bee Brick has been incorporated in construction and planning policy and practice. For example, Brighton & Hove Council (2022) has recently stipulated the planning requirement that a Bee Brick must be included in the vast majority of its new builds and Cornwall Council (2018) recommends that a Bee Brick be included in 50% of new builds. The Duchy of Cornwall has committed to containing a Bee Brick in new builds at Nansledan near Newquay and Poundbury near Dorchester; and eight construction companies to date now embed Bee Bricks in builds in Cornwall as a matter of course. Over 21,000 bricks have been sold worldwide including Europe, Brazil, USA, Canada, New Zealand (equating to a potential 350,000 new nesting cavities for solitary bees).

14 Potential limitations and future research

Some aspects of brick design – in particular, material used and tube length – were ultimately determined by the need for bricks to be a structural part of a building and to fit with existing standard brick dimensions rather than the best habitat for solitary bees. Current research into the use of bricks has been limited to occupancy rather than estimating any potential impacts on populations of cavity-nesting bees and wasps. The majority of species likely to use the bricks are common and widespread, so the bricks should not be considered a tool to support rare species, but rather as having the potential to support populations of common species. Concerns remain around the potential for artificial nest habitats to encourage non-native species (MacIvor and Packer, 2015). They may potentially result in increased pathogen or disease load, as has been documented in commercial cavity bee rearing operations (Bosch and Kemp, 2002). Bee Bricks may reduce parasitism compared to softer substances such as cardboard, but due to their impervious nature they may increase fungal and mould problems (e.g., Wilkaniec and Giejdasz, 2003). Further research into the prevalence of these issues, and whether any preventative measures are needed (such as cleaning between generations), is required.

15 Conclusions

The research process described in this article is one that set out to create a product to create ‘built in’ habitat for cavity-nesting bees and wasps in urban areas. There are many products already available for use in urban gardens, but existing designs are ornamental, short-lived, and designed mainly for aesthetic purposes. They also tend not to take a robust approach towards the balancing of practicality and aesthetics with biology, either in the design or in the information given to the customer. In designing the Bee Brick, then, the aim was to develop something that would be long-lasting, and that could be integral to an urban context rather than optional. Determined by the need to balance biological, practical, and aesthetic requirements, this holistic design approach has thus paved the way for a product that has robust potential to be successful both commercially and scientifically.

This increasing interest in a research-led design solution, and its widening impact, provides numerous opportunities for future research in which science and design work hand in hand as part of a holistic, iterative approach to addressing environmental issues. In particular, the widespread embedding of Bee Bricks provides opportunities to engage householders in supporting insect populations in urban areas, potentially via citizen science methods. Future research will be geared towards assessing the overall impact of the Bee Brick on solitary bee populations, using the findings as part of a feedback loop for future iterations: not only of the Bee Brick itself, but of policies and practices relating to environmental growth and incorporating nature into infrastructure as an integral component, not an add-on. By building on this central concept, and by carefully and robustly balancing the demands of aesthetics, practicality, and biology, this design approach allows integrated sustainable building materials to promote biodiversity within urban areas.

References

Ayers, A. and Rehan, S. (2021) 'Supporting bees in cities: how bees are influenced by local and landscape features', *Insects*, Vol. 12, No. 2, p.128.

Baldock, K., Goddard, M., Hicks, D. et al. (2019) 'A systems approach reveals urban pollinator hotspots and conservation opportunities', *Nat. Ecol. Evol.*, Vol. 3, No. 3, pp.363–373.

Baldock, K., Goddard, M., Hicks, D., Kunin, W., Mitschunas, N., Osgathorpe, L. and Memmott, J. (2015) 'Where is the UK's pollinator biodiversity? The importance of urban areas for flower-visiting insects', *Proceedings of the Royal Society B: Biological Sciences*, Vol. 282, No. 1803, p.20142849.

Bates, A., Sadler, J., Fairbrass, A., Falk, S., Hale, J. and Matthews, T. (2011) 'Changing bee and hoverfly pollinator assemblages along an urban-rural gradient', *PLoS One*, Vol. 6, No. 8, p.e23459.

Benyus, J. (1997) *Biomimicry: Innovation Inspired by Nature*, Harper Perennial, New York, USA.

