Efficient Sizing of a Cargo Rotorcraft

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A new cargo rotorcraft sized to meet the most demanding of the future combat airlift requirements being postulated by the U. S. Army could be unnecessarily large and expensive. Overall requirements could be satisfied more efficiently with a smaller aircraft by using multilift for infrequent peak demands. This paper describes a methodology for assessing the benefit of multilift and the influence of usage spectrum on required aircraft size and achievable overall productivity. For characteristic distributions of mission payload, radius of action, and ambients, it is shown that aircraft design gross weight could be reduced as much as 40% and overall productivity improved as much as 50% by using multilift for less than 5% of the missions.

Introduction

COMBAT of the future will be fast-moving and geographically dispersed. Success will depend on the capability to deploy forces rapidly, to provide tactical mobility to combat elements, and to maintain needed levels of ammunition and supplies. A vital part of the logistical system required to provide this capability is vertical airlift. Today's vertical airlift capability will have to be expanded and modernized to satisfy future demands for heavier payloads, longer ranges, and survivability against more lethal battlefield threats.

Recognizing this, the U. S. Army is formulating the requirements for a next-generation transport helicopter, designated the Advanced Cargo Aircraft (ACA), to replace its current fleet of CH-47's and CH-54's starting at the turn of the century. Preliminary ACA requirements call for a payload of up to 35 tons and a mission radius of up to 500 km. This is several times the capability of current helicopters.

Even with the new technology expected to be ready for ACA production in the late 1990's, an aircraft sized to meet these requirements and equipped with the needed survivability features would weigh well over 100,000 lb. An aircraft this large could be unaffordable in sufficient numbers, and would probably be underutilized. A way needs to be found to satisfy the Army's essential airlift requirements with a smaller, more cost-effective aircraft.

Helicopter Size Issues

Although the size of the ACA is the focus of this paper, it is useful to review the broader issue of the economic size for transport rotorcraft in general. Figure 1 shows that after 30 years of steadily increasing gross weight, maximum rotorcraft size appears to be leveling off. (The USSR has consistently opted for larger helicopters than the West, but because of differences in technology and design philosophy, useful loads are comparable.) Both the U. S. and the USSR have retrenched from their largest helicopter programs of the late 1960's and early 1970's, neither of which reached production status. Economic and operational factors, rather than technology limitations, appear to be responsible for this trend reversal.

Theoretically, economies of scale can make a larger aircraft more efficient to build and operate. Realistically, however, costs for the same total fleet lift capability are likely to be higher because the greater initial investment for development, qualification, and tooling must be amortized over fewer units. Operationally, a smaller number of larger aircraft can provide the same fleet lift capability with fewer pilots and ground crew, but fleet capability probably has to be greater to offset poorer average utilization. Geographic dispersion of field operations makes a significant reduction in fleet size impractical in any case. Problems can arise from having to manhandle large pieces of hardware in the field and from sharing a smaller spares inventory. A large aircraft is also easier to detect and less able to outmaneuver threats, reducing its combat survivability and making it less likely to be committed by field commanders.

A practical limit to the size of the ACA can be the unavailability of large-enough engines. The Modern Technology Demonstrator Engine (MTDE), currently under development, is in the 6000 hp class. Even assuming this engine can eventually be grown to 8000 hp, a gross weight of no more than 100,000 lb would be feasible for a three-engine solution. If the required ACA size is larger, or if a twin-engine solution is desired, it would probably be necessary to undertake an expensive new engine development.

Effect of Size on Productivity

Figure 2, derived from Ref. 2, shows how theoretically achievable transport productivity, defined as maximum payload times maximum cruise speed divided by weight empty, increases with helicopter size. Implicit in this trend is the assumption that there is always a payload requirement equal to the aircraft's lift capability.

Average overall productivity can be expected to trend differently. Actual usage will comprise combinations of payload,

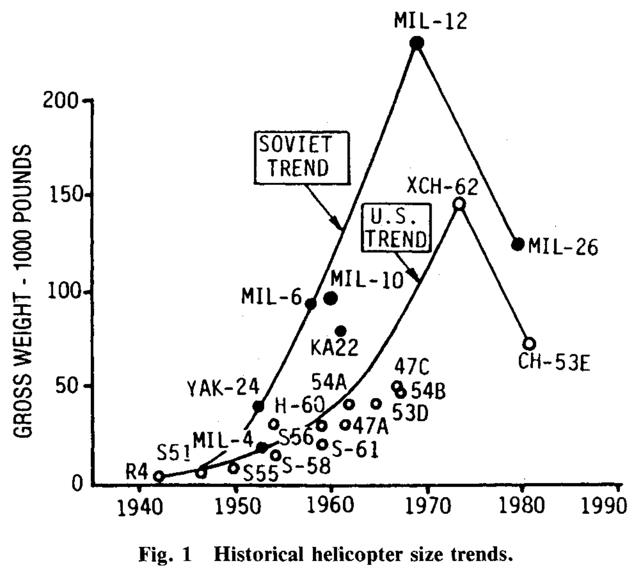

Fig. 1 Historical helicopter size trends.

