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The Outside Has To Be Bigger Than the Inside

Howard W. Smith*
University of Kansas, Lawrence, Kan.
and
Robert Burnham†
The Boeing Company, Seattle, Wash.

A method for calculating the volume requirements for an airplane and a design procedure for distributing the volume is described. A not-too-obvious necessity for providing enough total volume to contain the payload, fuel, structure, and systems is presented as a logical design procedure. With the outside mold lines being held to a minimum while the need to maximize the internal space for seats, cargo, and fuel capacity, a fundamental design dilemma is posed. Seat pitch, area ruling, fuel volume, and structural depth are discussed. Two examples, a short-haul transport and a supersonic fighter airplane, are presented. The method's versatility allows its use during preliminary, advanced, or production design phases.

Introduction

A NUMBER of years ago the authors and a few others in a preliminary design group were assigned to work on a supersonic airplane. In the process, we were introduced to the concept of area ruling. Area plots abounded and great emphasis was placed on obtaining high density with minimum cross-section area. Those who were to decide on the internal arrangements had to place the airplane landing gear, flight crew, engines, fuel, and all contents in very small spaces. It was commonly complained that the mold lines were too close together and in the wrong places and as the design developed the originally smooth area plot that the performance was based upon had a pronounced tendency to get lumpy.

In nature, stress brings about change and so our techniques began to evolve to reduce the frustration. The area plot itself suggested a system of volume accounting that would be appropriate. The area under the curve represents the total volume, and obviously the total must exceed the sum of the volumes of all the things that must go inside. An understanding thus was needed of how to predict the volume required for each item contained in the airplane; this has been done with the geometric limitations, weight, and volume of these items known. The area plot is also helpful in arranging things in the right places for efficient packaging and balance.

Application of volume accounting in the initial design stages has been found to result in designs with better performance, lower cost, and fewer iterations in the preliminary design process. It has been incorporated in computer-aided design programs which analyze weight, performance, and cost and describe optimum sets of design parameters. The technique has been found to be appropriate for a variety of airplane types from small subsonic rpv's to large supersonic transports.

Discussion

Volume accounting can be applied at various appropriate levels of design. For a very approximate solution the new design can be compared to existing similar airplanes. Figure 1 is a plot of density vs gross weight for a number of vehicles. Substantial scatter exists and the designer is given little reason why. This method should be considered only as a crude approximation.

Another approach considers each of the principal components to be an element in a group "volume" statement similar to a group weight statement. For example, Table 1 was developed for a parametric model of a supersonic transport in a Boeing experimental interactive computer-aided design system. The volume allowance for each item was developed from statistical and rational analysis. Volume allowed for passengers includes aisles and seating, exits, lavatories, galleys, and closets as functions of the number and class of passengers and body cross section.

Figure 2 and Table 2 show the statistical basis and coefficients for assumed linear functions. These data were built into the program to make the model geometry sensitive to payload entered as an input, in this case the number and class of passengers. The cabin floor occupies a substantial volume because of the structural beam depth required. In our model, the floor was assumed to serve as a conduit for controls, air ducts, and wiring. Total fuel was computed in a performance module and the wing fuel capacity was computed independently in a wing geometry module. The difference between these two is the body fuel volume required. The total volume was equated to a Sears-Haack least drag for a given volume and length-area distribution. Good correlation with existing designs was obtained.

Two more examples are offered to illustrate how this approach can be applied to widely different design objectives, a subsonic short-haul transport and a supersonic V/STOL fighter.

Example 1 Short-Haul Transport

This example is a twin turbofan-powered, 80 passenger airplane with a low wing, upper surface blowing, "T" tail, tricycle landing gear, and a circular-section pressurized body. Figure 3 is a simplified three-view drawing of the craft. Table 3 itemizes the principal elements which comprise the body volume. Since this airplane does not have fuel located in the body, the wing must have enough volume in the structural box to contain all of the fuel. The design optimization program would include wing-box volume as a constraint on the wing geometry. The total required body volume can be equated to the body geometry as shown by Fig. 4. The body cross section (Fig. 5) has been established by a requirement for four-abreast seating. Figure 6 is an area plot of the body showing the location of the items from Table 3. The nose and tail cone fineness ratios are 1.5 and 2.5, respectively, and were selected arbitrarily.

