Journal of Applied Physics

Hierarchy in air travel: Few large and many small

Cite as: J. Appl. Phys. **122**, 024904 (2017); https://doi.org/10.1063/1.4993580
Submitted: 12 April 2017 . Accepted: 28 June 2017 . Published Online: 14 July 2017

A. Bejan, R. Chen, S. Lorente, and C. Y. Wen

Hierarchy in air travel: Few large and many small

A. Bejan,[1] R. Chen,[2] S. Lorente,[3] and C. Y. Wen[2]
[1]*Department of Mechanical Engineering and Materials Science, Duke University, Durham, North Carolina 27708-0300, USA*
[2]*Department of Mechanical Engineering, The Hong Kong Polytechnic University, Hung Hom, Hong Kong*
[3]*Université de Toulouse, INSA, 135 Avenue de Rangueil, 31077 Toulouse, France*

(Received 12 April 2017; accepted 28 June 2017; published online 14 July 2017)

Here, we document the diversity of commercial aircraft models and bodies in use during the past five decades. Special emphasis is on the models that have moved humanity across the globe during the past three decades. The first objective is to show that the apparent diversity is in fact underpinned (sustained) by organization, which is a distinct hierarchy of "few large and many small" coexisting and moving people harmoniously everywhere. The second objective is to rely on the emerging hierarchy in order to predict for the future how few the even bigger models will be and how more numerous the even smaller models (e.g., drones for package delivery) will be, naturally. *Published by AIP Publishing.* [http://dx.doi.org/10.1063/1.4993580]

I. INTRODUCTION

Air travel is vehicled by airplanes of many types, sizes, and ranges. Recent work has shown that the apparent diversity of airplanes is underpinned by scaling relations that are predicted based on the physics principle of evolution of flow architecture everywhere, the constructal law.[1,2] Examples of theoretical relations are the proportionalities between the airplane body size and engine size and the fuel load and range (the distance flown with one fuel load). Another common feature is that airplanes of all sizes have evolved such that the wing span equals the fuselage length, which is why airplanes look like other airplanes and why birds look like other birds.

Equivalent scaling relations have been derived from theory for all the helicopter models adopted during the six decades of hovering flight.[3] The engine weight is roughly one tenth of the body weight, just like in jet airplanes. The rotor diameter is the same as the body length scale, which is why helicopters of all sizes look the same. The fuel load is proportional to the engine size and the body size.

All these theoretical scaling relations follow from the fundamental physics of the phenomenon of economies of scale: bigger flow systems are more efficient because their streams flow through larger openings (for fluid flow) and larger surfaces (for heat transfer).[4,5]

In the present article, we extend this physics-based framework to a previously overlooked feature of contemporary commercial aviation. The airplanes that carry us all over the globe (every minute of the day) exhibit "diversity," which is in fact underpinned by hierarchy. The bodies that are airborne are of many sizes; yet, the larger are fewer, and the smaller are more numerous. Hierarchy also characterizes the distances traveled by aircraft: the longer routes belong to the bigger and the shorter to the smaller.

We document this hierarchical organization in relation to other hierarchical flow architectures that emerge naturally. The types of data studied in this work do not allow for estimating specific scaling relationships, and as a consequence, the analyses performed throughout this work are of more qualitative nature.

II. HIERARCHY

Hierarchy is a good word for expressing what we see all around: the large are few, the small are many, and all of them belong together as they flow. We see this all across the board, from the inanimate movers on the planet (rivers, winds, and ocean currents) to the animate world. Scientists call this evolutionary flow architecture by many names that sound scientific: dendritic, complex, multiscale, diversity, fractal, and many more. They should take courage and start calling it hierarchy.

