DOC_{SYS} – A Method to Evaluate Aircraft Systems

Dieter Scholz

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1 Abstract

An evaluation of aircraft systems must be based on detailed system-specific parameters. These detailed parameters, however, are not part of conventional DOC (Direct Operating Cost) methods as applied for the entire aircraft. As a proposed solution, this paper describes a method called DOC_{SYS}, specifically tailored to the needs of aircraft *system* evaluations. DOC_{SYS} is based on classical DOC cost elements with optional system-specific extensions. The method has been checked with several real world problems. One of these problems is taken here to illustrate the method: The evaluation of design alternatives proposed for the water/waste system of the Megaliner/A3XX.

2 Introduction

Traditionally, *aircraft systems* have been evaluated by looking at

- weight,
- maintainability,
- reliability,
- system price, and
- other criteria depending on the aircraft system in question.

Different system proposals were compared by *separately* evaluating each criterion. The only possibility to come up with one single figure of merit of a proposal was to subjectively define a weighted sum of the results based on the individual criteria. (In German, this approach is called "Nutzwertanalyse" see e.g. [ZANGEMEISTER 76]).

In contrast to the above approach, an *aircraft* evaluation is traditionally based primarily on one economical figure: the Direct Operating Costs, DOC. Also DOC take account of criteria like weight, maintainability, reliability, and aircraft price, but DOC combine these separate parameters unambiguously by calculating their economical implications.

Aircraft DOC methods have been defined e.g. by:

- the Air Transport Association of America, 1967 [ATA 67],
- the Association of European Airlines, 1989 [AEA 89a], [AEA 89b],
- NASA / American Airlines, 1977 [NASA 77],
- Airbus Industrie [AIRBUS 88],
- Lufthansa [LUFTHANSA 82].

Unfortunately, these methods can not be taken "as is" for an aircraft *system* evaluation. In contrast to aircraft DOC methods, a DOC method on the systems level must incorporate many system-specific parameters. Therefore, a method called DOC_{SYS} has been developed [SCHOLZ 97a] which follows the principles of aircraft DOC methods as closely as possible, while taking aircraft system peculiarities into account as much as necessary.

The method has been checked with several real world problems:

- water/waste systems [SCHOLZ 98b],
- potable water and waste water tanks [SCHOLZ 97b], [SCHOLZ 98a],
- gray water treatment systems, [SCHOLZ 98c]
- alternative hydraulic and electric systems and
- VSCF (variable speed constant frequency) generators [SCHOLZ 98d].

DOC_{SYS} is very similar to the Cost of Ownership Methods as presented e.g. in [HONEYWELL 91] and [DECHOW 94]. These COO methods, however,

- consider primarily single parts (LRUs) and do not support as much the evaluation of systems or subsystems,
- rely heavily on detailed input from various aircraft manufacturer's departments (which makes these methods slow to react on changing fundamental input parameters).

In addition, it must be mentioned that the *term* "Cost of Ownership" is used also for the costs resulting in just *owning* an aircraft, system, or subsystem *without using* it [ODELL 93]. The term Direct *Operating* Costs, DOC, avoids these misinterpretations.

Since DOC_{SYS} are defined very similar to aircraft DOC (in fact, they are part of aircraft DOC), system proposals evaluated and selected on the basis of DOC_{SYS} will also help to reduce aircraft DOC. A detailed justification for a DOC method used for evaluating aircraft systems is given in [SCHOLZ 97a]. This reference also contains a summary of the state of the art of evaluation methods used in aircraft system design.

Summing up, DOC_{SYS} has several advantages over an evaluation

- based on separate criteria or
- based on COO methods:

DOC_{SYS}

- calculates a single figure of merit,
- eliminates subjectively weighted criteria,
- follows closely the well known and widely accepted DOC approach,
- is based as much as possible on readily available basic input parameters,
- ensures to optimize simultaneously also aircraft DOC.

3 DOC_{SYS} Cost Elements

Although it is heavily debated which cost elements do belong to *Direct* Operating Costs and which don't, it is generally accepted that DOC include those cost elements which depend on the aircraft itself. *Indirect* Operating Costs (IOC), in contrast, depend on the way an airline is run (see e.g. [BONDERGRAVEN 90]).

The "mother" of DOC methods, [ATA 67], considers as aircraft-dependent and hence part of DOC:

- cockpit crew costs,
- fuel costs,
- maintenance costs,
- depreciation,
- insurance (against hull loss).

DOC_{SYS} are considered to be a part of total aircraft DOC. **Cockpit crew cost** can be fully allocated to that part of aircraft DOC which are *not* DOC_{SYS}. This approach is valid as long as the number of members in the cockpit crew is not changed due to the system configuration in question.

Training costs for the crew or maintenance personnel traditionally do not belong to DOC. Hence, they are also not included in DOC_{SYS}.

Costs for insurance of an aircraft depend on the aircraft price and hence also on the price of aircraft systems. However, insurance policies are quite complicated and diverse. For simplicity and clarity of the DOC_{SYS} - method, insurance costs have been neglected. Insurance costs per aircraft and per year account for about 0.5% to 3% of the *aircraft* price [ROSKAM 90]. If desired, these percentages can also be considered for an insurance cost estimate for aircraft systems. In that case, the percentages have to be based on the *aircraft system* price.

Following from this discussion on DOC_{SYS} cost elements, we obtain the **fundamental DOC_{SYS}** from

$$DOC_{SYS} = Depr_{SYS} + Fuel_{SYS} + DMC_{SYS} \qquad (1)$$

$Depr_{SYS}$ depreciation of the system,

$Fuel_{SYS}$ fuel costs caused by the system,

DMC_{SYS} Direct Maintenance Costs caused by the system.

Airline practice revealed also an interest in further cost elements, especially when dealing with aircraft systems:

- delay and cancellation costs caused by aircraft systems,
- capital costs caused by necessary spare parts on stock.

Extended DOC_{SYS} - called $DOC_{SYS,ext}$ - take these additional cost elements into account:

$$DOC_{SYS,ext} = Depr_{SYS} + Fuel_{SYS} + DMC_{SYS} + Delay_{SYS} + SHC_{SYS} \qquad (2)$$

$Delay_{SYS}$ delay and cancellation costs caused by the system,

SHC_{SYS} capital costs caused by necessary spare parts on stock (Spare Holding Costs).