Biesmeijer, J. (2006) 'Parallel declines in pollinators and insect-pollinated plants in Britain and the Netherlands', *Science*, Vol. 313, No. 5785, pp.351–354.

Bosch, J. and Kemp, W. (2002) 'Developing and establishing bee, species as crop pollinators: the example of *Osmia* spp. (Hymenoptera: Megachilidae) and fruit trees', *Bulletin of Entomological Research*, Vol. 92, No. 1, pp.3–16.

Brighton & Hove City Council (2022) *Biodiversity and Nature Conservation SPD11* [online] https://www.brighton-hove.gov.uk/sites/default/files/2022-08/BNC%20SPD%20FINAL.pdf (accessed 30 September 2022).

Cane, J., Minckley, R., Kervin, L., Roulston, T. and Williams, N. (2006) 'Complex responses within a desert bee guild (hymenoptera: apiformes) to urban habitat fragmentation', *Ecological Applications*, Vol. 16, No. 2, pp.632–644.

Cornwall Council (2018) *Cornwall Planning for Biodiversity Guide*, Cornwall Council, Truro [online] https://www.cornwall.gov.uk/planning-and-building-control/planning-policy/adopted-plans/cornwall-planning-for-biodiversity-guide/ (accessed 30 September 2022).

Danforth, B., Minckley, R., Neff, J. and Fawcett, F. (2019) *The Solitary Bees: Biology, Evolution, Conservation*, Princetown University Press, Princetown, USA.

DEFRA (2015) *Biodiversity 2020: A Strategy for England's Wildlife and Ecosystem Services*, Department for Environment, Food and Rural Affairs, London [online] https://www.gov.uk/government/publications/biodiversity-2020-a-strategy-for-england-s-wildlife-and-ecosystem-services (accessed 30 September 2022).

Dicks, L.V, Showler, D.A. and Sutherland, W.J. (2010) *Bee Conservation – Evidence for the Effects of Interventions*, Pelagic Publishing, Exeter UK.

English Nature (2006) *Wildlife and Development: Working towards Natural England for People, Places and Nature*, Peterborough.

Evans, R. and Potts, S. (2013) *Iconic Bees: 12 Reports on UK Bee Species*, University of Reading report for Friends of the Earth [online] https://cdn.friendsoftheearth.uk/sites/default/files/downloads/Iconic%20bees%20report_1.pdf (accessed 30 September 2022).

Falk, S. and Lewington, R. (2015) *Field Guide to the Bees of Great Britain and Ireland*, British Wildlife Publishing Ltd., London.

Fauria, K. and Campan, R. (1998) 'Do solitary bees osmia cornuta latr. and osmia lignaria cresson use proximal visual cues to localize their nest?', *Journal of Insect Behavior*, Vol. 11, No. 5, pp.649–669.

Fauria, K., Campan, R. and Grimal, A. (2004) 'Visual marks learned by the solitary bee Megachile rotundata for localizing its nest', *Animal Behaviour*, Vol. 67, No. 3, pp.523–530.

Fecheyr-Lippens, D., Hsiung, B-K., Niewiarowski, P. and Kolodziej, M. (2015) 'Biomimicry: a path to sustainable innovation', *Design Issues*, Vol. 31, No. 3, pp.66–73.

Gaston, K., Smith, R., Thompson, K. and Warren, P. (2005) 'Urban domestic gardens (II): experimental tests of methods for increasing biodiversity', *Biodiversity and Conservation*, Vol. 14, No. 2, pp.395–413.

Giejdasz, K., Fliszkiewicz, M., Bednárová, A. and Krishnan, N. (2016) 'Reproductive potential and nesting effects of Osmia rufa (syn. bicornis) female (Hymenoptera: Megachilidae)', *Journal of Apicultural Science*, Vol. 60, No. 1, pp.75–86.

Graham, J. (2015) *Native Buzz : Citizen Scientists Creating Nesting Habitat for Solitary Bees and Wasps*, Invited Contribution: Citizen Science Programs in Florida.

