TECHNOLOGY ASSESSMENT OF FUTURE AIRCRAFT

SOCIO-ECO-EFFICIENCY IN CONCEPTUAL AIRCRAFT DESIGN

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Abstract

An extended methodology to evaluate and optimize civil aircraft in means of socio-eco-efficiency index is proposed in this study. Here, the aircraft is an element integrated into the air transportation system (ATS), which is described primarily by four main stakeholders:

- *AIRPORT*
- *OPERATOR (e.g. Airline or private owner)*
- *MANUFACTURER and*
- *AIR NAVIGATION SERVICE PROVIDER.*

Nowadays, the assessment is mostly driven by economic indicators, which consider environmental impacts peripherally and indirectly (e.g. noise charges, emission tax). In order to expand this evaluation perspective, a procedure is introduced, which considers and combines the 3 pillars of sustainability – SOCIETY, ECOLOGY and ECONOMY – in one aggregated value – the SEEindex

1 Methodology

1.1 Introduction

The aim is to quantify the performance of the three dimensions of sustainability with one integrated tool in order to direct - and measure - sustainable development in aircraft design, depending on the different stakeholder views. It enables and supports designers within the decision process in aircraft development and improvements, strategic planning, policy making or marketing. These applications are directly linked to the LCA guideline ISO 14040 [9], describing the only internationally standardized environmental assessment method. The ISO 14040 standard typically does not address the economic or social aspects of a product, but the life cycle approach and methodologies (overall framework) defined in this international standard could be applied to these other aspects too. At this point the international acknowledged UNEP/SETAC publication “Guidelines for Social Life Cycle Assessment of Products” [8] has to be highlighted. The latest developments indicate the following Formulation for Life Cycle Sustainability Assessment (LCSA), described in Kloepffer [7] and improved into its current form by Finkbeiner [2]:

$$LCSA = LCA + LCC + SLCA \qquad (1)$$

LCSA = Life Cycle Sustainability Assessment

LCA = Environmental Life Cycle Assessment

LCC = LCA-type Life Cycle Costing

SLCA = Social Life Cycle Assessment

Equation (1) suggests a separate execution of assessment for each dimension of sustainability, whereas the system boundaries of the three assessments should be consistent (ideally identical). In order to avoid double counting, external costs, which may occur in the future due to aviation environmental impacts, should not be monetized. Environmental impacts are dealt with as part of LCA in physical – as opposed to monetary – terms.

Costs occurring in the future, e.g. due to climate change or land demand are difficult, even impossible to estimate. External costs that are expected in the near future or that are already internalized, comprise real money flows, such as environmental landing charges or taxes and must be included in the LCC. Nevertheless, these internalized costs might not reflect the real environmental impacts; hence they have to be accounted separately in the LCA.

In accordance with Kloepfer [7] and Finkbeiner [2], Formula (1) can be rearranged by introducing the eco-efficiency term (3), appeared for the first time in 1990 [13]:

$$LCSA = EE + SLCA \qquad (2)$$

with

$$EE = \frac{\sum_{1}^{n} \text{desired Output} + \text{postive external Effects}}{\sum_{1}^{n} \text{ecology damage}} \qquad (3)$$

Several recently developed LCSA methods implement the SLCA method in eco-efficiency analysis. For example, Saling et. al [12] extended the BASF eco-efficiency analysis by adding a social component, transferring the two-dimensional eco-efficiency portfolio to a three dimensional one; the environment is called SEEbalance®. The idea behind this approach has inspired the development of the assessment approach presented in this paper. The fundamental architecture of the LCSA approach for measuring the air transportation systems' performance and impacts is described in Figure 2. After goal and scope definition (1st step), for each assessment the life cycle inventory analysis (2nd step) is the substantial part for all three dimensions. Therein the product's 'life cycle' is commonly subdivided into 4 phases (Figure 3).

1.2 General assessment process

The broadest analysis scope requires the ecological, economic and social inventory for each life cycle stage. Depending on the goal and scope settings, suitable indicators and impact categories (decision criteria) have to be chosen. The highest aggregated result is achieved by synthesizing each criterion to one value, here expressed as Socio-Eco-Efficiency index (SEEindex), expressing the efficiency of the evaluated aircraft design options. Its calculation requires normalizing all indicators in order to obtain a compatible dimension. Among others, the normalization method depends on the data available and the question to be answered. In accordance with the ISO 14040 [9] some examples of reference values are

- the total inputs and outputs for a given area that may be global, regional, national or local (e.g. the national GDP or CO2 emissions),
- the total inputs and outputs for a given area on per capita basis or similar measurement, and
- inputs and outputs in a baseline scenario, such as a given alternative product system (e.g. an existing aircraft or airport)

The overall synthesis is suggested to be performed by a 4-fold Multi Criteria Decision Analysis (MCDA) process; executed for the economic, environmental, societal area, and finally for aggregating the inventory results to the SEEindex. MCDA is a process that allows making decisions in the presence of multiple, potentially conflicting criteria. There are several existing MCDA methods, thus the selection of the most appropriate methods is critical. The use of inappropriate methods is often the cause of misleading design decisions. An intelligent knowledge-based system has been developed, consisting of a MCDA library storing the widely used decision making methods and a knowledge base providing the information required for the method selection process (Sun et al. [14]). An Appropriateness Index (AI) is proposed to evaluate the methods and identify the most suitable one.

Here, TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) has been recommended as the most fitting MCDA method to be applied. The decision matrices include the inventory results of each criterion for n alternatives as principally shown in Figure 1. If not avoidable, weighting can be applied by using the schemes in Table 1, separately or hybridized. Whether or not weighting has to be applied depends on the selected impact categories in the inventory analysis. Basically weighting is preventable, if one prefers comparable endpoint instead of midpoint impact indicators, also known as the damage-oriented approach, which considers the three areas of protection (AoP)

- human health,
- natural environment,
- natural resources.

