THE BIRTH OF THE ATLANTIC AIRLINER (1920-1940)

Part II Bigger Airplanes

Can Airplanes be made to Grow?

Faced with the question how to arrive at the proper dimensions for a truly large aircraft, the first idea that comes to mind is to select an existing smaller model that really flies well and simply enlarge it by the same factor in all dimensions. If one multiplies all its dimensions by the same number "S" (whereby the symbol S stands for a scale factor > 1) a larger airplane will appear on the screen that is exactly similar in form to its model. (It is "isomorphic" with its model.) It has been produced by so called isotropic scaling, or *uniform scaling* in all three dimensions.

Be well aware that if all linear dimensions of an aircraft are multiplied by the same scale factor S, the gross weight of the airplane would go up by a factor *S to the third* (weight being proportional to volume, and volume being the product of three linear dimensions). Even more critical from a point of view of structural design of a *monoplane*[1] the critical bending moment at the root of the wing would grow with a factor *S to the fourth.* To resist this larger moment, the height or "depth" of the spars (the supporting beams that run the length of the wing) *would need to grow with a factor greater than S.* In other words the spar depth would have to increase more in size than the other dimensions of the airplane.

[To illustrate this with a numerical example: suppose all dimensions of the model airplane are doubled (S=2), then the new gross weight will be 2^3 times (= 8 times) the old weight. The bending moment at the root of the wing will become 2^4 times (= 16 times) the model value. If we assume the wing spar is a beam with rectangular cross section, standing upright, an increase in height with S=2 will not be sufficient to prevent breaking. Instead the spar height will have to be increased by a factor S=2.83, or nearly three.]

To accommodate the bigger spar, the wing would have to be made relatively thicker than in the original model. Conclusion: it is impossible to make a larger isomorphic flying copy of the model airplane. *The resulting wing will always have to be different from the original.* And even more disconcerting: the internal structure will, relatively speaking, be heavier than the model structure. If the spar is not made heavier, the wings will break off in extreme flight conditions.

Indeed already *Galileo Galilei* (1564-1642) warned four centuries ago for careless thinking in this respect:

> ***"...you can plainly see the impossibility of increasing the size of structures to vast dimensions either in art or in nature; likewise the impossibility of building ships, palaces or temples of enormous size..***
>
> ***...nor can nature produce trees of extraordinary size because the branches would break down under their own weight"***

The breaking branches stand for failing wings. It is an unwelcome but undeniable fact that pure unlimited isotropic growth of this sort is possible for *virtual objects* only[2]. This may come as a surprise, because we are so used to changing at will the size of the image of all kinds of complicated things and creatures with our cameras, computers and copiers, that we are led to believe that we could treat the real

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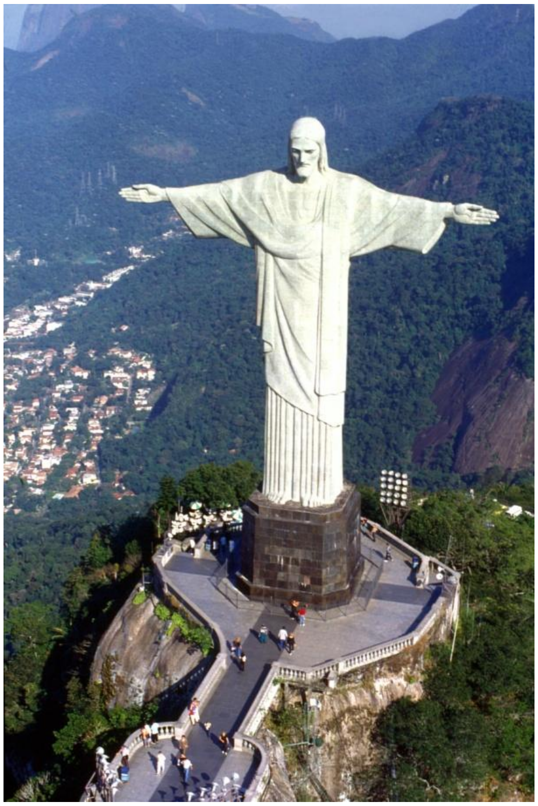
[1]) the only type worth considering for an Atlantic role.

