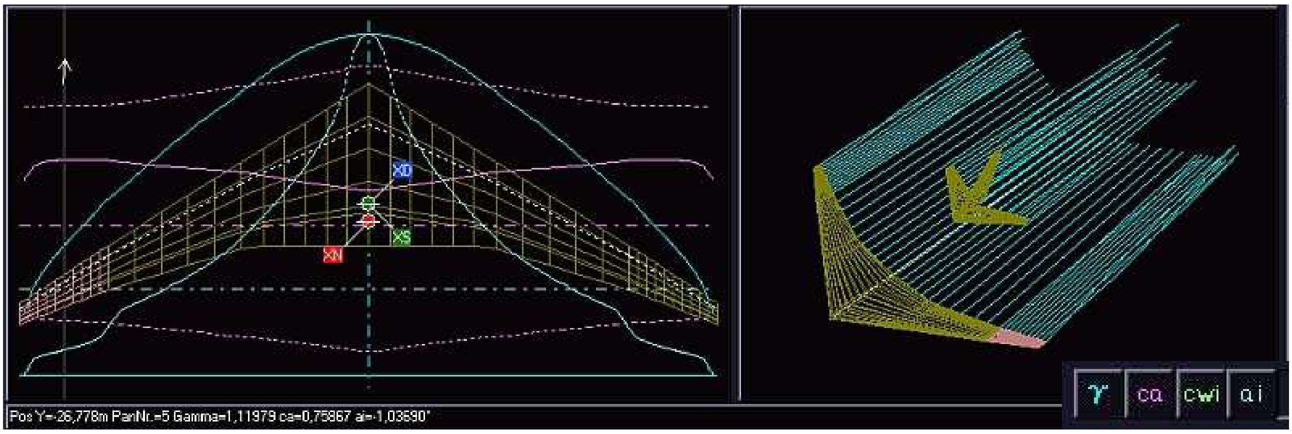
Influence of vertical stagger of the rear wing of a tandem biplane and diamond shaped aircraft with and without connected wing tips

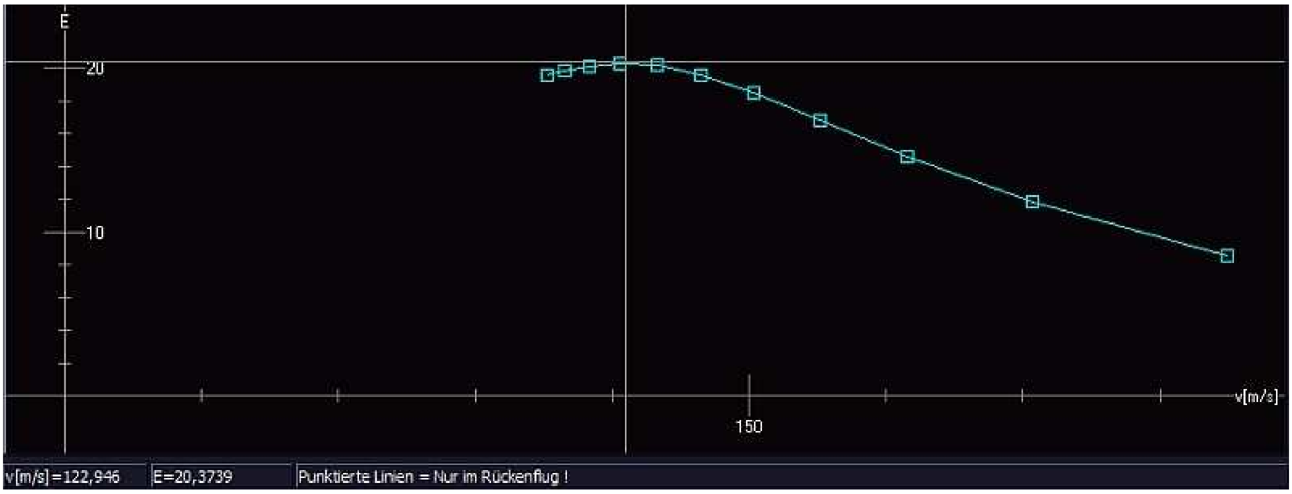
Important notice:
The following analysis does not claim to be accordant to scientific methods and it does not make any statements regarding the prospects of success for any box wing project. The only purpose of the analysis is to get clarity about the influence of vertical stagger of the rear wing of a tandem wing and a box wing for me personally. The used method is comparing a known wide body aircraft with deduced models with tandem and box wing surfaces during gliding flight at sea level. This method has only limited significance for higher velocities.

Reference configuration is a Boeing 777-200 with MTOW. It was modeled with its most important parameters within a vortex lattice program. The drag coefficient of the fuselage, the fuselage to wing junction and the parasite drag was manually set in order to have a glide ratio of 20 at a flight speed of 120 m/s at sea level, all engines out. This glide ratio resembles those of comparable aircraft and was used as reference for setting the unknown drag coefficents of the fuselage and all attached parts.

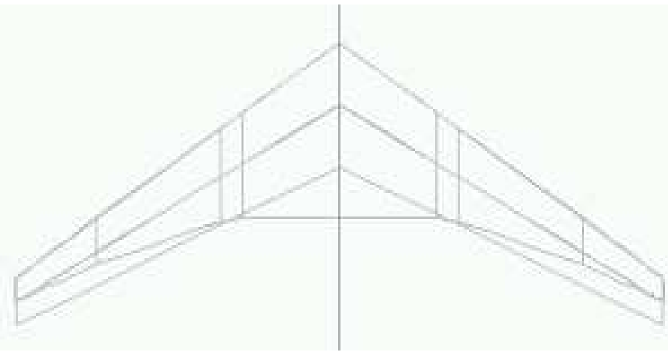
Below you see the model of the 777-200 and its glide ratio polar which was generated with the rudder function for sea level flight and using the airfoil of the Boeing 737. It could be shown in further tests that using the symmetric airfoils NACA 0009/0010 leads to comparable results. That is why these airfoils were finally used for the reference model and the deduced tandem aircraft. For simplification, the wing twist was set to -2° uniformly. The elevator was set so that it does not produce any lift during gliding flight at 120 m/s.