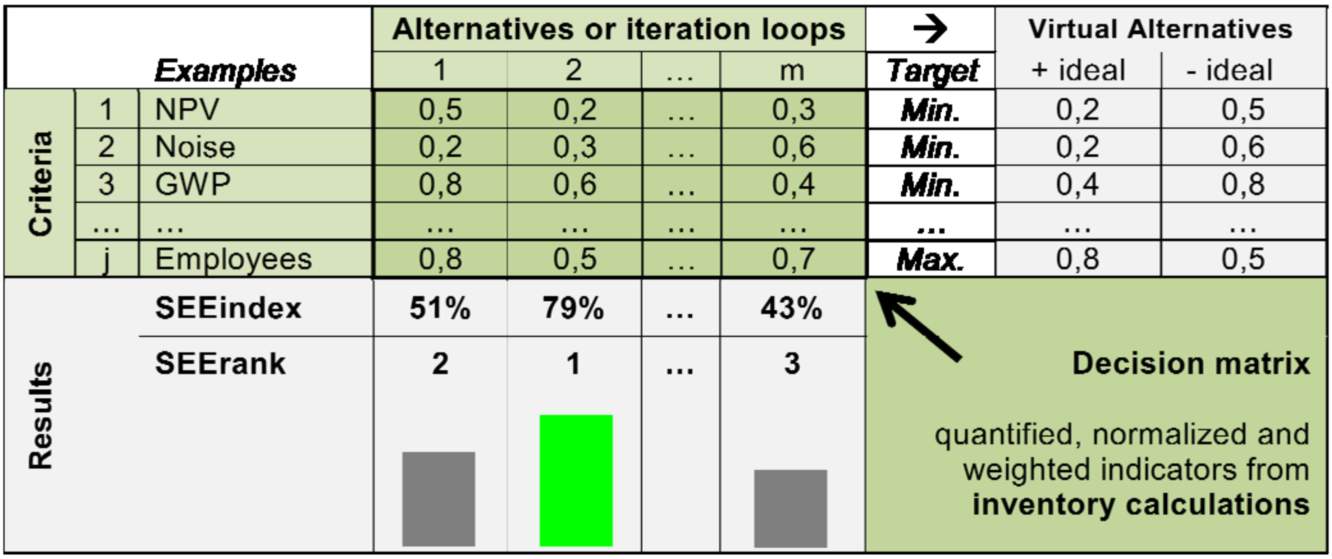
The resulted TOPSIS-Indices or partitioned as Ecology-Index, Economy-Index and Society-Index for each alternative are merged to the SEEindex by using TOPSIS again. The design alternative with the highest index might be the solution with the highest reachable sustainability compared to the other evaluated options. At this point it has to be differentiated between a post- and an in-loop assessment. In the post-assessment, the aircraft has already been designed and even introduced in the air transportation system being evaluated. In the in-loop assessment, the aircraft will be re-designed until the SEEindex reaches its highest possible value by changing the concepts of the propulsion, the aerodynamic of the structure, the overall systems integration respectively. For that, Sun et al. [15] suggest a new optimization framework in aircraft design, incorporating an enhanced MCDA technique, called as I-TOPSIS or Improved-TOPSIS.

The chosen approach depends on the question whether either the aircraft has to be optimized in respect of its economic, environmental or social performance only or in all three sustainable dimensions.

Non-monetary weighting methods
Proxy methods
  Ad hoc scoring
  Indicators in physical units
Distance-to-target methods
Panel weighting methods
  Ad hoc methods using expert assessments
  Guided stakeholder workshops

Monetary valuation methods
Revealed willingness to pay
  Market prices (damage costs)
  Hedonic pricing
Inputed willingness to pay
  Damage cost avoided method
Political willingness to pay
  Costs-to-reach-target
  Taxes
Avoidance costs

Table 1: Weighting procedures [1]



			Alternatives or iteration loops				→	Virtual Alternatives	
		Examples	1	2	…	m	***Target***	+ ideal	- ideal
Criteria	1	NPV	0,5	0,2	…	0,3	***Min.***	0,2	0,5
	2	Noise	0,2	0,3	…	0,6	***Min.***	0,2	0,6
	3	GWP	0,8	0,6	…	0,4	***Min.***	0,4	0,8
	…	…	…	…	…	…	**…**	…	…
	j	Employees	0,8	0,5	…	0,7	***Max.***	0,8	0,5
Results		**SEEindex**	**51%**	**79%**	**…**	**43%**	**Decision matrix** quantified, normalized and weighted indicators from **inventory calculations**		
		SEErank	**2**	**1**	**…**	**3**			

Figure 1: Principal scheme of TOPSIS as applied

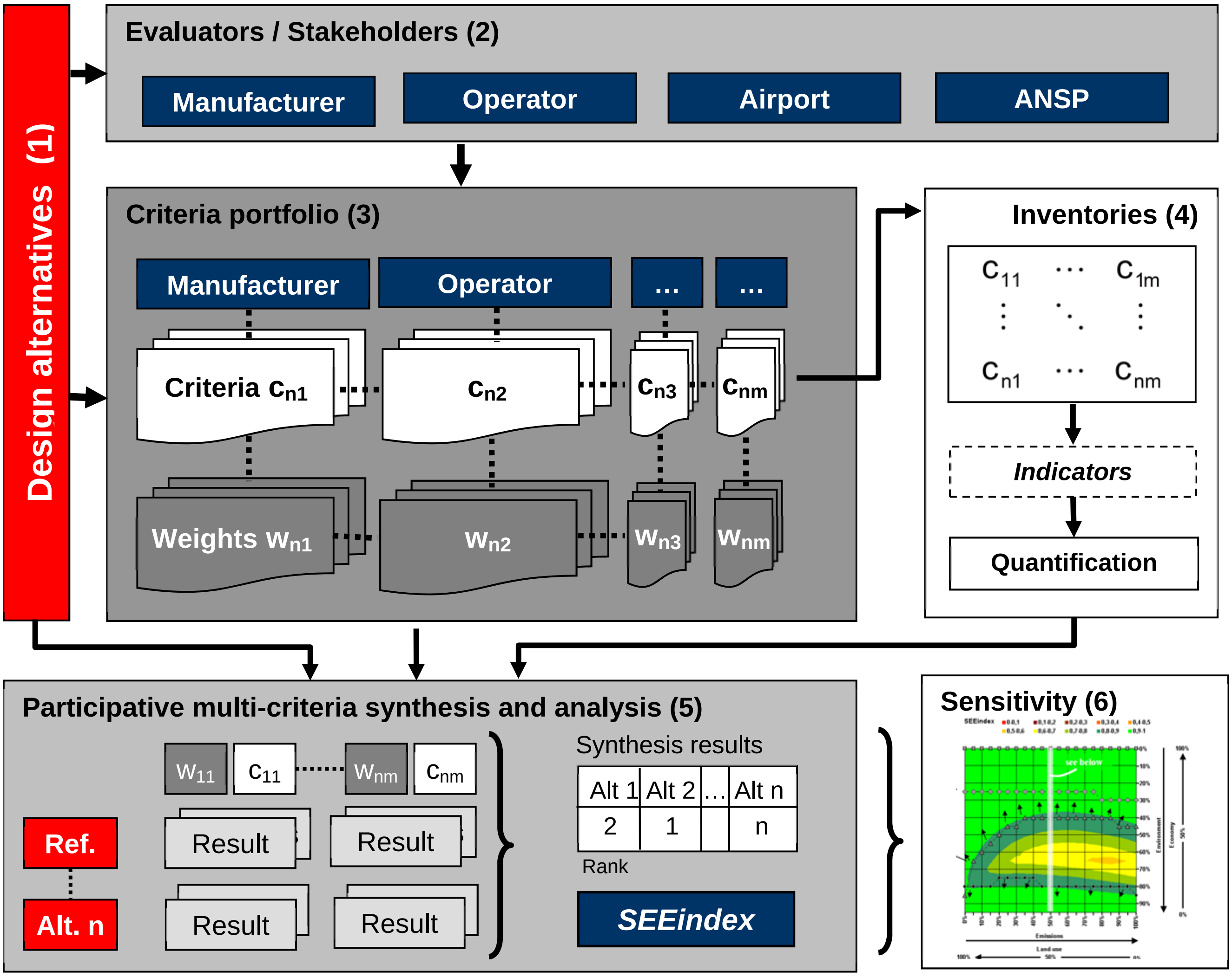


Figure 2: Scheme of the participative multi-criteria assessment in SEElab

1.3 Overall evaluation environment

Starting from the general process, discussed before, the system structure of a computer-supporting evaluation environment, named SEElab Assess, will be introduced briefly. The application's structure is generally based on the integration of the 4-stakeholder model, including their descriptive sub-elements, introduced in Weiss et al. [17], a predefined criterion tree and different synthesis techniques as well as visualization opportunities for mid- and endpoint analysis (Figure 2).