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mission radius, and ambient conditions that are generally less demanding than maximum aircraft capability. If the aircraft is sized to simultaneously meet the 90th percentile value of each of these mission requirements, it will typically be underutilized 98% of the time (Fig. 3). When effectiveness is measured by average productivity rather than by theoretically achievable productivity, a smaller aircraft can be considerably more effective, as illustrated in Fig. 4. The challenge is to find a way to take advantage of this without sacrificing the peak mission demands. The multilift concept provides such a way.

Multilift Concept

In the multilift concept, two or more helicopters team together to lift up to several times the capability of each acting independently. A lightweight spreader bar distributes the load and provides physical separation between aircraft. A type of master-slave system synchronizes flight control and allows one pilot to fly the formation. Figure 5 illustrates a twin-lift arrangement.

Multilift is not just a theoretical concept (Ref. 3). As early as 1970, two Sikorsky CH-54B Skycranes twin-lifted a 35,000 lb payload. The USSR is known to use twin lift with Mi-10's and Mi-26's, although there is no evidence that it uses spreader bars or synchronized flight control. On a somewhat smaller scale, some innovative commercial operators routinely use twin lift when requirements exceed the capability of one of their light helicopters.

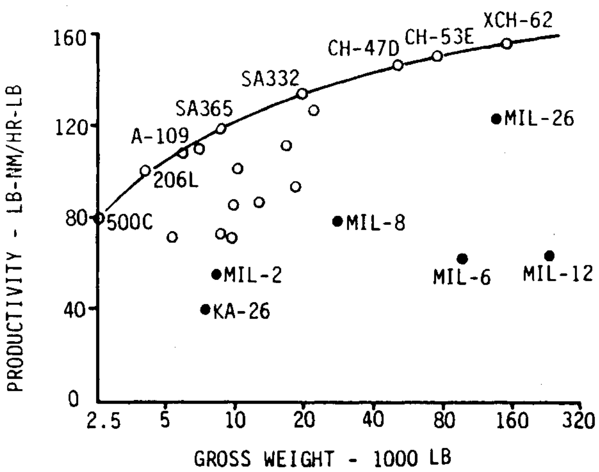


Fig. 2 Theoretical productivity vs size.

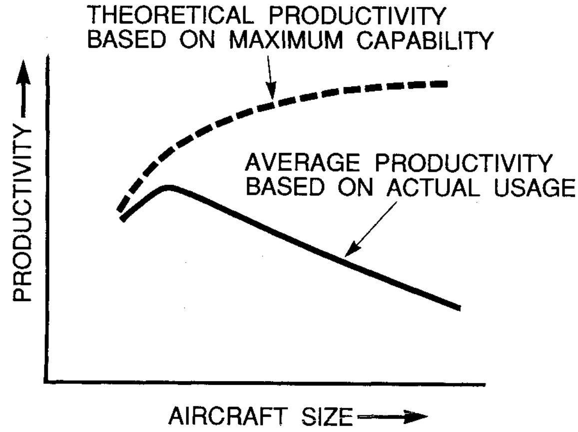


Fig. 4 Theoretical and actual productivity vs aircraft size.