The shown polar for gliding flight does not claim to be consistent with real data, but it is plausible and corresponds to known data for similar aircraft. The polar is only used for comparison.



For generating a tandem aircraft having two wings of double the aspect ratio of the reference wing, the sweep of the reference wing was kept unchanged for the front wing. The sweep of the rear wing was adjusted. The generated wings are linearly tapered and their arrangement was chosen in order to have the same plan view as the reference wing. Fusealge and empennage remained unchanged.

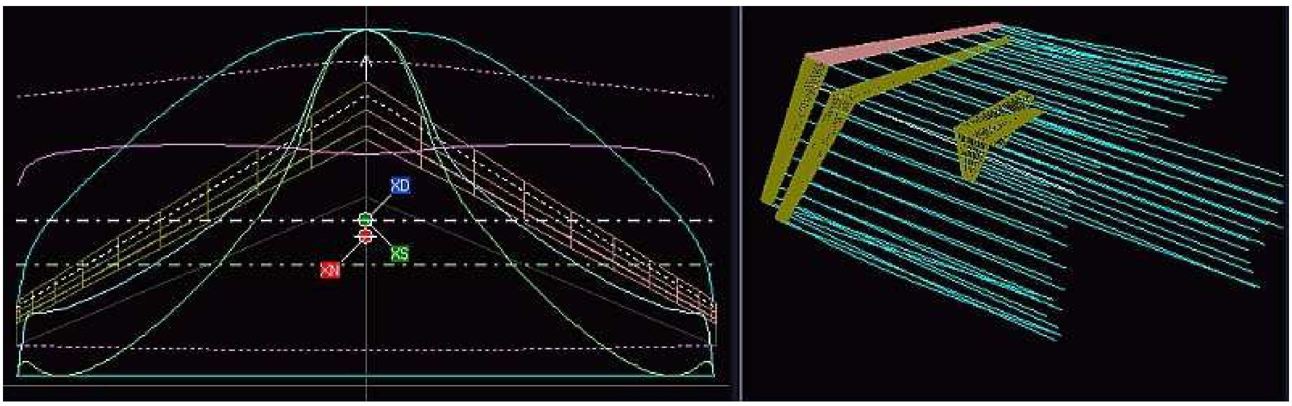


On the left you can see the position of the two generated wings over the reference wing. The aspect ratio of the individual wings is 17,6 , the aspect ratio of the total system is 8,8 , which is the same as for the wing of the B777-200.

The vertical stagger of the wings was 5,5 m, with the fuselage centered. The ratio of h/b was thus below 10%. The lower wing has a dihedral of 5°.

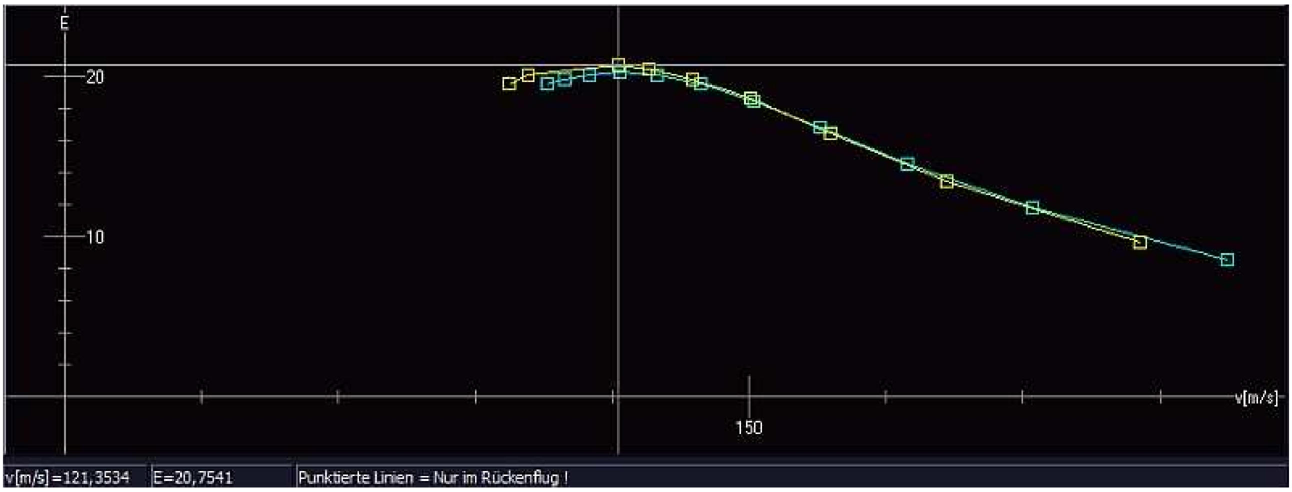
The static margin of the tandem aircraft was set equal to that of the reference aircraft. The polar for flight with all engines out on sea level was generated, using the rudder function (only flyable conditions were analysed).

The figure below shows the generated aircraft within the VL program.