The participative multi-criteria assessment is conducted in a 6 step procedure: According to Figure 2 the first step contains the definition of the goal or the problem, including the identification of possible design alternatives. The assessment participants relevant for the evaluation task and their perspectives are defined in the second step. It includes the 4-stakeholder model which can be extended specifically by other participants as for example political representatives. The participant's view is characterized by taking suitable criteria or impact indicators (participant specific choice) and their priorities (→ weighting) into account; finally, all information are gathered in a portfolio (step 3). The participant's subjective weighting can be further improved by using normalization or Distance-to-Target approaches. At this point, dynamic weighing (time-depend: e.g. Dynamic Analytic Hierarchy Process; Saaty [11]) can be implemented additionally. In step 4 the criteria are quantified within inventory calculations and if necessary other indicators must be derived, because the criterion itself can be the result of several single indicators. The defined analysis boundary determines whether the inventories are conducted over the whole life-cycle or at a specific time point only. Besides, the dynamic of the system can lead to a time-dependent variability of the number of criteria. In the 5th step the results of the quantified impact categories and the weightings oriented to participant (step 3 / step 4) are synthesized by using appropriate multi-criteria techniques (see 1.2). The endpoint results are outputted either in the ranks of alternatives (SEErank), or as SEEindex of the alternatives introduced above.

Within an optimization task the 2nd and 3rd step can be frozen once defined. The design itself will be changed (step 1), the inventory calculations (step 4) performed and the target value (setp 5: SEEindex) calculated again. Compared with earlier results the SEEindex needs to be maximized for optimizing the aircraft in all selected performance areas.

1.3.1 Mathematical Background

This paragraph describes shortly the mathematical set-up of the different decision matrices E, necessary and used in several available aggregation or decision models (e.g. TOPSIS, see Figure 1). The latter are introduced comprehensively in [14]. Following Equation (4), all criteria c, which were calculated separately in dependence of location and time, are summarized, normalized and weighted in the decision matrices. For that, the inventory matrix will be constructed firstly, independently for the economic, environmental and social pillar, respectively. Basically, it's an array presenting on the left axis (rows) the list of alternatives A, which are evaluated regarding, on the top axis (columns), the list of the selected criteria. In the style of Figure 3, uniform criteria are summed up for each life cycle stage and sub-elements considered (e.g. the overall aircraft or aircraft engines or its components or the aircraft demanded ground-based infrastructure elements etc.). This process requires that the addition of the indicators or the used metrics is done by using the correct scale, e.g. noise levels are logarithmically added together. Multiplying the inventory matrix with a weighting and

$$\underline{E} = \begin{array}{cc} & \begin{array}{ccc} \text{Criterion 1} & \cdots & \text{Criterion n} \end{array} \\ \begin{array}{c} A_1 \\ \vdots \\ A_m \end{array} & \underbrace{\begin{bmatrix} \sum_{t=1}^{4}\sum_{e=1}^{z} c_{1.1.e.t} & \cdots & \sum_{t=1}^{4}\sum_{e=1}^{z} c_{1.n.e.t} \\ \vdots & \ddots & \vdots \\ \sum_{t=1}^{4}\sum_{e=1}^{z} c_{m.1.e.t} & \cdots & \sum_{t=1}^{4}\sum_{e=1}^{z} c_{m.n.e.t} \end{bmatrix}}_{\textit{Inventory matrix}} \end{array} \cdot diag(\overrightarrow{w_K}) \cdot diag(\overrightarrow{n_K}) \qquad (4)$$

A_m Alternatives
$c_{mn,\dots}$ Quantified criteria, with
e Index of sub element with $\forall e = 1 \dots z$
t Index of life cycle phase with $\forall t = 1 \dots 4$
t = 1: Development; 2: Production; 3: Operation; 4: Disposal

diag diagonal matrix with
$\overrightarrow{w_K}$ weighting vector of criteria 1…n
$\overrightarrow{n_K}$ normalization vector of criteria 1…n

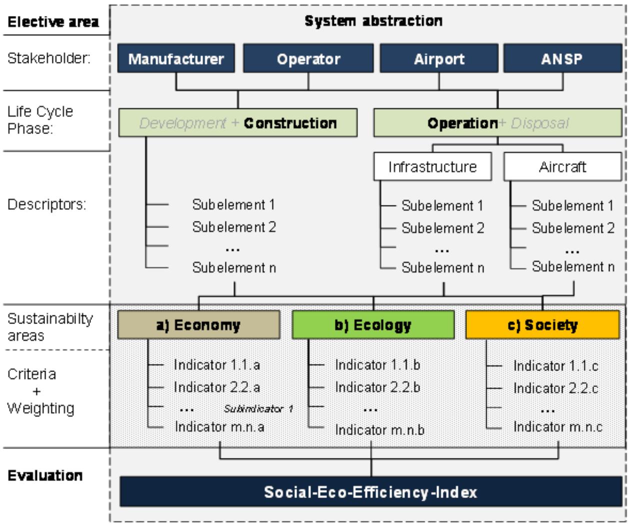


Figure 3: Abstracted aggregation procedure

normalization vector, both transformed in a diagonal matrix, results in the final decision matrix. The final decision matrix will be integrated in the preferred MCDA method, which compiles the SEEindex.

2 Application

The introduced procedure will be applied on two different aircraft examples, designed conceptually as a low noise and a low weight configuration. Both refer to the same reference aircraft, described synoptically in chapter 2.1 and in detail in [18]. Here, the focus is more on applying the SEEevaluation concept described before and less on the design procedure of the aircraft itself. Nevertheless fundamental aspects of the designs will be outlined.

2.1 Reference Aircraft

Figure 4: Reference aircraft

The reference aircraft (Figure 4) has been designed as a short-haul airplane with similar performance characteristics compared to the Airbus A322. Referring the reference to the Airbus A322 simplifies its geometrical and mass definition. Thus the main dimensions and the maximum takeoff weight are based on the published specifications. All other design dimensions such as the operating empty weight, the tank capacity or the moments of inertia were calculated. The engines have been modeled in accordance to the IAE V2500.

For the reference aircraft an operating empty weight (OEW) of 41.7 t was calculated. By the used maximum takeoff weight of 73.5 t the wing load is about 593 kg/m². The design scenario describes a flight with a maximum payload of 18.5 t in FL350 with M0.78. The calculated cruise polar of the reference aircraft has a small deviation to the A322. The maximum of the real polar against the calculated one is slightly shifted to lower lift coefficients. The correlation of the lift-to-drag number of both polar is very high below lift coefficients of 0.55.

