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It is entitled:
Biomimicry of Feathers for Airport Design

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Biomimicry of Feathers for Airport Design

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Abstract

Biomimicry refers to the work of people who realize that the organic structures or surviving outcomes of nature are not only seemingly beautiful but also durable and who apply them to human inventions by designing with the methods of nature. There are many projects around the world utilizing biomimicry, even from before the term was commonly used. Furthermore, biomimicry is increasingly employed in architecture. In this thesis, I will examine the design of an airport building through biomimicry. Because of a correlation between flights, airplanes, airports, and feathers, I have selected a feather for my biological inspiration. The structural pattern of feathers allows them to sustain their shape and function in flight. Understanding the principle of this structure, which is based on interlocking systems of hooks (barbicels) with three different hierarchies (rachis, barbs and barbules), allows a plausible formulation for a lightweight long-span structure of an airport by designing a feather-like canopy unit. The site I have selected for this examination is Cincinnati/Northern Kentucky International Airport (CVG), which is in decline due to decreased demand. Hoping for a revitalization, the airport management plans to combine Concourse A and Concourse B as one compact concourse in 2023 to reduce the waste, maintenance fees, and unnecessary spaces. Based on these needs
from CVG, I propose a new concourse by mimicking a feather’s structure to design an innovative new airport facility.
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01 INTRODUCTION

Architectural design has evolved alongside technological advances in the 21st century. Current technology enables the construction of innovative architectural forms with new building techniques and construction materials. However, even with significant innovations in technology, in many cases superior innovation exists already in nature. Compared to human invention, organic life has developed more delicate and structural architectural structures using no harmful chemicals and producing no unhealthy byproducts during the manufacturing process. Many people have recognized that we can imitate the work of nature to solve problems in a process known as biomimicry. In the early days of biomimicry, inventions were born from cooperation between biologists and engineers who were fascinated to learn from the natural world. Eventually, architects became interested in employing biomimicry to create architectural forms that solve current problems or extend architecture beyond current limitations.¹

In this project, I examine the microscopic properties in the structure of the feather to develop an architectural structure in an airport terminal. The feather is a crucial part of a bird’s body. It is one of the main characteristics defining these vertebrates as birds, differentiating

them from other animals. Feathers are useful to birds because they allow them to fly, but also to protect themselves through camouflage, to regulate their body temperature, to attract counterparts for mating, and to prevent them from getting wet. Even though all of these diverse functions are beneficial, the most fascinating quality of the feather is how it helps birds fly through the air with its lightweight and robust structure which endures powerful aerodynamic forces during their lift, gliding, and thrust. A lesson can be learned by adapting the feather structure to develop a new structure for an airport concourse building. Hence, a goal of this thesis is to design a lightweight, long span roof structure for an airport concourse by using the methodology of biomimicry: in this case feather-mimicry.

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02 Related Work

1) Biomimicry in General

In 15th-century, Leonardo Da Vinci designed a flying machine invention based on a bird, using biomimicry. In fact, in numerous cases humans have invented innovations by mimicking principles from nature even though the term biomimicry became officially known more recently, used by Janine Benyus in her 1997 book, “Biomimicry: Innovation Inspired by Nature.” The basic purpose of biomimicry is to seek sustainable solutions from nature, as opposed to problematic manmade inventions, by means of emulating eco-friendly patterns and strategies of nature that have survived and adapted over many thousands of years through harsh conditions.4 The first flying machine, designed by Leonardo da Vinci, can be deemed as an invention of biomimicry because the machine was inspired by birds and created through deep studies of a bird and its anatomy with Leonardo’s passionate sketch drawings.5 Velcro tape was created through biomimicry as well: Swiss engineer George de Mestral observed that burrs were clinging to his clothes and his

dog without any adhesives, and discovered that the burrs’ hooking structures allow
them to stick to clothes and furs. Mimicking this strategy, Velcro was developed as
an alternative “zipless zipper”.6 Using biomimicry, scientists have innovated and
upgraded existing products. For example, the Super Strong Ceramic was invented by
researchers in Laboratoire de Synthèse et Fonctionnalisation des Céramiques. By
mimicking the structure of mother-of-pearl, this super strong ceramic is 10 times
stronger than the original.

2) Biomimicry in Architecture

In the early days of biomimicry, scientists were most interested in the subject
and researched it actively. However, a handful architects began to see it as an
architectural design tool. Since the current advanced technology in building
construction methods and design tools enables naturalistic, organic architectural
design, I believe biomimicry in architecture has the potential to create new forms of
architecture, deviating from regular and commonly-used rectangular shapes. The
Eden Project (Grimshaw Architects) is an example of an architectural project
employing biomimicry. The project is in Cornwall, UK. Since a clay pit was still in the

process of mining during the design phase, it was impossible to avoid the continuously changing the landscape. In response to the unstable geological site, Grimshaw Architects came up with a solution from the shapes and principles of soap bubbles and pollen grain as a structural basis. The Spanish architect Santiago Calatrava has used biomimicry in his architecture. He designed a conspicuous form imitating the human eye in his L'Hemisfèric in Valencia, Spain. The inner center of the hemispheric dome is used as an IMAX theater shaping a pupil inside the eye. The outer skin of architecture is able be opened and closed in the same way as an eyelid works. Furthermore, Calatrava brought the reflective water near to the building. At night, the architecture shows the completed eye shape with the other half reflected from the water. Another case of biomimicry in architecture is in Melbourne, Australia, in a project designed by Mick Pierce and Design Inc. Council House 2 achieved healthy office environment through applying the natural ventilation instead of using a conventional HVAC system. The strategy of the natural ventilation was inspired by the structures of termites. Termites construct enormously high-rise

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“buildings” comparing to their body size, and keep a constant temperature inside their structures regardless of a wide range of fluctuating outside conditions using the thick insulated wall, the shape of mound, the operable opening, and wet muds. Applying the lessons from termites, an architect Mick Pierce designed the clever ventilation strategy based on biomimicry. In addition to the projects mentioned above, a number of architectural design projects using biomimicry are growing and being tried in various ways worldwide.