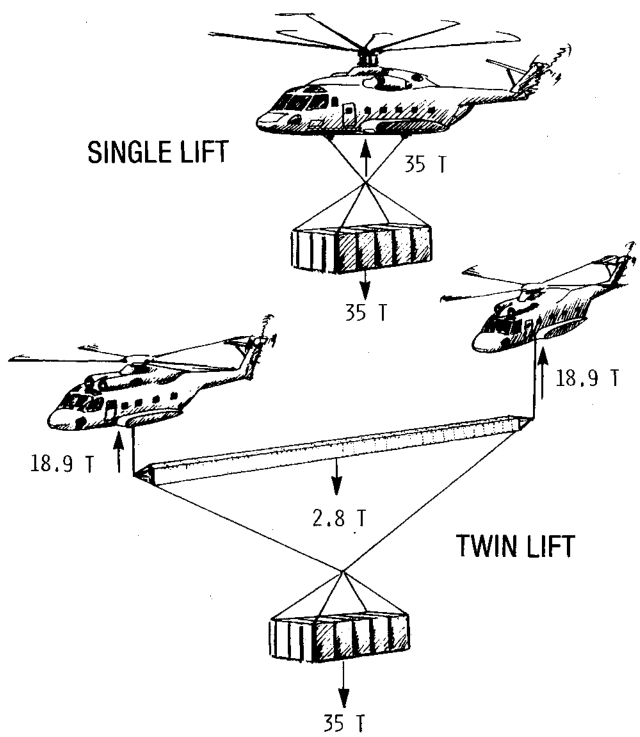


Fig. 5 Single and twin lift solutions to same payload requirement.

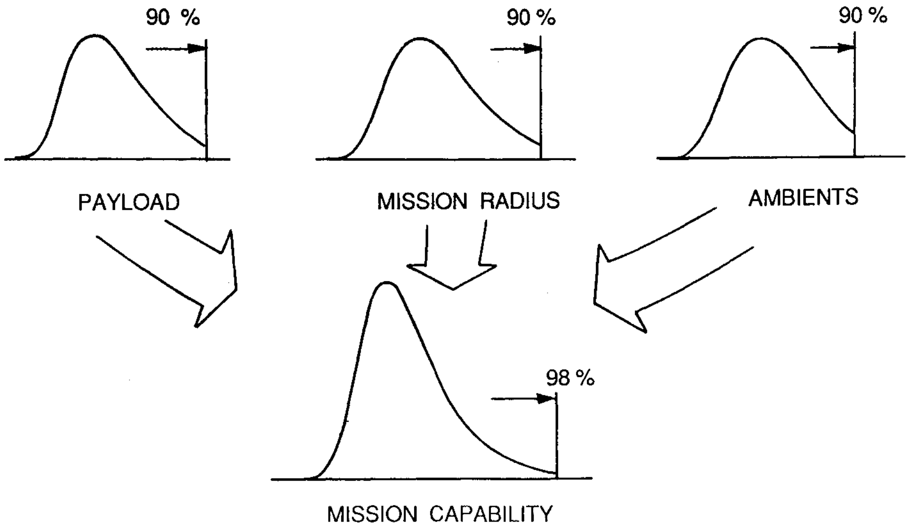


Fig. 3 Typical distributions of mission requirements.

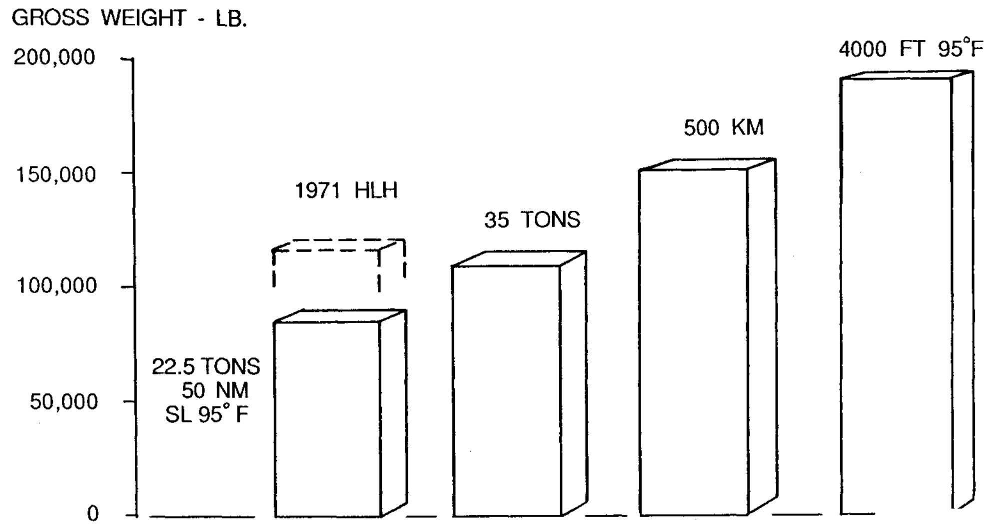


Fig. 6 Effect of requirements on ACA size.