Complex, or complicated does not say much because it means twisted together. Multi-scale and diversity suggest lines of many sizes in a stick drawing or balls of many sizes dumped into a sack. Even Aristotle's line "the many and the few" does not capture the physics because in reality the many are always small and moving slow and short, and the few are always big and moving fast and long. Here are a few examples:

Under persistent rain, the wet ground surprises us with rivulets that arrange themselves into an all familiar "tree" configuration – the tree morphs. It keeps rearranging itself to flow more easily to evacuate the water faster down the slope. The streams are a living body of "few large and many small." This natural tendency is obvious and undeniable, and it repeats itself. The streams arrange themselves hierarchically so that a larger stream flows because of its tributaries. The reverse is also true, as the flow of tributaries is possible only because the mother stream is flowing. Harmony of movement is hierarchy, and it happens naturally. Hierarchy is good for design.

Hierarchy is an integral part of the natural design of the flowing landscape and living world. The flows of nature evolve in time such that they flow more and more easily, for greater access. They attain this ever improving quality through the *generation of flow design*, that is, by acquiring configuration. Existing designs (literally, drawings) are replaced by new designs that flow more easily. This natural phenomenon is a manifestation of the constructal law.[1] In this mental viewing, we fit all the evolutionary scenarios of biology, the emergence of river basins and climate, and the evolution of technologies toward greater efficiency.

Flowing leads to easier flowing. Erosion, self-lubrication, shaping, uniting, becoming more efficient, getting smarter, and many more are just one phenomenon: evolution as physics.[1] From the mental viewing provided by the constructal law, the hierarchies that are visible in all the flow systems that cover the world map can finally be deduced. These architectures form a multi-scale weave of point-area and area-point tree flows, all superimposed, all sustaining everything that flows and "lives" on earth.

One example is the hierarchy of channel sizes and numbers in all the river basins that have been catalogued. From the constructal law, we deduced that the number of tributaries that feed a larger channel should be approximately four.[6] This prediction is in very good agreement with Horton's empirical correlation of river numbers, which states that the observed number of tributaries falls in the range between three and five.[7] Another hierarchy is in the distribution of city sizes and numbers (of cities of the same size) on large areas such as a continent.[8] Another example of natural distribution anticipated with the constructal law is the ranking of tree sizes and numbers in forests.[9]

What the constructal law predicted for multi-scale river basins, demography, and forests also applies to the design of societal flow.[10,11] In this paper, we reinforce the universality of this natural phenomenon by unveiling the hierarchy of aircraft for civil air traffic worldwide.

III. RESULTS

In Table I (supplementary material), we have compiled the data available for all commercial airplane models built and adopted since 1970. The data are collected from Refs. 12–15, official websites of manufacturers, the Type Certificate Data Sheet of the Federal Aviation Administration (FAA), and the European Aviation Safety Agency (EASA). The data for each model described the body size (maximum takeoff weight), introduction time, and the number that was built. While plotting the data, we did not take into account the Soviet aircraft given in Table I because only a few airplanes are in operation. Soviet models are included in Table II (supplementary material) because Table II is a compilation of all the aircraft in service in July 2016.

For the graphic display, we decided to use the more recent data by focusing on the models developed by the biggest manufacturers, Boeing, Airbus, Bombardier, and Embraer.[16–18] A first look is presented in Fig. 1, which shows 85 airplane models covering the two dimensional field of the model size on the abscissa *versus* the corresponding number of airplanes built.

The scatter in the data is evident, and it obscures a possible relation between sizes and numbers. To simplify the display, we condensed the data into five groups according to these size ranges: 1–100 tons, 101–200 tons, 201–300 tons, 301–400 tons, and over 400 tons. For each size range, we summed up the number of airplanes built in that range. In this way, we determined the five points shown with black-filled symbols in the upper part of Fig. 1. These points show in an aggregate way that there is a downward trend in numbers *versus* sizes, which is the quantitative meaning of a diverse distribution that is complemented by hierarchy. Broadly speaking, the bigger models tend to be less numerous than the smaller models.