[2]) or for man-made objects having a very basic form resting on the earth, such as cubes, cylinders or spheres, made out of some suitable hard material that does not sag under its own weight.



Rio de Janeiro: Cristo Redentor
(architecture.about.com)

objects in the same way. We must be conscious of the fact, however, that in the real world all things (natural or man-made) are *subjected to the forces of nature*. As a real object with a complex shape grows larger and larger it has to adapt its form and/or its internal structure to withstand the increasing physical forces to which it is subjected. Otherwise it may collapse under the forces of gravity, inertia or internal or external pressure, depending on its environment and use. ***So the absolute size and form of an object really do matter, as they determine the absolute stresses that occur internally***.

Professional artisans who are particularly familiar with this fact are the makers of statues: the stone mason, the sculptor and the founder of bronze. When the scale increases, the statues' outstretched arms of marble or bronze are prone to break off at the arm pit. The huge concrete figure of *Cristo Redentor* (Christ the Redeemer) at Rio de Janeiro, wears a cloak around his shoulders. The cloak supports the upper arms, not the other way around. For the same reason the statue of the Roman emperor Claudius as Jupiter in the Vatican Museum, Rome, has a cloak to support his uplifted left arm. How then shall we support the outstretched wings of giant aircraft, if cloaks are out and simple external bracing wires and struts are forbidden because of high air resistance during flight?

It is not surprising that at the beginning of the flying era, many were sceptical indeed about the possibility of creating large airplanes.

Among these turn-of-the century critics: *Simon Newcomb (1835-1909)*, Canadian American astronomer, who wrote a number of articles maintaining that the hope of heavier-than-air machines was a vain and foolish one. The failed experiments of Samuel *Pierpont Langley (1834-1906)* seemed to support his view, while the successes of the *Wright* brothers hardly convinced him. He at one time even doubted the possibility of carrying *one single person* by a heavier-than-air machine:

"...The limit which the rarity of the air places upon its power of supporting wings, taken in connection with the combined weight of a man and a machine, make a drawback which we should not too hastily assume our ability to overcome. The example of the bird does not prove that man can fly. The hundred and fifty pounds of dead weight which the manager of the machine must add to it over and above that necessary in the bird may well prove an insurmountable obstacle to success."

Rear Admiral George W. Melville (1841-1912), Chief of the Bureau of Steam Engineering of the U.S.Navy and responsible for all the Navy's propulsion systems, addressed in the same critical tone the difficulty of constructing large flying machines:

"...Should man succeed in building a machine small enough to fly and large enough to carry himself, then in attempting to build a still larger machine he will find himself limited by the strength of his materials in the same manner and for the same reasons that nature has."

Above quotations express the fear that as aircraft would be built bigger and bigger, the necessary strengthening of the structure of the airplane (especially the wing spars) would make it so heavy that in the end no lifting capacity would remain for fuel and payload. So, as with birds, there would seem to be an upper bound to the size of manmade things that can take to the air.

Although the last two stated opinions (not Galileo's warning) now seem to us rather preposterous, it cannot be denied that, as an airplane grows in size a natural limit will be reached at some time. As we pointed out there is a trend for the structure to become heavier. Also in nature it is an indisputable fact that, during evolutionary growth, the *relative weight of the skeleton increased with respect to the overall weight of the animal.* The skeleton needs extra strengthening as size goes up and large animals have *in proportion* larger bones than small animals.

How then were designers to proceed to build larger aircraft with sufficiently strong internal construction, at the same time striving for the ideal of "50 percent lightness"?

In hindsight we can state that the fundamental steps that were needed were:

1. Very careful design of the geometry of the airplane, especially with regard to the size and layout of the fuselage, wings, position of the engines, etc.
2. Very careful analysis of the loads to which an aircraft with this geometry is submitted during take-off, flight manoeuvres and landing,
3. Design of a structure to withstand these loads, using the most modern way of stress analysis to arrive at the structure with best strength/weight ratio.
4. Use of new light materials in new fashions (in the 1920's: duraluminium, stressed skin).
5. Use new insights in allowable stresses in constructions of sheet metal.