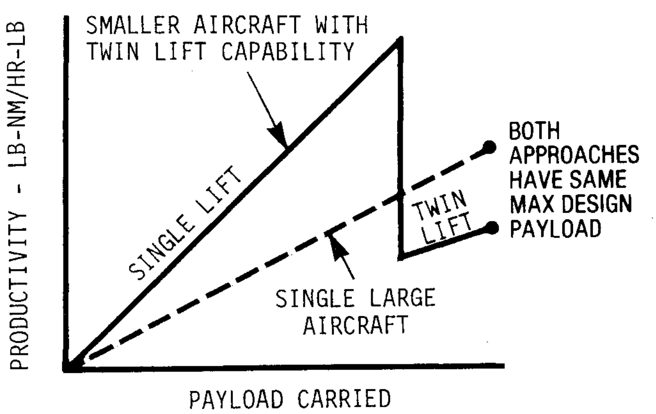


Fig. 7 Relative productivity of single- and twin-lift approaches having the same maximum lift capability as a function of payload actually carried.

The key issue affecting the suitability of multilift for the ACA role is not whether it can be made to work, but for what percentage of ACA missions it can realistically be used. Operational testing and evaluation are needed to address such issues as pilot workload, combat vulnerability, and field support requirements that could limit the acceptable frequency of multilift operations. As will be shown, however, multilift need not be used very often to substantially reduce the required size of the ACA solution.

Impact of Requirements on ACA Size

The size of the ACA will be very sensitive to its design mission requirements: specifically, how heavy a payload has to be lifted, for how far, and at what ambient conditions. The proposed XCH-62 heavy lift helicopter (HLH) technology demonstrator of the early 1970's had to carry 22.5 tons of payload a mission radius of 50 n.mi. (actually two 25 mile sorties), at sea level, 95°F. The resulting design had a gross weight of 118,000 lb. With 1990's technology, the same performance should be achievable for a gross weight of about 85,000 lb.

Even with advanced technology, however, the more demanding requirements being postulated today for the ACA would require a much larger aircraft, as shown in Fig. 6. Starting from the 85,000 lb solution to the 1971 HLH requirements as a baseline, an increase in required payload from 22.5 tons to 35 tons increases required gross weight to 115,000 lb. An increase in mission radius from 50 miles to 500 km (270 miles) brings the required weight to 150,000 lb. Finally, an increase

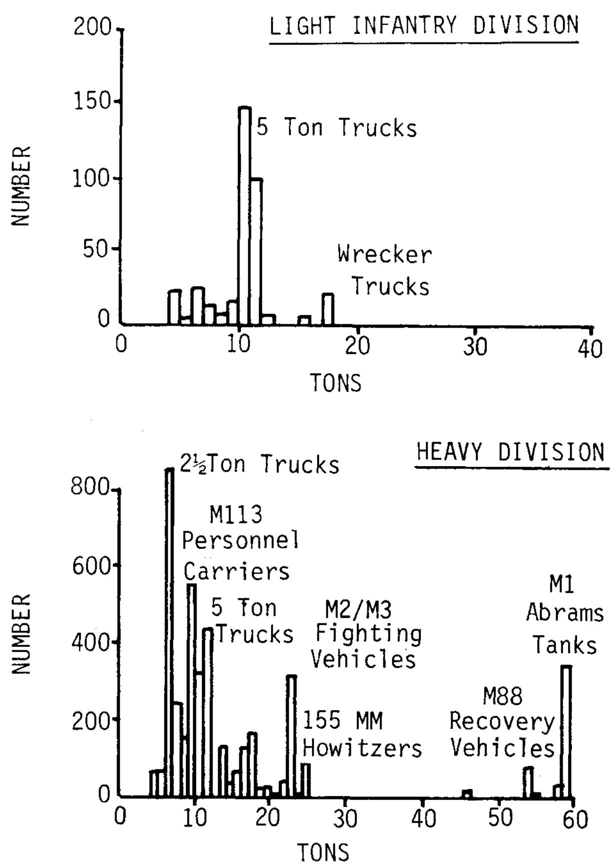


Fig. 8 Weight of U. S. Army combat equipment.

in design altitude from sea level to 4000 ft results in a gross weight approaching 200,000 lb.