3) Biomimicry for Structural Systems

Structure is the vital and fundamental element for an architectural building to be erected in safe manner. The structure is not only a supporting system for the building’s other components but also a design element for upgrading the aesthetic qualities of the architecture. Applying biomimicry to architectural structure, the performance of architecture can be improved while also creating intriguing form and providing a more pleasant experience to building users. One example of biomimicry in structural systems is the tree-like structures in Stuttgart Airport

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Terminal 3, designed by GMP (Architekten von Gerkan, Marg und Partner). 18 tree-imitating columns support a slanted roof. Optimization of load flow through the tree shape enables greater efficiency in structure and material use.\textsuperscript{10} Similarly, Architects at University of Stuttgart applied biomimicry in a structural pavilion. Researching on the elytron, the beetles’ outer wing that protects its abdomen, they designed a Carbon Fiber Pavilion. Based on biological structural principles and robotic technology, the pavilion succeeded in creating performative and materially efficient lightweight constructions.\textsuperscript{11} Another case of biomimicry in structure is the Eiffel tower in Paris, inspired by a femur bone. A femur has a hierarchy in structure that leads to strong material arrangement with a natural curve form. With multiple tubes called osteons in a bone, and multiple pieces of tubes called haversian in each osteon, the bone is structured with the form of a smaller bundles within the larger bundle. The architect, Gustave Eiffel, emulated the structural hierarchy of a femur equivalently. The Eiffel Tower is structured with large trusses carrying smaller


trusses that carry even smaller trusses, which give the tower strength against gravity and wind loads, as well as a harmonious curvature.\textsuperscript{12}

4) Biomimicry Using Feather-like Geometries

Feathers have been used as an architectural motif for many designers. Frei Otto designed a 6-meter tall installation called “The Feather,” made with 200 meters of wire.\textsuperscript{13} The structure was composed of feather substructures like rachis, barb, and barbule by way of Frei Otto’s interpretation. The Milwaukee Art Museum (designed by Santiago Calatrava) is sited near the lake, like a bird fluttering toward the water. The operable structural system with metal beams and steel cables mimics wings and feathers.\textsuperscript{14} In Zayed National Museum (designed by Foster + Partners), there are five wing-shaped solar towers, which operate similar to the feathers in wings of birds. These wing shapes help draw cool air in and push hot air out through the museum by way of the thermal stack effect.\textsuperscript{15}

\textsuperscript{12} Wired. What Your Bones Have in Common with the Eiffel Tower. 2015. Accessed by March 4\textsuperscript{th} 2017. \url{https://www.wired.com/2015/03/empzeal-eiffel-tower/}.

\textsuperscript{13} Flicker. Jon Reksten. 2007. Accessed by March 4\textsuperscript{th} 2017. \url{https://www.flickr.com/photos/jonhefel/2159404419}.


03 Feathers

Feathers are unique to birds. Merriam-Webster’s Dictionary defines bird as: “any of a class (Aves) of warm-blooded vertebrates distinguished by having the body more or less completely covered with feathers and the forelimbs modified as wings” (emphasis added).

This dictionary describes feather as: “any one of the light growths that make up the outer covering of the body of a bird” In a book called “Avian Flight”, the author described feathers as follows: “Feathers are the hallmark of birds. Birds are unique among the flying groups of animals because the capacity to fly is exclusively based on the highly complex modified scales.” We can assume how crucial feathers are for a bird’s flight.

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1) Functions

Feathers play important roles to birds. (Figure 3.1) First, birds can make a refined flight in the sky with effective steering toward the direction in which they intend to go. Second, birds use their feathers to woo potential mates and to express aggression through display. Third, some birds use the color of their feathers to hide themselves from their enemy. Fourth, feathers cover birds’ skin, functioning as insulation and protection against the elements. Fifth, feathers induce water to roll backward off the bird’s body, due to their organization in an overlapping pattern.¹⁹

There are several types of feathers whose particular structure varies depending on their function and location (even though their basic structure is similar).\textsuperscript{20} (Figure 3.2) In this paper, I would like to focus on the flight feather, which has a strong and clear logical structure.

3) Microstructures

Feathers are made up of beta keratin, which also appears in mammalian hair and reptilian scales. In general, feathers consist of structures as shown in Figure 3.3:

calamus, rachis, barbs, barbules (proximal & distal), and hooklets (barbicel).

The **calamus** is the hollow shaft of the feather that is attached to the bird’s skin. In a calamus, there are two traces of the blood supply point during growth of the feather. One is an inferior umbilicus located in the lower pointed end and closed from
the inside in a fully formed feather. The other is a superior umbilicus situated at the transitional point from calamus to rachis.\footnote{Videler, John J. Feathers for Flight. In Avian Flight, p 47. New York, NY: Oxford University Press, 2005.}

The \textit{rachis} is the central shaft of the feather, which is where part of the vanes are formed. Unlike calamus, rachis is solid, surrounded by a cortex (stiff wall), and filled with a pith (spongy tissue). Rachis has a unique section shape; on the dorsal side, it is smooth and convex. The sides of rachis are flat or slightly convex. On the ventral side, there is a groove in the middle making a rather concave shape.\footnote{Videler, John J. Feathers for Flight. In Avian Flight, p 47. New York, NY: Oxford University Press, 2005.}

The \textit{vane} is the fluffy and flat parts of the feather where the row of barbs is supported by the rachis. The form of the vane is created by the delicate arrangement of barbs, barbules, and barbicels.\footnote{Videler, John J. Feathers for Flight. In Avian Flight, p 47. New York, NY: Oxford University Press, 2005.}