DOC_{SYS} will be calculated per aircraft and per year. A conversion of DOC_{SYS} - figures in any other unit common to DOC is possible.

3.1 $Depr_{SYS}$ Depreciation

Technical depreciation is considered here as a time dependent depreciation (this is the same approach as followed in aircraft DOC)

$$Depr_{SYS} = \frac{Price - Residual}{N} = \frac{Price \cdot \left(1 - \frac{Residual}{Price}\right)}{N} \qquad (3)$$

Price price of considered aircraft system, subsystem, or single part,

Residual value of the aircraft system after *N* years (for this study chosen to be 15% of the aircraft system price),

N depreciation period (for this study chosen to be 15 years).

3.2 $Fuel_{SYS}$ Fuel Costs

Fuel costs are differentiated by means of their physical origin. This approach helps to pinpoint the origin of fuel costs and allows to effectively find measures to reduce fuel consumption. Causes of fuel consumption due to aircraft systems, subsystems, or single parts are:

- $Fuel_{mf}$ fuel costs due to transportation of **f**ixed **m**ass (mass that does not vary in flight),
- $Fuel_{mv}$ fuel costs due to transportation of **v**ariable **m**ass (mass that does vary in flight: e.g. water drained during flight),

- $Fuel_P$ fuel costs due to mechanical **p**ower off-takes from the engines (e.g. by electrical generators additionally loaded for pipe heating elements),
- $Fuel_B$ fuel costs due to **b**leed air off-takes,
- $Fuel_R$ fuel costs due to **r**am air off-takes,
- $Fuel_D$ fuel costs due to additional **d**rag caused by the presents of aircraft systems, subsystems, or single parts (e.g. due to drain masts).

$$Fuel_{SYS} = Fuel_{mf} + Fuel_{mv} + Fuel_P + Fuel_B + Fuel_R + Fuel_D \ . \qquad (4)$$

The fuel costs for each cause of fuel consumption X are calculated from

$$Fuel_X = m_{fuel,X} \cdot FuelPrice \cdot NFY \qquad (5)$$

$m_{fuel,X}$ mass of fuel consumed due to cause X during the whole flight,
$FuelPrice$ fuel price,
NFY number of flights per year.

3.3 Calculating $m_{fuel,X}$ the Mass of Fuel Consumed

The fuel consumption is calculated for 7 *flight phases* i:

i = 1, engine start,
i = 2, taxi,
i = 3, take-off,
i = 4, climb,
i = 5, cruise,
i = 6, descent,
i = 7, landing, taxi, engine shut down.

Fuel consumption has different *physical causes* or *cost elements*. Fuel consumption can originate from

- the transportation of fixed mass " $X = mf$ ",
- the transportation of variable mass " $X = mv$ ",
- shaft power off-takes from the engines " $X = P$ ",
- or additional drag " $X = D$ ",
- bleed air off-takes from the engines " $X = B$ ",
- ram air off-takes " $X = R$ ",

Fuel is used

- due to the physical cause $X \neq mf$ itself: $m_{fuel,i,X,f}$, or

- to carry a fixed mass $m_{i,X}$ (this fixed mass can also consist of the fuel, carried to have it available for a physical cause *X* during later flight phases); this fuel is named $m_{fuel,i,X,m}$.

The calculation of the mass of fuel consumed starts at the end of the flight. Mass at the *end* of flight phase No. 7 is equal to zero for all physical causes $X \neq mf$. For $X = mf$, the mass at the *end* of flight phase No. 7 is equal to the (fixed) system mass m_{SYS} under consideration

$$m_7 = m_{7,mf} = m_{SYS} \qquad \textbf{(6)}$$

$$m_{7,(X \neq mf)} = 0 \quad . \qquad \textbf{(7)}$$

By definition, fuel which was carried for the system or variable mass, is used up by this time. If for any reason fuel reserves or variable mass reserves have to be allocated to the system, these reserves can simply be included into the fixed system mass m_{SYS} .

The fixed mass which has to be carried during each flight phase is calculated for each physical cause *X* from the mass of the following flight phase:

1. For all physical causes $X \neq mv$ and $X \neq mf$ this fixed mass being carried is just the mass of fuel necessary for later flight phases

$$m_{(i-1),X} = m_{i,X} + m_{fuel,i,X,m} + m_{fuel,i,X,f} \quad . \qquad \textbf{(8)}$$

2. For the physical cause $X = mv$ the fixed mass consists of the mass of fuel necessary for later flight phases and of the variable mass leaving the aircraft during later flight phases. The corresponding equation reads

$$m_{(i-1),mv} = m_{i,mv} + m_{fuel,i,X,m} + m_{fuel,i,X,f} + \dot{m}_{i,mv} \cdot \tau_i \qquad \textbf{(9)}$$

with $\dot{m}_{i,mv} \cdot \tau_i$ being the change of mass within the flight phase i . The rate of change $\dot{m}_{i,mv}$ is assumed to be constant - and positive for mass leaving the aircraft.

3. For fixed mass ($X = mf$) there is no special term $m_{fuel,i,X,f}$ (i.e. $m_{fuel,i,mf,f} = 0$) and the corresponding equation simply reads

$$m_{(i-1),mf} = m_{i,mf} + m_{fuel,i,X,mf} \quad . \qquad \textbf{(10)}$$

Generally speaking, the fuel consumed during flight phase i for a physical cause X is

$$m_{fuel,i,X} = m_{fuel,i,X,f} + m_{fuel,i,X,m} \qquad \textbf{(11)}$$

and the total amount of fuel consumed for a physical cause X is

$$m_{fuel,X} = \sum_{i=1}^{7} m_{fuel,i,X} \quad . \tag{12}$$

For flight phases i = 1, 2, 3, 7, the fuel consumption is estimated from mass fractions m_i / m_{i-1} (see e.g. [RAYMER 89]) applying Equation (13). Proposed mass fractions are given in **Table 3.1**. They are based on [ROSKAM 90] and are adapted to aircraft systems as discussed in [SCHOLZ 95]. The fuel fractions are strictly speaking only valid for fixed mass. They are however also adapted here to other physical causes.

$$m_{fuel,i,X} = m_{i,X} \left(\frac{m_{(i-1),X}}{m_{i,X}} - 1 \right) \quad . \tag{13}$$

Table 3.1 Proposed mass fractions m_i / m_{i-1} for aircraft systems as used in Equation (13)

flight phase	1	2	3	7
m_i / m_{i-1}	1	1	0.995	0.996

For the main flight phases i = 4, 5, 6, fuel consumption is calculated from "first principles" depending on the physical cause for the fuel consumption. The fuel required to carry fuel *within* each flight phase is considered by integrating over the respective system mass.