The ACA can be smaller and still meet the peak mission requirements by using multilift. Since average requirements will be less demanding than design maximums, the capability of the smaller aircraft will be better utilized and overall productivity improved. The relationship of mission productivity to payload carried is compared notionally in Fig. 7 for single- and twin-lift solutions having the same maximum payload capability. For very heavy payloads, the single large aircraft has better productivity because total weight empty and mission time are less. However, when the required payload is light enough to permit the twin-lift partners to operate independently, the smaller aircraft is much more productive. The ben-

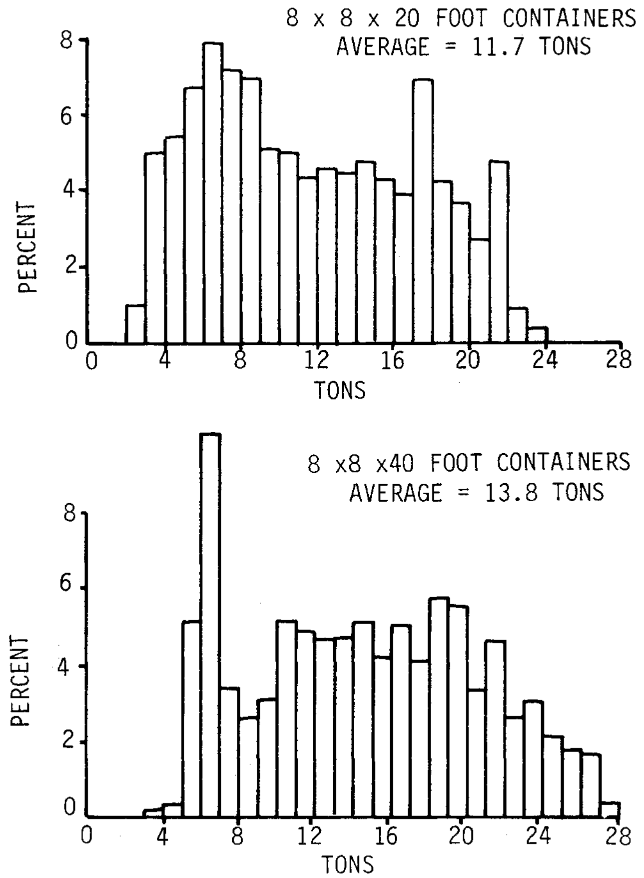


Fig. 9 Weight of loaded shipping containers from samplings taken in 1969–1970.

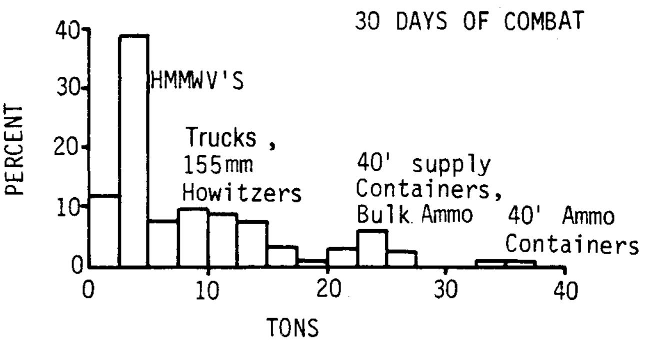


Fig. 10 Distribution of required payloads as projected in Ref. 4.

efit of multilift and the best aircraft size therefore depend on the frequency distribution of required payloads.

Usage Spectrum: Payload

ACA missions will include combat force movement and resupply, troop transport, engineer support, artillery placement and relocation, gap crossing, equipment recovery, and port clearance. The weight and frequency of individual mission payloads will vary widely. A payload frequency spectrum for the ACA has not yet been established, but equipment inventories of U. S. Army combat divisions and surveys of shipping container weights can provide some useful insight.

Figure 8 shows the weight distributions of the equipment in U. S. Army Light Infantry and Heavy Divisions.[4] All items weighing 4 tons or more are included. The light division has no equipment weighing more than 18 tons, and except for M1 tanks and M88 recovery vehicles, almost all of the equipment in the heavy division weighs less than 25 tons.

In addition to discrete items of equipment, the ACA will be required to transport containerized cargo. Figure 9 shows how

