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Conceptual 0D Sizing including Ticket Price of High-Speed Civil Transportation Aircrafts from Mach 4 to 8

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Abstract

This paper aims at presenting a tool developed by ONERA in order to support the designer during the initial conceptual design phase of high-speed civil transportation aircrafts. The tool helps to evaluate the long-term sustainability of operative concepts by providing a first optimized 0D sizing (maximum take-off mass, fuel mass, dry mass, volume, wetted surface, …) of a high speed civil aircraft as a function of range (3000 to 18000 km), number of passengers (10 to 300), type of fuel (kerosene, LCH4, LH2), cruise Mach number (4 to 8), ascent and descent accelerations (+/- 0.15g) and then by providing the associated ticket price per passenger. This paper, after introducing the sizing tool and the physical and implemented cost models, provides and discusses the results obtained for different missions. Particularly, links between the ticket price and the inputs mission specifications, geometric features, type of fuel are established.

Keywords: *high-speed aircraft, design, sizing, costs*

Nomenclature

a - Acceleration
D – Drag
g – Gravity acceleration
γ – Flight path angle
ISP – Specific impulse
L - Lift
LHV – Lower heating value
M – Mach number or Mass
$MTOM$ – Maximum take-off mass
PAX – Number of passengers
R – Range
S – Surface
T – Thrust
tf – Tuning factor
τ – Küchemann parameter
V – Volume or Velocity
z – Altitude

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1. Introduction

Nowadays, a few tools allow to assess the economic feasibility of high speed vehicles and mission concepts during conceptual design phases because of the lack of databases and statistical data in the field. The activities carried out by ONERA aspire to overcome this obstacle providing a numeric tool to size and estimate operational costs of concepts in their very first conceptual design phases. The tool and model used particularly focus on very high-speed conceptual aircrafts designed to performed point-to-point civil transportation.

Sect. 2 introduces the numeric tool developed by ONERA to solve cross-disciplinary coupled numerical models. Sect. 3 develops the main lines of the physical and cost models used here to size and estimate operational costs of the studied vehicle and mission concepts. Eventually, Sect. 4 aims at showing and analyzing the main results obtained with the application of the model and tool.

2. Simulation tool

The sizing tool is based on the analysis & optimization framework OpenMDAO developed by NASA and the associated GUI WhatsOpt [1] [2] developed by ONERA. WhatsOpt allows the user to integrate easily all the disciplines which take part in the coupled numerical model as well as their inputs, outputs and the coupled variables from one discipline to another. Then, WhatsOpt is also able to generate automatically some code in Python language to adapt the interface of the disciplinary modules to OpenMDAO framework. WhatsOpt is also embedding many functionalities for the monitoring of the multidisciplinary process: DOE (Design of Experiment), optimization, post-processing of results. Finally, as it is coupled with OpenMDAO and Python scientific libraries, many solvers are available.

The WhatsOpt model is composed of a first sub-model which sizes the aircraft accordingly to the mission and geometric inputs, a second sub-model which provides the lift and thrust requirements during the mission for the sized aircraft, and finally a third sub-model which provides Research & Development, Production, Operational costs associated to the mission and the sized aircraft.

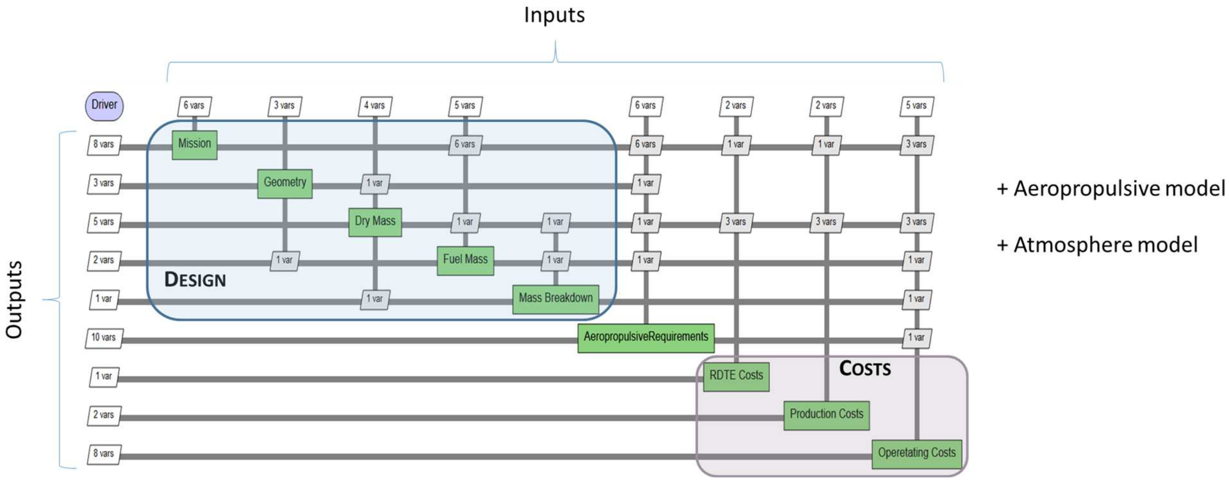

Fig 1. Multi-disciplinary process with WhatsOpt web application

This tool could be used in a pure multidisciplinary analysis mode where range, number of passengers, type of fuel, Küchemann parameter (cf physical models), cruise Mach number, ascent acceleration, descent deceleration are specified.