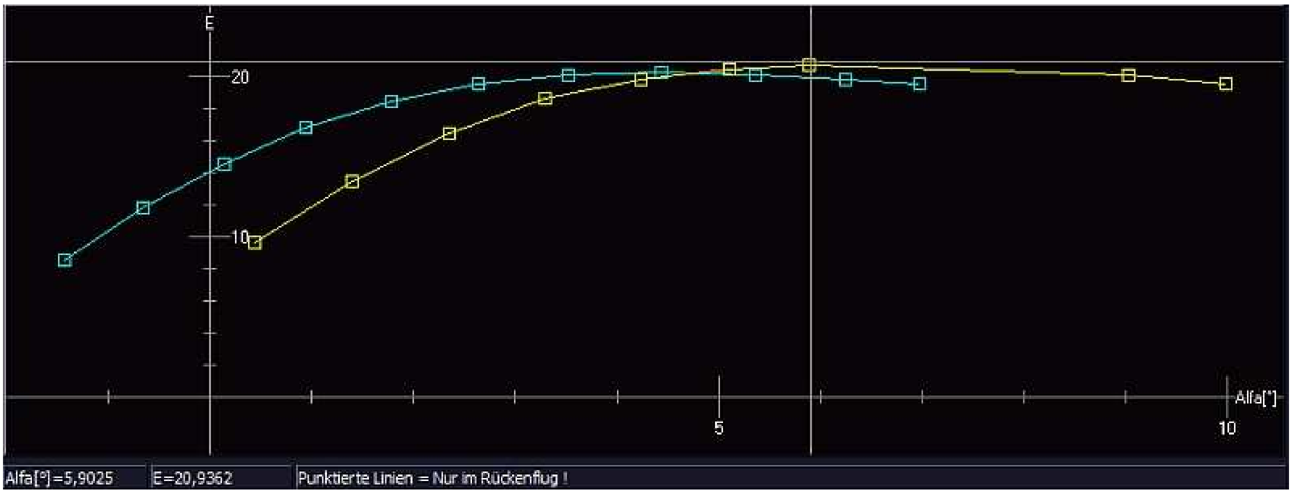


On the left the front wing of the swept and positively staggered biplane is shown together with the position of the neutral point and the determined centre of gravity.

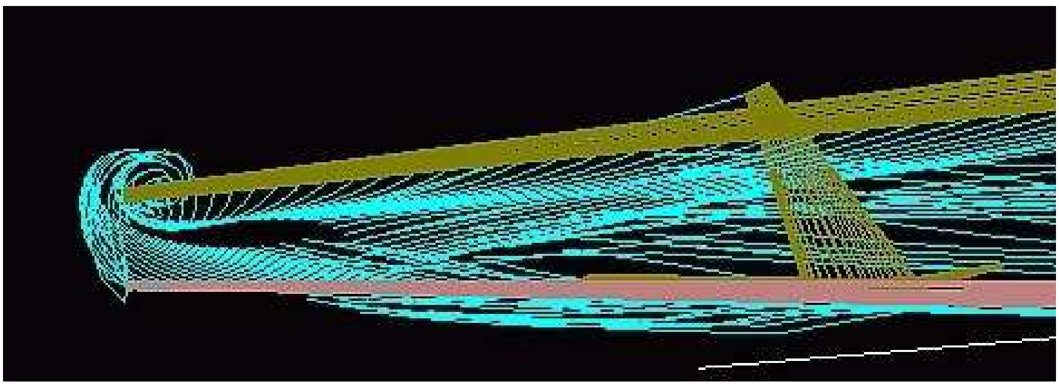
The polar of this aircraft only shows little difference to the polar of the assumed reference aircraft. The assumed polar of the B777-200 in blue, the biplane in yellow. The little difference is traced back to the small vertical distance of the wings. The effectivity of a horizontally staggered biplane significantly increases with the vertical distance of the wings. Here the small vertical distance is because of the height of the fuselage.

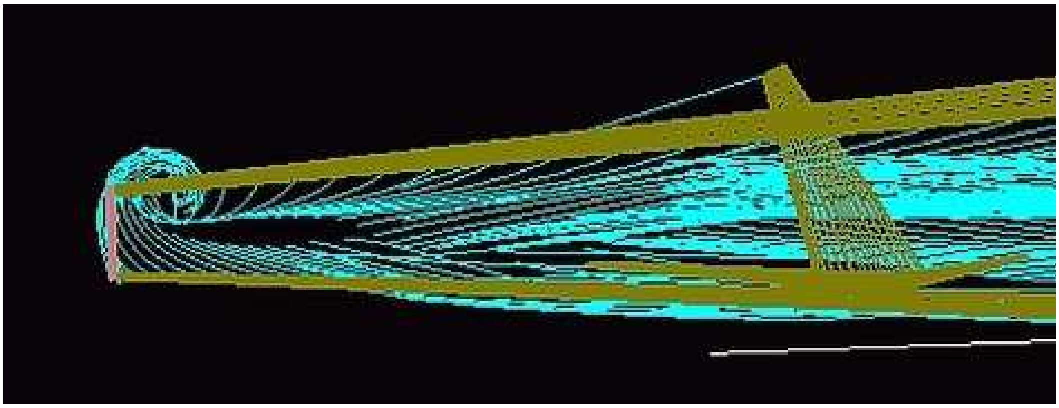


A plot of the glide ratio vs. the angle of attack shows that the graph of the biplane is just shifted to the right to higher angles of attack.