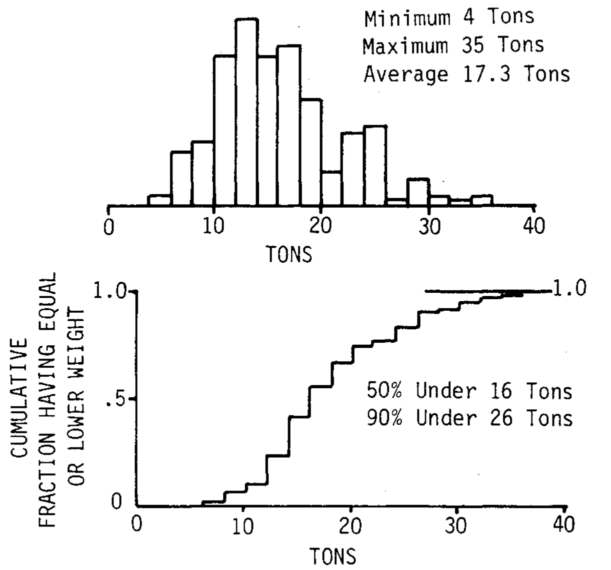
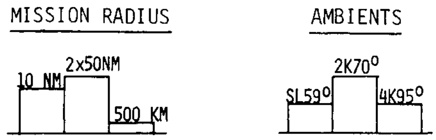


Fig. 11 Distribution of payloads assumed for sizing analysis.



	10 NM	2x50 NM	500 KM (270 NM)	TOTAL
Sea Level, 59°F	.100	.125	.025	.250
2000 Ft, 70°F	.200	.250	.050	.500
4000 Ft, 95°F	.100	.125	.025	.250
TOTAL	.400	.500	.100	1.000

Fig. 12 Distribution of mission radii and ambients.

the weight of loaded 8×8×20 ft and 8×8×40 ft shipping containers was found to vary in a sample taken during 1969 and 1970.[5,6] In both cases, the spread of weights was very wide. The weight of 8×8×20 containers peaked at 24 tons, but the average was only 12 tons. The larger containers weighed up to 28 tons, with an average of about 14 tons.

Other ACA loads will include palletized ammunition and supplies, fuel and water drums, and loose cargo. These kinds of loads are generally divisible into small enough units to match whatever the aircraft can accommodate, and should not drive the size of the ACA.

Just as important as the weight of individual ACA payloads is the relative frequency with which they need to be transported in a combat situation. Figure 10 shows unclassified results from analysis of 30 days of operation in a hypothesized future combat scenario, as reported in Ref. 7. It shows that the majority of individual sortie payloads is expected to be under 27 tons, with a limited number of large containers weighing up to 35 tons. The actual payload distribution will be skewed even more toward lighter weights, since the analysis in Ref. 7 assumed the maximum weight for each load category.

To illustrate the sizing approach described in this paper, the payload distribution shown in Fig. 11 was used. Payloads were assumed to range from 4 to 35 tons with an average of 17.3 tons. Fifty percent of individual mission loads are under 16 tons, and only 10% are over 26 tons.

Usage Spectrum: Mission Radius and Ambients

Although payload required is a key driver of required ACA size, mission radius and ambient requirements are just as im-

	10NM	2x50NM	500 KM
SEA LEVEL, 59°F	2.10	1.90	1.58
2000 FT. 70°F	1.92	1.74	1.44
4000 FT. 95°F	1.43	1.26	1.00*

*DESIGN POINT

Fig. 13 Aircraft payload capability relative to design point.