Fuel Consumption due to Fixed Mass

The fuel consumption due to fixed mass during flight phase i is

$$m_{fuel,i,X,m} = m_{i,X} \cdot \left(e^{t_i \cdot k_{E,i}} - 1 \right) \quad . \tag{14}$$

This equation is just another form of the well known *Breguet Range Equation*. The form presented here is a general form, considering not just cruise flight but also climb and descent (this becomes apparent in Equation (18)).

Parameters in Equation (14) are:

t_i duration of flight phase i ,

$m_{i,X}$ mass at the end of flight phase i due to physical cause X ,

$$t_4 = \frac{h}{R / C_4} \tag{15}$$

h	cruise altitude
R/C_4	rate of climb, $R/C_4 = R/C$

$$t_6 = \frac{h}{-R/C_6} \tag{16}$$

$-R/C_6$	rate of descent, $-R/C_6 = R/D$

$$t_5 = FT - t_4 - t_6 \tag{17}$$

FT	flight time, airborne time

$$k_{E,i} = SFC_i \cdot g \cdot \left(\frac{\cos\gamma_i}{L/D_i} + \sin\gamma_i \right) \tag{18}$$

SFC	thrust specific fuel consumption,
g	earth acceleration,
γ	flight path angle,
L/D	lift to drag ratio.

Fuel Consumption due to Variable Mass

The mass flow rate $\dot{m}_{i,mv}$ is considered *positive* if mass is *leaving* the aircraft. It is assumed that the mass flow rate is constant during each flight phase. The water-/waste system is an example where mass leaves the aircraft: Gray water from the sinks in the lavatories and from the galleys leaves the aircraft via drain masts. Let $\tau = 0$ be the time at the beginning of a flight phase *i*. The change of mass $dm_{i,mv}$ during a small time interval within flight phase *i* is

$$dm_{i,mv} = \dot{m}_{i,mv} d\tau \quad . \tag{19}$$

Exchanging the index "*m*" by "*f* " in Equation (14) (because we will deal here with fuel consumption *not* due to a fixed mass) differentiating with respect to m_i and substituting Equation (19) into the result yields

$$dm_{fuel,i} = \left(e^{\tau \cdot k_{E,i}} - 1 \right) \cdot \dot{m}_{i,mv} \cdot d\tau \quad . \tag{20}$$

This integrated over a flight phase *i* from $\tau = 0$ to $\tau = t_i$ gives finally the fuel consumed due to the physical cause "variable mass", *X=mv*, during a flight phase *i* (compare this result also with [AIR 1168])

$$m_{fuel,i,mv,f} = \frac{\dot{m}_{i,mv}}{k_{E,i}}\left(e^{t_i \cdot k_{E,i}} - 1\right) - \dot{m}_{i,mv} \cdot t_i \quad . \qquad (21)$$

Fuel Consumption due to Mechanical Power Off-Takes from the Engines

Mechanical power is taken off the engine as shaft power from the accessory gear box when driving generators or hydraulic pumps. This power taken off in flight phase *i* is labeled P_i. The evaluation of data from various engines of passenger aircraft shows that the thrust specific fuel consumption *SFC* is increased by shaft power off-takes. Let's call the difference between SFC with and without shaft power extraction ΔSFC. Further findings showed that

- ΔSFC is proportional to the amount of mechanical power extracted.
- With constant power off-takes, ΔSFC decreases with increasing engine size (the engine size measured by the nominal take-off thrust $T_{T/O}$).

With this knowledge, $\Delta SFC / SFC$ was plotted via relative power extraction from the engine $P / T_{T/O}$. The result is shown in **Fig. 3.1**. As can be seen, data is scattered only slightly about a straight line with a slope of $k_P = 0.0094$ running through the origin of the plot. Each data point in Fig. 3.1 was obtained as the average of $\Delta SFC / SFC$ calculated for flight altitudes of 0, 10000, 20000 and 35000 ft at Mach numbers of 0.30, 0.60 and 0.85 at maximum continuous thrust. In each case, shaft power of 100 hp = 74,57 kW was extracted from the engine.

In case that the demanded shaft power *P* can be delivered by a number of *n* engines, the *relative* power off-take is reduced and the term $P / T_{T/O}$ has to be substituted by $P / (n \cdot T_{T/O})$. Fig. 3.1 expressed in form of an equation - considering multiple engines - yields

$$\Delta SFC_i = SFC_i \cdot k_p \cdot \frac{P_i}{n \cdot T_{T/O}} \quad . \qquad (22)$$

The fuel flow due to shaft power off-takes is

$$\dot{m}_{fuel,P,i} = P_i \cdot \left(SFC_i\right)_P = \Delta SFC_i \cdot T_{req,i} = \Delta SFC_i \cdot m_{A/C} \cdot g \cdot \left(\frac{\cos\gamma_i}{L/D_i} + \sin\gamma_i\right) \quad . \qquad (23)$$

$\left(SFC_i\right)_P$ is called the power specific fuel consumption. For simplicity, $T_{req,i}$ is calculated here from an average airplane mass $m_{A/C}$ assumed to be

$$m_{A/C} = \frac{MTOW + MZFW}{2} \quad . \tag{24}$$

Keeping in mind that $\dot{m}_{fuel,P,i}$ is a mass flow rate, similar to a "variable mass" as discussed above, we get with Equation (23)

$$m_{fuel,i,P,f} = \frac{P_i \cdot k_p \cdot m_{A/C}}{n \cdot T_{T/O}} \left(e^{t_i \cdot k_{E,i}} - 1 \right) \quad . \tag{25}$$