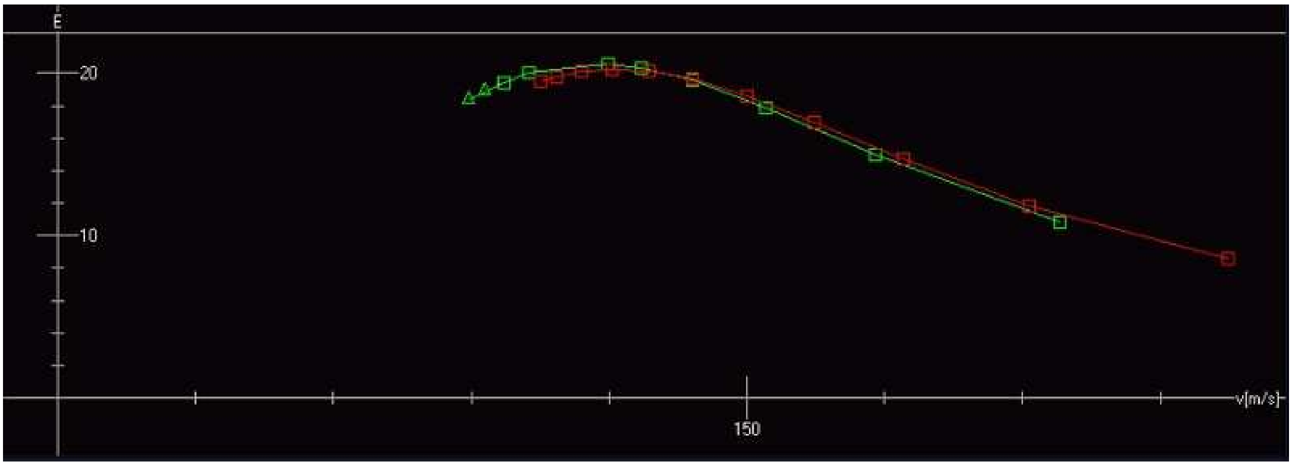


In the following the wing tips of the biplane were connected with simple endplates to form a box wing. Below the formation of vortices without endplates, on the next page with endplates:

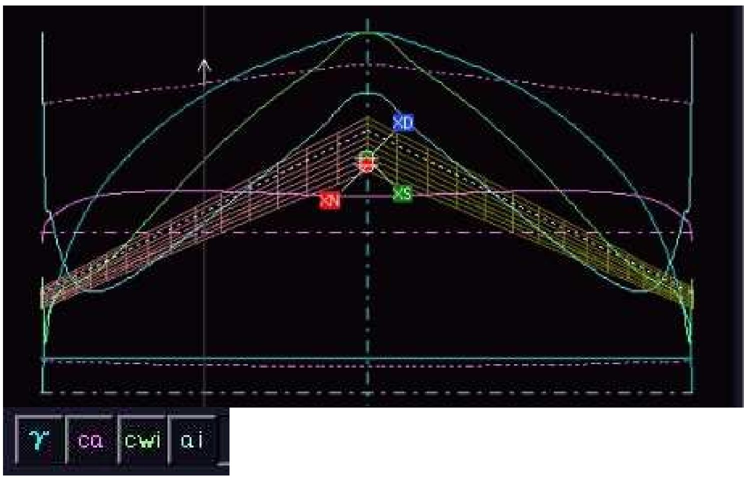


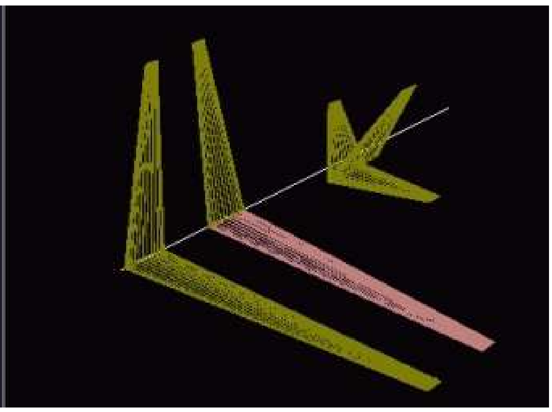


The corresponding polar (generated with a small wake) did not show a significant increase of glide performace within the analysed range. It is noted that the vertical distance of 5,5 m between both wings with a span of 60 m (fuselage diameter of 6,2 m) was not expected to generate a significant improvement. In green you see the polar of the box wing, which is positively staggered. In red you see the polar of the B777-200 modeled as reference.



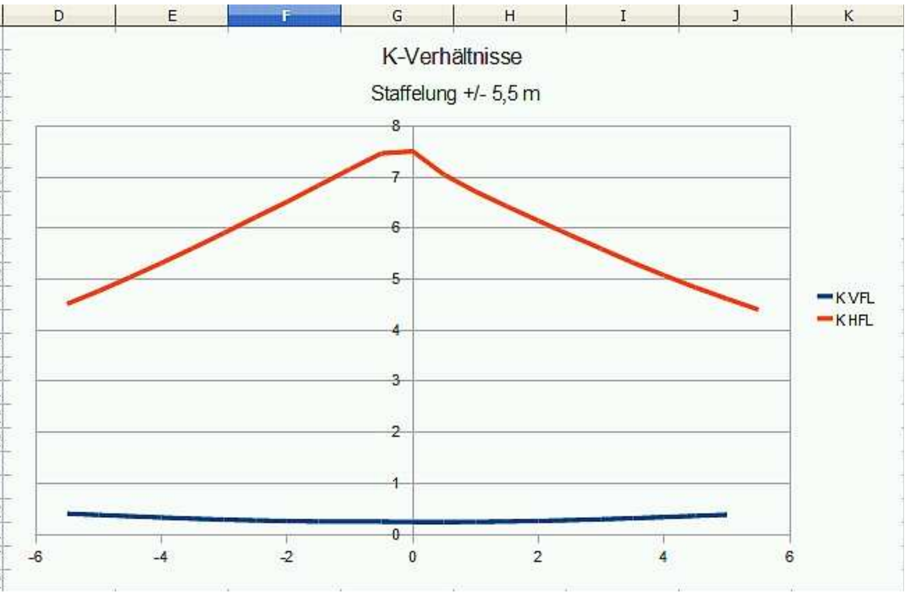
Next the influence of a more distinctive stagger of both biplane wings along the x-axis should be analysed, considering different vertical distances as well. For that the leading edge of the front wing root had the same position as the root leading edge of the reference wing. The rear wing was positioned so that its root leading edge was 2,2 root chord lengths behind. The incidence angle of the front wing is 2°, that of the rear wing 0,2° and that of the elevator 0°. Below you see the resulting tandem aircraft: the wings have the same vertical position. Additionally the lift distribution of the rear wing is shown at a speed of 120 m/s and a static margin of 15%.