The \textit{barbs} are the numerous branches off of two sides of the rachis that form the vanes. The barbs make acute angles at the meeting point of rachis, pointing in the direction of the tip. The section of a barb is similar to the shape of the crescent moon,
having proximal barbules on the convex side and distal barbules on the concave side above the proximal barbules.\textsuperscript{24}

The \textbf{barbules} are tiny extensions from barbs. There are two kinds of barbules; proximal barbules and distal barbules; they are held together by barbicels. The barbules play an important role to hold each barb together so that they stay in a flat canopy shape from both sides from the rachis.\textsuperscript{25}

The \textbf{barbicels} are tiny hooklets that interlock the proximal and distal barbules together to hold the shape of the vane. Since the barbicels are dead cells, they cannot move to interlock again once disturbed or separated by external factors. (This is the reason many birds preen so often to arrange their feathers and prepare for flight.)\textsuperscript{26}

Figure 3.4 shows the feather’s growth from the skin of a bird. Like human hair, feathers grow from follicles inside the skin. During the growth of a feather, it receives nutrients from arteries and veins through the umbilici of feathers. At this stage, a feather is called a blood feather. A blood feather starts out from the skin with a pliant keratin sheath that shields it from damage. When the feather becomes fully mature, the blood supply turns off and the sheath starts to come off and is entirely removed by the bird.\textsuperscript{27}

\textsuperscript{27} The Cornell Lab. Feather. 2014. Accessed by March 4\textsuperscript{th} 2017. \url{https://academy.allaboutbirds.org/feathers-article/4/}. 
5) Molting and Regeneration

After the growth process, a feather is not a living entity anymore, but rather a dead structure, meaning the feather cannot repair itself once it is damaged. Because feathers are crucial to birds’ survival in terms of keeping them safe and flying, birds must regularly molt their old feathers and replace them with new ones. Once the newborn feathers have matured, molt starts and new regeneration develops before the next molt cycle when feathers are unexpectedly damaged.\(^28\) Figure 3.5 shows the feather in sheath after the regeneration process.

04 Analysis of Feather Structure

a. Structure

i. Grasshopper Feather Rebuilding Process

1) The first step is to build rachis and calamus with natural curvilinear shape and squashed round section shape.

2) The second step is to create slightly curved barb structures branching out from the rachis.

3) The third step is to generate distal barbules branching from the barbs. The length of barbules is not consistent.

4) Last, the proximal barbules and hooks attach such that they interlock with the distal barbules to sustain an individual feather shape.

*Figure 4.1*  
Feather building process
A final feather outcome by Grasshopper is shown on the right side, compared with a real feather on the left. Due to the parametric flexibility of the Grasshopper software, it is possible to adjust variable inputs to create diverse feather shapes.
1) The length and shape of Rachis and shapes of both vane profile are variables for the feather.

2) The profile of rachis section and the length of calamus are the variables for the feather.

3) The angle between barb and rachis can vary on the right and left side of the vane.

4) The length and curvature of distal barbules and proximal barbules and the size and number of hooks are variables for the feather.

*Figure 4 1*

*Grasshopper scripts for building a feather*
These variable input factors enable diverse forms of feathers.

Figure 4.2 Various shapes of feathers using different parameters with same scripts.
ii. Karamba Structural Analysis

Karamba is a plug-in program operating within Grasshopper to analyze a three-dimensional structure composed of beams or trusses under arbitrary loads.\(^{29}\) Based on this function, the structural performance of a feather under gravity can be analyzed by interpreting structures of a feather (rachis, barb, and barbule) as round tube beams.

Firstly, the structures of a feather (rachis, barb, and barbule) need to be redrawn as linear lines. The lines are then converted to beams in Karamba.

Since exact material properties of feathers are not available, we model the beam material as aluminum tube, available in Karamba’s material library. For this reason, the result may be exaggerated, but still shows similar behaviors.

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\(^{29}\) Food4Rhino. Karamba. Accessed by 12\textsuperscript{th} Feb. \url{http://www.food4rhino.com/app/karamba}. 
Next, a support point is set at the endpoint of the calamus, where the feather attaches to a bird’s skin. As can be seen below, by changing the figures of deformation, the feather performs as one structure.

Figure 4.5 shows the outcomes from Karamba analysis. The left figure shows the displacement. The darker pink color means high degree of transformation, and the right one renders the utilization. The blue color indicates the part of the feather with the highest load. From this study, one can determine that the feather structure acts in bending as the transformation increases. The feather structure can arguably be utilized effectively in arch shaped structures.
iii. Light-Weight Long-Span Structures

A bird’s feather sustains its form, which is a canopy-like or fan-like structure, based on an interlocking system composed of many distal and proximal barbules. Analogizing this interlocking concept with many lightweight structural members to a real structure, I would like to examine the possibility of a light-weight long-span structure.

b. Material

i. Bending Active Structure

The term “bending-active structure” was introduced by Julian Lienhard, author of the paper “Bending-Active Structures”. In his paper, he states, “Bending-active structures are structural systems that include curved beam or shell elements which base their geometry on the elastic deformation from an initially straight or planar configuration.” This definition indicates the feather belongs to the category of bending-active structures. (We can see how the feather structure behaves when diverse loads are applied to it from the Karamba analysis above)

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(Figure 4.4). The canopy-like flat feather transformed into an arch-like curved shape as heavier loads are added. In the regard that the Karamba analysis did not account for the elastic material attributes of the feather, it could be assumed that real feathers are even more eligible than the simulation as bending-active structures (given the flexibility and elasticity of a real feather’s keratin).