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*Professor, Aerospace Engineering Department. Associate Fellow AIAA.

†Principal Engineer, Boeing Military Airplane Co. Member AIAA.

Table 1 Supersonic transport volume buildup[a]

Item	Volume, ft^3	
Passenger provisions	8,075	All tourist class, 34.5 ft^3/pass. (Fig. 2a and Table 2)
Cabin exits	746	3.18 ft^3/pass. (Fig. 2b and Table 2)
Lavatories	527	2.25 ft^3/pass. (Fig. 2c and Table 2)
Galleys	527	2.25 ft^3/pass. (Fig. 2c and Table 2)
Closets	94	$V_{CL}=K_7$ (cabin depth) $\times N_p$ (Table 2)
Baggage and cargo	2,230	$\mathrm{Vol}_{B/C}=K_4\times N_p+K_5$ (Table 2)
Floor	1,104	From body geometry
Avionics	300	Specified
Auxiliary power unit	64	Gross weight/10,000 (statistical)
Flight deck	480	120 × 4 (four-man crew) (statistical)
Body fuel	7,820	Total required, less wing fuel
Nose landing gear	175	Rational determination from gear geometry module
Main landing gear	1,525	
Misc. systems	990	30 lb/ft^3, 29,700 lb
Wing through box	1,453	Rational determination from wing geometry module
Wing fuel	8,720	Included in exposed wing, not assumed, determined in wing geometry module
Exposed wing	10,675	Rational determination from wing geometry module
Total	36,785	

[a] 234 passengers, 635,000 lbs gross weight.

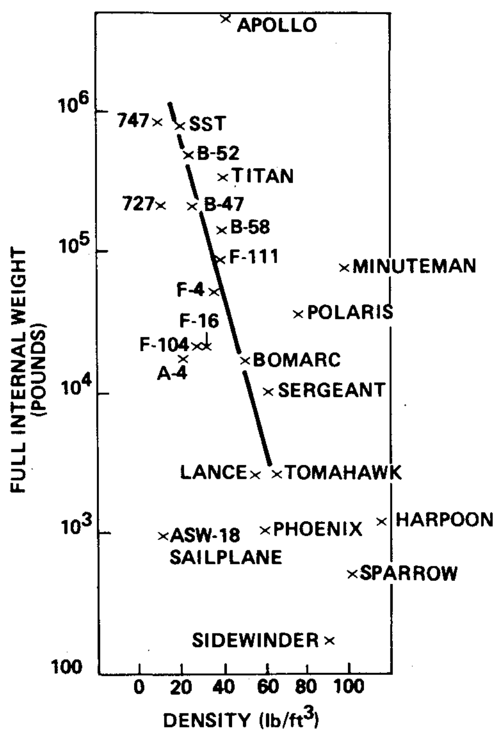


Fig. 1 Full internal weight vs density of air vehicles.

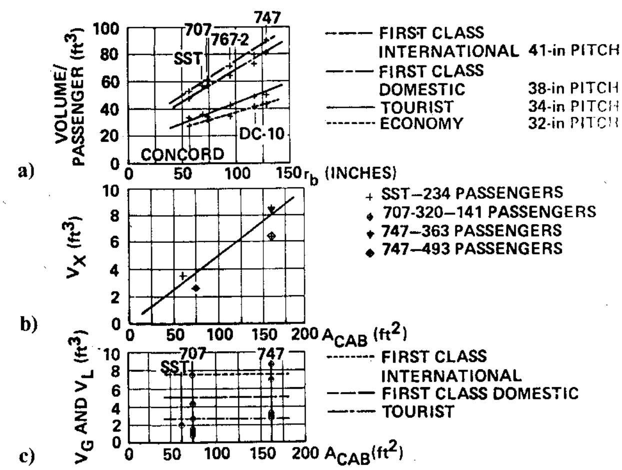


Fig. 2 Volume available per passenger as a function of cabin cross-section area. a) Cabin volume. b) Exit volume. c) Galley and lavatory volume.