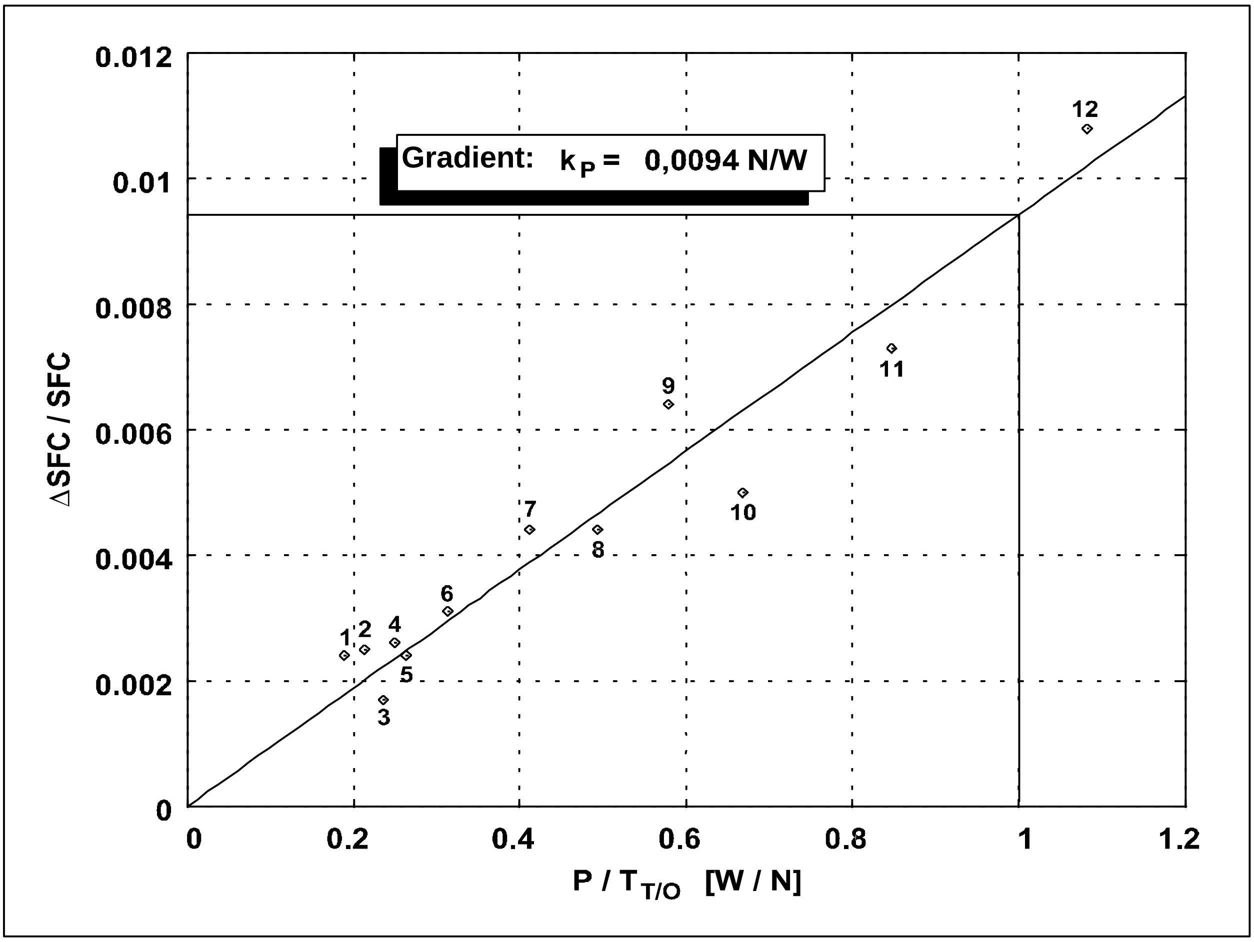

Fig. 3.1: Relative change in specific fuel consumption $\Delta SFC / SFC$ as a function of relative engine load $P / T_{T/O}$

Fuel Consumption due to Additional Drag

Aircraft systems can cause additional drag. In this context, drag is considered "additional" if it is not due to e.g. the wings and the fuselage but due to excrescencies as antennas, drain masts and air data sensors. The additional drag is calculated from

$$D_i = \frac{1}{2} \cdot \rho_i \cdot v_i^2 \cdot c_{D_i} \cdot A_{ref} \tag{26}$$

with

A_{ref}	reference area for the component(s),
c_{D_i}	drag coefficient of the component(s),
v_i	true air speed,
ρ_i	air density

for each flight phase *i*. The fuel flow due to the additional drag is

$$\dot{m}_{fuel,i,D} = SFC_i \cdot D_i \quad . \tag{27}$$

Using again Equation (23) for the derivation we obtain

$$m_{fuel,i,D,f} = \frac{SFC_i \cdot D_i}{k_{E,i}} \left(e^{t_i \cdot k_{E,i}} - 1 \right) \quad . \tag{28}$$

Fuel Consumption due to Bleed Air Off-Takes

If bleed air is taken off the engines, the fuel flow can be estimated which is required to maintain constant thrust. Following [AIR 1168], this fuel flow is

$$\dot{m}_{fuel,B} = k_B \cdot T_{tb} \cdot \dot{m}_B \quad . \tag{29}$$

In this equation $k_B = 3.015 \cdot 10^{-5}\ 1/K$, T_{tb} is the turbine inlet temperature and $\dot{m}_B$ is the bleed air flow. Furthermore

$$m_{fuel,i,D,f} = \frac{k_B \cdot T_{tb} \cdot \dot{m}_B}{k_{E,i}} \left(e^{t_i \cdot k_{E,i}} - 1 \right) \quad . \tag{30}$$

Fuel Consumption due to Ram Air Off-Takes

It is assumed that the air being taken in is decelerated down to a velocity of zero with respect to an aircraft fixed coordinate system. To overcome drag resulting from this deceleration of surrounding air, requires a fuel flow of

$$\dot{m}_{fuel,R} = SFC \cdot \rho \cdot Q \cdot v \quad . \tag{31}$$

ρ and v are the respective air density and true air speed, Q is the required air flow rate. Fuel consumed due to this physical cause in a flight phase *i* is

$$m_{fuel,i,R,f} = \frac{SFC_i \cdot \rho_i \cdot Q_i \cdot v_i}{k_{E,i}} \cdot \left(e^{t_i \cdot k_{E,i}} - 1 \right) \quad . \tag{32}$$

3.4 DMC_{SYS} Direct Maintenance Costs

The calculation of Direct Maintenance Costs is based on fundamental input parameters from the maintenance department

$$DMC_{SYS} = \left(MMH_{on} + MMH_{off} \right) \cdot LR + MC \tag{33}$$

MMH_{on}	Maintenance Man Hours On Aircraft,
MMH_{off}	Maintenance Man Hours Off Aircraft,
LR	Labor Rate,
MC	Material Costs.