However, the bending-active structure is not a definite structural typology; It is rather an approach to name a formation process during its elastic bent.\(^{31}\)

Therefore, the behavior of an elastic bending feather can be understood with the term of bending-active structure, and can lead to the potential of inspiring new arch-shaped architectural structures.

ii. Carbon fiber

Researchers at Southampton University has researched feathers. Their research shows bird feathers have properties similar to carbon fiber. Carbon fiber is nowadays considered an innovative material for architectural structures, possibly

as an eventual replacement for steel, as carbon fiber is much stronger than steel and 90% lighter. \(^{32}\)

iii. Application in Architecture

The carbon fiber tube as a structural material is not yet widely used in architecture, though there are many bicycles that are made with carbon fiber to improve the strength and reduce weight. An architectural website refers to carbon fiber material as the replacement of the steel. \(^{33}\) Also, there are several built bridges in Maine, USA, using carbon fiber tubes with arch shapes as a supporting structure (Neal Bridge, 2008 / McGee Bridge, 2009 / Royal River Bridge, 2010 / Jenkins Bridge, 2010 / Farm Access Underpass, 2011). \(^{34}\) Therefore I assume the plausible architectural application of carbon fiber tube structure in the future with additional tension supplements like cables to reinforce the main structure.


05 Agglomeration of Feathers

The feather works on the body of a bird is not discretely but in an arrangement together. A common rule of basic arrangements on the wings and the tail is described in this chapter, though differences in shapes and coloration among different kinds of birds exists. Further explorations based on agglomerations built in Grasshopper are included.

A. Observation

i. Wing

A feather’s crucial role is to enable flight. Though an individual feather has a unique structure, there are also organized structural arrangements of feathers on the wing to help adjust for flight functions and cover the skin of the bird. As can be seen in Figures 5.1, 5.2, and 5.3, the agglomeration of feathers forms different shapes on the wing during gliding, flapping, and sitting.
“The shape of a wing is only marginally determined by the internal anatomy; it is the feathers that make a wing fly.”  

A bird has largely three parts of wing skeletons: hand, arm, and humerus. (Figure 5.2) As can be seen in Figure 5.3, feathers are organized in the hand bone part are called primary feathers, in the arm bone part, secondary feathers, and in humerus bone part, tertial feathers.  

Feathers are layered such that vanes of feathers cover calamus parts, preventing them from falling off easily from the skin of a bird. Because of agglomeration of feathers, they not only keep the body warm but also stick together strongly on the wing. Furthermore, a bird can easily manage its wings, folding and unfolding them like a folding fan.  

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ii. Tail

Birds have feathers not only on their wings but also on their tail, which are termed retrices. There are diverse shapes and sizes of retrices, varying by species. (Figure 5.4)

The shape of tail is altered by folding and spreading like foldable fans. Generally the right side and left side of a feather from the center of vertebra are symmetrical, but depending on the amount of spreading or tilting, they could be shaped with a high degree of asymmetry as well. Somewhat similar to feathers on wings, feathers on the outer side of the body are asymmetrical and on the inner side near to the vertebra are symmetrical. Asymmetrical...
outermost feathers feature more narrow vanes outside than inner vanes nearer to the center.\textsuperscript{38}(Figure 5.5)

iii. From Feather Arrangement to Architectural Design.

Inspiration from the arrangement of feathers is key to the design of a new terminal for CVG airport. Using Grasshopper enables the construction of the wing structure based on observation.

06 Airport Terminal and Feather

In order to apply the designed structure, inspired from feather, to the CVG airport, a brief discussion of the site, basic information for airport terminal design, and exploration of future needs in CVG airport will all be described in the following sections.

A. Site (CVG Airport)

i. History

President Franklin D. Roosevelt approved the site for the development of the Greater Cincinnati Airport in 1942 as a part of the US Army Air Corps during World War II. Because of the poor location of Lunken airport and the lobbying of officials from Kentucky Counties, Cincinnati’s airport was built in Boone County, KY, immediately across the Ohio River from the city itself. The airfield of CVG opened in 1944 for the Air Corps. Commercial flights to and from the airport began in 1947.39


ii. Current
The current location of CVG airport is 3087 Terminal Dr., Hebron, KY 41028. Total land area is 7,000 acres (28.3 km²). As an international airport, CVG serves both international and domestic passengers. CVG is Delta’s second hub airport. Although CVG was once one of the fastest growing airports, the number of passengers has declined sharply since the 2008 economic recession. As can be seen in the graph(Figure 6.1), the number of passengers in 2010 was less than half the amount of 2005.

At the same time, Terminal 1, Terminal 2, and Concourse C have been demolished due to vacancy and wasteful maintenance fees.40

Figure 6.1 Annual passengers

Currently only Terminal 3, Concourse A, and Concourse B remain operational for passengers. (Figure 6.2)

iii. Future (2035 master plan)

The CVG airport managing company has established goals for 2021, such as increasing traffic to 9,000,000 passengers, developing a leasing business, increasing economic profit to boost $5 billion annually, elevating the services, and attaining higher ranking. CVG has also worked on a 2035 master plan, which is anticipates the combination of concourses A and B to manage the airport more efficiently.41

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B. Airport Research

i. Functional Types of CVG Airport Terminal

1. Domestic and International terminals

In contrast with domestic terminals, international terminals must incorporate customs and immigration zones. Domestic terminals at one time were much simpler than international terminals in the past. However, due to the increased security and anxiety over recent terrorist attacks, domestic terminals have been required to increase passenger and baggage security, which causes the complication of the organization of the facilities, raising their complexity to near the level of International terminals.42

2. Midfield concourse

Figure 6.3 Midfield concourse type

Midfield concourse types have independent passenger buildings independent from landside terminals. (Figure 6.3) Typically, they are located between two parallel runways and separated from other passenger buildings by major taxiways. There are two basic shapes for midfield concourses: linear and x-shaped. The terminal form of CVG Airport is the midfield concourse type.