Example 2 V/STOL Supersonic Fighter

Figure 7 is a three-view drawing of this design. The main features are an arrow planform wing, canard, dual aft fuselage and fins, a nose inlet, and vectoring engine nozzles at the airplane center of gravity. A single pilot is enclosed in a bubble canopy. A three-strut landing gear with a large tread and wheelbase provide high ground stability, a feature of great value during operation from ship-based helicopter pads. The forward strut extends for STOL operation. Weapon racks are located on the lower side of extensions from the dual aft bodies. The disposable load is thus placed free of interference with the vectoring nozzles and jet blast and near the center of gravity for minimum effect on longitudinal balance. Reaction jet nozzles located at the tips of the aft bodies are supplied by air bled from the fan ducts of the engines. Fuel, avionics, and the aft landing gears are contained in the aft bodies.

The volume buildup for this design is shown in Table 4. A group weight statement is usually available to the designer early in the design cycle and one is included here for comparison (Table 5).

The densities are established by statistical data from existing systems or, where sufficient information is available, by layout and rational analysis. Wing volume is computed from the wing planform and section data. The following equation is appropriate for a wing with linear plan and thickness ratio taper. More complex planforms can be developed as a series of such shapes.

$$V=Kc_R^2\left(\frac{t}{c}\right)\frac{b}{12}[\zeta+\phi\psi]$$

where:

K = section area coefficient
c_R = root chord
t/c = thickness ratio at root
b = span
ζ = $3+2\lambda+\lambda^2$
ψ = $1+2\lambda+3\lambda^2$
λ = plan taper ratio = c_t/c_r
ϕ = t/c taper ratio = $(t/\bar{c}_t)/(t/c_r)$

Table 2 Passenger accommodation volume factors

K_N	Tourist	First class domestic	First class international
K_1	0.293	0.46	0.50
K_2	14.00	22.00	24.00
K_3	2.25	5.0	7.5
K_4	8.25	8.25	8.25
K_5	300.00	300.00	300.00
K_6	2.25	5.0	7.25
K_7	0.005	0.00833	0.00833
N_p	= number of passengers		
R_B	= body radius, in.		
A_{cab}	= cabin cross-section area, ft^2		
h_{cab}	= cabin height (floor to ceiling), in.		
W_F	= floor width, in.		
$N_{A/B}$	= number of passengers abreast		
Pass. vol, V_p	$=N_p(K_1 R_B + K_2)$		
Exit vol, V_x	$=N_p(A_{cab}/20)$		
Lavatory vol, V_l	$=N_p(K_3)$		
Baggage and cargo	$=N_p(K_3)+300$		
Galley vol, V_G	$=N_p(K_6)$		
Closet vol	$=N_p(K_7 \times h_{cab})$		
Floor vol	$=N_p(0.065\, W_F^2)(3/N_{A/B}+4.85/A_{cab}+0.05)/144$		

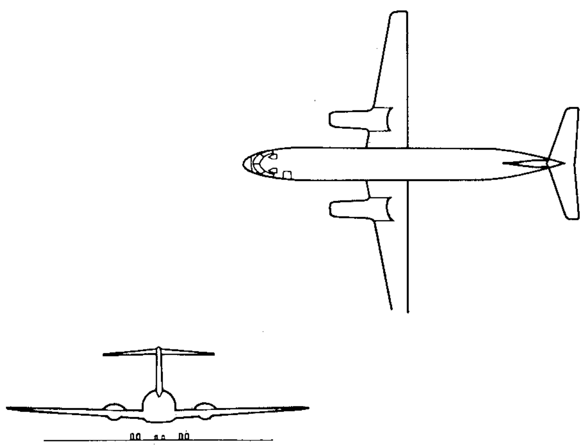


Fig. 3 Three-view drawing of short-haul transport.

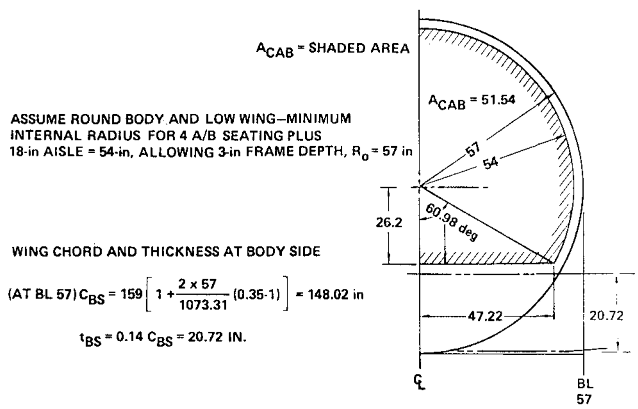


Fig. 5 Body cross-section geometry of short-haul transport.

