Analysis of Design of Flowers and Honeybees in the Pollination Process

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Abstract

Pollination is a crucial ecological process for the sustainment of both natural and agricultural systems. Approximately 85% of flowering plants depend on animal pollinators for successful reproduction. Over 75% of global food crops rely on pollinators, making them indispensable for sustaining human populations. The pollination process is accomplished by wind, water, insects, birds, bats, mammals, amphibians, and mollusks. The pollination process in angiosperms is robust because of the efficacious design features of flowers and pollinators. The axiomatic design offers a methodology to judge if a design is good or bad. This paper analyzes the design features of flowers and honeybees related to the pollination process. The functional requirements (FRs) of components of a flower and a honeybee are tabulated and mapped onto nature-chosen design parameters (DPs). The "independence axiom" of the axiomatic design methodology is applied to analyze couplings and to evaluate if the features of a flower and a honeybee form a good design (i.e., uncoupled design) or a bad design (i.e., coupled design). The analysis revealed that the flowers and honeybees are a good design to support pollination. This approach to judging whether nature's entities are good or bad designs can be valuable for biomimicry studies. This approach can also be useful in teaching design considerations of biology and bio-inspired innovation.

Keywords
Pollination process, Axiomatic design, Nature design, Design evaluation, Sustainability.

1. Introduction

Pollination is a vital ecosystem service, required by 76% of global crops, and an estimated 87.5% of all flowering plants. The most important crop pollinator species globally is the western honeybee (Apis mellifera L.), enabling roughly 50% of global crop pollination. Honeybees pollinate about hundred or so plants such as strawberries, apples, pomegranates, beans, sunflowers, cotton, coffee plants, sesame, okra, and many more as presented by Pariona (2019).

Honeybees have had a long history of associations with humans and are the most widely domesticated pollinator species globally (Stanley et al. 2020). A detailed account of the pollination process is given by Proctor et al. (2009).

2. Axiomatic Design

In this paper the anatomies and functionalities of a flower and a honeybee are analyzed using the axiomatic design methodology.. This paper focuses only on the first axiom known as independent axiom which professes that a good design has mutually independent functional requirements (FRs). This independence of FRs is possible when each FR has a dedicated design parameter (DP). When FRs share a common DP, that DP creates coupling between the FRs. Changes in the common DP result in a significant impact on all FRs that share the DP. The axiomatic design methodology uses a design matrix-based analysis to assess and mitigate the effects of coupling. There are three types of designs: (1) uncoupled design, (2) decoupled design, and (3) coupled design. In uncoupled designs, FR-specific DPs are determined to satisfy FRs without cross-interference. In decoupled design, DPs are determined to satisfy FRs independently only if DPs are realized in a certain order. In a coupled design, due to lack of a feasible solution, DPs are determined such that they affect multiple FRs, which means FRs are no longer independent. According to axiomatic design methodology, the best design is a functionally uncoupled design that has minimum information content, and a coupled design is the least desirable one (Suh 2001). Scientists have discovered that the DPs for FRs of flowers and honeybees have coevolved over millions of years. In this analysis, the FRs are mapped on to DPs to check for the couplings in the flower and honeybee designs. The relationship between FRs and DPs can be represented by the following design equation.

$$\{FR\} = [A]\ \{DP\}$$

where [A] is the design matrix.

$$FR_i = \sum_{j=1}^{n} A_{ij}\ DP_j$$

In this paper, the independence axiom applied to examine the anatomy of a flower and a honeybee..