3. Hub terminals (CVG is still a Delta Hub Airport)

A hub terminal is designed to support an airline hub operation which in turn is a system of scheduled flights converging on an airport within a short time. Comparing to point-to-point airports, hub airports are the most efficient way of connecting many points. (Figure 6.4)

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ii. **Basic Spatial Requirement**

Below is a list of the required programs in the design of terminal buildings.\(^{45}\)

1. **Airline operation**

   A. Passenger and baggage-handling counters
   
   B. Office space adjacent to passenger-handling counter
   
   C. Baggage claim area
   
   D. Information counter
   
   E. Telecommunication facilities
   
   F. Space for handling and processing of mail, express, and light cargo
   
   G. Aircraft Optional activities
   
   H. Catering activities
   
   I. Crew rest facilities

2. **Passengers convenience**

   A. A central lobby (waiting area for passengers)
   
   B. Facilities for dispensing food or beverages
   
   C. Nursery for small children

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D. Toilets

E. Concessions (Bank, Gift shop, Car rental, Flight insurance, etc.)

3. Airport management office
   A. Accounting, Maintenance, Operation, and public relations.

4. Federal Government office
   A. Federal Aviation Agency
   B. The Weather Bureau
   C. Communications facilities
   D. Post Office Department
   E. Customs control
   F. Passport and health control
iii. Circulation

1. International and Domestic Passengers, Baggage

Since the advent of new security procedures for safety purposes, both passengers and baggage have to pass through a tiresome and time-consuming route as can be seen in Figure 6.5. Therefore, modern airport terminals require an efficiently-controlled circulation system for guiding passengers and baggage to their destinations. Furthermore, the segregation between international and domestic passengers is crucial because additional control and regulation processes for international travel are needed for immigration, customs, and health controls and security according to international codes. Thus, it is important to consider the
demands and security of both international and domestic passengers to plan separate circulations.46

2. Departure, Arrival and Transfer of Passengers and Baggage

Figure 6.6 shows the complex circulation of passengers and baggage with different destinations from car to gate and vice versa. Just as segregation between international and domestic passengers is essential, careful division of departure, arrival, and transfer passengers is critical to effective circulation so that passengers using the airport can begin, end, or continue through their trips without getting

lost or delayed inside the terminal building. The most plausible way to divide the
routes of departure, arrival, and transfer passengers is using multi-levels for each.
For instance, the first level is effective for baggage handling, second for departure
passengers, and third for arrivals. Also, there need to be additional small security
checkpoints for transfer passengers on the arrival level.47

iv. Case Study_ Chhatrapati Shivaji International Airport, Terminal 2

Chhatrapati Shivaji International Airport is in Mumbai, India. The Terminal 2 is an
X-shaped terminal designed by Skidmore, Owings & Merrill. 95 flights per day
operate out of the terminal, carrying 40 million passengers per year. The terminal
opened in 2014. The total floor area is 4,843,760 sf (450,000 m²) over four levels.
The first floor is mostly for serving baggage handling or airline maintenance, the
second for arrivals, the third for domestic passengers, and the fourth for
international passengers.48 (Figure 6.7)

C. CVG airport

i. Existing Terminal 3 and Concourse A&B Program Diagram

Originally there were three terminals (Terminal 1, 2, 3) and three concourses (Concourse A, B, C) on the site. However, due to declining demands, outdated design, and economic issues, Terminal 1 and 2 and Concourse C have been closed
and demolished. Currently, only Terminal 3 and Concourse A&B are functioning as CVG airport facilities.

![Figure 6.8: Existing programs at CVG airport](image)

Figure 6.8 shows the current programs in Terminal 3, Concourse A, and Concourse B. The programs of each facilities are categorized based on the main users of the spaces. The blue color indicates the programs for airline companies, the red for the commercial stores, the yellow for the passengers, the cyan for the CVG airport company, and the green for the government agencies located in the airport. By comparison of size among the facilities, Concourse B (893,987 sf) is the largest, Terminal 3 (378,510 sf) of intermediate size, and Concourse A (350,057 sf) the smallest. Even though Concourse B is the largest, its proportion for passenger is the
lowest of the three. Each facility has a relatively small portion of retail services despite the fact that CVG is a hub and international airport. On average, the largest proportion of the space is for passengers, then airline companies, then airport companies, then government agencies, and finally retail stores.

ii. Proposing a New A&B Combined Concourse Diagram

CVG airport has a future plan in an official document “Cincinnati/Northern Kentucky International Airport 2035 Master Plan Update” which has been uploaded on its main website. In this document, the CVG airport outlines its intention to
combine Concourse A and Concourse B together by 2035. (Figure 6.9) Thus, in this thesis, the new combined concourse proposed will be based on the airport’s future goal.

D. Methodology

i. Layout

Using existing infrastructures, the proposal begins from Terminal 3 and ground transportation to airside Concourse. When passengers arrive at the concourse building, they first encounter spacious retail facilities with food, beverages,

Figure 6.10 Program layout diagram

promotions, and duty free stores. From the entry, one direction leads to international gates and the other to domestic destinations. (Figure 6.10)

By vertically separating levels for arrival passengers, departure passengers, and baggage handling, the airport buildings can avoid chaotic and congested circulation or baggage problems. Therefore the studies for vertical section shown in Figure 6.11 were essential to developing the concourse.

![Figure 6 11 Vertical segregation studies](image)

ii. **Roof structure**

As mentioned earlier, the interlocking system of feathers enables their flexible, bending arch shape and light weight with robust features. This system inspires the feather-shaped structures that have potential for the airport roof to create a long span arch structures for the airport concourse facility. Designing a unit structure that can be connected continuously by adding and interlocking more unit in order
to make a long span structure was the first step. In addition, the methods of agglomeration studied from birds’ wings enabled increasing the width of interior spaces without adding other design languages into the building. Lastly, the building material was chosen not to hide but rather to reveal the architecturally designed structures.

1. Interlocking Unit Structures

The unit structure was inspired from the pattern of the feather interlocking. (Figure 6.12) The individual feather-like structure is arrayed and alternately flipped by 180° to enable interlocking barbs from each side of individual structure. The dot lines of the figure below are continuous tensile elements to hold the individual feather’s rachis and barbs together and then to support one side of the vanes so that the next adjacent feather is oppositely placed.