For instance, rather than a mechanical, uniform, scaling up of a *complete* airplane in three dimensions, designers may choose to focus first on increasing the load carrying volume of the *fuselage.* Its length may be stretched and its diameter enlarged to accomodate the necessary number of passengers. Of course its structure must be reinforced accordingly, as must be the wings. The overall shape of the wing may however be left unaltered as much as possible. Its position with respect to the fuselage may be changed. Even in the most recent project of creating the biggest airliner in the world (the *Airbus 380,* anno 2001) this approach was taken. The designers loaded more passengers into an existing, proven type of aircraft by increasing its body diameter and even introducing a second passenger deck, *without extreme changes in other external dimensions such as the span of the wing*... In this case we are no longer dealing with uniform growth but with a carefully controlled increase of the size and loading of fuselage and wings, while at the same time strengthening their internal structures.

While these points focus attention on the strength aspects of the airplane, the designer shall not forget the all important aerodynamic aspects. Requirements of strength shall not sacrifice aerodynamic quality: for instance (in the 1920's) drag inducing shapes or supporting structures shall be eliminated. The shape of the wing is of utmost importance: in particular its *aspect ratio* (wingspan over width). Slender wings have low induced drag and are therefore preferable for long range aircraft. On the other hand, long spans produce high bending moments at the wing root. At the same time wings of *minimal area* are to be preferred. However, small wings with a high *wing loading* necessitate powerful engines.

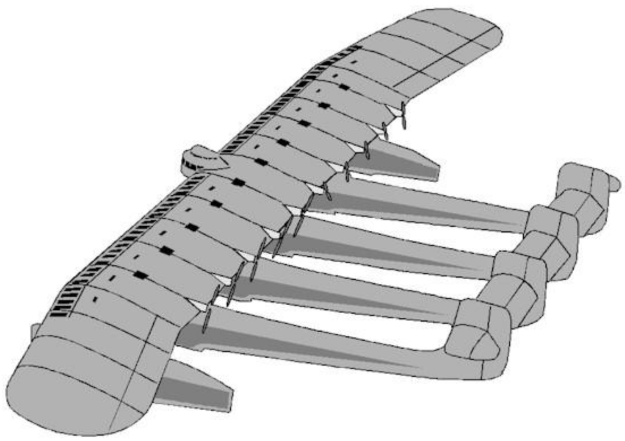
The above makes clear, that the design of a (large) airplane involves many interrelationships which have to be carefully studied for each particular design. It would therefore be safe to say that for the nineteen twenties the design of a large Atlantic Airliner was anything but a matter of simply "scaling up" a suitable small model.

High Wing Loadings: Key to Bigger and Faster

If the larger aircraft is produced by uniformly scaling up of a certain model with a linear factor *S*, the "wing loading" (the gross weight divided by the wing area) also increases with *S*, because weight goes up by a factor *S to the third*, whereas wing area only grows with a factor *S squared*. Therefore, with geometrically similar aeroplanes, the *wing loading increases by the same factor as the principal dimensions of the airplane.*

To put it in simple terms: when the size of an airplane (or bird) is doubled, its **wing load** will also double. This makes us aware of the fact that uniformly upscaling produces an airplane that has, in relation to its weight, smaller wings than the model plane.

A further consequence, which may come as a surprise, is that the larger plane got to be **faster**, in order to *take-off with* smaller wings. In our example, when the size and wing-load are doubled (scale factor 2), the starting speed of the plane has to increase by a factor 1.4 (= $\sqrt{2}$), while the required propulsive starting *power* increases in the same proportion. Because of the speed requirement at take-off, the attention of the designers of large aircraft in the 1920's shifted from land planes to flying boats, as high speeds and long take-off runs could be realized more easily on the surface of lakes and wide rivers than on grassy airfields.



Edmund Rumpler Atlantic Project ca. 1925

During the early Twenties, a great deal of debate went on regarding the question what the proper size of the wings of larger airplanes should be. In general, aircraft builders of the early years were very reluctant to use wing loads larger than the values they had experience with. When faced with the task of building bigger airplanes they would prefer not to use the uniform growth model, but rather give the bigger airplane more wing surface as is shown for instance by the *Caproni Transaero*. One other extreme expression of this feeling was the proposal by the Austrian designer *Edmund Rumpler (1872-1940)*, producer of the well known Taube fighter of the First World War. When he designed a 100 passenger Atlantic Airliner, he simply connected four 25-passenger flying boats wing-to-wing, completely avoiding in this way the feared higher loading and take-off speeds. It is highly doubtful if the resulting apparatus would have been a practical flying machine.