If we look deeper, we find that in all groups the top two models in terms of the numbers built occupy over 60% of the total number built in its own group, see Table III (supplementary material). We see two reasons why several models monopolize the commercial aviation market. First, the high-tech industry and core technologies are held in few companies or the government plays a significant role in developing a new airliner.[19] Next, the lesser models mean cost-saving for the maintenance of airlines. Usually, airlines do not operate many different models at the same time.[20]

A clearer view is presented in Fig. 2, which retained from Table II only the commercial jet and turbo-powered transport aircraft that was in service in July 2016. The plotted data exclude the aircraft carrying less than 14 passengers or equivalent (small) cargo. The hierarchy is revealed by the cumulative data indicated with black symbols, which

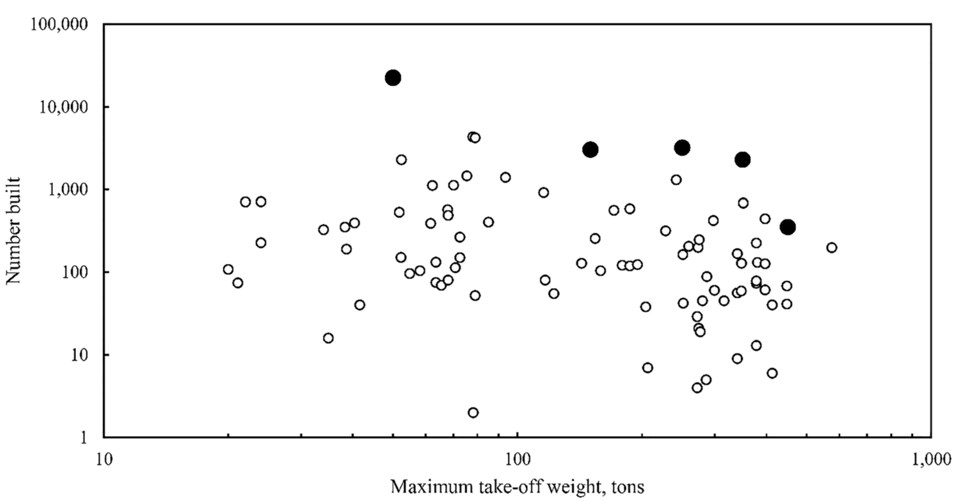

FIG. 1. Sizes and numbers of airplane models introduced after 1970 by Boeing, Airbus Bombardier, and Embraer. The data are from Table I (supplementary material), excluding Soviet aircraft.

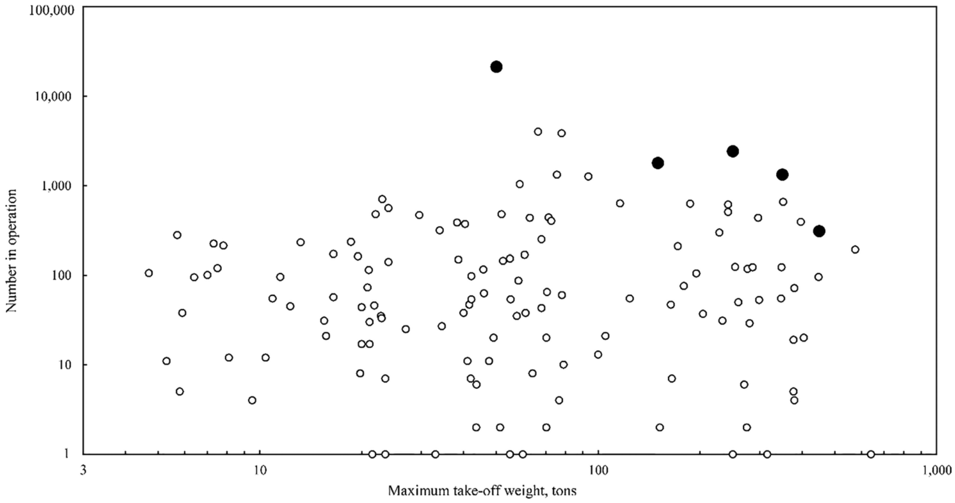

FIG. 2. The hierarchy of aircraft flying in July 2016. The data are from Table II (supplementary material) and cover all commercial jet and turbo-powered transport aircraft currently in service, excluding aircraft that carries less than 14 passengers or equivalent cargo.

correspond to the five size ranges indicated in the preceding paragraph.