The tool could also be used in a multidisciplinary optimization mode where Küchemann parameter, cruise Mach number, ascent acceleration, descent deceleration could be parameters to be optimized so as to minimize maximum take-off mass (MTOM). In this case, a truncated Newton method (TNC) solver is used as a first step to reduce quickly the solutions space and then a Nelder-Mead solver is used as a second step to finalize the optimization process.

3. Conceptual sizing & Costs models

3.1. Physical model

Atmosphere: the atmosphere model is ISA US 76 model.

Mission: the mission is composed of three phases: ascent, cruise, descent.

The cruise phase is performed at steady Mach number and steady altitude which is determined by the Mach number using the following correlation based on statistic data for different conceptual aircrafts assessed in European/Japanese project HIKARI [4]:

$$z_{cruise}(km) = 2.2838\, M_{cruise} + 15.13$$

The ascent phase is performed at constant acceleration along a straight trajectory and the cruise Mach number is reached exactly at the end of the ascent phase. This last condition determines the constant flight path angle of the ascent phase.

The descent phase is performed at constant deceleration following the same philosophy.

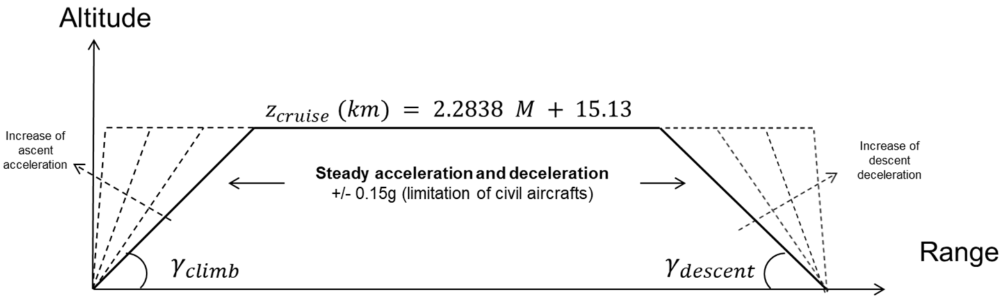

Fig 2. Mission model

Aerothermodynamics: the following lift to drag ratio formula is used:

$$\frac{L}{D} = \min\left(14; \frac{6(M+2)}{M}\left[\frac{1.0128 - 0.2797\ln\left(\frac{\tau}{0.03}\right)}{1-\frac{M^2}{673}}\right]\right)(1 + tf_1) \text{ with } \tau \text{ the Küchemann parameter}$$

where tf_1 is a tuning factor calculated from deviations between lift-to-drag formula proposed in [3] and tabulated data for existing concepts assessed in the European/Japanese project HIKARI [4]:

$$tf_1 = 2.8332\,\tau - 0.3769$$

For low Mach numbers, the lift-to-drag ratio is saturated to $14\ \times (1 + tf_1)$ because high lift-to-drag ratios provided by the formula cannot be reached by the specific geometries adapted to high-speed flight domains.

Propulsion: the specific impulse for LH2 engines is based on piecewise linear functions dependent only from the Mach number:

$$ISP_{LH2} = (7000 - 1070\,M)(1 + tf_2) \text{ for } M < 3.12$$

$$ISP_{LH2} = (4660 - 320\,M)(1 + tf_2) \text{ for } M > 3.12$$

where tf_2 is a propulsive tuning factor calculated from deviations between ISP obtained with the linear model and tabulated data for conceptual aircrafts assessed in the European/Japanese project HIKARI [4]. For turbojet+(sc)ramjet combined cycle engines, tf_2 varies from 5% to 10%, for pre-cooled turbojets tf_2 varies from -20% to -25%. This tuning factor was calculated with respect to ISP obtained for the cruise Mach number of the different aircrafts.

For other fuels, the specific impulse is deduced from the specific impulse of LH2 engines by applying a ratio of the lower heating values:

$$ISP_{LCH4} = \frac{LHV_{LCH4}}{LHV_{LH2}} \times ISP_{LH2} \text{ with } LHV_{LCH4} = 50.03\ MJ\ /kg \text{ and } LHV_{LH2} = 119.93\ MJ\ /kg$$

$$ISP_{kerosene} = \frac{LHV_{kerosene}}{LHV_{LH2}} \times ISP_{LH2} \text{ with } LHV_{kerosene} = 43.15\ MJ\ /kg \text{ and } LHV_{LH2} = 119.93\ MJ\ /kg$$

Volumes & Surfaces:

Payload volume: $V_{payload}(kg) = 1400 \times \frac{PAX}{300}$

Fuel volume: $V_{fuel} = \frac{M_{fuel}}{\rho_{fuel}}$

Total volume: $V_{total} = \frac{V_{payload}+V_{fuel}}{cr}$ with $cr = 0.7$

Plan surface: $S_{plan} = \left(\frac{V_{total}}{\tau}\right)^{2/3}$ with τ the Küchemann parameter

Wet surface: $S_{wet} = K_w \times S_{plan}$ with $K_w = \tau \times e^{\left(1.414-1.415\ln\tau-0.731(\ln\tau)^2-0.272(\ln\tau)^3-0.031(\ln\tau)^4\right)}$

Dry mass:

Payload mass: $M_{payload}(kg) = 200 \times PAX$

Airframe mass: $M_{airframe}(kg) = ISTR\ \times S_{wet}$ with $ISTR = 51436 - 0.0565 \times MTOM$

Systems mass: $M_{systems}(kg)$=$M_0 + 0.1 \times MTOM$ with $M_0 = 5000$ kg

Engine mass: $M_{engine}(kg) = \frac{MTOM}{\left(\frac{T}{M_{engine}}\right)_{cruise}\left(\frac{L}{D}\right)_{cruise}}$ with $\left(\frac{T}{M_{engine}}\right)_{cruise}$ =2 for pre-cooled turbojets and 1.4 for turbojet+(sc)ramjet combined cycle engines. Those mean values are based on statistic data collected during the European/Japanese project HIKARI [4].