While Rumpler's and Caproni's designs are extreme, the general feeling was that one should be very careful in adapting higher values. *Adolf Rohrbach* was in this respect a revolutionary: he was willing to really increase the wing load and construct in this way faster and more compact airplanes with indeed *smaller* wings. He was hampered in this line of development by the lack of powerful engines.

An Example of 'simple upscaling': the Remarkable Dornier Do-X

Although true uniform scaling is not the indicated way to go about building a larger airplane, we may use it as a theoretical exercise to investigate the result of the design work by that great German designer of the early twentieth century, *Claudius Dornier*.

As a starting point we consider first his *Dornier Wal (Whale)* flying boat. Although not exactly beautiful according to our modern standards, this all-metal monoplane flying boat gives the spectator in its outward appearance a certain "gut feeling" of power and good proportions. By 1924 the 'boat had proven to be both sea- and airworthy. It had been used worldwide by many operators and it had won many records and citations. It possessed a span of 22.5 meters; weighed 3630 kg empty and about 6000 kg fully loaded and had a wing area of approximately 96 m². This results in a wing load of approximately 60 kg/m2 (an accepted figure for those days) and a rather unfavorable lightness of 64 percent. The aspect ratio of the wing of the *Wal* was 22.5 x 22.5 **:** 96 = 5.3

Now, as a thought-experiment, let us decide to build a hypothetical *Dornier Wal* twice as big in all dimensions. With a span as well as a wing chord double in size, the wing area would become 96 x 2 x 2 = 384 m². As we expect the gross weight to become eight times as large (see before), the new wing load would be: 48000 **:** 384 = 125 kg/m², or nearly twice as high as the original one..

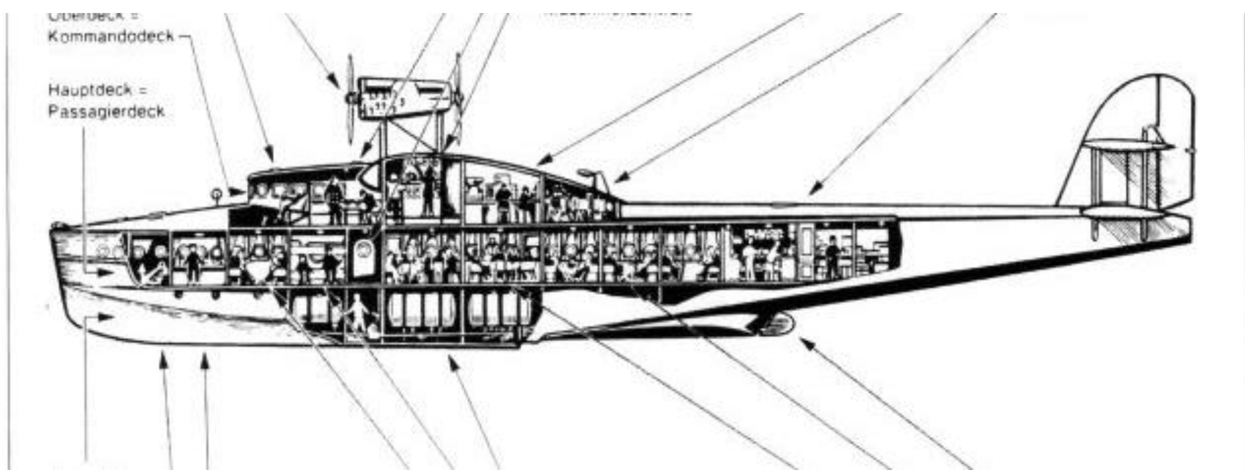
Dornier Wal at the same scale as the Do-X below

There exists a remarkable agreement between the results of this 'thought-experiment' and the relevant characteristics of the real giant monoplane flying boat which Dornier constructed in 1929. We refer of course to the renowned *Dornier Do-X* .