In Fig. 3, we grouped the data of Table I according to the model name and not the range of sizes. Plotted are the averages of these groups (the black-filled symbols) and the size range occupied by each of the indicated models. This new display reveals two trends: (1) the downward trend associated with the hierarchical distribution of airplane models in the global population that was produced and (2) a group of outliers (A330, B777, and B747) that form their own group, to the right of the hierarchical trend. The outliers are present in numbers greater than the numbers that would be expected from the main hierarchical trend. This deviation may be due to the fact that not all models served the same number of years. For example, B757 has been in service for 25 years, while B747 has been flying for half a century.[21]

The deviation of the outlying group from the expected trend may also be due to the history of commercial aircraft development. For a long time since the 1970s, especially after the retirement of L1011 and DC10, Boeing 747 was the main carrier on intercontinental and transoceanic routes. As the demand for long distance civil air travel increased, the greater flow of passengers had to be met by increasing the production of B747, which still continues today. The same mismatch between increasing flow of passengers and the availability of new airplane models is the reason why the demand for the few new models (A330 and B777) was greater than it would have been in the presence of more new models. Noteworthy is that as the new large-size models have entered the market (B787, A350, and A380), the hierarchical trend was re-established, such that the bigger are fewer and the smaller are more numerous.

An alternative presentation of the groups of Fig. 3 is provided in Fig. 4, where on the ordinate is plotted the number of aircraft of each model in operation (flying) in July 2016.[15] The data are from Table II. The down-slope alignment of the groups in Fig. 4 is more evident than in Fig. 3 and conveys the message that movement itself is instantaneously hierarchical, with few large and many small in the air, carrying the global population. The flow architecture hierarchy (Fig. 4) is underpinned by the hierarchy in the population of vehicles (Fig. 3).

An even sharper view of the hierarchical distribution is presented in Fig. 5, for which the data are taken from Table IV (supplementary material). The number on the ordinate indicates the average annual production of the aircraft belonging to each model. On the abscissa, we plotted the

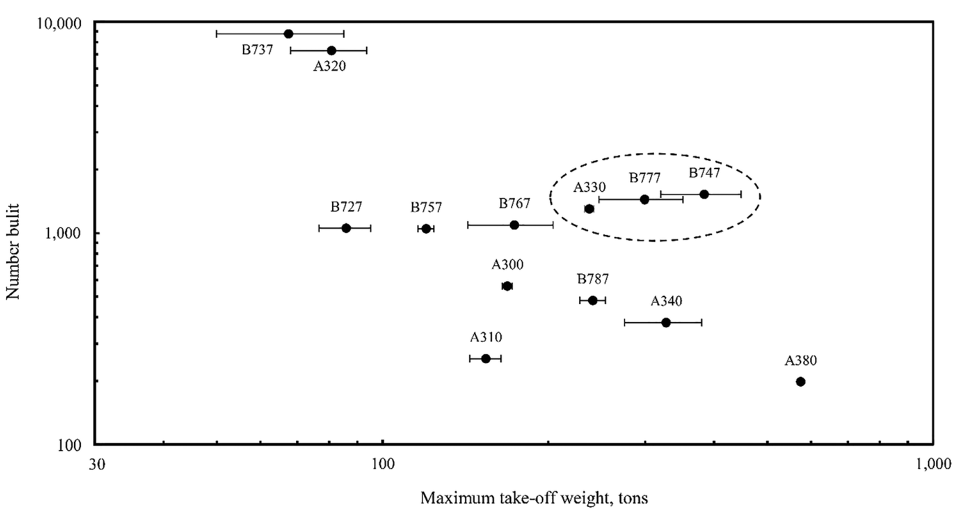

FIG. 3. Sizes *versus* numbers of leading groups of aircraft models compiled in Table I (supplementary material).