3. Flower Anatomy

Flowering plants are called angiosperms. There are about 300,000 species of flowering plants, the largest and most diverse group within the kingdom Plantae. Angiosperms represent approximately 80 percent of all the known green plants now living (Cronquist et al. 2023). Molecular phylogenetic studies estimate the age of origin of angiosperms to be about 140 million years. Once angiosperms arose, they proliferated rapidly into several distinct lineages and gradually replaced gymnosperms as the dominant plant life form on the earth. Flowers are not only visually captivating but also intricate structures that serve a crucial role in plant reproduction. A detailed anatomy of a flower is explained by Simpson(2019). The major parts of the body of a typical flower and their functions include sepal, petal, stamen, pistil, nectaries, receptacle, and floral diagram and formula given by Ronse De Craene (2010) and Simpson(2019). Each floral part serves a specific purpose in the intricate process of reproduction, ensuring the production of seeds and the continuation of plant species. Various structural elements at the base of a flower support ovary, style, and stigma. Xylem facilitates the flow of water, minerals, and nutrients. Phloem enables the flow of sugars. The structure of xylem and phloem are described by Cutler et al. (2007). Parenchyma cells constitute vascular tissue, which provides a mechanism for the exchange of materials within and between the xylem and the phloem. The functions of Parenchyma cells are given by Wist and Davis (2006). The role of Indole-3-acetic acid (IAA) in the pollen tube growth is presented by Wu et al. (2008). The role of microsporangia in pollen development called microsporogenesis is described by Rudall (2020). In many species, self-incompatibility is genetically controlled by a single, highly allelic locus called the S-locus (S-alleles). Self-incompatibility not only prevents plants from self-fertilizing but also from self-fertilizing by genetically related individuals. This reduces the level of inbreeding in self-incompatible populations (Dodds et al. 1996). Calcium is a critical element that is strongly related to pollen germination and pollen tube growth. Calcium ion (Ca^{2+}) dynamics mediate these interactions among cells to ensure that pollen reaches the embryo sac (Zheng et al. Q 2019). Scientific studies strongly suggest that the plant hormone auxin is involved in coordinating the integrative development of the embryo (Perez-Grau 2002). Mucilage is a polysaccharide substance extracted as a viscous or gelatinous solution from flowers, plant roots, and seeds. This helps pollen to adhere to the stigma. Flowers' enticing colors, shapes, and fragrances, coupled with their specialized reproductive structures, have evolved to attract, and engage a variety of pollinators. The FRs and DPs of these parts are presented in the following design equations. The master design matrix of the overall functions of a flower is given in Table 1.

Flower
FR_0 = Facilitate pollination

FR_1 = Support and supply substances
FR_2 = Support various parts of a flower

$$\begin{Bmatrix} FR_1 \\ FR_2 \end{Bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{Bmatrix} \text{Pedicel} \\ \text{Receptacle} \end{Bmatrix}$$

Pedicel
FR_1 = Support and supply substances
FR_{11} = Support structurally
FR_{12} = Facilitate the flow of water, minerals, and nutrients
FR_{13} = Facilitate the flow of food

$$\begin{Bmatrix} \mathrm{FR}_{11} \\ \mathrm{FR}_{12} \\ \mathrm{FR}_{13} \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ 0 & X & 0 \\ 0 & 0 & X \end{bmatrix} \begin{Bmatrix} \text{Stalk} \\ \text{Xylem} \\ \text{Phloem} \end{Bmatrix}$$

Receptacle
FR_2 = Support various parts of a flower

$$\begin{Bmatrix} \mathrm{FR}_{21} \\ \mathrm{FR}_{22} \\ \mathrm{FR}_{23} \\ \mathrm{FR}_{24} \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 \\ 0 & X & 0 & 0 \\ 0 & 0 & X & 0 \\ 0 & 0 & 0 & X \end{bmatrix} \begin{Bmatrix} \text{Nectary} \\ \text{Perianth} \\ \text{Stamen} \\ \text{Pistil} \end{Bmatrix}$$

FR_{21} = Accommodate nectaries
Nectary
FR_{211} = Contain parts of nectary
FR_{212} = Transport nutrients
FR_{213} = Secrete nutrients

$$\begin{Bmatrix} \mathrm{FR}_{211} \\ \mathrm{FR}_{212} \\ \mathrm{FR}_{213} \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ 0 & X & 0 \\ 0 & 0 & X \end{bmatrix} \begin{Bmatrix} \text{Epidermis} \\ \text{Phloem} \\ \text{Parenchyma cells} \end{Bmatrix}$$