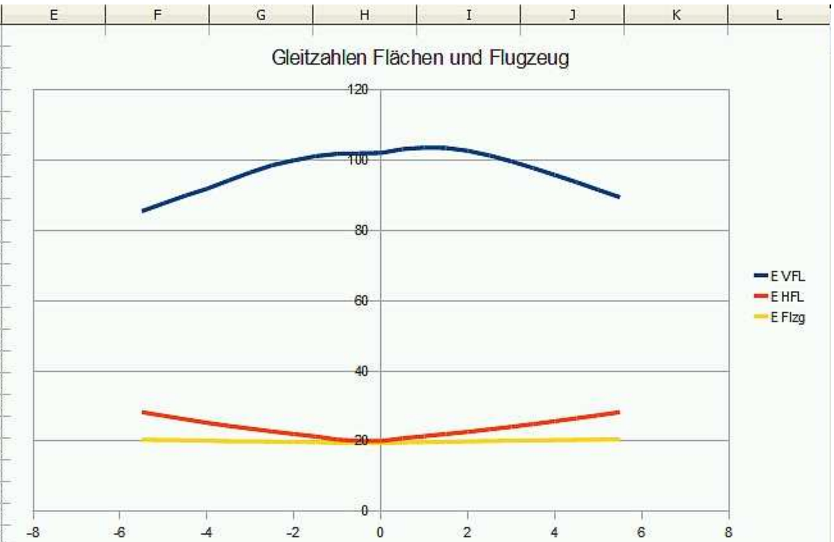
After setting these basic parameters the rear wing was staggered in steps of 0,5 m to a vertical distance of +/- 5,5 m. The program determined the k-factor of both wings [k = C_D,i / (C_D,i)ell] at a speed of 120 m/s, together with their individual glide ratios (E) and the glide ratio of the total system. These data were exported to a calculation program and plotted.

Höhe HFL	K VFL	K HFL
5,5	0,39	4,41
5	0,36	4,62
4,5	0,34	4,84
4	0,32	5,08
3,5	0,3	5,33
3	0,28	5,6
2,5	0,27	5,87
2	0,25	6,15
1,5	0,25	6,43
1	0,24	6,72
0,5	0,25	7,05
0	0,25	7,51
-0,5	0,25	7,47
-1	0,26	7,16
-1,5	0,26	6,84
-2	0,28	6,52
-2,5	0,29	6,22
-3	0,31	5,91
-3,5	0,33	5,61
-4	0,36	5,32
-4,5	0,38	5,04
-5	0,41	4,77
-5,5	0,44	4,52



Column A contains the vertical stagger. Columns B and C contain the k-factors of the front and the rear wing. The k-factor of the rear wing (red line) changes significantly with vertical stagger, whereas the k-factor of the front wing remains at a level between 0,25 and 0,44. This is also reflected by the glide ratios:

Höhe HFL	E VFL	E HFL	E Flzg
5,5	89,48	28,29	20,56
5	91,59	27,41	20,48
4,5	93,77	26,55	20,41
4	95,83	25,71	20,33
3,5	97,82	24,9	20,25
3	99,71	24,13	20,17
2,5	101,39	23,39	20,08
2	102,71	22,7	19,99
1,5	103,54	22,06	19,89
1	103,62	21,46	19,78
0,5	103,21	20,83	19,65
0	102,11	20,05	19,47
-0,5	101,98	20,11	19,48
-1	101,87	20,45	19,55
-1,5	101,2	21,37	19,73
-2	100	22,06	19,83
-2,5	98,62	22,79	19,93
-3	96,58	23,57	20
-3,5	94,28	24,38	20,03
-4	91,91	25,26	20,19
-4,5	89,94	26,27	20,29
-5	87,75	27,27	20,37
-5,5	85,52	28,29	20,45



Column A contains the vertical stagger. Columns B and C contain the glide ratios of the front and the rear wing. Column D contains the glide ratio of the whole aircraft.

The glide ratios of both wings differ significantly (front wing in blue, rear wing in red), whereas the whole aircraft (yellow) does not benefit from splitting the reference wing. The model of the B777 has a glide ratio of 20 under the same conditions. However, it is noteworthy that the glide ratio of the front wing increases to values higher than 100 because of the presence of another wing downstream. The rear wing has a positive influence on the wake of the front wing and drops its k-factor to 0,24. (elliptical lift distribution of a single wing: k = 1)

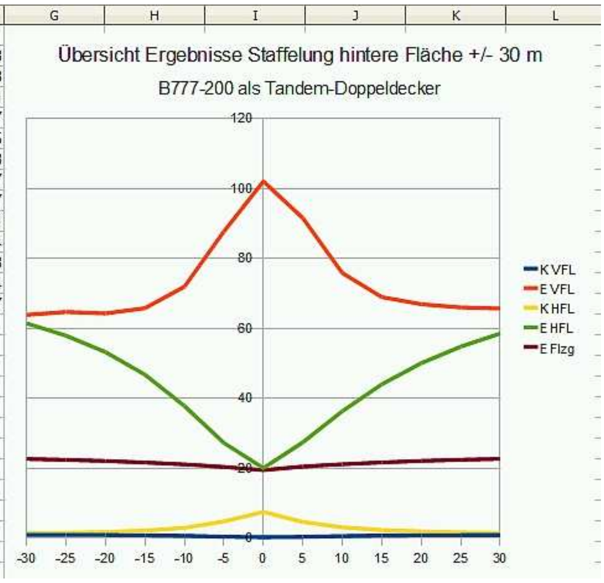
Based on these results it could not be concluded that splitting the reference wing with AR = 8,8 into two single wings, having AR = 17,6 and positioned in tandem configuration with vertical stagger, increases the performance of the whole aircraft significantly.

However, theoretic investigations of Prandlt, one of the prime fathers of aerodynamics, which lead to the “best wing” (the box wing), showed that the performance of these staggered configurations depends on the ratio of h/b and on the condition that both wings have the same lift distribution.

Now the influence of vertical stagger was analysed by staggering the rear wing in steps of 5 m to a vertical distance of +/- 30 m (= half of the wing span) to the front wing. Fuselage and empennage unchanged.