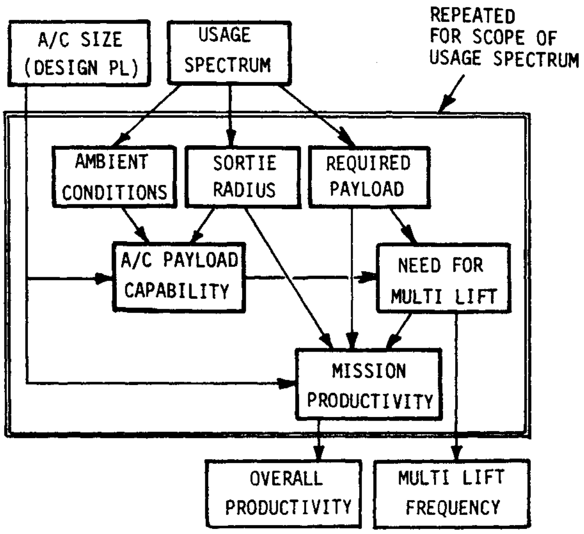


Fig. 14 Aircraft sizing methodology

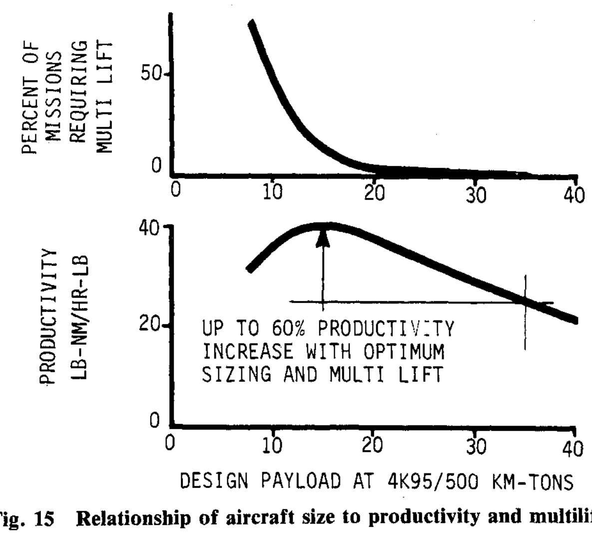


Fig. 15 Relationship of aircraft size to productivity and multilift frequency.

portant because they influence aircraft capability to lift payload. This was evident from Fig. 6, which showed that for the same design payload of 35 tons, increasing mission radius from 50 miles to 500 km and operating altitude from sea level to 4000 ft nearly doubled the required ACA design gross weight.

Design-point conditions of 4000 ft, 95°F, and 500 km mission radius are extremes of what is expected to be encountered in operation. The 4000 ft, 95°F ambients correspond to the 95th percentile for the Middle East, so conditions there can be expected to be less stringent 95% of the time. In Europe, the 95th percentile ambients are only 2000 ft, 70°F. The 500 km mission radius corresponds to the expected limit of the combat theater, but many of the heaviest payloads will be required only during much shorter range operations such as gap crossings.

To account for these effects in the ACA sizing analysis, the frequency distribution of mission radius and ambients shown in Fig. 12 was used. Ten percent of the missions were assumed to require the maximum 500 km radius of action, and 25% to involve operation at the most critical 4000 ft, 95°F ambients. Assuming radius of action and ambients to be independent, the design mission combination of 500 km and 4000 ft, 95°F is therefore required for only 2.5% of the missions. For a typical aircraft design, Fig. 13 shows how maximum payload capability varies for the same matrix of mission conditions. For very short missions at sea level standard day, maximum payload capability is typically over twice the design payload (although this will vary with the degree of flat rating incorporated in the design). Based on the relative frequency of mission conditions assumed, average payload capability is 1.7 times design payload.

Measure of Effectiveness

To assess ACA size tradeoffs, a measure of effectiveness is required. An appropriate measure for a transport aircraft is specific productivity, defined as useful work done per h/lb of aircraft weight empty:

$$\text{specific productivity} = \frac{\text{payload} \times \text{radius of action}}{\text{mission time} \times \text{weight empty}}$$

This definition is similar to the productivity index used in Ref. 2 and and shown in Fig. 2, except that maximum cruise speed is replaced by mission block speed (radius of action divided by total mission time), assuming that payload is carried one way only. Mission time also includes an allowance for load acquisition and drop off. As a result, the numerical value is less than half that of Fig. 2, although the units are the same.

For multilift, weight empty is simply the sum of individual aircraft weight empties. However, payload is less than the sum of individual aircraft lift capabilities by the necessary weight of spreader bars, cabling, and added mission fuel. Payload multipliers of 1.8 for twin lift and 2.4 for triple lift were assumed. Mission time for multilift was increased to account for assumptions of lower cruise speed (100 kt vs 150 kt) and slower turnaround (10 min vs 5 min), compared to single-aircraft operation.

Sizing Methodology

Figure 14 is a schematic of the sizing methodology. Inputs are the usage spectrum frequency distributions of required payload, radius, and ambients. Outputs are average overall productivity and required multilift frequency, both as a function of aircraft size.

For a specified aircraft size, the combination of sortie radius and ambient conditions establishes payload capability. This capability is compared with the required payload to determine if multilift is needed. Mission productivity is then calculated, accounting for appropriate block speed and weight empty penalties if multilift is used. The process is repeated for the full usage spectrum, and the resulting overall average productivity and multilift frequency are cumulated. Aircraft size is then varied to develop trends of productivity and multilift frequency with size. These trends are shown in Fig. 15 for the assumed usage spectrum.

Results

Figure 15 shows that for the assumed usage spectrum, maximum overall productivity is achieved with an aircraft sized for a design payload of 15 tons. This solution requires multilift operation for about 12% of the missions. If this usage of multilift is considered too high, aircraft size has to be increased. For a 1% multilift frequency, design payload is about 24 tons. The characteristics of the alternative solutions are tabulated in Fig. 16.