![Figure 6.12 Feather Pattern and Interlocking Design](image)
The next step in the design process was examining several methods of making three-dimensional structures from two-dimensional patterns of interlocking above.

Figure 6.13 shows the first trial version to build up in a three-dimensional manner. The interlocked pattern of barbs is placed on the flat top to make up a planar roof. The limitation of this model is the abrupt curvature at one point between rachis and calamus. This will cause a structural weak point. Moreover, this is not comparable to the natural behavior when a real feather bends.
Figure 6.14 shows the next trial, making up for shortcomings of the design shown in Figure 6.13. This model has a more natural curved roof without abrupt bending points. Its natural bent arch-shape shows a more stable structure and is more akin to the shape of bending feathers.

Figure 6.15 shows the possibility of dynamic structures along the lines shown in Figure 6.14. By incorporating different heights, the building can be shaped like waves on the sea.
2. Agglomerating Unit Structures

In chapter 5, it was mentioned how the feathers come together on the birds’ wing with several layers. Following this principle of agglomeration, the interlocked structures can have multiple layers to expand to the space of the building.

Figure 6.16 shows two layers of interlocking unit structures overlaid and intersecting together with an agglomerating method. This agglomeration allows expansion of the building width, allowing for more continuous interior space. Furthermore, each layer can be followed by essential circulation corridors to make efficient trips for passengers and users.
3. Material Strategy

Carbon fiber structure has been identified as a potential replacement for steel because of its superior strength and minimal weight.\textsuperscript{50} In relation to the fact that the material composing feathers is similar to carbon fiber, the feather-like airport structure is designed with carbon fiber tubes to have the characteristics of light weight and robust strength. The material choice of ETFE and glass fulfills the purpose of revealing the feather like structure to the exterior and adding feather-like effects to the building.

iii. Volume studies

The volume of concourse studied and developed by building surfaces with Grasshopper. The surface serves as a base for aligning the unit structures.

The volume (Figure 6.19) was developed through several trials of spline rails to have a rational shape aligned with passenger circulations (Domestic departure,
Domestic arrival, International departure, and International arrival (Figure 6.20)

and a beautiful curved appearance.

The final volume largely consists of three layers. The middle layers start from the

ground station and stretches out to the both sides, west to domestic gates and east
to international gates, which are in parallel with circulation for departure
passengers (left for domestic and right for international destinations to readily
handle the security process). The first and third layers are leading arrival
passengers from each gate to the ground station, and the bottom spaces of the
arrival floor are reserved for departure gate lounges. The space resulting from
splitting the middle and third volumes is a courtyard that gives an eco-friendly
environment to the concourse. The two layers which are added to the north side of
the courtyard are high, open spaces for commercial and other necessary activities.
E. Final Design

i. Site Plan

The new concourse is proposed on the position between existing concourses A and B. The existing ground transportation from the terminal 3 is passing through the center of the new facility below. (Figure 6.21)
Figure 6.22 shows the floor plans of the concourse. In sequence from bottom, they are 1st floor plan, 2nd floor plan, and 3rd floor plan. Each floor is designated with its own purpose to control efficient circulation as a concourse building. The first floor
serves as a main hall for passengers coming from terminal 3 or the arrival gates.

The green space indicates the courtyard. The pink areas are commercial services
mainly for shopping, and dining. The blue areas are spaces for the offices
supporting the airline companies, airport, government agencies, baggage handling,
etc. The second floor delivers departure passengers to the gate lounges, which are
colored in yellow. The darker yellow indicates the supporting spaces for departure
passengers such as toilets, nursery rooms, newspapers, and Internet rooms. The
pink areas are continuous space from the first floor with commercial services. The
third floor serves arrival passengers. The orange color is the space for arrival lounge
and circulation, and the darker orange serves as the supporting areas such as
toilets, nursery rooms, newspapers, and Internet rooms.
iii. Section

Figure 6.23 shows the section of the concourse building. As can be seen from the section, the circulation of arrival and departure passengers is separated by floor to minimize congestion. The offices on the first floor serve airport maintenance and airlines easily because of their location near to the ground.

Figure 6.23 Section Isometric View
iv. Exterior

The new combined concourse building is designed by a feather mimicry structure with ETFE and glass panels. A perspective rendering is shown on the left side and a top view rendering on the right side. (Figure 6.24)

*Figure 6.24 Final perspective and top view rendering*
v. Interior

Figure 6.25 is the interior rendering image which is the central commercial area looking through the domestic wing side. (First Floor)

Figure 6.26 is the interior image rendering the passage way and the gate lounges. (Second Floor)
Figure 6.27 shows the interior image of the arrival passage way. (Third floor)
vi. Detail

To accomplish an undivided feather-mimicry concourse architecture, the feather-like structure has to work alongside exterior materials to save and improve the clarity of its image.

Thus, the translucent ETFE and transparent glass are suitable to preserve an impressive image of the structures for both interior and exterior views. Figure 6.28 is the idea sketch for detailed match with structures, ETFE, and glass. The ETFE materials will cover the vane parts of the feather-like structures and produce dimply roof surfaces, reminiscent of the fluffy vane of the feather. The glass will be enveloped on the calamus sides of the feather-structure, which are the wall sides of the arch volume, to make a clear view and access to outside or the bridges from gates to airplanes.
Figure 6.29 shows how the ETFE connects to the carbon-fiber tube structures with the air supplier system.

Figure 6.30 shows the detail of how the glass walls are attached and connected to the gate bridges.
07 Evaluation

In this section, I will evaluate this thesis project, focusing on what was successful and the remaining difficulties.

The purpose of the thesis—designing concourse architecture by using biomimicry—is consistently pursued with logical procedures of solid research, analysis, and studies of designs to the end. Specifically, in order to mimic a feather to develop the concourse building, the essentiality of the feather, the microscopic structure and its nature, was studied from a plethora of materials, written by biologists and scientists, which enabled me to rebuild a feather with Grasshopper and analyze its structural behavior with Karamba.