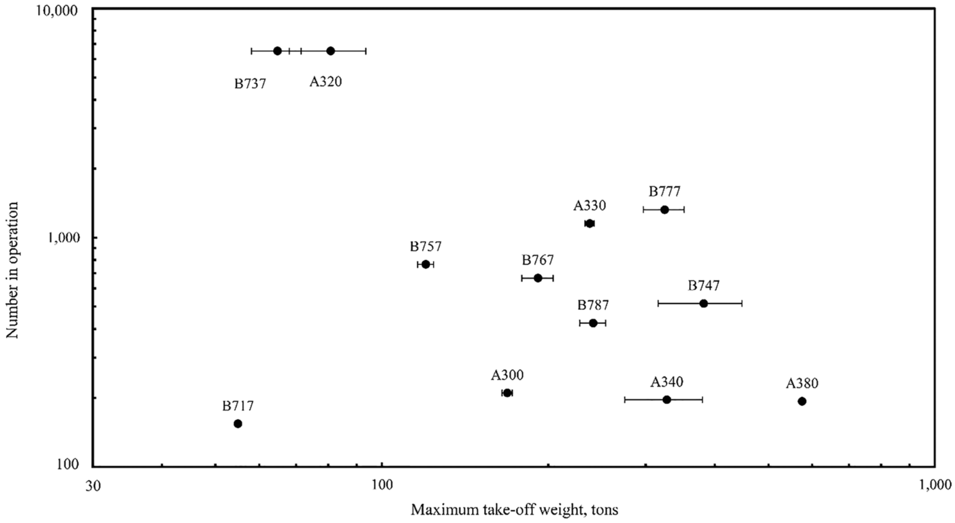

FIG. 4. Sizes *versus* numbers of leading groups of aircraft models compiled in Table II (supplementary material).

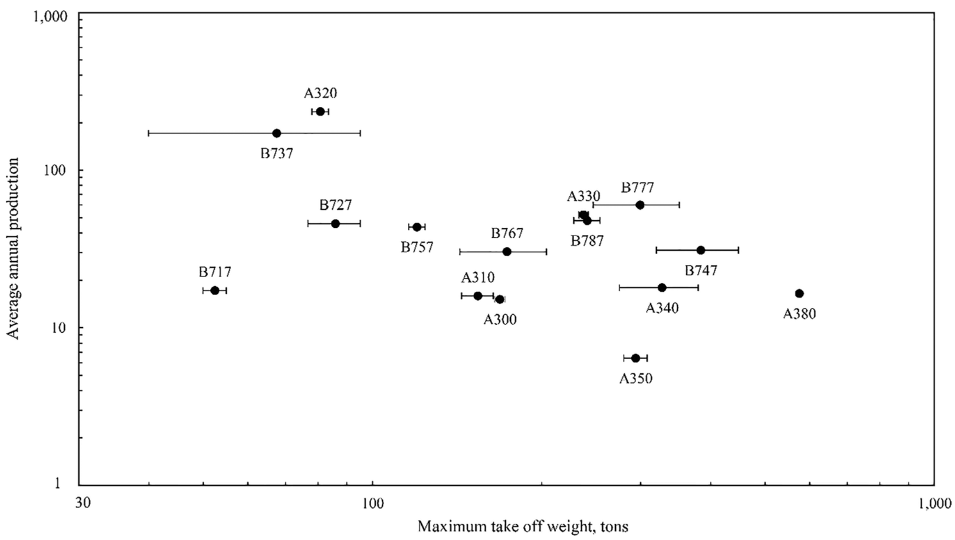

FIG. 5. The number of aircraft built annually *versus* maximum takeoff weight (MTOW). The data are from Table IV (supplementary material).

size. Because of the logarithmic axes, the downward trend of the plotted group is approximated by a straight line with a slope comparable to –1, as in the natural hierarchies documented in Refs. 8 and 9.