If such information is not available, a comparison method can be applied. Airbus Industrie uses the "Airbus Industrie Comparison Method", AICM [POUBEAU 89] which seems to be based on [BRINK 73].

3.5 SHC_{SYS} Capital Costs Caused by Spare Parts on Stock

Spare Holding Costs, *SHC*, defined here as the interest paid on bound capital of spare parts on stock, can reach considerable sums of money. By definition, total stock keeping costs belong to Indirect Operating Costs, IOC and not to DOC. Nevertheless, especially the capital costs of the spares on stock depend on parameters which are primarily aircraft dependent. For this reason, these Spare Holding Costs will be included into *extended* Direct Operating Costs of Aircraft Systems, DOC_{SYS} .

$$SHC_{SYS} = \frac{SPF \cdot SPR}{RED} \cdot Price \cdot \frac{RQS_{req}}{FS} \cdot r \tag{34}$$

SPF	Spare Part Factor: Spare part price divided by initial purchase price,
SPR	Spare Part Ratio: Portion of costs of spare parts in total amount of parts for the aircraft system, or subsystem,
RED	average redundancy level (resulting in equal parts) in the system or subsystem,
RQS_{req}	required amount of spare parts (depends on the "on average" required amount of spare parts and the required probability of having a required spare part on stock),
FS	fleet size,
r	interest rate.

$$RQS_{eff} = RQS_{av} + z \cdot \sqrt{RQS_{av}} \tag{35}$$

RQS_{av}	"on average" required amount of spare parts,
z	availability factor.

$$RQS_{av} = RED \cdot TATR \cdot FS \cdot \frac{FT \cdot NFY}{MTBUR} \qquad \textbf{(36)}$$

TATR	Turn Around Time Ratio, ratio of repair time and considered time interval (here, the considered time interval is one year),
FT	Flight Time, airborne time,
NFY	Number of Flights per Year,
MTBUR	Mean Time Between Unscheduled Removals.

$$MTBUR = FTRR \cdot MTBF \qquad \textbf{(37)}$$

FTRR	Failure To Removal Ratio,
MTBF	Mean Time Between Failure.

The availability factor z depends on the required availability $\Phi(z)$ of spares on stock. z is the inverse function of the *cumulative Gaussian normal distribution*

$$\Phi(z) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{z} e^{\frac{-x^2}{2}} dx \qquad \textbf{(38)}$$

The inverse function z can not be derived analytically, however, the inverse function exist in tabulated or graphical form as given in **Table 3.2** or **Fig. 3.2**.

Table 3.2: Availability factor z given as function of spare part availability $\Phi(z)$

$\Phi(z)$	0.900	0.950	0.975	0.990	0.999
z	1.282	1.645	1.960	2.326	3.090

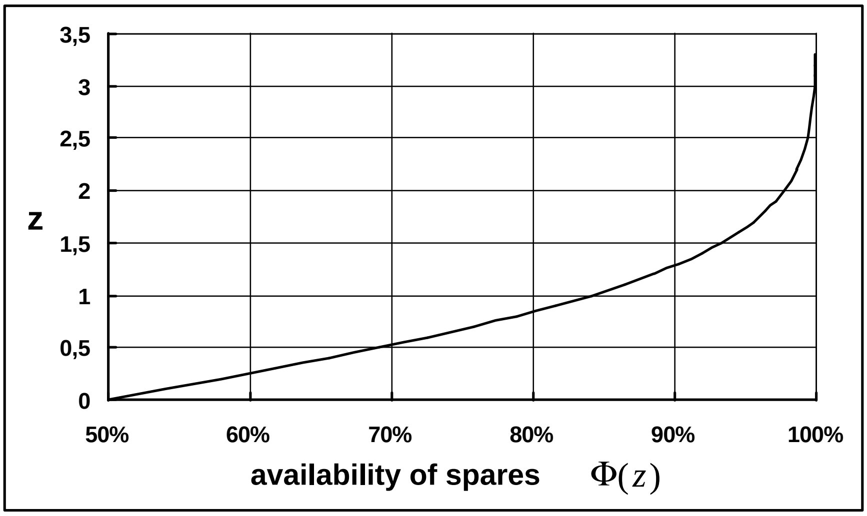

Fig. 3.2:
Availability factor *z* given as function of spare part availability $\Phi(z)$

3.6 $Delay_{SYS}$ Delay and Cancellation Costs

$$Delay_{SYS} = \left(D_I \cdot C_I + D_{II} \cdot C_{II} + D_{III} \cdot C_{III} + D_C \cdot C_C\right) \cdot NFY \quad . \qquad (39)$$

Delay and cancellation costs, $Delay_{SYS}$, are calculated here based on three delay categories (taking account of different lengths of delays) and one category for cancellations:

D_1 probability for a delay of up to 29 min.,
D_2 probability for a delay between 30 min. and 59 min.,
D_3 probability for a delay of equal or more than 60 min.,
D_C probability for a cancellation,
C_1 cost of a delay of up to 29 min.,
C_2 cost of a delay between 30 min. and 59 min.,
C_3 cost of a delay of equal or more than 60 min.,
C_C cost of a cancellation.

The **probability of delays and cancellations** depends on the aircraft system considered. Statistical evaluations by American Airlines and Lufthansa for ATA-Chapters 21 to 49 are given in [NASA 77] and [SCHOLZ 97a] respectively.