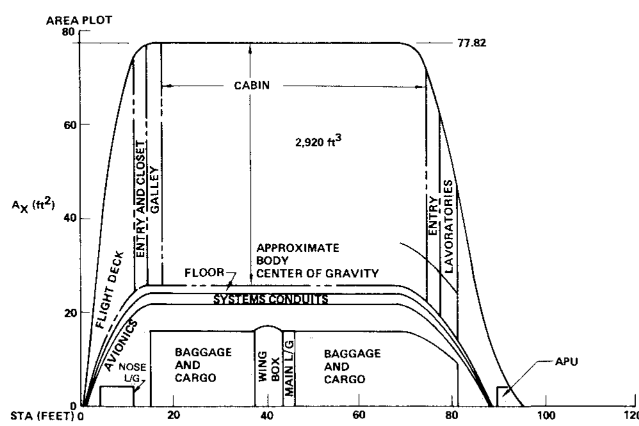


Fig. 6 Body area plot of short-haul transport.

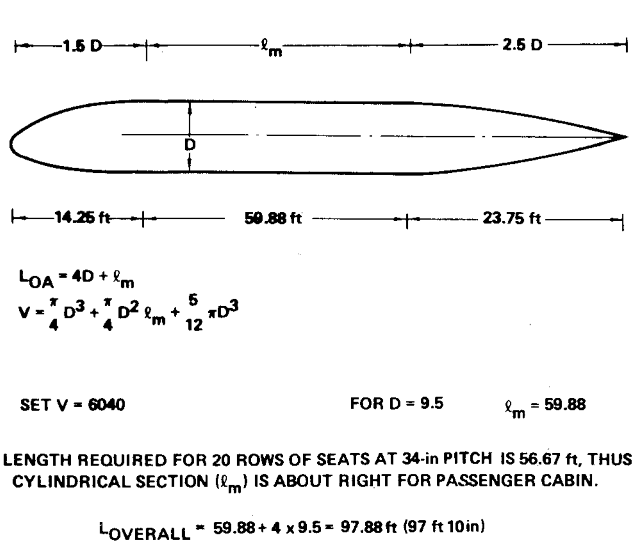


Fig. 4 Required internal volume related to body geometry of short-haul transport.

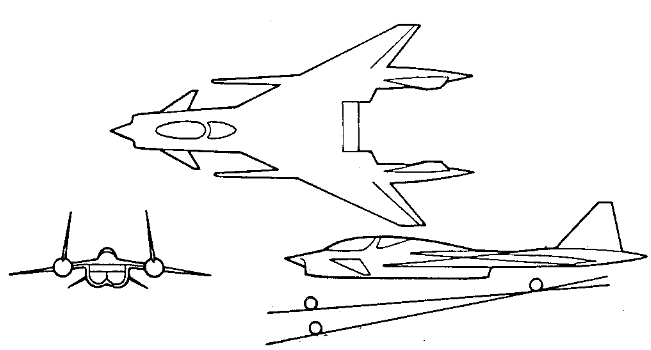


Fig. 7 Three-view drawing of V/STOL supersonic fighter.

Table 3 Short-haul transport volume buildup

Item	Volume, ft^3	Volume functions[a]
Passengers (single class)	2546	$N_p (K_1 R_{10} + K_2) = 80 \times 30.7$
Exits	289	$N_p (A_{cab}/20)$
Lavatories	180	$N_p (K_3)$
Baggage and cargo	960	$N_p (K_4) + 300$
Galley	180	$N_p (K_6)$
Closet	32	$N_p [K_7 (h_c + h_f)]$
Floor	312	$N_p [(W_F^2 \times 0.065 \times (3/N_{A/B} + 4.85/A_{cab} + 0.05)]$
Misc. systems	200	$2 \times \ell_B$
Avionics	100	Specified
Auxiliary power unit	8	Gross weight/10,000
Flight deck	360	$N_{crew} \times 120 = 3 \times 120$
Nose landing gear	6	Computed from geometry
Main landing gear	20	Computed from geometry
Radome (nose)	10	$(D_{rad})^3 \times 2$
Wing through box	101	$A_{box} \times 2y_{bs}$
Structure	27	$W_{body}/\rho_{aluminum}$
Unused (12% total)	710	
Total	6040	