The overall performance characteristics of the reference aircraft is reflected most comprehensively in the payload range diagram (Figure 5). In the diagram, the corners highlight the performance of the aircraft in particular: The reference aircraft flies with a maximum payload of 18.5 t a range of 1789 nm (3313 km). With maximum fuel the airplane transports a payload of 11.5 t to a range of 3075 nm (5695 km). Without payload the range radius extends to 3453 nm (6395 km). For comparison reasons the payload-range capability of A322 is illustrated in Figure 5 too, whereas no uniform data were available, hence, deviations from the original performance are inevitable. Nevertheless, the payload-range characteristics of both aircraft are highly comparable. In Figure 5 the development of the reserve fuel over the range is on the secondary axis: With decreasing payload the required fuel for holding and alternate flights also decreases, because the gross weight of the aircraft is lower at the end of the flight.

The main data of the reference aircraft are summarized in Table 2.

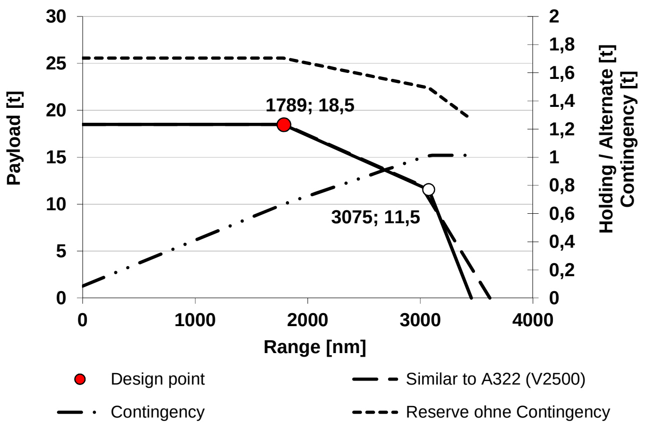


Figure 5: Payload-Range-Diagram

Design properties	
MTOW [t]	73,5
OEW [t]	42,3
Max payload [t]	18,5
Range at max payload [nm]	1789
Payload at 2500 nm [t]	14,6
Fuel consumption (DP) [t]	10,3 | 12,7$^{*)}$
Range w/o payload [nm]	3453
Climb rate (< FL100, 250 kt) [m/s]	Ø 21,0
Climb rate (FL350) [m/s]	2,0 (71t, M0,72) 1,4 (71t, M0,78)
Climb time to FL350 [min]	24
Climb distance to FL350 [nm]	156
TOFL (FAR, MSL, ISA) [m]	2288
v_2 [m/s]	78,8
Assessment indicators Mission: MTOW, max. payload	
Noise Flyover take-off	85 EPNdB
Flyover approach	95 EPNdB
Side-line	93 EPNdB
GWP per flight *)	49,9 t CO2-eq.
per manufactured aircraft **)	240 t CO2-eq.
AP per flight *)	38,3 kg SO2-eq.
per manufactured aircraft **)	530 kg SO2-eq.
Land-use ***)	0,111 km²
Abiotic resource depletion	10,3 t (Fuel)
Direct operating costs / Year	20,7 mill. $
Direct operating costs / SKO	0,0431 $/pax/km
No. of crew members	24
Cabin comfort (reference index)	1

*) including fuel production **) material production only
***) take-off field area only

Table 2: Data of reference aircraft

2.2 Low noise aircraft

Aircraft noise is one of the major concerns and challenges in operating the current and future air transportation system. Thus a conceptual design reducing the aircraft noise is introduced and evaluated in this chapter. As before, the developed assessment environment is not applied comprehensively concerning all areas of the air transportation system, but in extracts.

Goal: Development of low noise aircraft

Performance areas selected:
- Ecology (A)
- Economy (B)
- Society (C)

Stakeholders involved:
1. Aircraft manufacturer
2. Aircraft operator
3. Airport

Performance indicators used:
- Global warming potential; A: (1), (2)
- Acidification potential; A: (1), (2)
- Abiotic resource depletion; A: (1), (2)
- Certification noise levels; A: (1), (2), (3)
- Land-use; A: (3)
- Direct operating cost; B: (2)
- Cabin comfort; C: (2)
- Number of employees, C: (2)

Table 3: Abstracted assessment environment

For designing a low noise aircraft, an assessment environment has been defined as described in Table 3: All areas of sustainability will be addressed and the stakeholders manufacturer, aircraft operator and airport have been selected. 8 performance indicators have been chosen, whereas its correlation to the performance area and stakeholders are indicated with the letters A, B, C and numbers 1, 2, 3 in Table 3.

2.2.1 Design overview and performance

Detailed information about the design features as well as flight performance, cost and emission calculations have been published in [18], thus, a short overview will be given only:

Referred to Figure 6, the conceptually designed aircraft has two jet engines embedded fully into the rear part of the fuselage. Thus, the configuration is named Rear Mounted Propulsion Low Noise Aircraft (RMP-LNA). Both turbofans breathe air through two long S-bended ducts. Besides its primary function as intake, the ducts are equipped with sound absorbing liner materials for attenuating the forward emitted noise, especially from the fan and compressor. In order to control the jet noise, an ejector has been installed, movable in order to optimize its efficiency depending on the flight phases (Figure 6 middle). The aircraft was designed with back (RMP-LNA-DT) and forward (RMP-LNA-V) swept wings. Due to the integration of the turbofans and S-ducts, the cabin has been configured with a dead end zone: reducing passenger comfort at the rear part, complicating evacuation/ de-boarding procedures as well as serviceability. The decreased engines' accessibility and the higher load of the turbo machinery worsen its maintainability additionally. Several aspects have been disregarded in the detailed inventory analysis due to lack of information, but peripherally considered with sensitivity studies.