FR_{22} = Accommodate perianth
Perianth
FR_{221} = Support calyx
FR_{222} = Support corolla

$$\begin{Bmatrix} FR_{221} \\ FR_{222} \end{Bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{Bmatrix} \text{Sepals} \\ \text{Petals} \end{Bmatrix}$$

FR_{23} = Accommodate stamen
Stamen
FR_{231} = Support filament
Filament
FR_{2311} = Provide structural support to anther

FR_{2312} = Carry nutrients to anther
FR_{232} = Support anther
Anther
FR_{2321} = Produce pollen
FR_{2322} = Position pollen for insects to pick-up

$$\begin{Bmatrix} FR_{231} \\ FR_{232} \end{Bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{Bmatrix} \text{Structural element} - 1 \\ \text{Structural element} - 2 \end{Bmatrix}$$

$$\begin{Bmatrix} FR_{2311} \\ FR_{2312} \end{Bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{Bmatrix} \text{Stalk} \\ \text{Phloem} \end{Bmatrix}$$

$$\begin{Bmatrix} FR_{2321} \\ FR_{2322} \end{Bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{Bmatrix} \text{Microsporangia} \\ 2 - \text{lobed tip} \end{Bmatrix}$$

FR_{24} = Accommodate pistil
Pistil
FR_{241} = Support ovary
Ovary
FR_{2411} = Contain ovules
FR_{2412} = Initiate fertilization and development

FR_{242} = Support style
Style
FR_{2421} = Connect stigma and ovary
FR_{2422} = Grow pollen tube
FR_{2423} = Control self-incompatibility

FR_{243} = Support stigma
Stigma
FR_{2431} = Allow pollen to adhere
FR_{2432} = Start pollen germination

$$\begin{Bmatrix} FR_{241} \\ FR_{242} \\ FR_{243} \end{Bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{Bmatrix} \text{Structural element} - 3 \\ \text{Structural element} - 4 \\ \text{Structural element} - 5 \end{Bmatrix}$$

$$\begin{Bmatrix} FR_{2411} \\ FR_{2412} \end{Bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{Bmatrix} \text{Embryo sac} \\ \text{Auxin} \end{Bmatrix}$$

$$\begin{Bmatrix} FR_{2421} \\ FR_{2422} \\ FR_{2423} \end{Bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{Bmatrix} \text{Style} \\ \text{Indole 3} - \text{acetic acid (IAA)} \\ \text{S} - \text{allele} \end{Bmatrix}$$

$$\begin{Bmatrix} FR_{2431} \\ FR_{2432} \end{Bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{Bmatrix} \text{Mucilage} \\ \text{Calcium} \end{Bmatrix}$$

Table 1. Master Design Matrix of the Overall Functions of a Flower

		DP_1 (Pedicel)			DP_2 (Receptacle)														
		DP_{11} (Stalk)	DP_{12} (Xylem)	DP_{13} (Phloem)	DP_{21} (Nectary)			DP_{22} (Perianth)		DP_{23} (Stamen)				DP_{24} (Pistil)					
					DP_{211} (Epidermis)	DP_{212} (Phloem)	DP_{213} (Parenchyma cells)	DP_{221} (Sepals)	DP_{222} (Petals)	DP_{231} (Filament)		DP_{232} (Anther)		DP_{241} (Ovary)		DP_{242} (Style)		DP_{243} (Stigma)	
										DP_{2311} (Stalk)	DP_{2312} (Phloem)	DP_{2321} (Microsporangia)	DP_{2322} (2-lobed tip)	DP_{2411} (Embryo sac)	DP_{2412} (Auxin)	DP_{2421} (IAA)	DP_{2422} (S-allele)	DP_{2431} (Mucilage)	DP_{2432} (Calcium)
FR_1	FR_{11}	1	0	0															
	FR_{12}	0	1	0															
	FR_{13}	0	0	1															
FR_2	FR_{21}	FR_{211}			1	0	0												
		FR_{212}			0	1	0												
		FR_{213}			0	0	1												
	FR_{22}	FR_{221}						1	0										
		FR_{222}						0	1										
	FR_{23}	FR_{231}	FR_{2311}							1	0								
			FR_{2312}							0	1								
		FR_{232}	FR_{2321}									1	0						
			FR_{2322}									0	1						
	FR_{24}	FR_{241}	FR_{2411}											1	0				
			FR_{2412}											0	1				
		FR_{242}	FR_{2421}													1	0		
			FR_{2422}													0	1		
		FR_{243}	FR_{2431}															1	0
			FR_{2432}															0	1