A regression on data form [NASA 77] corrected with data from Lufthansa and Airbus Industrie (details in [SCHOLZ 98b]) yields **delay and cancellation costs** that can be estimated from

$$costs = m \cdot x + b \qquad (40)$$

with *m* and *b* from **Table 3.3** with *x* being the number of spec seats. Note: A coefficient of determination *r* = 1.0 means a perfect fit.

Table 3.3: Parameters *a* and *b* for calculating delay and cancellation costs with Equation (40) as 1992$. The coefficient of determination given as r

parameter	delay 0-29 min	delay 30-59 min	delay >=60 min	cancellation
m	0.291	0.753	2.251	2.900
b	82.2	207.2	1125.7	1499.4
r	0.989	0.963	0.953	0.950

3.7 Other Cost Elements

Other cost elements depend very much on the respective aircraft system in question. E.g. in case of water/waste systems, such other cost elements could be:

1. water costs for filling the potable water tanks,
2. costs for precharging the waste tanks with special fluid for disinfection.

A decision has to be made in which way (if at all) such additional cost elements shall be included in the calculation.

4 Case Study: Evaluation of Alternative Water Waste Systems for the A3XX

4.1 Water/Waste System Design Alternatives

Four different design concepts or *alternatives* (called A, B, C, and D) of aircraft water/waste systems as given in **Table 4.1** were considered for the Megaliner/A3XX. These four concepts result from combinations of two fundamental design characteristics

- the gray water treatment system and
- the drain mast system.

Both of these (sub)systems can either be present or not in a design concept. **Table 4.1** and **Table 4.2** define the system alternatives.

Table 4.1: Evaluated water/waste system design concepts

A	system **without** gray water treatment system; **with** drain mast (**open** system)
B	system **without** gray water treatment system; **without** drain mast (**closed** system)
C	system **with** gray water treatment system; **with** drain mast (**open** system)
D	system **with** gray water treatment system; **without** drain mast (**closed** system)

Table 4.2: Basic principles of evaluated water/waste system design concepts

A	Gray water leaves the aircraft via drain masts, toilet rinse water (taken from potable water tanks) and waste water is fed into the waste water tanks.
B	Gray water, toilet rinse water (taken from potable water tanks) and waste water is fed into the waste water tanks.
C	Toilet rinse water is generated by gray water treatment systems from wash basin water. Surplus wash basin water and galley water leave the aircraft via drain masts. Toilet rinse water and waste water is fed into the waste tanks.
D	All gray water and waste water is fed into the waste tanks. Due to the gray water treatment systems gray water is partially used as toilet rinse water

The evaluation of the alternatives includes all subsystems from ATA 38 plus "ice protection of water supply and drain lines" designated ATA 30-70.

- **Alternative A** is the "*Airbus-Standard*" water/waste system design solution. This design solution can be found on all present Airbus aircraft.
- **Alternative D** is the *Megaliner Baseline* water waste system design solution
- **Alternatives B and C** present further design solutions under discussion.

The evaluation will be based solely on the Direct Operating Cost for the systems as defined in Chapter 3. Not considered in the evaluation of alternatives is the feasibility of a specific design concept and its

- development risk,
- passenger appeal,
- airline appeal,
- commonality to existing aircraft in a mixed fleet.

It is assumed that all design alternatives are designed in detail to certification standards and will show industry standard operational reliability, safety, and availability.

4.2 Input Data

Without any doubt, the most time consuming activity in an evaluation consists of gathering all necessary data and converting this data into a form which is acceptable to the evaluation method. This paper does not make an attempt to go to the roots and details of the aircraft water/waste system. Nevertheless, some system-specific information must be provided:

Following experience, potable water is used in the form as follows:

- 33.3 % toilet rinse water,
- 12.3 % galley water, \
  ---> 66.6% gray water
- 54.3 % wash basin water. /

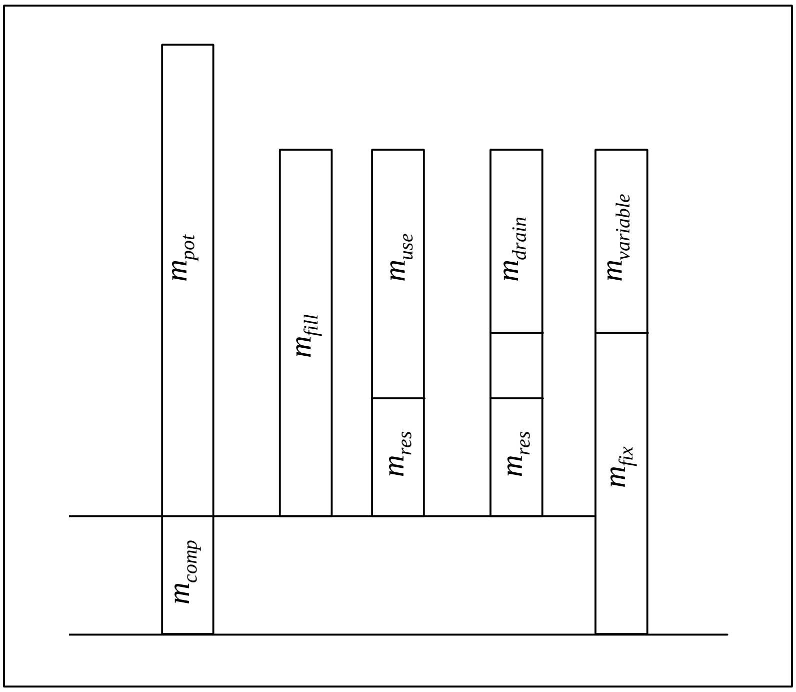

Fig. 4.1:
Systematic of mass nomenclature for potable water tanks

The relative amount of water reserves and used water are specified by

$$k_{res} = \frac{m_{res}}{m_{pot}}, \quad k_{use} = \frac{m_{use}}{m_{pot}} \quad . \tag{41}$$

Component mass differences among the alternatives are listed in **Table 4.3** and are due to

- drain masts,
- gray water treatment systems,
- galley transfer units,
- lavatory transfer units,
- waste water and potable water tank size.