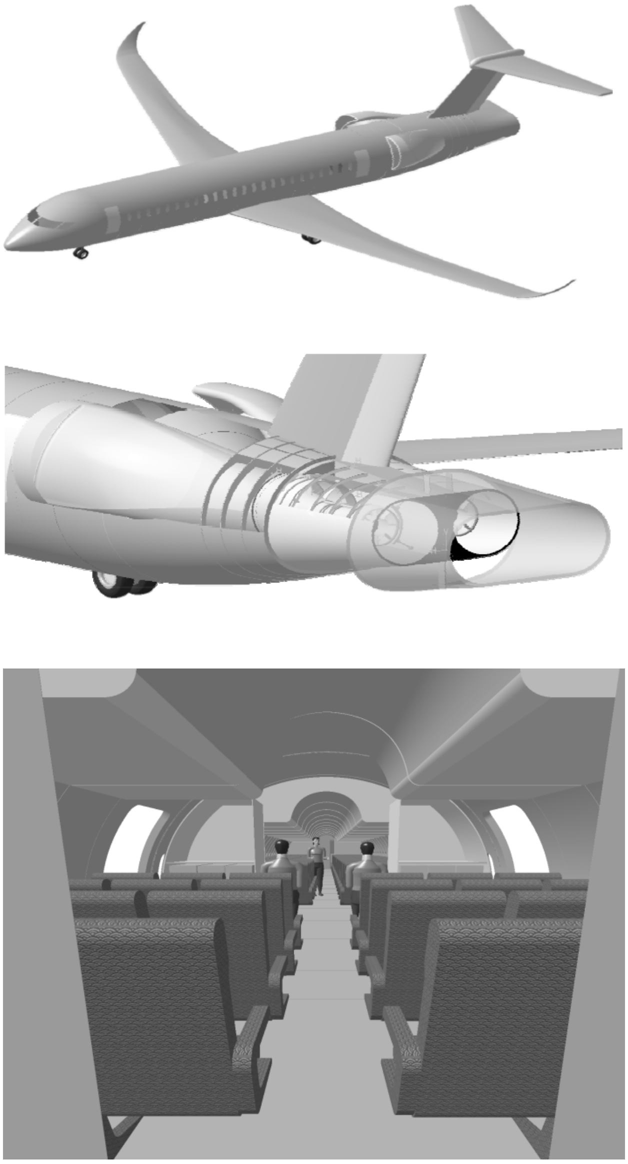


Figure 6: RMP-LNA (top); Deployed ejector (middle); Cabin dead-end-zone

Deviation to reference ➔ Table 2	RMP-LNA-DT	RMP-LNA-V
MTOW [t]	+3,7%	+4,6%
OEW [t]	+3,8%	+4,3%
Max payload [t]	0,0%	0,0%
Range at max payload [nm]	0,0%	0,0%
Payload at 2500 nm [t]	0,0%	-1,4%
Fuel consumption (DP) [t]	+8,7%	+12,6%
Range w/o payload [nm]	-2,4%	-5,2%
Climb (< FL100, 250kt) [m/s]	-1,9%	+2,3%
Climb rate (FL350) [m/s] (M072; M078)	0,0% 14,3%	0,0% -35,7%
Climb time to FL350 [min]	+4,3%	0,0%
Climb distance to FL350 [nm]	+5,1%	+4,2%
TOFL (FAR, MSL, ISA) [m]	-3,8%	-0,8%
v_2 [m/s]	+2,2%	+2,3%

Table 4: Performance deviations from both LNA to the reference aircraft

The calculations are principally focused on the fuel burn, emissions (pollutant / noise), and seat-kilometers specified direct operating costs. The results are tabularized as deviations to the reference aircraft at the operation point 'max range - max payload' in Table 4. For a better understanding a generic cabin comfort index (e.g. accounting cabin noise, space, and accessibility) was considered. Besides that, the changed material demand has been estimated and it production's emissions calculated as part of the manufacturing process. The results of all concerning inventories are summarized in Table 5 as relative change to the reference aircraft data (Table 2). As one can see, assuming an unchanged operational profile (domain and utilization), the RMP-concepts have in all inventory fields a worsen performance, except their aircraft noise levels. They are reduced approximately by 8% at the flyover take-off, 9% at the flyover approach and 7% at the side-line point. But it has been shown in [18], lower aircraft noise levels could increase the aircraft utilization by extending the operation time into the night. Besides the reduced specified direct operating costs (see Table 5), concerning the aircraft operators, there are additional advantages by increased capacity, concerning the airport and ANSP (→ economic and socio-economic). Latter aspects are not investigated in this study.

Deviation to reference → Table 2		RMP-LNA-DT	RMP-LNA-V
Noise	Flyover take-off	-7,8%	-8,0%
	Flyover approach	-9,2%	-9,6%
	Side-line	-7,0%	-7,0%
GWP	per flight	+9,9%	+14,4%
	per manufactured aircraft	+12,5%	+16,7%
AP	per flight	+7,6%	+11,2%
	per manufactured aircraft	+11.3%	+13,2%
Land-use		-3,8%	-0,8%
Abiotic resource depletion		+8,7%	+12,6%
Direct operating costs / Year		+3,4%	+3,9%
Direct operating costs / SKO		+3,4%	+3,9%
→ with increased utilization		-3,4%	-2,6%
No. of crew members		+25%	+25%
Cabin comfort		-15%	-15%

Table 5: Deviations from both LNA to the reference aircraft

2.2.2 Assessment results

The novel configurations show a worse SEEindex compared to the reference aircraft, considering all criteria listed in Table 5, in the standard operation mode (Table 6 top). The decreased noise levels of the RMP-LNA do not compensate the other disadvantages (e.g. higher fuel consumption, higher emissions or higher operating costs). Only extending the aircraft operation time into the night (by definition between 10.00pm and 06.00am) improves the SEEindex of the present configurations, resulting in the first and second rank of both configurations (Table 6 below). Thereby, the higher utilization reduces the specific DOC (economic) and demands an additional crew (social: → higher number of employees). Besides that and as mentioned before other socio-economic benefits are expectable by increased airport capacity.

	Reference	**RMP-DT**	**RMP-V**
Standard operation			
SEEindex	***61,4%***	***45,6%***	***38,6%***
SEErank	**1**	**2**	**3**
use 50% night-time *)			
SEEindex	***20,4%***	***87,2%***	***77,1%***
SEErank	**3**	**1**	**2**

*) night-time: 10.00pm – 06.00am, RMP aircraft only

Table 6: Socio-Eco-Efficiency of aircraft with overall equal weighting of criteria

The comprehensive assessment and ongoing optimization require the analysis of the sustainability of all design alternatives in detail. The influence of the different indicators priority and its selection as well as of design changes must be identified; otherwise, no efficient optimization strategy can be applied. For that, the SEEindex has to be disaggregated in his components again as well as its response to changed priorities of the criteria has to be evaluated. The response indicates the robustness of the results (eventually of the decision). In the following, some examples of this kind of analysis are shown graphically. The multi-dimensional character of the assessment complicates its visualization and interpretation. Thus, here a survey can be given only.