[a]Coefficients ($k_1 - k_7$) are obtained from Fig. 2.
N_p = number of passengers
$h_c + h_f$ = distance body centerline to cabin overhead and floor
W_F = floor width
$N_{A/B}$ = number of passengers abreast
A_{cab} = cabin interior cross-section area (Figs. 4-6)
ℓ_B = body length
N_{crew} = number of crew
D_{rad} = radar dish diameter
A_{box} = box cross-section areas
y_{bs} = B.L. box rib
W_{body} = body weight

Table 4 V/STOL supersonic fighter volume buildup

Item	Weight, lb	Density, lb/ft^3	Volume, ft^3
Wing through box structure (in body)	750	150	5
Wing structure	1,650	150	11
Body structure	3,000	150	20
Tails	500	33.33	15
Canards	100	50	2
Landing gear (400 lb each)	1,200	120	15
Inlet	200	2	100
Nacelle	400	150	2.67
Engines (including accessories)	2,700	30	90
Nozzles and afterburners	1,600	15	106.67
Fuel system	450	—	In fuel vol
Avionics (excluding antennas and cockpit)	800	40	20
Equipment (hydraulics/pneumatics, electrical, armaments, etc.)	1,750	30	58.33
Cockpit (crew, control, furnishings, etc.)	820	13.67	60
Controls (including reaction control system)	500	10	50
Gun and ammunition	1,000	50	20
Antenna (radar)	100	20	5
Trapped fuel and oil	200	—	In fuel vol
Payload	2,000	—	External
Fuel (6.5. lb/gal + 10%)	10,000	43.76	Internal
Total	27,720 + 2,000 payload	39.8	697 (Total × 1.2)

Table 5 V/STOL supersonic fighter group weight statement

Item	Weight, lb
Structure	
Wing	2,400
Body	3,100
Tail	500
Landing gear	1,200
Nacelle and Inlet	600
Total	7,800
Propulsion	
Engines	4,200
Controls	50
Accessories	50
Starters	50
Fuel system	450
Total	4,800
Equipment	
Instruments and navigation	100
Surface control	600
Hydraulics/pneumatic	300
Electrical	500
Avionics	1,000
Armament	300
Furnishings	400
AC and AI	400
Gun and provisions	1,000
Total	4,600
Operating items	
Crew	200
Crew provisions	20
Payload provisions	100
Trapped fuel and oil	200
Total	520
Overall weight	17,720
Payload	2,000
Fuel	10,000
Gross weight	29,720

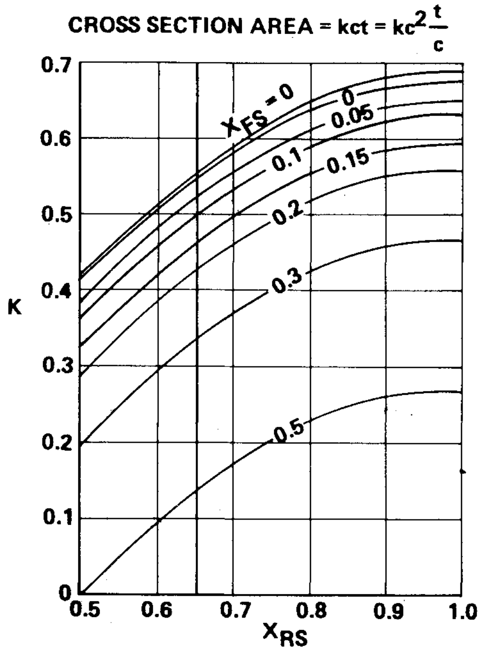
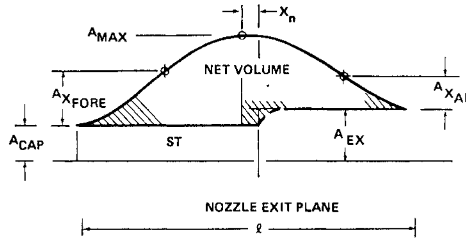


Fig. 8 Airfoil cross-section area between front and rear spars.