Fuel mass: Let's define M_0 and M_1 the total mass of the aircraft corresponding respectively to the beginning and ending of a phase of the mission.

Cruise phase: $M_{fuel\_cruise} = M_1\left(e^{\frac{R_{cruise}}{\left(\frac{L}{D}\right)_{cruise} ISP_{cruise} V_{cruise}}} - 1\right)$

Ascent/Descent phases: $M_{fuel\_Ascent/Descent} = M_1(e^{-I} - 1)$ where $I = \int_{t_0}^{t_1} i(t)dt$

$$\text{with } i(t) = -\frac{a}{g}\frac{\left[1+\frac{gsin(|\gamma|)}{V(t)}(t-t_0)\right]}{\left[V(t)ISP(t)\left(1-\frac{D}{T}(t)\right)\right]} \text{ and } \frac{D}{T}(t) = \frac{1}{1+\frac{\left(\frac{L}{D}\right)(t)}{cos\gamma}\left(\frac{a}{g}+sin\gamma\right)}$$

By supposing that all fuel is consumed at the end of the mission, it is possible to determine the mass of fuel corresponding to each phase of the mission.

3.2. Cost model

Direct Operating Costs

The direct operational costs (DOC) are calculated following the methodology developed initially by NASA in 1973 [5] and adapted by Politecnico di Torino in 2017 for modern high-speed civil transportation aircrafts [6] by considering different hypothesis for the cost of fuel [7].

The equations provided by NASA and Politecnico di Torino are based on different parameters which are clarified below.

Parameter	Commentary
$inflation\_rate\_1972\_2021 = 6.44$	Inflation rate in $ between 1972 and 2021
$inflation\_rate\_2012\_2021 = 1.17$	Inflation rate in $ between 2017 and 2021
$inflation\_rate\_2017\_2021 = 1.10$	Inflation rate in $ between 2012 and 2021
$labor\_rate = 5.3 \times inflation\_rate$	Average labor rate per hour in dollar for maintenance (based on NASA report)
$annual\_utilization = 3000$	block hours /year (based on NASA report)
$depreciation\_life = 10$	years (based on NASA report)
$time\_operation\_ratio_{TJ} = 0.3$	Time of operation of the turbojet engines as a ratio of time flight (based on NASA report)
$time\_operation\_ratio_{RJ} = 1$	Time of operation of the ramjet engines as a ratio of time flight (based on NASA report)
$K_{LTJ} = 2$	Turbojet maintenance labor ratio (high speed turbojets to present subsonic turbojets)
$K_{MTJ} = 2$	Turbojet maintenance material ratio (high speed turbojets to present subsonics turbojets)
$K_{LRJ} = 2$	Ramjet maintenance labor ratio (high speed ramjets to present subsonic turbojets)
$K_{MRJ} = 3$	Ramjet maintenance material ratio (high speed ramjets to present subsonic turbojets)
$nb_{RJ} = 4$	Number of ramjets installed
$nb_{RJ} = nb_{TJ}$	Number of turbojets installed
$T0_{TJ} = T0/nb_{TJ}$	Maximum sea level static thrust of each turbojet engine
$area\_inlet = 7.73$	m² (based on example in NASA report)
$reserve\_fuel\_fraction = 0.08$	Reserve fuel fraction : 8%
$load\_factor = 0.75$	Load factor : 75%
$time\_block = time\_flight + 0.25$	Time (hours) including flight and taxi time
$speed\_block = \dfrac{Range}{time\_block}$	km/h

Table 1. Parameters for costs model

All the following DOC equations from NASA report, adapted by Politecnico di Torino for fuel costs and maintenance costs, are given as costs per ton-miles in 2021 using the system units specified in this report.

- Fuel:

In [7], Politecnico di Torino proposed four hypothesis for the cost of fuel per kg: kerosene, LCH4, LH2, future LH2 using innovative means of production.

$$Cost_{fuel} = 0.55\ (\text{kerosene})\ ;\ 1.26\ (\text{LCH4})\ ;\ 3.50\ (\text{LH2})\ ;\ 1.50\ (\text{future LH2})\quad (\$/\text{kg})$$

$$DOC_{fuel} = \frac{1460 \times Cost_{fuel} \times \left(\frac{mass_{fuel}}{MTOM}\right) \times (1 - reserve\_fuel\_fraction)}{load\_factor \times \left(\frac{mass_{payload}}{MTOM}\right) \times range} \quad (\$/\text{ton-miles})$$

- Crew:

$Cost_{Crew} = 320 \times inflation\_rate\_1972\_2021$ ($/block hour)

$$DOC_{crew} = \frac{\frac{Cost_{Crew}}{MTOM}}{0.725 \times load\_factor \times \left(\frac{mass_{payload}}{MTOM}\right) \times Mach \times \left(\frac{speed_{block}}{speed_{cruise}}\right)}$$ ($/ton-miles)