Table 4.3: Results from the water/waste system mass estimates for the Airbus A3XX-100: *Mass differences* relative to design alternative A

Mass differences relative to alternative A		A	B	C	D
empty system	-	0 kg	-71 kg	+30kg	-174 kg
filled system	$k_{res} = 0.5;\ k_{use} = 0.5$	0 kg	+263 kg	-470 kg	-508 kg
filled system	$k_{res} = 0.25;\ k_{use} = 0.75$	0 kg	+430 kg	-387 kg	-341 kg

System alternatives A and B include drain masts. The parasitic **drag** is caused by two forward and two rear drain masts. The total drag coefficient for the drain masts on an A3XX-100 amounts to 0.0253 drag counts [BURELL 97]. This equals to a drag of about 21 N in cruise flight. Electric power requirements stem from drain mast and pipe heating to prevent freezing (**Table 4.4**). These power requirements cause mechanical power off-takes from the engines. This evaluation is based on a fuel price of 0.2 US$/l. Aircraft utilization puts a weighting factor on fixed and variable costs. A3XX utilization was assumed to be similar to A340 utilization. A regression of A340 utilization data shows Fig. 4.2. Further input data can be found in [SCHOLZ 98b]

Table 4.4: Electrical power requirements

part	quantity	specific power	A	B	C	D
drain mast	4	113 W	452 W	-	452 W	-
drain mast pipes	13.3 m	37.5 W/m	499 W	-	499 W	-
lavatory pipes	18.0 m	37.5 W/m	675 W	-	-	-
galley pipes	18.0 m	37.5 W/m	675 W	-	675 W	-
sum	-	-	2301 W	0 W	1626 W	0 W

$$UTIL,HOUR = a \cdot (FT - b)^2 + c \qquad (42)$$

with $a = -\ 0.007960$ 1/h²
$b = 8.124370$ h
$c = 0.525433$.

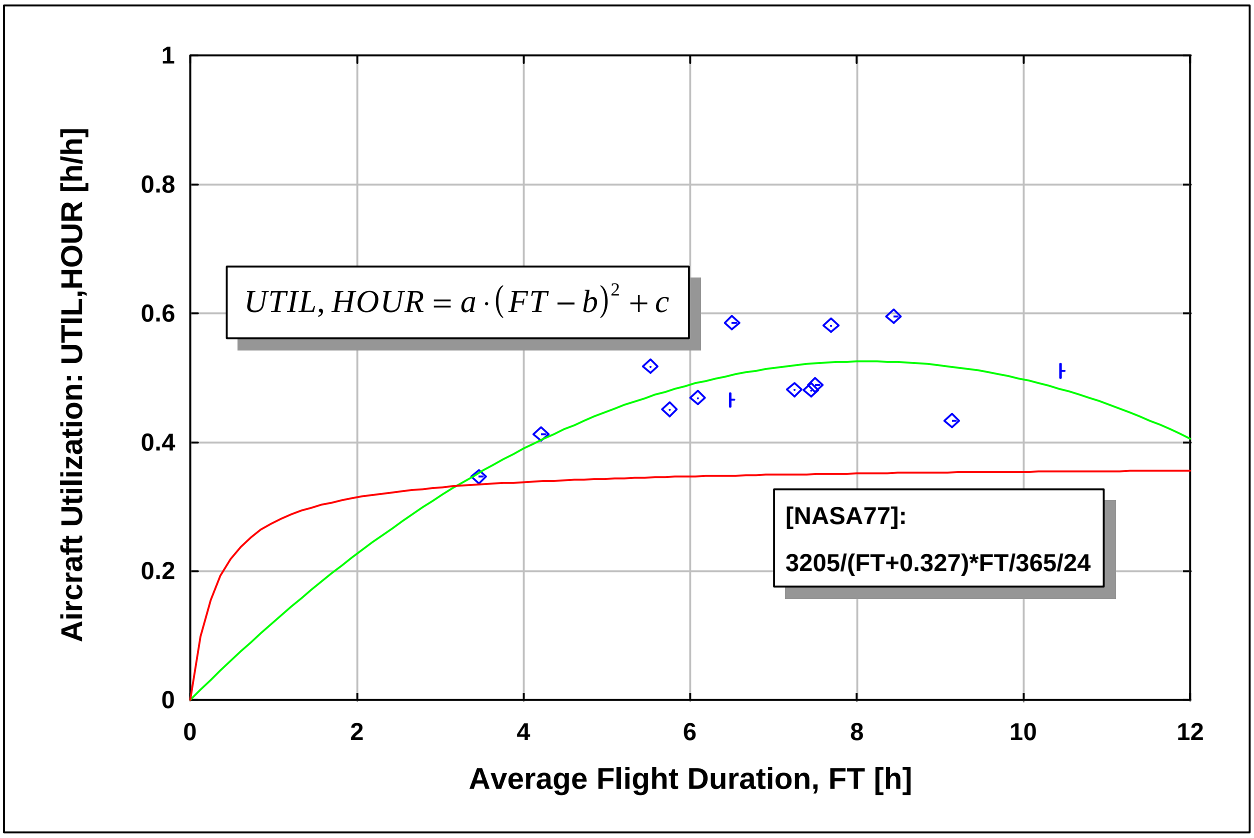

Fig. 4.2: Relationship of flight time, *FT*, and hourly aircraft utilization, *UTIL,HOUR*. Data from A340 fleet [AIRBUS 96] compared with a relationship from [NASA 77] and a correlation of A340 fleet data.

4.3 Results of DOC_{SYS} Evaluation

The input data was evaluated for the parameter space given in **Table 4.5**. Results were obtained as given in **Fig. 4.3** and **Fig. 4.4**.