$A_{EX} = 850\ in^2 \times 2 = 1{,}700\ in^2\ (11.81\ ft^2)$

$A_{CAP} = 707\ in^2 \times 2 = 1{,}414\ in^2\ (9.82\ ft^2)$

$\ell = 55\ ft\ 4\ in,\ \ell/2 = 332\ in\ (27.67\ ft)$

$X_n = 4\ ft$

$VOL_{NET} = 705\ ft^3$

$$VOL_{NET} = \frac{3}{16}\pi \times \frac{\ell}{2} A_{MAX} + \frac{3}{16}\pi \frac{\ell}{2} (A_{MAX} - A_{EX} + A_{CAP}) + X_n (A_{EX} - A)$$

$$705 = \frac{3}{16}\pi \times 27.67\ (2 \times A_{MAX} - 11.81 + 9.82) + 4(11.81 - 9.82)$$

$$705 - 7.86 = \frac{3}{16}\pi \times 27.67\ (2 \times A_{MAX} - 1.99)$$

$$\frac{697.04}{3/16\ \pi \times 27.67} = 2 \times A_{MAX} - 1.99$$

$$A_{MAX} = 22.38\ ft^2$$

FOR S-H AREA DISTRIBUTION WITH MINIMUM DRAG,
GIVEN LENGTH AND VOLUME

Fig. 9 Required airplane volume related to area plot of V/STOL supersonic fighter.

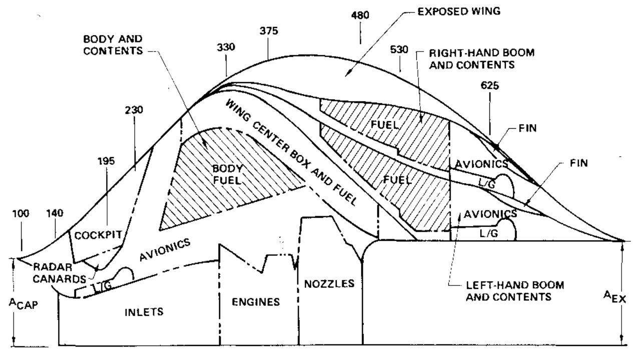


Fig. 10 Internal arrangement shown in area plot of V/STOL supersonic fighter.

Figure 8 provides section area coefficients for the given front and rear spar locations. The wing structural box penetrating the fuselage is included as part of the body volume. Table 4 also includes the fuel contained in the fuselage.

Since this is a supersonic airplane the area plot shape has aerodynamic significance. Figure 9 shows how the required volume is equated to a Sears-Haack minimum drag shape. The maximum cross-sectional area is placed at midlength and the fineness ratio was selected as 10/1. The step in the aft portion of the plot accommodates the expanded exhaust stream.

Figure 10 correlates the items from Table 4 with the locations in the area plot. At first glance the area plot suggests a nose-heavy airplane. The cockpit enclosure and engine inlets, both located in the nose, have relatively low densities however. Table 6 itemizes moments and arms to confirm a properly balanced design.

Table 6 V/STOL supersonic fighter balance check

Item	Weight, lb	Arm, in.	Moment, in.-lb
Wing through box	750	390	292,500
Wings	1,650	440	726,000
Body	3,000	440	1,320,000
Tails	500	640	320,000
Canards	100	190	19,000
Nose landing gear	400	200	80,000
Aft landing gear	800	620	496,000
Inlet	200	250	50,000
Nacelle	400	390	156,000
Engines	2,700	375	1,012,500
Nozzle after burners	1,600	445	712,000
Fuel system	450	430	193,500
Avionics, nose	200	230	46,000
aft	600	630	378,000
Equipment	1,750	430	752,500
Cockpit	829	195	159,900
Controls	500	470	235,000
Gun and ammunition	1,000	330	330,000
Radar antenna	100	140	14,000
Trapped fuel and oil	200	440	88,000
Payload	2,000	410	820,000
Wing fuel	4,240	430	1,823,200
Forward body fuel	1,820	330	600,600
Aft body fuel	3,940	530	2,088,200
Overall	29,270	422	12,553,000

Conclusion

Volume accounting at the conceptual and preliminary design stages provides a means of organizing the inside of the airplane in an optimum way. Organization provides higher density without crowding and thus better performance and lower cost. A more profound understanding of the configuration is obtained at the first design stage. This leads to fewer "surprises" later and sometimes new and better ideas. Serendipity is given a boost.