- Acquisition costs for calculation of insurance, depreciation, maintenance costs:

$Cost_{airframe} = 855 \times mass_{airframe}^{0.68} \times Mach^2 \times inflation\_rate\_1972\_2021$ ($)

$Cost_{RJ} = 33900 \times area_{inlet}^{0.9} \times Mach^2 \times inflation\_rate\_1972\_2021$ ($)

$Cost_{TJ} = 6300 \times nb_{TJ}^{-0.15} \times T0^{-0.33} \frac{thrust_{take\,off}}{g_0} \times inflation\_rate\_1972\_2021$ ($)

$Cost_{systems} = 2760 \times mass_{systems} \times inflation\_rate\_1972\_2021$ ($)

$Cost_{aircraft} = Cost_{airframe} + Cost_{RJ} + Cost_{TJ} + Cost_{systems}$ ($)

- Insurance:

$$DOC_{insurance} = \frac{insurance\_rate \times \left(\frac{Cost_{aircraft}}{MTOM}\right)}{0.725 \times load_{factor} \times \left(\frac{mass_{payload}}{MTOM}\right) \times Mach \times \left(\frac{speed_{block}}{speed_{cruise}}\right) \times annual\_utilization}$$ ($/ton-miles)

- Depreciation:

$$DOC_{depreciation} = \frac{1.1 \times \left(\frac{Cost_{aircraft}}{MTOM}\right) + 0.3 \times \left(\frac{Cost_{TJ} + Cost_{RJ}}{MTOM}\right)}{0.725 \times load_{factor} \times \left(\frac{mass_{payload}}{MTOM}\right) \times Mach \times \left(\frac{speed_{block}}{speed_{cruise}}\right) \times annual\_utilization \times depreciation\_life}$$

($/ton-miles)

- Maintenance of airframe (labour):

$$DOC_{MAFL} = \frac{(3.70 + 2.18 \times time\_flight) \times \left(0.05 \times \left(\frac{mass_{airframe} + mass_{systems}}{MTOM}\right) + \left(\frac{3000}{MTOM} - \frac{315\,000}{MTOM \times \left(2 \times \frac{mass_{airframe} + mass_{systems}}{1000} + 120\right)}\right)\right) \times Mach^{0.5} \times labor\_rate}{load\_factor \times \left(\frac{mass_{payload}}{MTOM}\right) \times range}$$

($/ton-miles)

- Maintenance of airframe (materials)

$$DOC_{MAFM} = \frac{(10.57 + 5.22 \times time\_flight) \times \left(\frac{Cost_{aircraft} - Cost_{TJ} - Cost_{RJ}}{MTOM}\right)}{load\_factor \times \left(\frac{mass_{payload}}{MTOM}\right) \times range \times 1000}$$ ($/ton-miles)

- Maintenance of turbojets (labour):

$$DOC_{MTJL} = \frac{\left(\frac{thrust_{takeOff}}{g_0 \times MTOM}\right) \times (1 + time\_operations\_ratio_{TJ} \times time\_flight) \times \left(0.1 + \frac{9.91}{T_0/1000}\right) \times labor\_rate \times K_{LTJ}}{load\_factor \times \left(\frac{mass_{payload}}{MTOM}\right) \times Range}$$ ($/ton-miles)

- Maintenance of turbojets (material)

$$DOC_{MTJM} = \frac{\left(\frac{Cost_{TJ}}{MTOM}\right)\times\left(0.042+0.034\times time\_operations\_ratio_{TJ}\ \times time\_flight\right)\times K_{MTJ}}{load\_factor\times\left(\frac{mass_{payload}}{MTOM}\right)\times range} \quad \text{(\$/ton-miles)}$$

- Maintenance of ramjets (labour):

$$DOC_{MRJL} = \frac{\left(1+time\_operations\_ratio_{RJ}\times time\_fligh\right)\times\left(0.1+\left(\frac{1.01\times\frac{L}{D}\times nb_{RJ}}{\frac{MTOM}{1000}}\right)\right)\times labor\_rate\times K_{LRJ}}{\frac{L}{D}\times load\_factor\times\left(\frac{mass_{payload}}{MTOW}\right)\times range} \quad \text{(\$/ton-miles)}$$

- Maintenance of ramjets (materials)

$$DOC_{MRJM} = \frac{\left(\frac{Cost_{RJ}}{MTOM}\right)\times\left(0.042+0.034\ \times time\_operations\_ratioe_{RJ}\ \times time\_flight\right)\times K_{MRJ}}{load\_factor\times\left(\frac{mass_{payload}}{MTOM}\right)\times range} \quad \text{(\$/ton-miles)}$$

- Total:

$DOC_{total} = DOC_{fuel} + DOC_{crew} + DOC_{insurance} + DOC_{depreciaition} + DOC_{maintenance}$ (\$/ton-miles)

with $DOC_{maintenance} = DOC_{MAFL} + DOC_{MAFM} + DOC_{MTJL} + DOC_{MTJM} + DOC_{MRJL} + DOC_{MRJM}$

Then, those DOC provided in dollars per ton-miles are converted in dollars per flight by applying the following equation:

$$DOC_{total}[\$/flight] = DOC_{total}[\$/tons\ miles] \times load\_factor \times mass_{payload}\ [tons] \times range[miles]$$

Indirect Operational Costs (IOC)

Indirect operational costs (IOC) are mainly related to specific airline operating strategies and may vary from one airline to another. Data provided by IATA [8] in 2012 and ICAO [9] in 2017, in use in the aeronautics, are used as a reference by Politecnico di Torino to assess indirect operational costs.