Do-X prototype as built :	48000 kg,	span 48m,	wing area 451m²,	wing load 106 kg/m²
Do-X[1] (2 x Wal would be):	(48000)	(45)	(384)	(125)
Do-Wal is:	6000	22.5	96	62.5

As shown, the actual Do-X comes very close to the results of theoretical uniform scaling (in brackets). The Do-X as built had a somewhat larger wing and in this way Dornier reduced its load to a more comfortable value of 106 kg/m^2

For the empty weight of the Do-X, the design of Dornier aimed at 25000 kg, but the actual construction came out at 28250 kg, giving the Do-X a “lightness” of 59%, which is still 5% lighter than the Wal.[3]



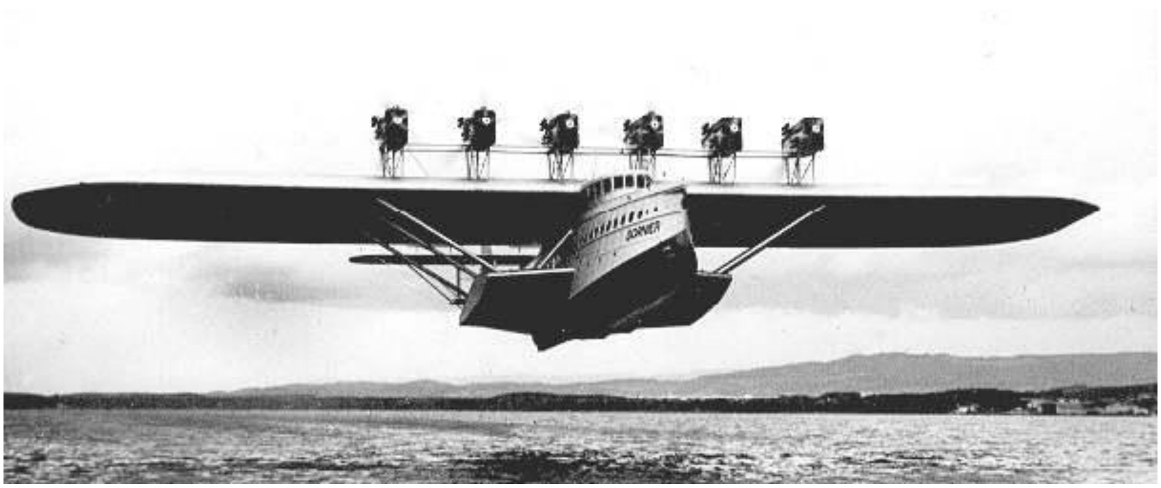
Dornier Do-X Cross Section

Professor Claudius Dornier clearly succeeded in creating a true gigantic airplane with a take-off weight of almost exactly eight times the earlier Do-J Wal, scaling up the dimensions of the smaller plane by a linear factor of approximately 2. Surprisingly, the final construction came out *lighter* than predicted by the pessimistic theorists and in this way dumbfounded those who had predicted a (much) heavier skeleton. He demonstrated convincingly that Galileo’s natural limit of size could be pushed back. In fact, as we mentioned, he had been aiming for an even lighter internal construction.

[3] This extra overrun in weight of 3250 kg of the structure represented the equivalence of the weight of 30 passengers and in fact was one of the reasons that the Do-X failed as a practical Trans-Atlantic airliner.

Up to this time an all metal aeroplane construction had been considered to be *inherently too heavy*. Dornier, however, proved conclusively that large, light structures of duraluminium were perfectly possible, even on a large scale. He did so while employing design and calculation methods that were conservative and straightforward and 'standard practice' in other branches of industry. The wing girders of the Do-X bore a great resemblance to the trusses of an old-fashioned railway bridge. Just as conservative, the hull of the flying boat looked more or less like a well-built metal yacht or tug boat (albeit with a planing bottom). In neither the construction of the wing nor the hull revolutionary shapes or techniques were to be found. The secret of Dornier's success in keeping the weight of the construction down hinged on a careful shaping and dimensioning of the truss-like spars and other load bearing members, such as ribs, keel and bulkheads. They were mostly built out of aluminium profiles, castings and forgings that were specifically designed for maximum strength-weight effectiveness. High strength material such as steel was used in locations where high stresses were encountered. Also it must be noted that the original Wal was probably not as sharply designed as the Do-X, i.e. it had probably many parts in its structure that were plenty strong in relation to the maximum allowable stress. These sections did not need to be 'beefed up' in the same proportion as the rest.