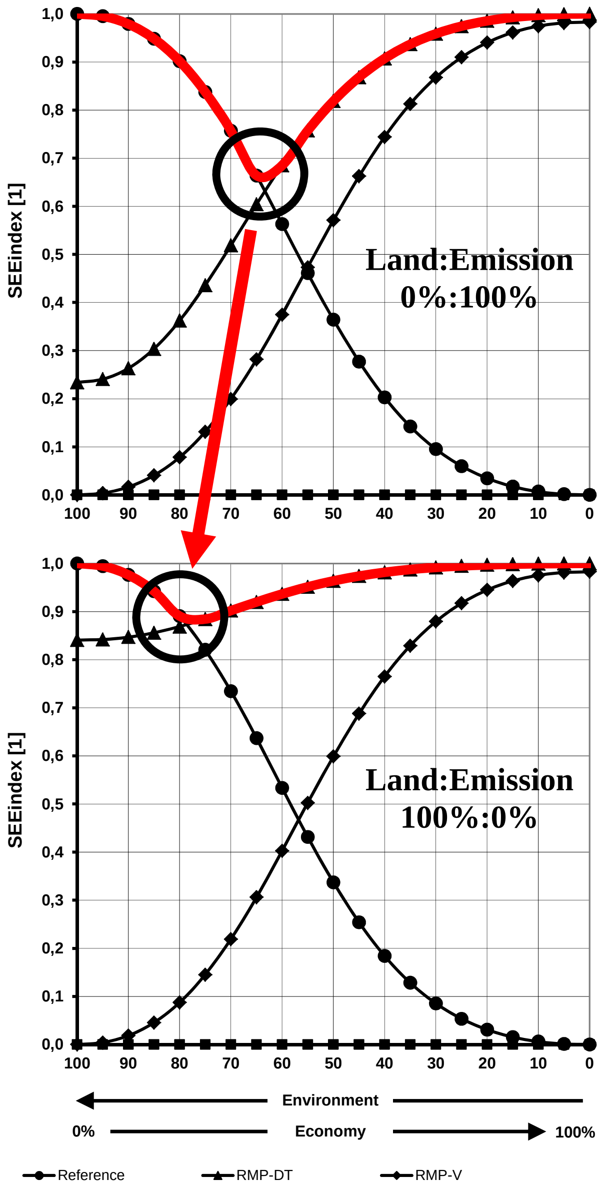


Figure 7: SEEindex sensitivity studies

Basically, in Figure 7 the SEEindex response to different weighting between the key performance areas ecology and economy (also social if required) is charted. Besides the criteria land-use and emission, all remaining criteria weights are kept constant in this example. Especially the curve intersections (‘switch’-ratios) have to be highlighted in the diagram. Each of them represents a changed order of optimal design, such as 65% ecology weight and beyond, where the reference aircraft is the best solution compared to the other alternatives if land-use is negligible (Figure 7 top). In other words, the rank of the best fitting aircraft switches between the configurations. If the emission is insignificant instead of land-use, the decisive weight ratio moves to 80% ecology and 20% economy (Figure 7 bottom). Thus, there is a low response to weight changes between emissions and land-use. The order of alternatives at different weight ratios between ecology and economy is shown in Table 7.

SEErank				
KPA Environment	100%	60%	40%	0%
KPA Economy	0%	40%	60%	100%
Reference	1	2	3	3
RMP-LNA-DT	2	1	1	1
RMP-LNA-V	3	3	2	2

Table 7: Order of alternatives at different weight ratios

For the overall assessment, this analysis has to be performed for all criteria and priority combinations. For visualizing and investigating the influence of different weighting factors on the overall result, the SEEtrade diagram was developed (Figure 8). In SEEtrade the results of a parametric analysis are combined to one diagram by calculating the SEEindex in dependence of the weight ratio for 4 different indicators. With SEEtrade the maximum SEEindex within all alternatives at a specific weight ratio can be found (different coloured in the diagram). The lower the SEEindex, the greater the distance to the (virtual) best solution.

Additionally, for each aircraft design a curve has been inserted in SEEtrade which indicates the boundary of a SEEindex up to 90%. For example, at an environment-economy ratio of 80:20 the reference aircraft performs best against other alternatives (SEEindex > 90%), almost independent of the weight ratio between emission and land-use. For the aircraft design RMP-LNA-DT, its SEEindex is noticeably influenced by the interrelation of the weight ratios of the key performance areas (ecology vs. economy) and the performance areas (land-use vs. emissions). The higher the relevance of land-use the less important is the weighting ratio between the key performance areas economy and ecology. This reasoned by an increased take-off performance, requiring less runway area (→ land-use), as well as improved overall economics (→ higher utilization).

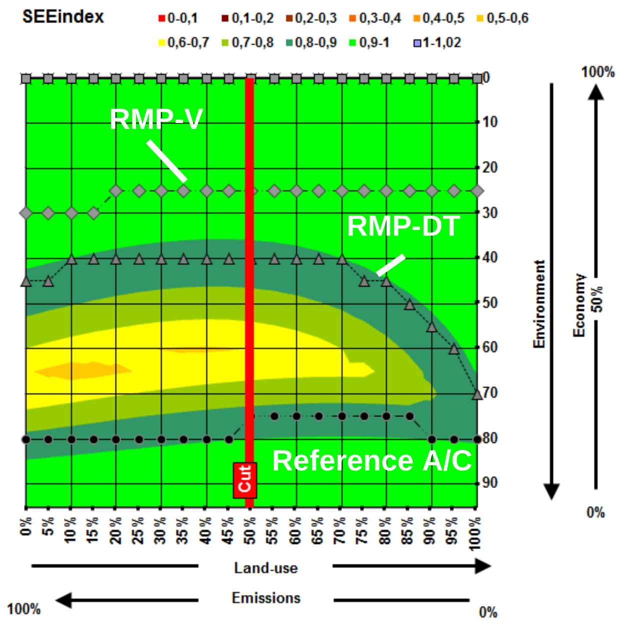


Figure 8: SEEtrade-diagram

If one gets or derives more detailed information about the criteria weights, the pre-processed results enable the user to make a decision about the configuration to be selected in order to match the future demand properly. For the case of using end-point assessment indicators, as mentioned in chapter 1.2, weighting and hence these sensitivity analysis step can be avoided.

For refining the optimization strategy or the assessment in general, the contribution of the indicators to the SEEindex needs to be understood in more detail. Thus, the indicators have to be subdivided into their fundamental elements step-by-step. A radar diagram is one helpful opportunity to visualize this procedure. Exemplarily shown in Figure 9, the normalized and equal weighted environmental indicators are plotted in such a diagram, called ECOradar, scaled the worst indicator to 1 (here: noise of the reference aircraft). Here, it indicates the most disadvantages of the RMP configurations in gaseous emissions (GWP, AP) and in abiotic resource depletion (Fossil resources → Fuel consumption). Hence, the optimization strategy must be realigned with stronger focus on improving the aircraft performance concerning these indicators. In parallel, all measures which reduced the noise levels of the RMP designs should be applied again and, of course, be enhanced. The ECOradar area is a midpoint figure of merit compared to the SEEindex. In a design process, the procedure above has to be iterated until the ECOradar area, Formula (5) converges. In this regard, it must be noted that the used indicators are comparable (e.g. by weighting or taking end-point indicators). Besides the ECOradar, there are also radar diagrams in the social and economic field. In the upstream evaluation all radar indicators are aggregated to the SEEindex, in the downstream process the radar indicators are subdivided gradually into its sub-indicators, ending at the technical design descriptors.

$$ECOradar = \frac{1}{2}\sum_{i=1}^{n} c_i \cdot c_{i+1} \cdot \sin\left(\frac{360}{n}\right) \qquad (5)$$