- Data from IATA in 2012:

$IOC_{station\ ground} = 9.2E-3\ [\$/available\ seat\ km]$
$IOC_{passenger\ service} = 7.9E-3\ [\$/available\ seat\ km]$
$IOC_{reservation\ sales} = 7.6E-3\ [\$/available\ seat\ km]$
$IOC_{general\ administrative} = 7.2E-3\ [\$/available\ seat\ km]$
$IOC_{airport\ navigation\ charges} = 8.3E-3\ [\$/available\ seat\ km]$

- Data from ICAO in 2017:

$IOC_{traffic\ service} = 15\ [\$/enplaned\ pax]$
$IOC_{aircraft\ servicing} = 800\ [\$/flight]$

The total IOC per flight is calculated thanks to the following equation:

$$\begin{aligned} IOC_{total}[\$/flight] &= \left(IOC_{station\ ground} + IOC_{passenger\ service} + IOC_{reservation\ sales}\right. \\ &\quad \left. + IOC_{general\ administrative} + IOC_{airport\ navigation\ charges}\right)\times\ pax\ \times range\ [km] \\ &\quad \times inflation\_rate\_2012\_2021 + \left(IOC_{traffic\ service}\ \times pax\ + IOC_{aircraft\ servicing}\right) \\ &\quad \times inflation\_rate\_2017\_2021 \end{aligned}$$

Ticket price

Finally, ticket price can be calculated thanks to the following equation and considering a 10% of operating costs profit margin, and a 75% load factor [6]:

$$Ticket\ price = \frac{(1 + profit\_margin) \times (DOC_{total} + IOC_{total})}{pax \times load\_factor}$$

4. Some results for a 100 passengers aircraft based on turbojet+(sc)ramjet combined cycle engines

The following figure is presenting some results of the tool used in the multidisciplinary analysis mode. MTOM is calculated for a LH2 aircraft considering a pure cruise flight (i.e. no ascent and descent) along a 18000 km mission. tf_2 factor was set equal to 7.5%. A DOE (Design of Experiment) is performed by varying the specified cruise Mach number and the specified Küchemann parameter as inputs.

For this specific mission, it is possible to emphasize an optimal cruise Mach number equal to 7.2 and an optimal Küchemann parameter equal to 0.2. Especially, the optimal Küchemann parameter is resulting from a trade-off between high Küchemann parameters promoting high lift-to-drag ratio and low Küchemann parameters promoting light airframe mass. It should also be noted that the optimal cruise Mach number was found to be very dependent from the implemented specific impulse

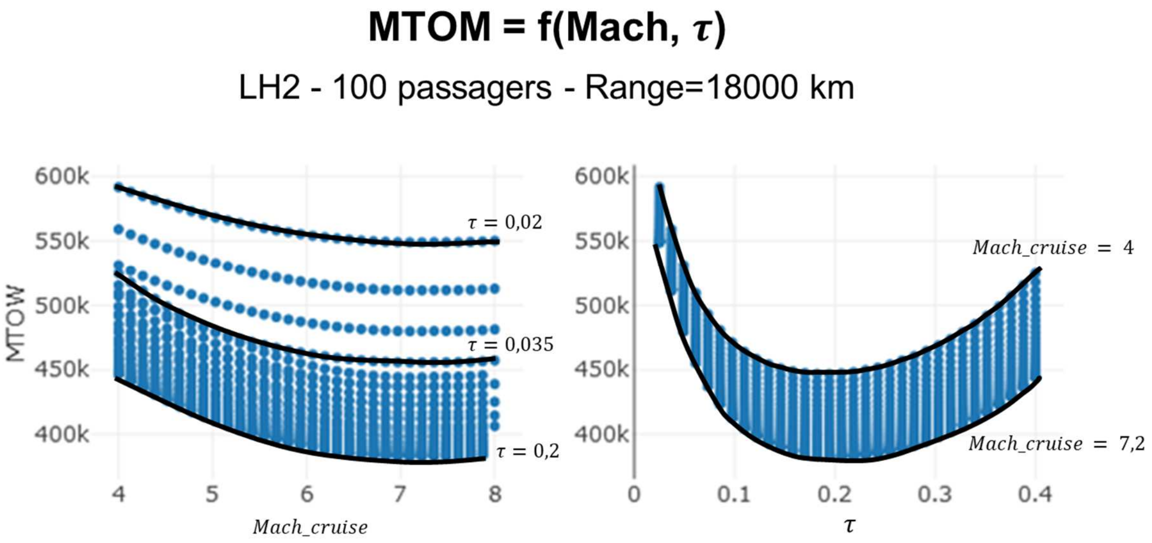

Fig 3. : Effects of cruise Mach number and Küchemann parameter on MTOM

The next figure is presenting some results of the tool used in the optimization mode for a complete mission including ascent and descent phases. Optimal MTOM is calculated for aircrafts considering different fuels (LH2, LCH4, kerosene) and different ranges (3000 to 15000 km). The optimized input parameters are cruise Mach number, Küchemann parameter, ascent and descent accelerations (saturated to +/- 0.15g).