Table 4.5: Parameter space of DOC_{SYS} evaluation

	k_{use} = 0.75	k_{use} = 0.50
FT = 10 h	**baseline**: FT = 10 h; k_{use} = 0.75	variation: FT = 10 h; k_{use} = 0.50
FT = 7 h	variation: FT = 7 h; k_{use} = 0.75	variation: FT = 7 h; k_{use} = 0.50

FT : flight time, airborne time

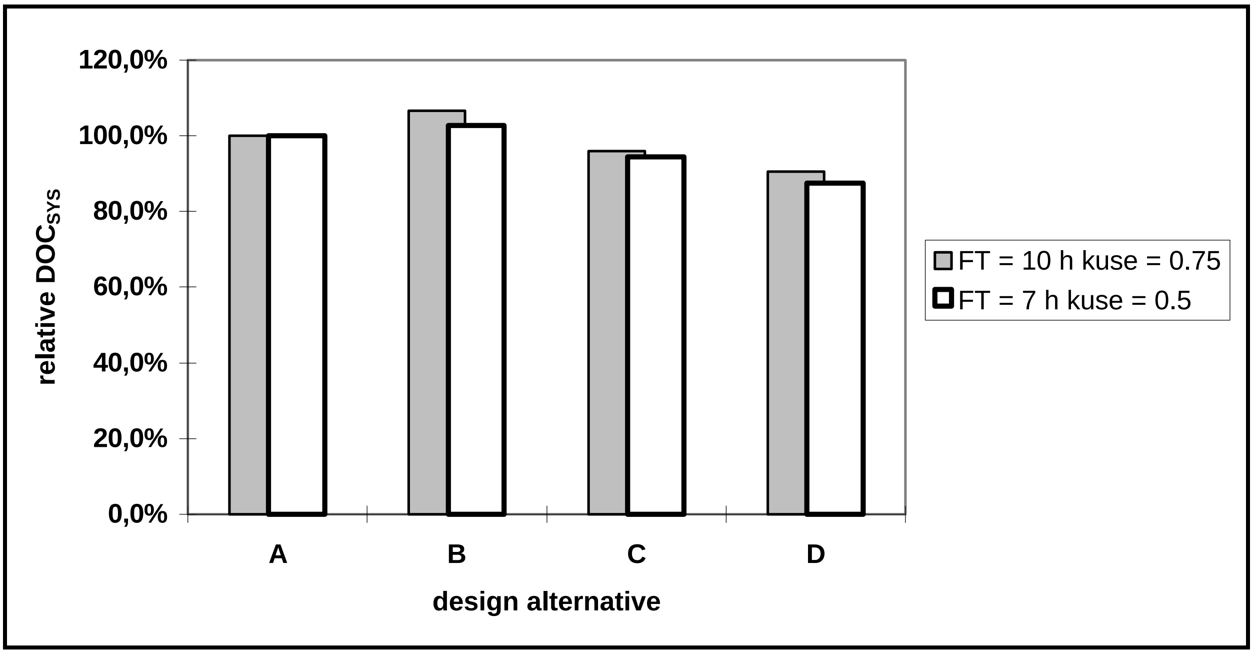

Fig. 4.3: Evaluation results relative to alternative A

5 Conclusions

A method - called DOC_{SYS} - to evaluate aircraft systems has be presented. Cost elements considered in the method are: depreciation, fuel costs, DMC (Direct Maintenance Costs), cost due to delays and flight cancellations, spare holding costs. Fuel consumption is calculated separately for different physical causes. There is fuel consumption due to: fixed and /or variable mass, mechanical power off-takes from the engines, additional drag, ram air off-takes and due to bleed air off-takes.

The proposed method has already been applied to various aircraft systems, subsystems and parts. Here, a summary of one of these studies is presented: Four design alternatives of water/waste systems for the Megaliner/A3XX have been evaluated: alternatives with and without drain mast (i.e. open and closed system) as well as alternatives with and without gray water treatment. The evaluation was done by calculating DOC_{SYS}. The DOC analysis of the four systems showed that it is possible to save DOC with new design concepts like those with gray water treatment. A closed system without gray water treatment produces more DOC than a conventional system.

6 Acknowledgement

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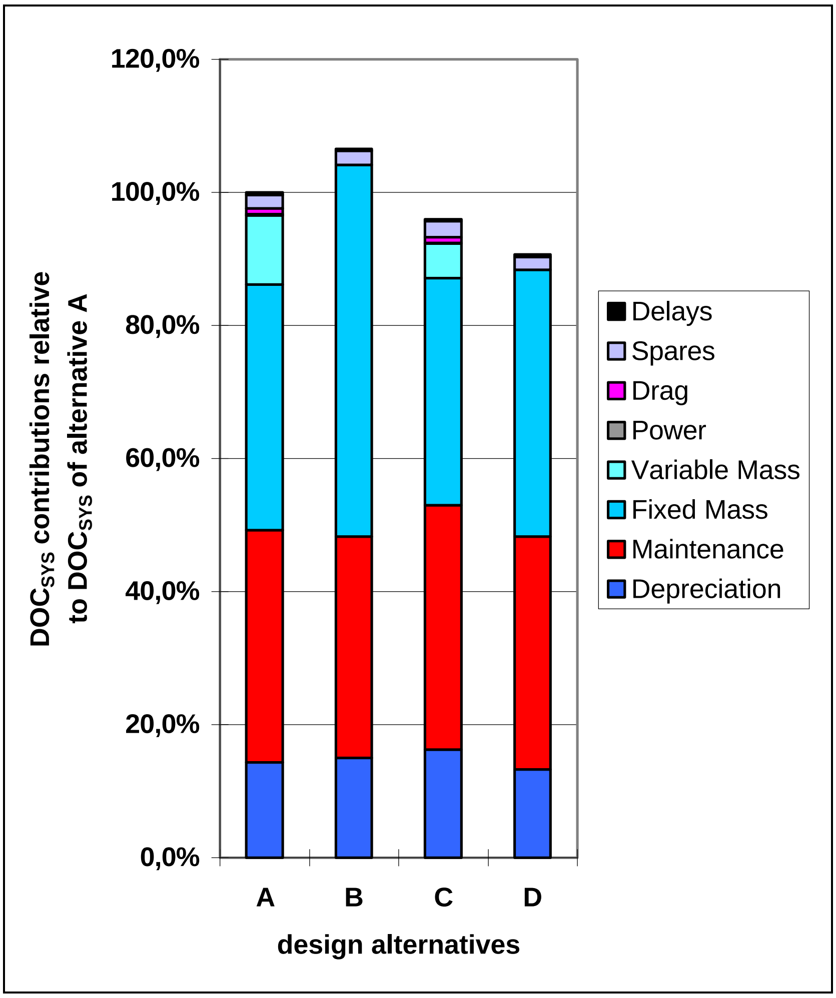

Fig. 4.4: Contributions of different cost elements to total DOC_{SYS} of four water/waste system design alternatives. Flight time, FT = 10 h, k_{use} = 0.75

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