Figure 6 shows a bird's eye view of the information concerning Boeing's production since 1959, which is included in Table I and Figs. 1 and 3. This figure is based on Table V (supplementary material). On the vertical are the numbers of

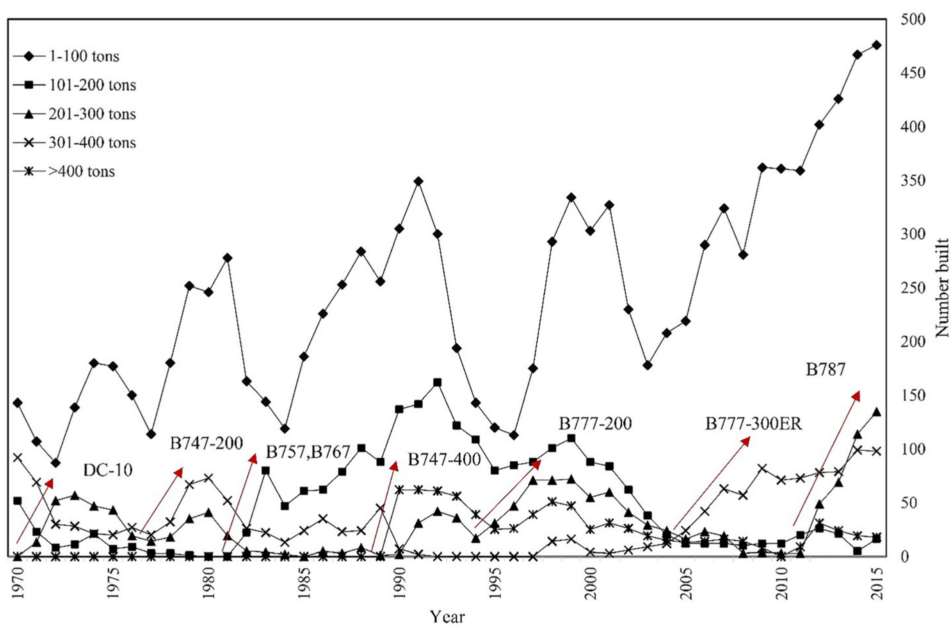

FIG. 6. The evolution of the annual production of all Boeing aircraft since 1970. The data are from Table V (supplementary material).

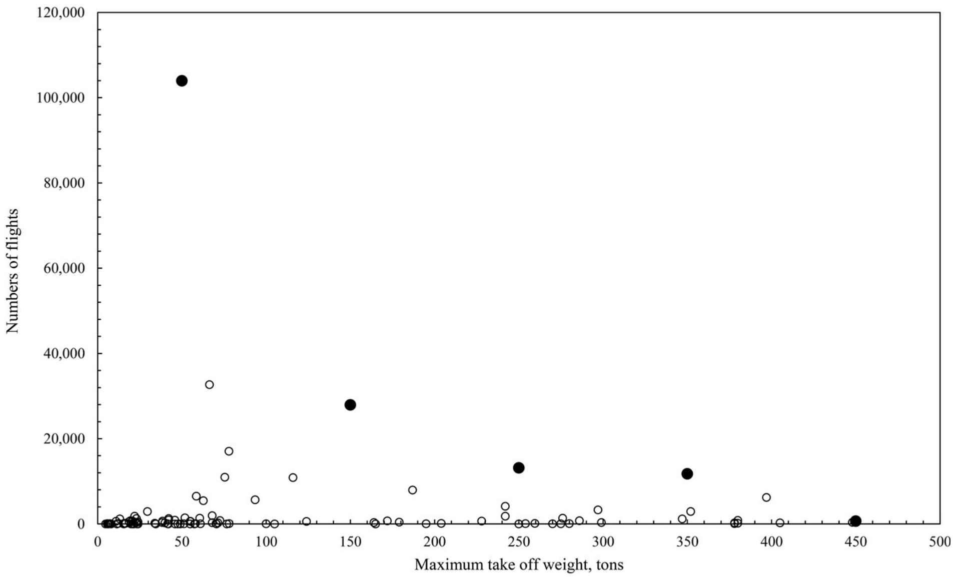

FIG. 7. The number of flights *versus* maximum takeoff weight (MTOW). The data are from Table VI (supplementary material).

airplanes built according to the five size groups indicated in the upper-left corner. The time line shows that all the built numbers have been increasing over time, while the hierarchical trend continued: the small continued to be many and the big continued to be few. Several steep rises in production occurred after the introduction of new (better) models, for example, Dreamliner B787.[22] At the same time, the production of older models usually drops.