4. Honeybee Anatomy

Honeybees are fascinating creatures that play a vital role in pollination and honey production. To understand these industrious insects better, it is crucial to explore the anatomy that equips them with their unique abilities. The honeybee's external anatomy consists of several distinct body parts that serve specific purposes: head, thorax, and abdomen. Inside the honeybee's body, there are various internal structures and organs that support its vital functions: digestive system, respiratory system, circulatory system, and nervous system. A detailed description of the anatomy of a honeybee is presented by Gould and Gould (1998) and Snodgrass (1956). Maeterlinck (1901), winner of the 1911 Nobel Prize in Literature, gives deep insights into the various aspects of the bee's life, including their organization, communication, reproduction, and the roles of different types of bees within the hive. A detailed description of honeybees in building colonies, reproduction, nest building, food collection, temperature control and colony defense is given by Seeley (1985). The anatomy of a honeybee is intricately designed, allowing them to perform a wide range of functions within their complex social structure. A honeybee has external parts and internal parts. The external anatomy has head, thorax, and abdomen. A detailed scientific account of the senses of a honeybee is presented by Chittka (2022). Worker-bee mouthparts consist of the glossa, the galeae and the vestigial labial palp, and it is these structures that enable bees to feed themselves. The morphology, dynamics, and energy-saving strategies of honeybee's hairy tongue is given by Wang et al. (2021). Honeybees face many problems for their survival. Among the many biotic stressors, the parasitic mite Varroa destructor is considered one of the main causes of colony losses. Honeybees use their mandibles to mutilate and kill Varroa mites (Smith et al. 2021). The detailed anatomy and functions of hypopharyngeal gland of worker bees that contributes to the production of the royal jelly fed to queens and larvae is presented by Klose et al. (2017). The gland consists of thousands of two-cell units that are composed of a secretory cell and a duct cell and that are arranged in sets of about 12 around a long collecting duct. The pheromones secreted by the Nasonov gland is the most well-known worker-exclusive pheromone in honeybees. The gland consists of a mass of cells located beneath the intersegmental membrane, between the sixth and seventh tergites. The details are given in the book chapter by Bortolotti and Costa (2014). The FRs and DPs of these parts are presented in the following design equations. The master design matrix of the overall functions of a honeybee is given in Table 2.

Honeybee
FR_0 = Facilitate pollination

FR_1 = Accommodate various parts of the head
FR_2 = Support various parts of the thorax
FR_3 = Support various parts of the abdomen

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{Bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{Bmatrix} \text{Head} \\ \text{Thorax} \\ \text{Abdomen} \end{Bmatrix}$$

Head
FR_1 = Accommodate various parts of the head

FR_{11} = Detect light
FR_{12} = Assist with Sun's orientation
FR_{13} = Store and process information and control body parts
FR_{14} = Produce royal jelly
FR_{15} = Detect scent
FR_{16} = Prevent pollen to stick to body
FR_{17} = Support and protect mouth parts
Labrum
FR_{171} = Mold wax and chew food
FR_{172} = Move glossa on the upper side
FR_{173} = Move glossa on the lower side
FR_{174} = Suck fluids
FR_{175} = Lap fluids