	AIRCRAFT DESIGN PAYLOAD		
	35 TONS	24 TONS	15 TONS
PERCENT MULTI LIFT MISSIONS	NONE	1%	12%
DESIGN GROSS WEIGHT - LB	185,000	131,500	90,000
WEIGHT EMPTY - LB	83,600	60,700	44,200
INSTALLED POWER - SLS IRP	45,800	31,200	19,425
PRODUCTIVITY - LB-NM/HR-LB	24.5	33.3	40.0

Fig. 16 Alternative aircraft solutions for the assumed usage spectrum.

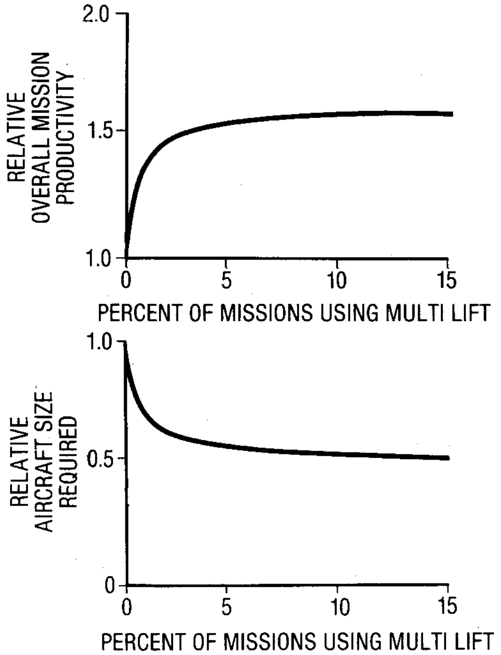


Fig. 17 Aircraft size reduction and productivity improvement achieved with multilift.

Figure 17 shows relative aircraft size and productivity as a function of multilift usage. The "knees" in the curves correspond to a size reduction of about 40% and a productivity improvement of about 50%, both for less than 5% commitment to multilift usage.

Effect of Assumed Usage Spectrum

Aircraft size trends are highly dependent on the assumed usage spectrum. For this reason, the absolute values derived in the previous example should not be considered necessarily appropriate for the ACA. To show how conclusions might change, the sizing exercise was repeated for a less demanding payload spectrum. Figure 18 compares the results.

The revised spectrum has the same maximum payload of 35 tons, but average payload is reduced from 17.3 to 8.3 tons. The resulting aircraft size corresponding to 1% multilift frequency decreases from a design payload of 24 to 15 tons, and productivity increases by about 25%. The most productive aircraft size would be even smaller if the requirements for mission radius and ambient conditions were also redistributed downward.

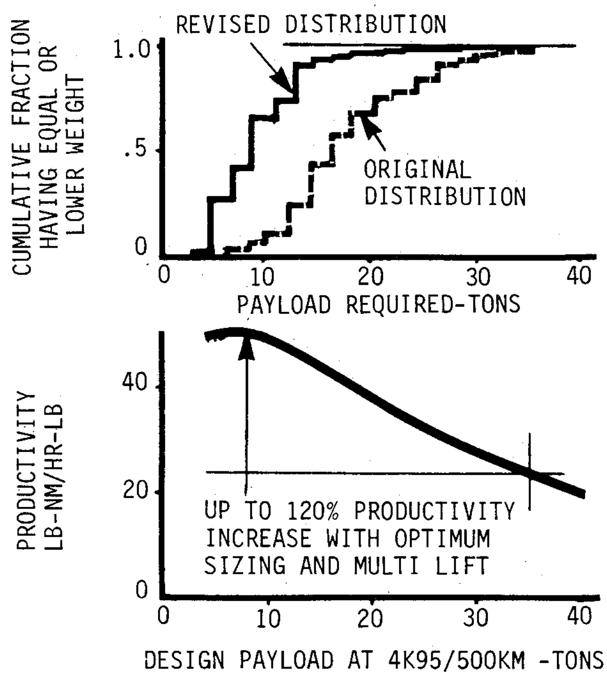


Fig. 18 Effect of assumed payload distribution.

Conclusions

1) Correct sizing of the ACA is essential to achievement of an efficient and affordable solution.

2) Use of multilift makes it possible to field a smaller, more efficient ACA without sacrificing peak mission capability.

3) The best size for the ACA is highly sensitive to usage spectrum and to the acceptable operational frequency of multilift.

4) To proceed with the ACA sizing decision, operations analysis is needed to establish a realistic usage spectrum, and operational testing of multilift is needed to determine an acceptable mission frequency.

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