And indeed, although the external dimensions seemed to indicate that the Do-X was simply a scaled-up version of the Wal, its innards were completely designed afresh. For one thing the position and number of the engines of the two aircraft differed greatly, giving a totally different weight distribution. The six engines on top of each half wing may have actually reduced the bending moments at the wing roots and reduced the necessary size of the main girders during lift off. (Maybe the impacting load on landing really governed the size of the structure?) Also the external bracing struts that run halfway the main wing to the 'sea wing' below, will certainly have reduced the bending stresses in the spars.[4]



Dornier Do-X, after having been modified, takes off with the full power of its 12 Curtiss engines

Important is that Dornier's flying giant demonstrated the early predictions to be far too pessimistic. In part they were based on untrue premises. It is not difficult to point these out. An airplane is not a single monolithic, homogeneous solid body like a marble statue. By contrast, it has two principally cylindrical parts, elongated vessels that are chiefly hollow. These main parts are the fuselage (nowadays often resembling a true cylinder) and the wing (which may be considered a flattened cylinder). Each part

[4]) The determination of the maximum stresses that occur in such a so-called 'redundant' structure may not have been simple. Fact is that the Do-X, while taxiing, suffered major structural damage in the Atlantic by a high ocean roller that struck the ship broadside, exactly at this location. No detailed report on this damage has been found by the author.

obtains its load carrying capacity from its own typical skeleton and its skin. While the wing skeleton is formed by an internal spar-construction that resembles in some way the spine in the human body, the fuselage has an ‘exo-skeleton’, namely the skin and its underlying reinforcement. Now when the outside dimensions of an aircraft are 'scaled up', it does not follow automatically that all detail-dimensions of the 'old' skeleton are to be scaled up blindly by the same factor in order to produce a 'new' skeleton of sufficient strength. Instead the engineers have the opportunity to start from scratch within the new, larger outlines of the new aircraft to calculate a new internal structure that will be able to carry the higher loads. As the so-called skeletons are nowadays principally sheet metal assemblies, the engineer will be able to redefine the material thickness of webs, flanges and plates in the most advantageous way. He can also use his creativity to find new shapes or configurations of the component parts. He may use methods of more exact stress analysis. He may even leave out certain reinforcements that were needed in the lighter structure to prevent buckling or vibrating and that are no longer required. In short, using advanced design methods and materials, it may very well be that in the end the larger structure will turn out (relatively) lighter than the one that served as a point of departure.

If Professor Dornier had followed the rules of uniform scaling more closely, the Do-X would have received a span of only 45 m, a wing area of 384 m² and a wing load of 125 kg/m² instead of 106 kg/m². This somewhat smaller wing would have reduced the empty weight and drag of the machine, but would have increased the required take-off speed and power. Unfortunately, it was exactly on the issue of required and available power that the big ship showed serious problems. The engines available in 1928 were simply not powerful enough and Dornier had to settle for an arrangement on top of the wing of no less than six pairs of air-cooled Siemens Jupiter engines of 575hp each, mounted in tandem fashion. Right from the beginning there were cooling problems with the six rear engines, which drove pusher propellers and could not be run at full throttle for a prolonged time. In a major rebuilt, the air-cooled Siemens were replaced by slightly more powerful American liquid cooled Curtiss engines.

Also, the plan form of the rectangular, stubby wing may be criticized from a modern aerodynamic point of view. Its aspect ratio amounted to a mere 5.1, which is even less favourable for long distance flight than the wing of the Wal. Equally disastrous was the complete lack of streamlining of the hull, the engine mountings and empennage, creating a large amount of unnecessary drag. Taking all these factors together, the resulting range, speed and load-carrying capacity of the big machine fell far short of expectations. (An unwelcome fact that for a long time was not discussed in the German press.)

From a structural point of view though, Dornier had convincingly advanced the state of the art.