Figure 6 also shows that the new aircraft did not revolutionize the way we fly, in spite of the technological advances. The biggest airplanes remain few among all the aircraft flying today. Yet, people travel more and more. Note the steep slope in the number of airplanes with a take-off weight below 100 tons built in the last decade. They are the highly successful B737 family, and this is a manifestation of the need for humanity to fly everywhere on the globe, including the most distant, smallest, and inaccessible pockets of inhabited land. In contrast, the decline of 100–200 ton airliners is notable. Let us take B757 as an example: Boeing 737NG (next generation) is almost the same as B757 in range and passenger capacity, while Boeing 737NG is much more fuel efficient. As a result, Boeing 737 captured the market and Boeing 757 came to an end.[23]

In Fig. 7, we replaced the numbers built with the number of flights. The data are from Table VI (supplementary material) and were collected by mining the information available on the web. We collected information of approximately 150 000 flights of the year 2016, including the flight number, aircraft model, departure, and arrival. Although the codeshare and flight number changes may cause a duplicate count, it does not affect the large trend that the small are many and the large are few, which is delivered by the figure.

IV. CONCLUSIONS

The hierarchy of current air travel illustrates how all of us as a society exhibit the natural tendency to generate hierarchical flow architectures for our movement. This tendency is universal. Commerce and knowledge (science, education, and news) flow in one direction: from those who have it to those who seek it because they are empowered by it: they are set in motion, new territories open up for them, and they become more free and wealthier. When both ends of such river basins have it and know it, the flow stops. What is not new and useful does not travel.

Science and education flow through a natural vascular tissue of student and professor paths to universities,[10] each university being connected to and sustained by the entire globe. The older universities have dug the first channels, which are now the larger channels that irrigate the student landscape. From this theoretical view followed the prediction that the hierarchy of universities should not change in significant ways.[10] Rigidity is a characteristic of all hierarchical flow architectures because such architectures occur naturally.

Scientists shy away from using the word "hierarchy" because in daily life and political disputes, hierarchy has acquired a negative connotation. Hierarchy is wrongly used to describe inequality, exploitation, oppression, and subjugation. Hierarchy did not always have a bad name. Without hierarchy, humanity would not have evolved to have churches, armies, governments, and universities.

Nonuniformity does not mean inequality. It means that the absence of a single size in the flowing architecture evolves naturally because of freedom. The single size is absent because it is not part of nature, just like the lungs, the river basin, and the city traffic. Given freedom, the flowing whole equips itself with a hierarchical nonuniformity that enables every component of the whole to flow—to live—as well as possible. With freedom, each component of the whole has "equal" access to change, to collaborate, and to associate to pursue an easier, longer, and safer life.

Follow up studies of the hierarchy of air travel may include economic considerations, such as the profitability of short range *versus* long-range flights, the changes in the market structure, and the evolution of alternative transportation markets (train and maritime). Economic considerations may be useful in the analyses of how and why the hierarchy of air traffic emerges and ways of predicting hierarchy. In the present paper, we focused strictly on the *descriptive* part of the hierarchy phenomenon. Steps toward *predicting* hierarchy can be made with a model of air transport on the earth's surface, where the configuration of air traffic is free to morph such that the overall measure of the cost of air traffic is minimal.

The simplest kind of overall measure is the cost of the total amount of fuel used in order to keep all the airplanes flying. Other costs that accompany the daily operation of commercial air travel can then be added to the model, for example, aircraft maintenance, cabin cleaning, food services, airport usage fees, and the purchasing power of the inhabitants of particular countries that are served by global air traffic. The domain of applied physics that shows how to construct such models is *thermoeconomics*, and its literature was reviewed most recently in Ref. 24, Sec. III.

A thermoeconomic analysis is expected to reveal the effect of economies of scale, which is the physics phenomenon presented in Ref. 5. This phenomenon empowers the analysis to shed light predictively on the hierarchical structure of the flow architecture: how few the large, how many the small, and where they should fly together on the earth's surface.

SUPPLEMENTARY MATERIAL

See the supplementary material for Tables I–VI described in this manuscript.