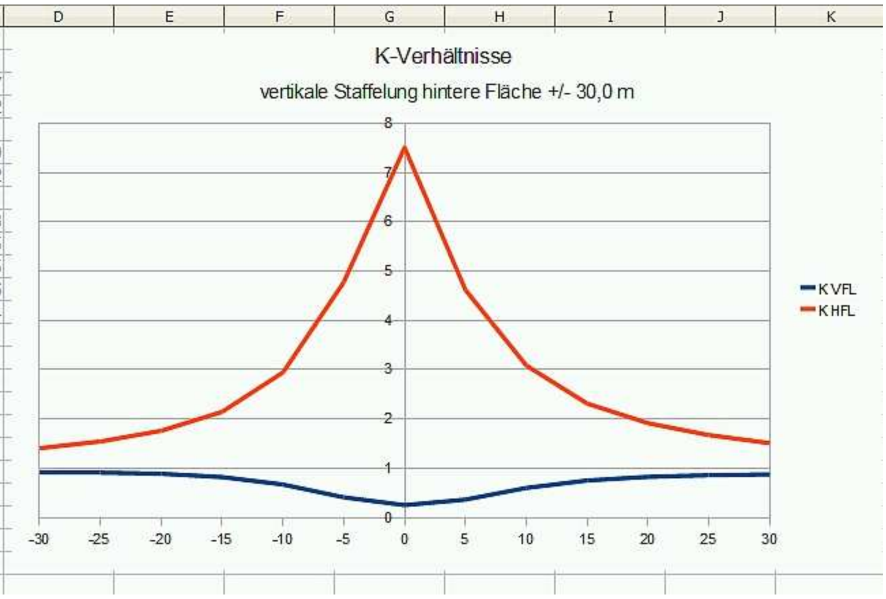
Despite the partially absurd arrangement of the wings, flight conditions of sufficient static margin were produced at a speed of 120 m/s (the program adjusts the location of the centre of gravity!). The data in a general survey:

Höhe HFL	K VFL	E VFL	K HFL	E HFL	E Flzg
30	0,87	65,71	1,51	58,55	22,68
25	0,86	66,02	1,67	54,79	22,43
20	0,83	66,94	1,92	50,07	22,11
15	0,75	68,98	2,31	44,02	21,67
10	0,6	75,89	3,09	36,31	21,15
5	0,36	91,59	4,62	27,41	20,48
0	0,25	102,11	7,51	20,05	19,47
-5	0,41	87,75	4,78	27,27	20,37
-10	0,67	71,96	2,95	37,85	21,1
-15	0,82	65,8	2,15	46,78	21,64
-20	0,89	64,3	1,76	53,25	22,08
-25	0,91	64,73	1,54	57,94	22,4
-30	0,92	63,9	1,41	61,48	22,67



The survey shows that the glide ratio of the front wing (red) decreases from E > 100 to a value of E > 60 with increasing vertical stagger (positive and negative). The glide ratio of the rear wing increases from 20 to 60 (green). But for the total system (brown) only small improvements are shown, which furthermore are shown in ranges where both wings can be seen as almost isolated.

Höhe HFL	K VFL	K HFL
30	0,87	1,51
25	0,86	1,67
20	0,83	1,92
15	0,75	2,31
10	0,6	3,09
5	0,36	4,62
0	0,25	7,51
-5	0,41	4,78
-10	0,67	2,95
-15	0,82	2,15
-20	0,89	1,76
-25	0,91	1,54
-30	0,92	1,41



Höhe HFL	E VFL	E HFL	E Flzg
30	65,71	58,55	22,68
25	66,02	54,79	22,43
20	66,94	50,07	22,11
15	68,98	44,02	21,67
10	75,89	36,31	21,15
5	91,59	27,41	20,48
0	102,11	20,05	19,47
-5	87,75	27,27	20,37
-10	71,96	37,85	21,1
-15	65,8	46,78	21,64
-20	64,3	53,25	22,08
-25	64,73	57,94	22,4
-30	63,9	61,48	22,67

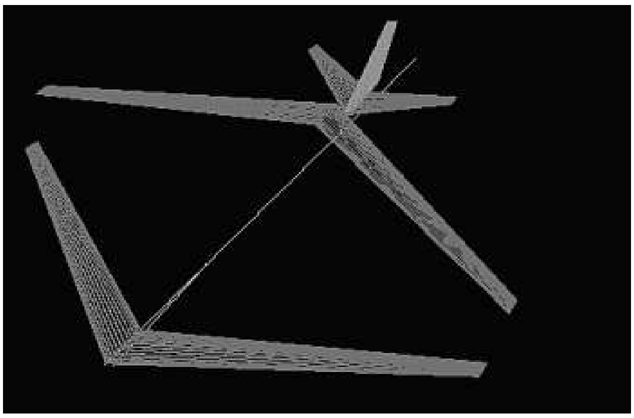
For assessing whether the shown results are probably just valid for a swept tandem biplane, the configuration was changed in order to form a diamond shape, as it is the basic configuration of a modern box wing.

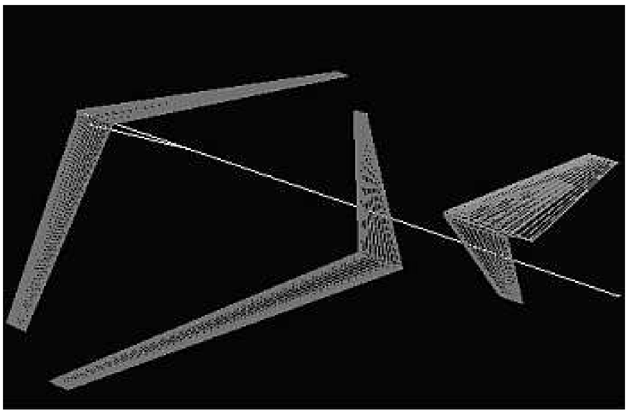
For that the rear wing of the biplane was swept 26,5° forward instead of 26,5° aft. Additionally it was shifted 10,5 m aft (based on the root leading edge). The front wing was shifted 15,6 m forward. The tips of both wings could then be connected by a winglet having a sweep angle of about 25°.