With those sequential processes, an arch-shaped canopy was designed as the unit structure and it was able to interlock to shape the long-span space into the concourse building. Furthermore, emulating the agglomeration of feathers, the lengthy interlocked structure was placed overlaid with several layers to create the wider width of the building. This design process results in the consistent design language to the building. Three layers of the interlocked structure were designed continuously and smoothly. However, two ends of the building had to be flat glass facades to work as functional spaces for gate lounges and to
have clear and rational detail connections, which could be seen as sharp-cut sides from the volume. Also, since two layers of the interlocked structure curved and stretched out sharply around 90 degree, the center of the building had a large empty space. Two layers of the interlocked structure and a center courtyard was added to the empty space for connecting each side of wings and adding central interior programs. These structures are not connected smoothly compared to other parts, but they connected with the middle layer without hampering the circulation for users, because of a ten-meter interval between columns. These parts are located in a convenient position for the central shopping and eating places without impeding the critical passengers’ circulation.

The spatial plan was scrutinized and newly proposed as an architectural type, airport facility, because it is very crucial to segregate each space for its purpose and to control the circulation for passengers’ safe trips. When compared to the new-fashioned airport (Chhatrapati Shivaji International Airport, Terminal 2, built in 2014), CVG airport was not well segregated with either departure and arrival passengers or international and domestic passengers, even though the CVG is an international and hub airport. In fact, in the case of CVG airport it may not need the segregation and works well without it. However, since this is a thesis project, the design pursues the future needs so that the spaces were horizontally
divided between international flights (east wing) and domestic flights (west wing) and the building was vertically segregated by three stories: top floor (Arrival), middle floor (Departure), first floor (Center Hall and Office Spaces). Thus, the spaces of the concourse are planned with rational and practical segregations in both the horizontal and vertical manner. Furthermore, the monotonous and tedious outcomes for journeys of passenger was avoided by adding a converging hall with an eco-friendly visible courtyard in the center, with natural organic arch shapes, overlaying structures, and differing scales of spaces.

The material selection was very significant as much as the aesthetic appearance is very important in an architectural aspect. The basic columns, designed to be constructed from carbon fiber tubes, suggest not only the geometry of feathers but also the future replacement of steel. By applying ETFE on the vane part of the carbon fiber structure, a fluffy vane image was accomplished without concealing the main structure. Also, the material selection of ETFE was a good choice to accommodate bending as the floating part of canopy could be slightly flexible. Glass was chosen for the calamus parts for installation of the doors and connections to the gate bridges. The glass was a good choice since the calamus parts were more rigid than the vane parts, and the transparency persistently continues throughout the façade with ETFE. However, the situation of overlapping parts of
the vanes is not fully resolved with detail connections because of its complexity and limited time. These will need a fair amount of additional time and effort.

08 Conclusions

Using biomimicry to develop an architecture offers a foundation for a logical design process if the purpose of design and the attributes mimicked work well together as counterparts. The feather provides the idea for a pattern and structure that excels over a normal column structure in respect to the design of flexible, lightweight, and long-span features.
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01 Introduction


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05 Agglomeration of Feather


06 Airport Terminal and Feather


Appendix A


Appendix B


**Appendix C**


**Appendix D**


Appendix A _ Biomimicry

Origin of a word “biomimicry” is from Greek, meaning nature imitation. Biomimicry Institute describes the term on its front website “Biomimicry is an approach to innovation that seeks sustainable solutions to human challenges by emulating nature’s time-tested patterns and strategies. The goal is to create products, processes, and policies—new ways of living—that are well-adapted to life on earth over the long haul. The core idea is that nature has already solved many of the problems we are grappling with. Animals, plants, and microbes are the consummate engineers. After billions of years of research and development, failures are fossils, and what surrounds us is the secret to survival. Humans are clever, but without intending to, we have created massive sustainability problems for future generations. Fortunately, solutions to these global challenges are all around us.”

In her book “Biomimicry: Innovation inspired by nature”, Janine insisted that “Unlike the Industrial Revolution, the Biomimicry Revolution introduces an era based not on what we can extract from nature, but on what we can learn from her.” She also commented “With the help of these “invisible hands,” the biomimics hope we may be able to sculpt with geometric precision, and do away with “heat, beat, and treat”

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Precedent 1. Solar Cells inspired by Leaf

Scientists at Princeton University achieved major gains in light absorption and efficiency of solar cells after being inspired by the wrinkles and folds on leaves. The team created a biomimetic solar cell design using a relatively cheap plastic material that is capable to generate 47 percent more electricity than the same type of solar cells with a flat surface. The team used ultra-violet light to cure a layer of liquid photographic adhesive, alternating the speed of curing to create both shallower wrinkles and deeper folds in the material, just like a leaf. The team reported in the journal Nature Photonics that these curves on the surface made a sort of wave guide that channeled more light into the cell, leading to greater absorption and efficiency. The genius Nature is always teaching us lessons on how to make technology better.54

Mother-of-pearl, which covers the shells of abalone, is 95% composed of calcium carbonate, a breakable substance that is still very hard. Mother-of-pearl is similar to a pile of small bricks, conjoined with mortar comprising proteins. Its hardness is because of its intricate, hierarchical structure where impedes the propagation of crack. This structure inspired the researchers from the Laboratoire de Synthèse et Fonctionnalisation des Céramiques (CNRS/Saint-Gobain). As a base ingredient, a common ceramic powder was used in the form of microscopic platelets. The outcome of the artificial mother-of-pearl is ten times tougher than a conventional alumina ceramic. This zigzag pathway prevents it from crossing apart the material easily. 