Use of LCH4 fuel instead of kerosene is not leading to a significant decrease of MTOM. This poor advantage could be due to the additional airframe mass induced by the lower density of LCH4 fuel. On the contrary, in spite of the additional airframe mass, the very low density of LH2 fuel is leading to significant decreases of MTOM, especially for high ranges.

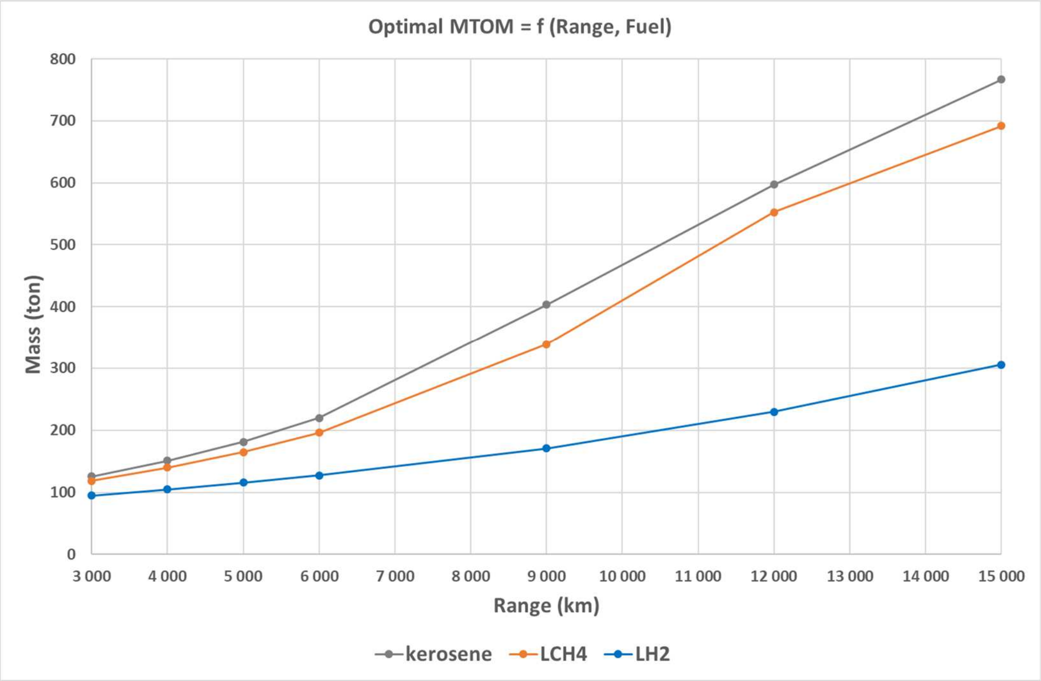

Fig 4. Optimal MTOM for different ranges and types of fuel

The associated ticket price was calculated, considering a near term and a long term production cost for LH2 fuel. Prices are expensive but in the same order of magnitude than current first class tickets in subsonic airliners. Considering a near term hypothesis for the cost of LH2 fuel, kerosene is still the cheapest option. Nevertheless, considering a long term production cost of LH2 fuel thanks to innovative means of production, ticket prices are significantly reduced.

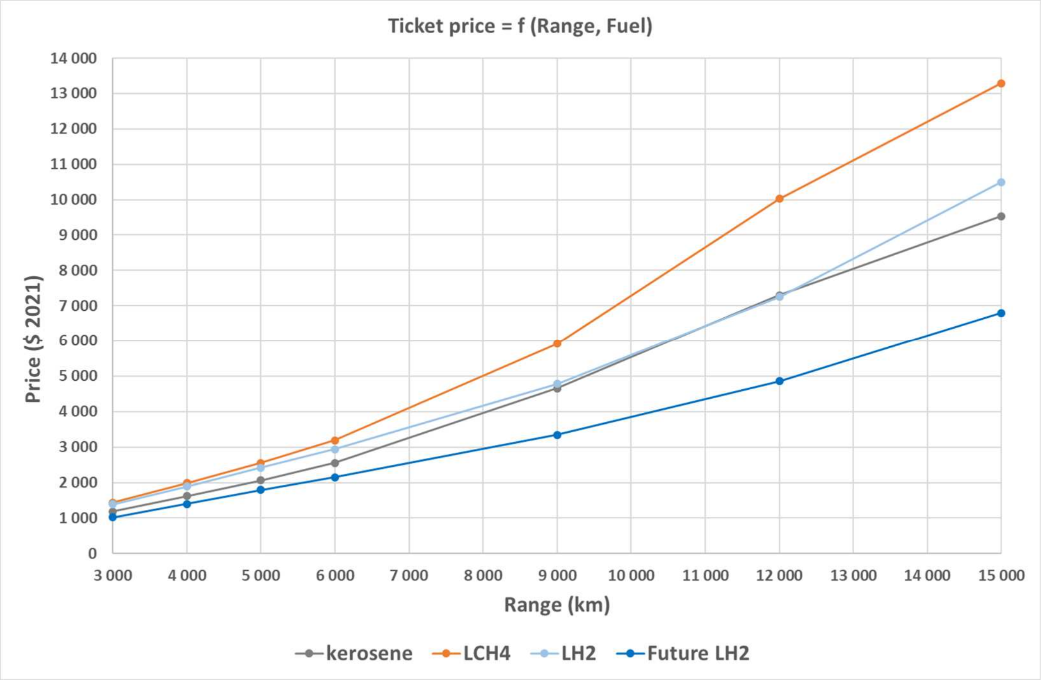

Fig 5. Ticket price associated to optimal MTOM for different ranges and types of fuel

Finally, the last figures are presenting the corresponding cruise Mach numbers, Küchemann parameter, descent acceleration for the different ranges and type of fuel. The optimal ascent acceleration is not presented because it is always equal to the maximal authorized value +0.15g.