For this aircraft the centre of gravity was determined in order to allow stable flight conditions. For keeping the static margin of the previous analysis, both wings got the same angle of incidence of 2°.

The images show the extremes of the analysed vertical distances of the rear wing (+/- 6 m) leading to several positively staggered diamond shaped wings, which are the basis of today's box wing proposals.

For getting comparable data, the size, position and incidence angle of both the vertical and horizontal stabilizer were kept unchanged as well as the drag coefficients of the fuselage.

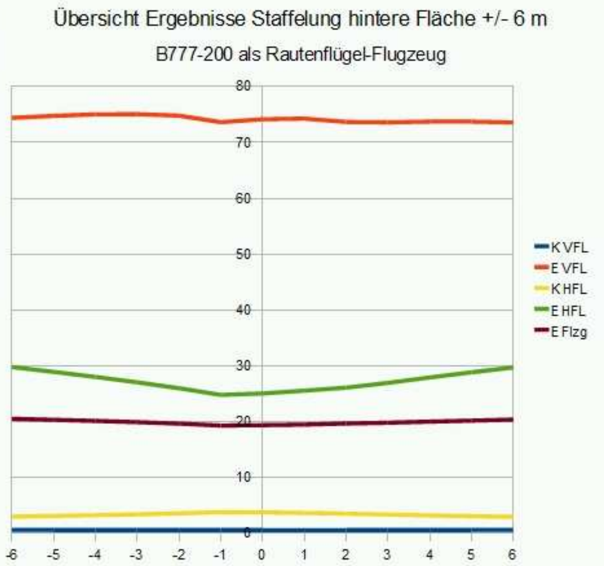




For a speed of 120 m/s at sea level and the use of NACA 0009 and NACA 0010 airfoils (same as the reference aircraft), the following results were attained:

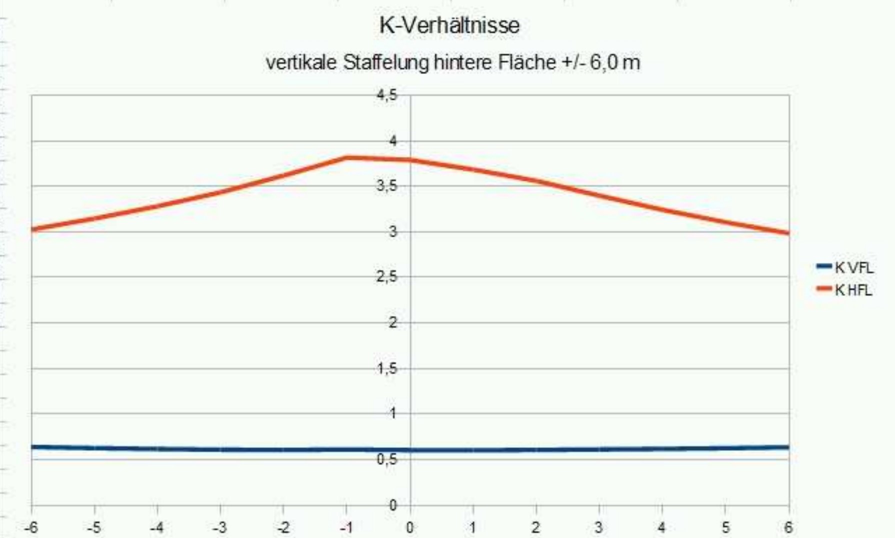
Overview:

Höhe HFL	K VFL	E VFL	K HFL	E HFL	E Flzg
6	0,63	73,61	2,99	29,74	20,4
5	0,63	73,76	3,11	28,86	20,22
4	0,62	73,76	3,24	27,94	20,03
3	0,61	73,62	3,4	26,97	19,84
2	0,61	73,69	3,56	26,11	19,7
1	0,6	74,28	3,68	25,58	19,51
0	0,6	74,18	3,79	25,07	19,4
-1	0,61	73,65	3,82	24,82	19,32
-2	0,61	74,82	3,62	26,02	19,67
-3	0,61	75,09	3,44	27,07	19,94
-4	0,62	75,06	3,28	28,04	20,16
-5	0,63	74,77	3,15	28,94	20,36
-6	0,64	74,41	3,03	29,81	20,54



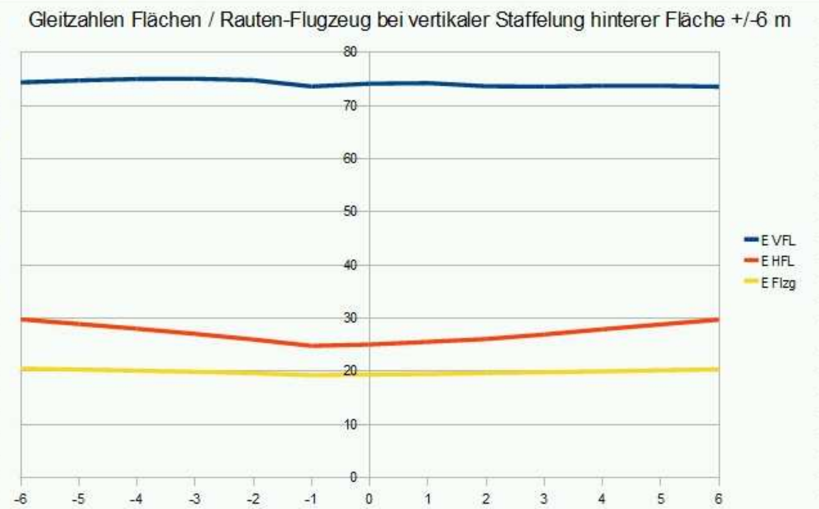
k-factors:

Höhe HFL	K VFL	K HFL
6	0,63	2,99
5	0,63	3,11
4	0,62	3,24
3	0,61	3,4
2	0,61	3,56
1	0,6	3,68
0	0,6	3,79
-1	0,61	3,82
-2	0,61	3,62
-3	0,61	3,44
-4	0,62	3,28
-5	0,63	3,15
-6	0,64	3,03



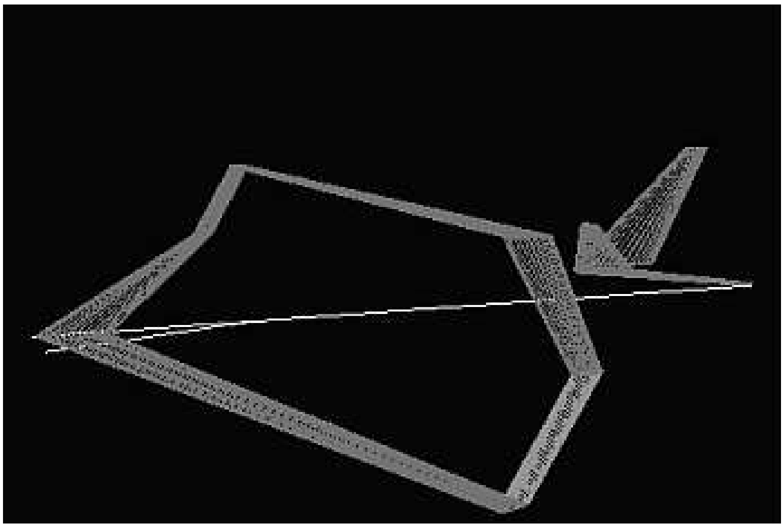
glide ratios:

Höhe HFL	E VFL	E HFL	E Flzg
6	73,61	29,74	20,4
5	73,76	28,86	20,22
4	73,76	27,94	20,03
3	73,62	26,97	19,84
2	73,69	26,11	19,7
1	74,28	25,58	19,51
0	74,18	25,07	19,4
-1	73,65	24,82	19,32
-2	74,82	26,02	19,67
-3	75,09	27,07	19,94
-4	75,06	28,04	20,16
-5	74,77	28,94	20,36
-6	74,41	29,81	20,54

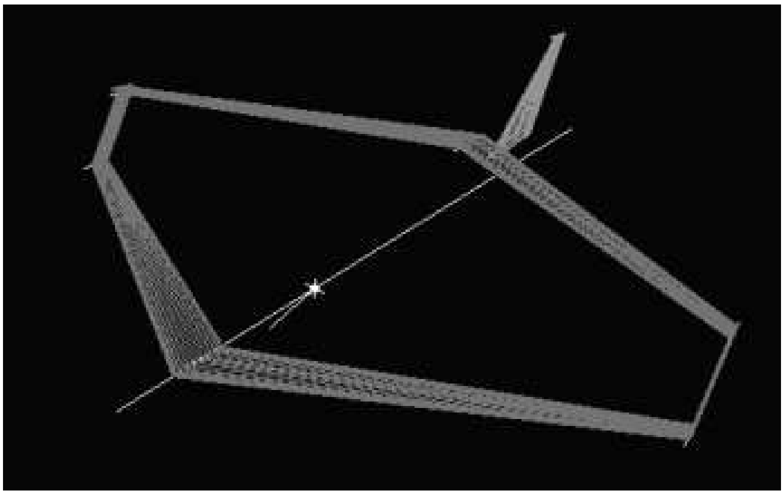


The results are similar to those of the swept biplane and a significant increase in glide ratio compared to the Boeing 777-200 (E = 20) could not be observed for a speed of 120 m/s and all engines out.

Because today most proposed box wings have negative stagger, finally a diamond shaped wing having negative stagger was chosen. Its front wing was stretched, so that its tips could be treated as winglets pointing up/rearwards rectangularly. The sweep of the winglet generated like this was 25°. The vertical distance of the wings (no dihedral/anhedral) was 6 m for this box wing – equaling 0,1 b (b = 60,9 m).



After this the aircraft was calculated for a gliding speed of 120 m/s again and it reached a glide ratio of 20,23. The simple “winglets” did not improve the performance. But for excluding the possibility of the elevator to produce an additional and significant drag, the angle of attack was fixed within the program after the determination of the glide ratio and the elevator was removed – thus stability was not demanded.



<u>Because of this the glide ratio was increased from 20,23 to 23,33!</u>

For regaining stability, the rear wing of the box wing needed to have a smaller incidence angle than the front wing (difference in angle of incidence is 1,6°). With this setting the aircraft finally reached a glide ratio of 22,29 for a speed of 120 m/s, whereas the reference aircraft (Boeing 777-200) reached a glide ratio of about 20 for the same speed and under the same conditions.

This is an improvement of 11,5% which was achieved without an optimization of this box wing, whereas the glide ratio of 20 in the end corresponds to an already optimized system, because the used drag coefficients for the fuselage and its attached parts are based on this glide ratio.

It cannot be stated that, after all, optimizing a box wing could not be realized with the help of an elevator (being significantly smaller). In this context stability and control are an important matter, together with other aspects.

Conclusion:

Of course the results do not make any absolute statement about the compared aircraft, because the analysis was based on simplifications and did not incorporate an optimization of incidence angles, wing twists etc. Additionally a not referenced VL program was used making calculations based on a short wake. The results only indicate some tendencies.

Attention should be paid to the fact that the presence of a second wing in the wake of a first one increases the glide ratio of the first wing up to values higher than 100, because this effect can also be produced with the help of smaller wings in downstream position or other methods, which improve the flow off of an upstream wing.

3.2.2011 Dieter M. Schulz-Hoos, München
www.sunny-boxwing.de