→ min

c_i	Indicator (e.g. Noise, GWP, etc.)
n	number of indicators

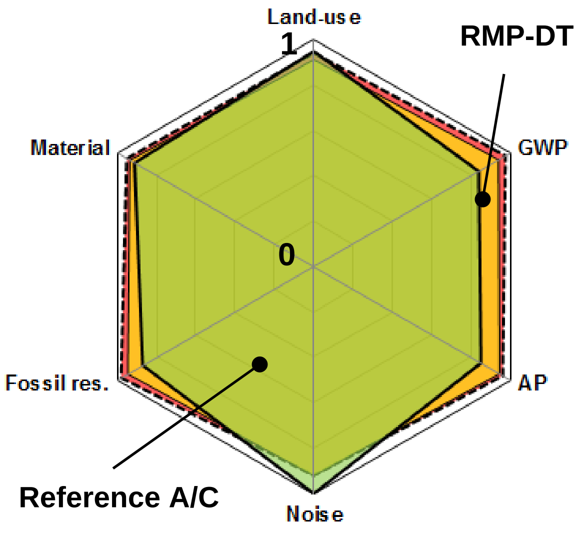


Figure 9: ECOradar-diagram

2.3 Low weight aircraft

As another example of using the presented assessment above, a specific evaluation will be introduced briefly, concerning the aircraft operation profile. Therein, the economic, ecological and social performance over range are calculated and merged to a SEE-Range-Diagram. For showing the procedure, it will be applied on the reference aircraft (chapter 2.1) and a low weight configuration, which has been designed conceptually. The overall assessment is strongly reduced to economic and ecological concerns by the aircraft operation only.

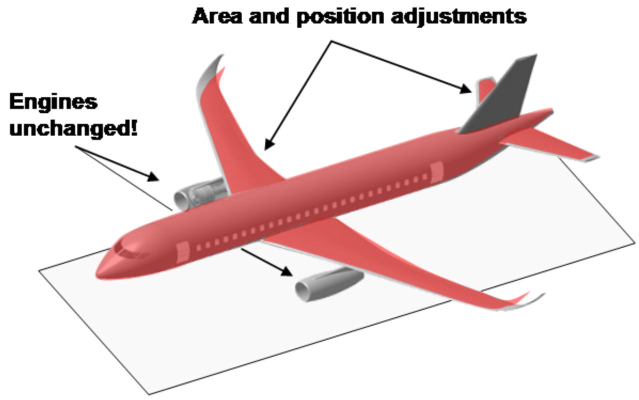


Figure 10: LWA design

2.3.1 LWA design

By using lightweight materials or components, the aircraft flight performance can be increased significantly. Decreasing gradually the wing and fuselage weight of the reference aircraft results in a block fuel saving potential as plotted in Figure 11, operating a 500 nm mission. For the LWA design it has been decided to reduce the wing weight by 30% and the fuselage weight by 20%, in accordance to realistic potentials. The wing area and position have been re-designed as well as the empennage, taking all re-design effects (→ "snowball" e.g. gear design etc.) into account. The reference engines remain unchanged, but are rated. In general, the operating empty weight is reduced to 37.1 t or by 10.9% to the reference aircraft. The maximum take-off weight has been decreased by 7.1%. In the design mission (MTOW and max. payload), the block fuel declines by 5%, the GWP100 by 8,1%. The essential deviations to the reference aircraft are listed in Table 8 and plotted in Figures 12 & 13.

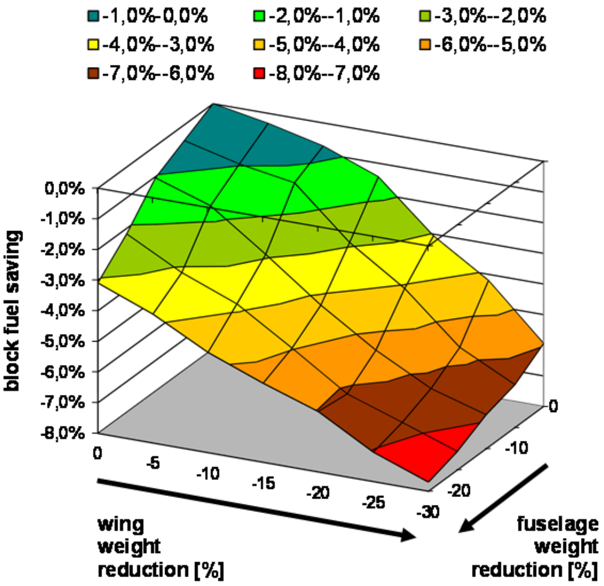


Figure 11: Blockfuel vs. weight reduction, assuming a 500nm mission

Design properties	Deltas refer to Table 2	
MTOW [t]	68,3	-7,1%
OEW [t]	37,1	-10,9%
Wing weight [t]	5,9	-30%
Wing area [m²]	115	-7,3%
Fuselage weight [t]	6,2	-20%
HTP Weight [t]	0,6	-12,1
Gear weight [t]	2,8	-7,0%
Direct operating costs → Figure 12, Figure 13		
Abiotic resources depletion	Fuel [kg]	
500 nm	3029	-6,6%
1000 nm	5460	-5,4%
1500 nm	8164	-5,1%
2000 nm	10780	-4,9%
2500 nm	13191	-4,7%
Noise Flyover take-off	-Δ2,1 EPNdB	
Flyover approach	-Δ1,1 EPNdB	
Side-line	-Δ0,6 EPNdB	
GWP100 [t-CO2-eq.]		
500 nm	12,1	-6,3%
1000 nm	23,9	-6,8%
1700 nm	41,4	-8,1%
Land-use (TOFL)	2020 m	-11,7%

Table 8: LWA design properties

The preparation for the final assessment requires additionally a sensitivity analysis of the influence of changed airframe and maintenance cost to the reference. Due to lack of reliable data at this design stage, a parametric study has been conducted, calculating such influence on the direct operating cost as plotted in Figure 12. Basically, the results for the LWA can be interpreted preliminarily in two ways:

An increase of airframe cost must be below 20% in average in order to match the reference direct operating costs. Plus, a sequence increase by 10% airframe maintenance costs rises the direct operating costs by 0,9%. Both aspects have to be considered in a finalized assessment, if necessary, with parametric plotted results again. Assuming no increase in both aspects, the improved DOC to the reference are equal to them plotted in Figure 13 top.