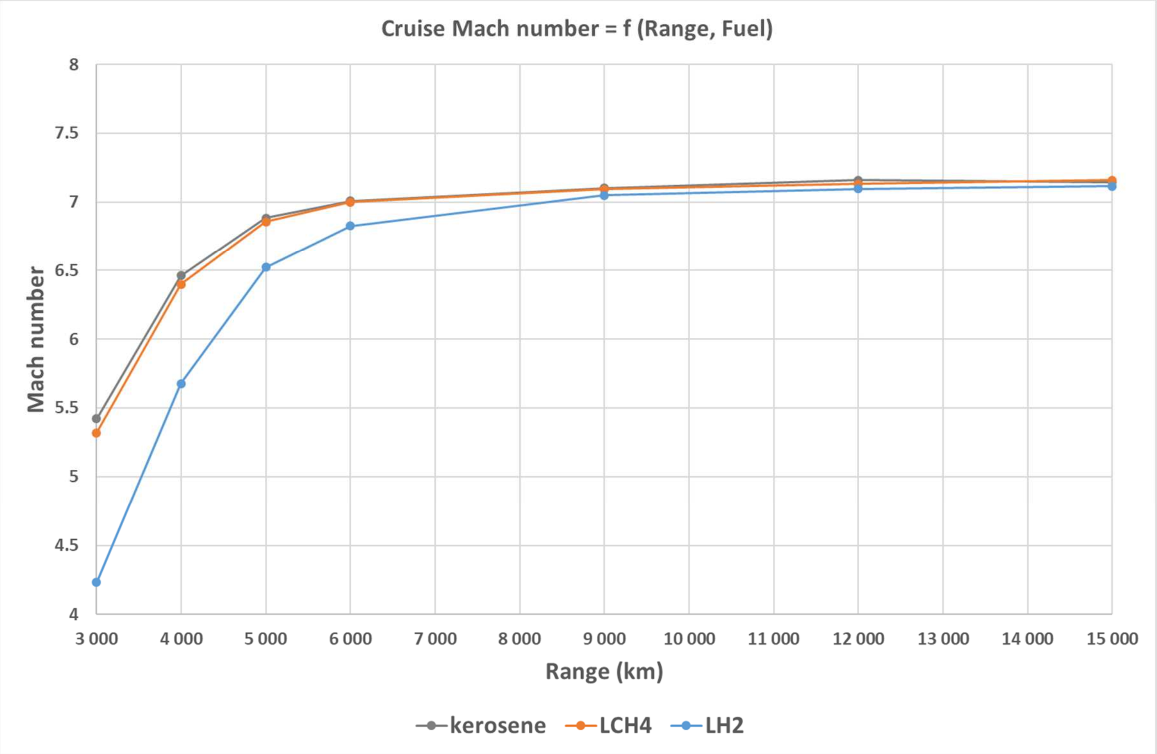

Fig 6. Cruise Mach number associated to optimal MTOM for different ranges and types of fuel