FR_{176} = Work in conjunction with other mouth parts in food collection

$$\begin{Bmatrix} FR_{11} \\ FR_{12} \\ FR_{13} \\ FR_{14} \\ FR_{15} \\ FR_{16} \\ FR_{17} \end{Bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{Bmatrix} \text{Compund eye} \\ \text{Ocelli} \\ \text{Brain} \\ \text{Hypopharyngeal glands} \\ \text{Antennae} \\ \text{Hair} \\ \text{Labrum} \end{Bmatrix}$$

$$\begin{Bmatrix} FR_{171} \\ FR_{172} \\ FR_{173} \\ FR_{174} \\ FR_{175} \\ FR_{176} \end{Bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{Bmatrix} \text{Manidble} \\ \text{Maxilla} \\ \text{Labial palp} \\ \text{Proboscis} \\ \text{Glossa} \\ \text{Galea} \end{Bmatrix}$$

Thorax
FR_2 = Support various parts of the thorax

FR_{21} = Accommodate front legs and facilitate breathing
Prothorax
FR_{211} = Grooming and manipulation
FR_{212} = Breath air

FR_{22} = Accommodate middle legs and facilitate flying and communicate
Mesothorax
FR_{221} = Walk and climb
FR_{222} = Enable flight
FR_{223} = Power the wings
FR_{224} = Producing sound vibrations during “waggle dance”

FR_{23} = Accommodate hind legs and facilitate breathing
Metathorax
Pollen collection
FR_{231} = Enable flight maneuvers
FR_{232} = Breath air
FR_{233} = Move pollen to pollen basket

$$\begin{Bmatrix} FR_{21} \\ FR_{22} \\ FR_{23} \end{Bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{Bmatrix} \text{Prothorax} \\ \text{Mesothorax} \\ \text{Metathorax} \end{Bmatrix}$$

$$\begin{Bmatrix} FR_{211} \\ FR_{212} \end{Bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{Bmatrix} \text{First pair of legs} \\ \text{Prothoracic spiracles} \end{Bmatrix}$$

$$\begin{Bmatrix} FR_{221} \\ FR_{222} \\ FR_{223} \\ FR_{224} \end{Bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{Bmatrix} \text{Legs} \\ \text{Forewings} \\ \text{Flight muscles} \\ \text{Forewings} \end{Bmatrix}$$

$$\begin{Bmatrix} FR_{231} \\ FR_{232} \\ FR_{233} \end{Bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{Bmatrix} \text{Hind wings} \\ \text{Metathoracic spiracles} \\ \text{Brushes} \end{Bmatrix}$$

Abdomen

FR_3 = Support various parts of the abdomen

FR_{31} = House and protect the parts of abdomen (Skeleton. cuticular protein and Chitin)
FR_{32} = Store nectar (Honey stomach)
FR_{33} = Breath air (Respiratory system)
FR_{34} = Transports nutrients, hormones, and oxygen (circulatory system)
FR_{35} = Break down food and absorb nutrients (Digestive system)
FR_{36} = Filter waste materials (Malpighian tubules)
FR_{37} = Produce pheromones (Dufour's glands)
FR_{38} = Produce beeswax (Wax glands)
FR_{39} = Carry pollen (Scopae)
FR_{310} = Excrete waste (Rectum)
FR_{311} = Produce venom (Venom gland)
FR_{312} = Defend colony (Stinger)

$$\begin{Bmatrix} \mathrm{FR}_1 \\ \mathrm{FR}_2 \\ \mathrm{FR}_3 \\ \mathrm{FR}_4 \\ \mathrm{FR}_5 \\ \mathrm{FR}_6 \\ \mathrm{FR}_7 \\ \mathrm{FR}_8 \\ \mathrm{FR}_9 \\ \mathrm{FR}_{10} \\ FR_{11} \\ FR_{12} \end{Bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{Bmatrix} \text{Skeleton} \\ \text{Honey stomach} \\ \text{Respiratory system} \\ \text{Circulatory system} \\ \text{Digestive system} \\ \text{Malpighian tubules} \\ \text{Nasanov glands} \\ \text{Wax glands} \\ \text{Scopae} \\ \text{Rectum} \\ \text{Venom gland} \\ \text{Stinger} \end{Bmatrix}$$