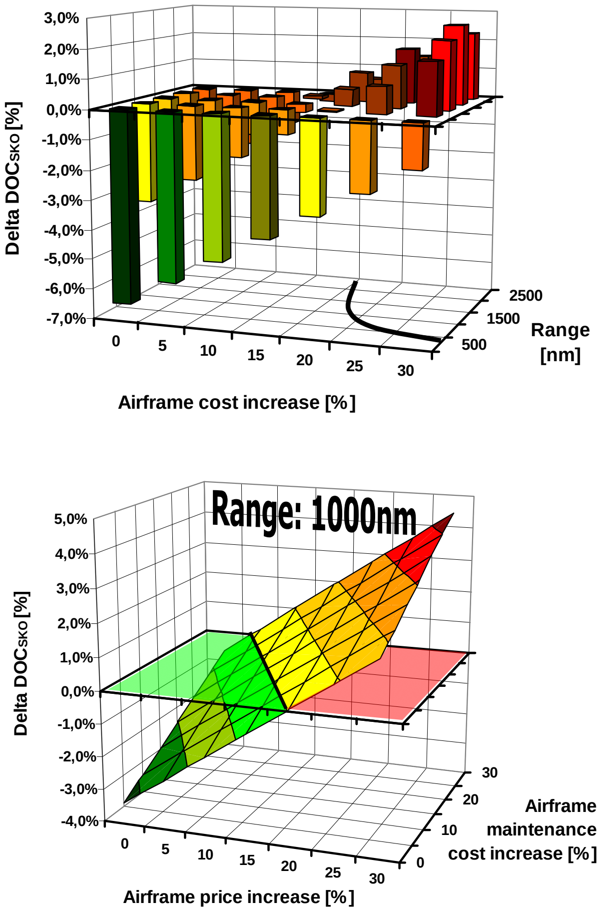


Figure 12: DOC$_{SKO}$ vs. change in airframe, maintenance costs

2.3.2 Assessment of LWA

The presented assessment in this chapter may be seen as a part of the overall procedure, introduced before. It focuses on extending the usual aircraft design performance diagrams by incorporating (socio-) ecological criteria as well. All performance characteristics are plotted against mission range and finally merged to a SEE-range-diagram, which indicates the range with the highest Socio-Eco-Efficiency. Thus, in a design process, the optimization strategy has to be defined in a way, that the optimal or sustainability range matches the target range, defined in the design requirements.

The SEErange-diagram of an aircraft with light weight structures and its development are shown in Figure 13: In this example, it is the result of a combination of the direct operating cost and an environmental indicator, both specified to the unit of transport work tonnes-km, with the assumption of an equal relevance. These criteria are range dependent. In the first evaluation, it is seen that the range with the highest eco-efficiency does not match the range with highest economic benefit; it is smaller. The range with the lowest environmental impact (here: GWP) is even more less. In the first interpretation, this is caused by two aspects: The lower the range the smaller is the climate sensitive cruise phase. Additionally, the point with the highest fuel burn efficiency is not located at the point of maximum range and maximum payload. Nevertheless, the fuel burn efficiency also declines if the flight trajectory is progressively dominated by energy consuming flight phases such as climb, at short range missions consequently.

The sustainable range can strongly deviate from the widely used design range target, fulfilling the transport requirement with the highest economic benefit. As one can see in the SEE-range-diagram, the sustainable range is about 1600 nm (equal weighting applied) and about 10% below the economic range (1789nm). Preferring a 100% ecological operation, the corresponding mission range is even lower, about 1230 nm or 31% below the economic design range. Compared to the reference aircraft, the sustainable range of the

LWA is slightly shorter. Nevertheless, the SEEindex of the LWA is higher in all range segments until 2500nm, from that range the reference aircraft performs better. In next iteration loop, design measures have to be taken to increase the sustainable range to the required design point (max. payload / 1800nm).

Finally, it has to be mentioned, that the SEEindex was scaled to the best solution for each aircraft individually. Hence, the values are not comparable directly.

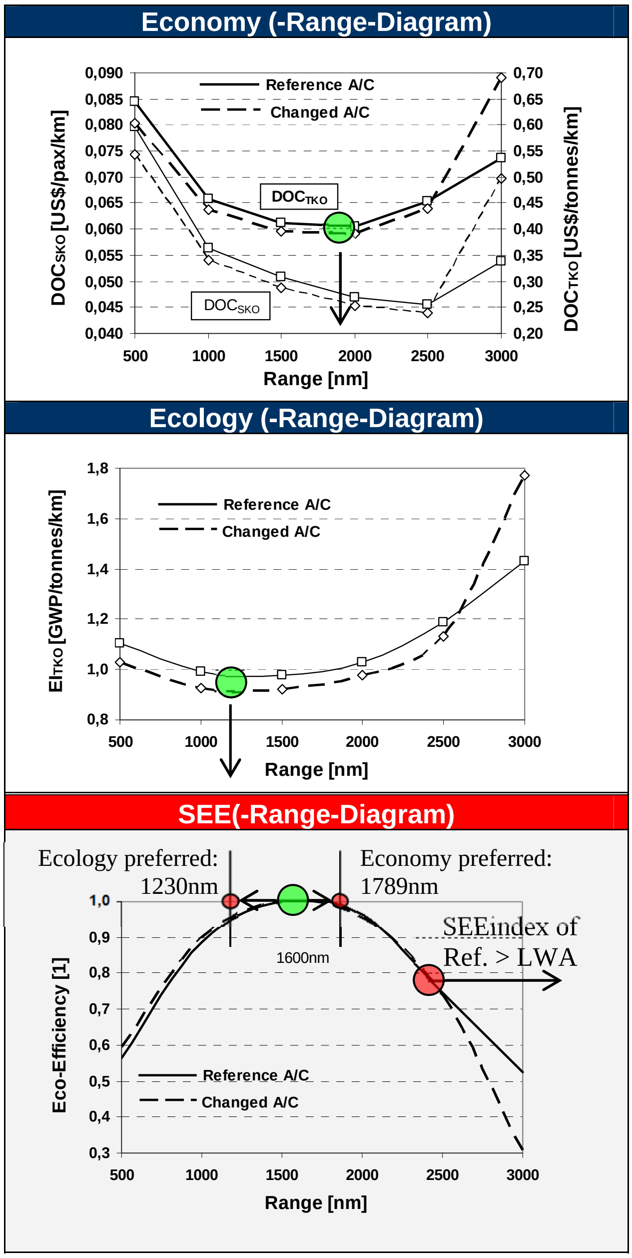


Figure 13: SEE-range-diagram

3 Conclusion

For the assessment of the Air Transportation System a comprehensive process has been developed, which merges the three pillars of sustainability (society, ecology, economy) to one figure of merit – Social-Eco-Efficiency-Index (SEEindex). The SEEindex is the final output of a multi-participative, multi-criteria evaluation and synthesis procedure. Here, the synthesis is conducted by a MCDA method whereas TOPSIS or I-TOPSIS have been recommended as the most fitting one to be applied. The calculated SEEindex is intended for both as a flexible target value to be optimized as well as a fixed value to indicate the socio-eco-efficiency. Thereby, it has to be differentiated between a post- and an in-loop assessment. In comparison to the post-assessment, where the alternatives have already been designed and introduced in the system, in the in-loop assessment the alternatives can be re-designed for optimizing their sustainability (SEEindex → max).

The procedure has been used partly on new aircraft design assessment concerning a low noise and a low weight configuration. An overview is given, how the assessment of both has to be proceeded. Thereby, a more general approach for the low noise aircraft and a more aircraft special one for the low weight design have been used. Among others, the results are visualized in the so called SEEtrade, ECOradar or SEErange diagrams. In SEEtrade the response of the social-eco-efficiency to different weighting of ecological and economic or social criteria is depicted against a selected weighting ratio of performance indicators, e.g. emissions vs. land-use or energy consumption. It assembles the weight-dependent SEEindices of all examined alternatives in one picture. In ECOradar the normalized and weighted components of a disaggregated SEEindex are plotted. The resulting area can be used as figure of merit for a midterm optimization strategy. The SEE-range-diagram is an extension of the usual aircraft design performance diagrams by incorporating social and ecological criteria too.

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