Guédot, C., Bosch, J., James, R. and Kemp, W. (2009) 'Effects of three-dimensional and color patterns on nest location and progeny mortality in alfalfa leafcutting bee (Hymenoptera: Megachilidae)', *Journal of Economic Entomology*, Vol. 99, No. 3, pp.626–633.

Homes England (2018) *Strategic Plan 2018-2023*, Homes England, London [online] https://www.gov.uk/government/publications/homes-england-strategic-plan-201819-to-202223 (accessed 30 September 2022).

Kemp, W., Trostle, G. and Pitts-Singer, T. (2009) *Solitary Bee Emergence Box*, US Patent No. 7,556,552 B1.

MacIvor, J.S. (2017) 'Cavity-nest boxes for solitary bees: a century of design and research', *Apidologie*, Vol. 48, No. 3, pp.311–327.

MacIvor, J.S. and Packer, L. (2015) ''Bee hotels' as tools for native pollinator conservation: a premature verdict?', *PLOS ONE*, Vol. 10, No. 3, p.e0122126, https://doi.org/10.1371/journal.pone.0122126.

Mader, E. (2010a) 'Mason bees', in Mader, E. et al. (Eds.): *Managing Alternative Pollinators: A Handbook for Beekeepers, Growers, and Conservationists*, pp.54–74, *Sustainable Agriculture Research and Education, Handbook*, p.11, Natural Resource, Agriculture, and Engineering Service (NRAES), Ithaca, New York.

Mader, E. (2010b) 'The alfalfa leafcutter bee', in Mader, E. et al. (Eds.): *Managing Alternative Pollinators: A Handbook for Beekeepers, Growers, and Conservationists*, pp.75–93, *Sustainable Agriculture Research and Education, Handbook*, p.11, Natural Resource, Agriculture, and Engineering Service (NRAES), Ithaca, New York.

O'Toole, C. (2001) *The Red Mason Bee*, Osmia Publications Ltd., Sileby, Leicestershire, UK.

Osorio-Canadas, S., Arnan, X., Bassols, E., Vicens, N., Bosch, J. (2018) 'Seasonal dynamics in a cavity-nesting bee-wasp community: shifts in composition, functional diversity and host-parasitoid network structure', *PLoS ONE*, Vol. 13, No. 10, p.e0205854.

Powney, G., Carvell, C., Edwards, M. et al. (2019) 'Widespread losses of pollinating insects in Britain', *Nat. Commun.*, Vol. 10, No. 1, p.1018.

Raw, A. (1988) 'Nesting biology of the leaf cutter bee Megachile centuncularis (Hymenoptera, Megachilidae)', *Entomologist*, Vol. 107, No. 1, pp.52–56.

Rossin, K. (2010) 'Biomimicry: nature's design process versus the designer's process', *WIT Transactions on Ecology and the Environment*, Vol. 138, p.559.

Senapathi, D., Carvalheiro, L., Biesmeijer, J., Dodson, C., Evans, R., McKerchar, M. and Potts, S. (2015) 'The impact of over 80 years of land cover changes on bee and wasp pollinator communities in England', *Proceedings of the Royal Society B: Biological Sciences*, Vol. 282, No. 1806, p.20150294.

Vanbergen, A. (2013) 'Threats to an ecosystem service: pressures on pollinators', *Frontiers in Ecology and the Environment*, Vol. 11, No. 5, pp.251–259.

Vanderhoff, C.L. (2018) *Solitary Bee Nesting Shelter*, US Patent No. 0255748.

Volstad, N. and Boks, C. (2012) 'On the use of biomimicry as a useful tool for the industrial designer', *Sustainable Development*, Vol. 20, No. 3, pp.189–199.

Von Königslöw, V., Klein, A-M., Staab, M., Pufal, G. (2019) 'Benchmarking nesting aids for cavity-nesting bees and wasps', *Biodiversity & Conservation*, Vol. 28, No. 14, pp.3831–3849.

Wilkaniec, Z. and Giejdasz, K. (2003) 'Suitability of nesting substrates for the cavity-nesting bee Osmia rufa', *Journal of Apicultural Research*, Vol. 42, No. 3, pp.29–31.

Winfree, R. (2010) 'The conservation and restoration of wild bees', *Annals of the New York Academy of Sciences*, Vol. 1195, No. 1, pp.169–197.