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Appendix B _ Biomimetic Architecture

Biomimetic architecture is an architectural movement branched out from Biomimicry. At the beginning of biomimicry, it was mostly done by cooperation between biologists and engineers to create new way of products, processes, and policies learned from deep studying from what nature already have well adapted over the long haul. Afterwards, some architects found this idea could be applied to the architecture. Biomimetic architectures are outcomes from architects who believe that innovative design solutions can be come up from understanding the principles behind the nature’s forms in resolving the problems or enhancing current building system with more sustainable way.\(^5^6\)

**Precedent 1. Eden Project, Biomimicry in Architecture**

![Figure B 01 Eden Project](image)

The Eden project is one of many examples using biomimicry for designing architecture. This world’s largest greenhouse project was designed by Grimshaw Architects. It was built in

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Cornwall, England, and opened in 2001. Later it becomes the second popular paid visitor’s place in England. The hardest difficulty of this project was the incessantly changing site which was on a reclaimed Kaolinite mine. Since the site was on the process of quarry even during design phase, it could not hardly tell where the final ground level is going to be. Then Grimshaw Architects brought an idea of a series of bubble shapes as a structure to easily adjust to the current site situation. Studying pollen grains, radiolarian and carbon molecules, they discovered that hexagon and pentagon shapes are most efficient structure formation to make this project possible. Since the hexagon and pentagon shapes of structures caused glass is not a suitable material for this in terms of the limitation of size and heavy weight of it, the solution was the Ethylene Tetra-fluoro-ethylene (ETFE), which can be 7 times of size of glass and 1% of weight of double glazing. It ends up that the weight of structure became less than the air under the structure.  

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Terminal 1 was designed by gmp(Architekten von Gerkan, Marg and Partner) and completed in 1991. The characteristic design feature of Terminal 1 is using the tree-shaped columns of the load-bearing structure. Similarly, the main structure of Terminal 3 is the tree structure with a same roof incline but a strained building height. 18 steel trees support the stepped roof in Terminal 3, and 12 trees in Terminal 1. By utilizing the tree-like column, gmp accomplished not only the aesthetic aspects but also the widen depth and an increased floor area on the apron side.  

Precedent 3. L’Hemisfèric, Calatrava

The architecture inspired by the human eye, L’Hemisfèric is one of the buildings included in the City of Arts and Sciences in Valencia, Spain. The architect Santiago Calatrava designed L’Hemisfèric composed of an IMAX theatre, a Planetarium and a Laserium. The pupil part of the hemispherical dome roles as the IMAX theatre and the eyelid-like component can operable like blinking eyes by using hydraulic lifts to operate the steel and glass shutter. This imposing architecture is placed at the coulee near the river Turia. Calatrava intended to bring water back to the region by making a pool which reflects the other half of hemispherical dome to create an entire eye shape with a stunning artistic display especially at night.59

Appendix C _ Airport Design

Basic airport terminal forms

a. Linear terminals

![Linear Terminal Configuration](Image)

This type of terminals has a linear building with relatively thin structure. Normally they are using centralized passenger processing. Some can be curvilinear. Disadvantages are longer walking distances for transfer passengers, they require duplication of terminal facilities and amenities, and not applicable for intensive activity but primarily for low-activity.\(^6\)

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b. Piers: single or multiple

Piers type terminals are widely adopted since they introduced in 1950s. Advantages are high aircraft capacity and simplicity in design, maximizing the number of A/C parking spaces with fewer infrastructures, and preferable when the level of transfer traffic is low. Disadvantages are long walking distances and adding constraints with the mobility of aircraft movement in the apron. 61

![Pier Finger Terminal](image)

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c. Satellites: single or multiple

Satellite type terminals are extension of T-shaped finger piers. These types need a single terminal to process passengers. Connected to this are numerous concourses that lead to one to more satellite structures. Disadvantage is a requirement of high quality transportation system causing high capital, maintenance and operation cost. 62

![Satellites Configuration](image)
d. Transporter

In Transporter type terminals, passengers are transported to and from the building to the parked airplane. Specially designed buses carry passengers between the terminal and the aircraft. This minimizes walking distances. Airplane taxiing time to and from the runway is decreased. However, this is an expensive option for airport operators. Inconvenient delays happen for short haul passengers. 

Appendix D _ Long span structures

a. Space truss (Space frame)

In a Dictionary of Architecture and Landscape Architecture, the term of space frame is described “Complex three-dimensional structural framework, capable of spanning and containing very large volumes, constructed using pyramidal, hexagonal, and other geometrical figures, often made of lightweight tubing. It has advantages as a single integral unit, and can resist loads in any direction. Space-frame designers include Buckminster Fuller, Bruno Taut, and Konrad Wachsmann.”

Space truss is 3-dimensional structures. The basic shape is a tetrahedron which is a polygon composed with 4 triangle shape sides. Simple space truss has 6 members and 3 joints as the picture on the left. Joints have ball-and-socket joints. A space frame is lightweight rigid structure constructed from interlocking struts in a geometric pattern. Space frames can be used to large span with few columns. The assembled linear elements are transfer the load. Each strut can carry tension, compression, and bending moment. Space frames have 2 systems. One is modular system which is constructed from prefabricated modular

Figure D 01 Space truss application

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units. The other is nodular system that individual members assembled together using different types of connectors or nodes.65

**Precedent.** United States Air Force Hangar / Konrad Wachsmann (1951)

![Figure D.02 Model of United States Air Force Hangar](image)

Wachsmann invented the steel space-frame, including the complex joints making it feasible. (Figure D.02)

**b. Pneumatic structure**

Pneumatic structure is a structure supported by air. The material is very light and fabricated membrane without any pervious part to support the structure by the different air pressure between interior and exterior. Fans assist to keep the interior air pressure marginally over normal atmospheric pressure so that the danger of deflating

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and collapsing structure can be avoided. This structure is popular in use as a temporary enclosed structure or sports facilities such as swimming pool or stadium.66

c. Cable

Cable structure can be easily used as a long-span structure supporting tension load and in the form of suspension cables for support. The cable structure is usually found in a long span bridge structure with cable suspended between two points. In architecture, architect Frei Otto had been used in his architecture to create 20 Century looking architectures.67