Table 2. Master Design Matrix of the Overall Functions of a Honeybee

		DP_1 (Head)							DP_2 (Thorax)			DP3 (Abdomen)											
		DP_{11} (Eyes)	DP_{12} (Ocelli)	DP_{13} (Brain)	DP_{14} (H. Gland)	DP_{15} (Antennae)	DP_{16} (Hairs)	DP_{17} (Labrum)	DP_{21} (Prothorax)	DP_{22} (Mesothorax)	DP_{23} (Metathorax)	DP_{31} (Exoskeleton)	DP_{32} (H. Stomach)	DP_{33} (R. System)	DP_{34} (Circulatory system)	DP_{35} (Digestive system)	DP_{36} (M. Tubules)	DP_{37} (N. Glands)	DP_{38} (Wax glands)	DP_{39} (Scopae)	DP_{310} (Rectum)	DP_{311} (Venom gland)	DP_{312} (Stinger)
FR_1	FR_{11}	1	0	0	0	0	0	0															
	FR_{12}	0	1	0	0	0	0	0															
	FR_{13}	0	0	1	0	0	0	0															
	FR_{14}	0	0	0	1	0	0	0															
	FR_{15}	0	0	0	0	1	0	0															
	FR_{16}	0	0	0	0	0	1	0															
	FR_{17}	0	0	0	0	0	0	1															
FR_2	FR_{21}								1	0	0												
	FR_{22}								0	1	0												
	FR_{23}								0	0	1												
FR_3	FR_{31}											1	0	0	0	0	0	0	0	0	0	0	0
	FR_{32}											0	1	0	0	0	0	0	0	0	0	0	0
	FR_{33}											0	0	1	0	0	0	0	0	0	0	0	0
	FR_{34}											0	0	0	1	0	0	0	0	0	0	0	0
	FR_{35}											0	0	0	0	1	0	0	0	0	0	0	0
	FR_{36}											0	0	0	0	0	1	0	0	0	0	0	0
	FR_{37}											0	0	0	0	0	0	1	0	0	0	0	0
	FR_{38}											0	0	0	0	0	0	0	1	0	0	0	0
	FR_{39}											0	0	0	0	0	0	0	0	1	0	0	0
	FR_{310}											0	0	0	0	0	0	0	0	0	1	0	0
	FR_{311}											0	0	0	0	0	0	0	0	0	0	1	0
	FR_{312}											0	0	0	0	0	0	0	0	0	0	0	1

5. Discussion and Conclusions

In real-world designs, some DPs do multiple tasks. For example, a kitchen knife is used for peeling, cutting, chopping, dicing, slicing, mincing, separating tasks. Similarly, the mandibles of a honeybee located on the sides of the head act like a pair of pliers. The mandibles are used for any chores in a hive such as grasping or cutting wax to construct the comb, biting into flower parts (anthers) to release pollen, carrying detritus out of the hive, and gripping enemies during nest defense. In his case, many FRs are fulfilled by a single DP. This looks like a coupled design. Coupled designs are created when the number of DPs selected to satisfy a given set of FRs is less than the number of FRs. In an ideal design, the number of FRs and the number of DPs are the same. But a careful analysis will reveal that all FRs are not fulfilled at the same time. Honeybees use mandibles (single DP) to satisfy multiple FRs at different times. Therefore, it is not a coupled design, but an ideal design.

Axiomatic design is a general design methodology that can be applied to evaluate the couplings of very small to very large systems. It can be applied to product design, service design, machine design, tooling design, software design, manufacturing system design, or logistics design. This paper focused only on the evaluation of the design features of a flower and a honeybee to test if the FRS and DPs are coupled or not. The analysis revealed that the anatomical features are uncoupled, and therefore it can be concluded that they are a good design.

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