ACKNOWLEDGMENTS

Professor Bejan's work was sponsored by the U.S. National Science Foundation. Professor Wen and Mr. Chen thank the Research Grants Council, Hong Kong, for the financial support under Contract No. C5010-14E and the Innovation and Technology Commission, Hong Kong under Contract No. ITS/334/15FP.

[1]A. Bejan, *The Physics of Life: The Evolution of Everything* (St. Martin's Press, New York, 2016).
[2]A. Bejan, J. D. Charles, and S. Lorente, "The evolution of airplanes," J. Appl. Phys. **116**, 044901 (2014).
[3]R. Chen, C. Y. Wen, S. Lorente, and A. Bejan, "The evolution of helicopters," J. Appl. Phys. **120**, 014901 (2016).
[4]A. Bejan, "Why the bigger live longer and travel farther: Animals, vehicles, rivers and the winds," Sci. Rep. **2**, 594 (2012).
[5]A. Bejan, A. Almerbati, and S. Lorente, "Economies of scale: The physics basis," J. Appl. Phys. **121**, 044907 (2017).
[6]A. Bejan, S. Lorente, A. F. Miguel, and A. H. Reis, "Constructal theory of distribution of river sizes" in *Advanced Engineering Thermodynamics*, 3rd ed., edited by A. Bejan (Wiley, Hoboken, 2006), Sec. 13.5.
[7]R. N. Rosa, "River basins: Geomorphology and dynamics," in *Bejan's Constructal Theory of Shape and Structure*, edited by R. N. Rosa,A. H. Reis, andA. F. Miguel (Évora Geophysics Center, University of Évora, Portugal, 2004).
[8]A. Bejan, S. Lorente, A. F. Miguel, and A. H. Reis, "Constructal theory of distribution of city sizes," in *Advanced Engineering Thermodynamics*, 3rd ed., edited by A. Bejan (Wiley, Hoboken, 2006), Sec. 13.4.
[9]A. Bejan, S. Lorente, and J. Lee, "Unifying constructal theory of tree roots, canopies and forests," J. Theor. Biol. **254**(3), 529–540 (2008).
[10]A. Bejan and S. Lorente, "The physics of spreading ideas," Int. J. Heat Mass Transfer **55**, 802–807 (2012).
[11]A. Bejan, "Why university rankings do not change: Education as a natural hierarchical flow architecture," Int. J. Des. Nat. **2**, 319–327 (2007).
[12]See http://www.boeing.com/commercial/#/orders-deliveries for information about orders and deliveries of Boeing.
[13]See http://www.airbus.com/company/market/orders-deliveries/ for information about orders and deliveries of Airbus.
[14]*Jane's All the World's Aircraft 2011-2012*, edited by P. A. Jackson, K. Munson, and L, Peacock (Jane's Information Group, 2011).
[15]D. Thisdell and A. Fafard, in World Airliner Census, Flight International, 9–15 August 2006.
[16]D. A. Irwin and N. Pavenik, "Airbus versus Boeing revisited: International competition in the aircraft market," J. Int. Econ. **64**, 223–245 (2004).
[17]A. Goldstein, "EMBRAER: From national champion to global player," in Cepal Review No. 77 (2002).
[18]L. MacDonald, "The Bombardier story," Aircr. Eng. Aerosp. Technol. **75**(2), 215 (2003).
[19]G. Warwick, "Boeing 777—The inside story," Flight Int. **140**, 33 (1991).
[20]Y. Ozdemir, H. Basligil, and M. Karaca, "Aircraft selection using analytic network process: A case for Turkish airlines," in Proceedings of the World Congress on Engineering (2011), Vol. II.
[21]D. J. Ingells, *747: Story of the Boeing Super Jet* (Aero Publishers, 1970).
[22]M. Wagner and G. Norris, *Boeing 787 Dreamliner* (Zenith Press, 2009).
[23]D. L. Greene, "Energy-efficiency improvement potential of commercial aircraft," Annu. Rev. Energy Environ. **17**(1), 537–573 (1992).
[24]A. Bejan, "Evolution in thermodynamics," Appl. Phys. Rev. **4**, 011305 (2017).