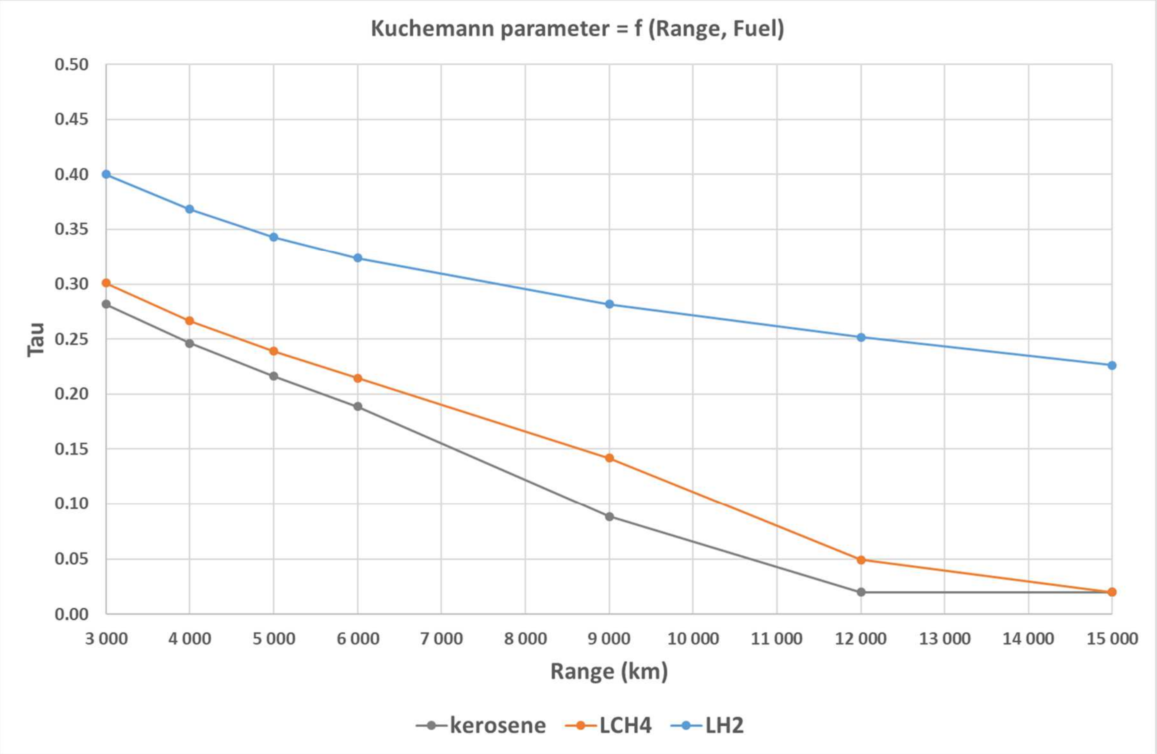

Fig 7. Küchemann parameter associated to optimal MTOM for different ranges and types of fuel

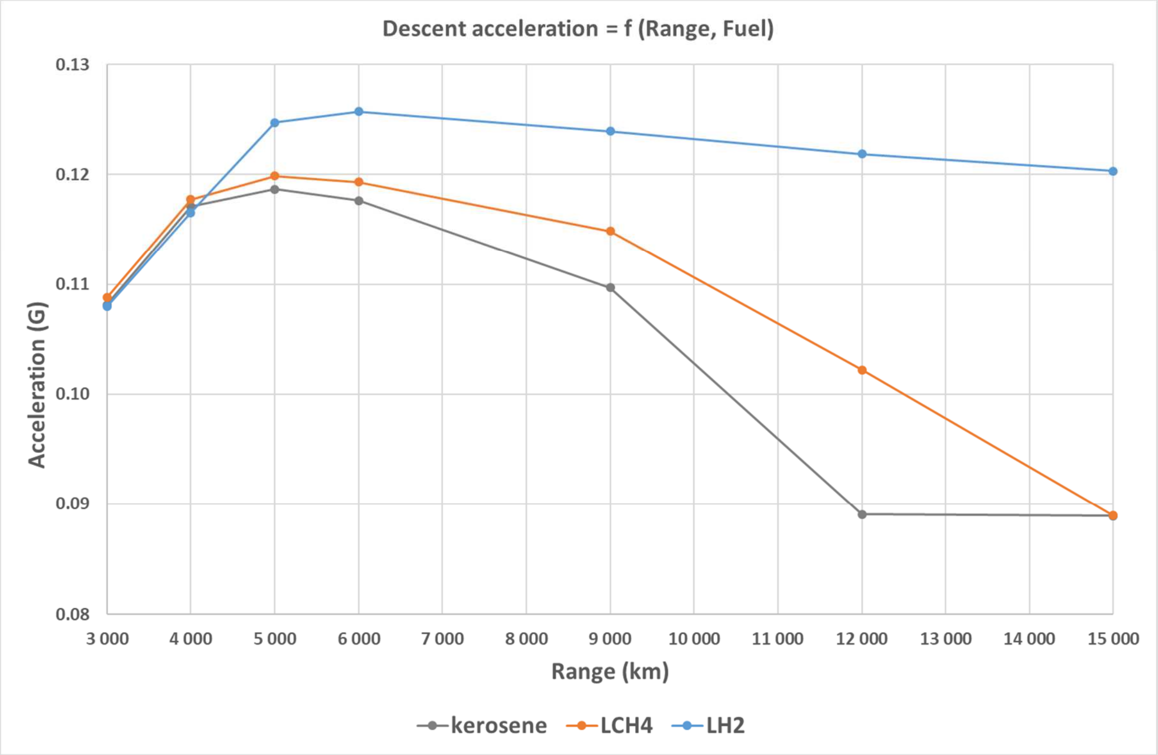

Fig 8. Descent deceleration associated to optimal MTOM for different ranges and types of fuel

For ranges higher than 7000 km, the optimal cruise number is 7.2. For lower ranges, the optimal cruise Mach number is reduced mainly because the aircraft is not able to reach a higher Mach number during the mission before starting the descent.

The optimal Küchemann parameter is decreasing when the range is increasing. This means that the trade-off between high lift-to-drag ratio and light airframe mass is in favor of light airframe mass for low ranges and in favor of high lift-to-drag ratio for high ranges.

It is also possible to emphasize an optimal descent deceleration lower than the maximal authorized value -0.15g. The optimal deceleration is decreasing when the range is increasing.

5. Conclusion and future perspectives

This paper presents a 0D sizing tool of high-speed civil transportation aircrafts based on OpenMDAO framework and WhatsOpt GUI developed respectively by NASA and ONERA. It is able to calculate the basic features of an aircraft corresponding to specified top level inputs (range, number of passengers, cruise Mach number, ascent and descent acceleration, type of fuel, Küchemann parameter) but it is also able to optimize MTOM by optimizing cruise Mach number, ascent and descent acceleration, Küchemann parameter for a specified range, number of passengers, type of fuel.

The results provide essential feedbacks about the long-term sustainability of operational concepts such as dimensional features of the aircraft (MTOM, volumes, areas, …), mission characteristics (fuel consumption, time of flight) and costs estimations like an assessment of the ticket price. It is important to notice that for a given geometry and most ranges, MTOM and ticket price are minimal around Mach 7 considering the implemented laws of specific impulse that needs to be further investigated. An optimal Küchemann parameter is also existing for each mission and the optimal Kücheman parameter is decreasing when the range is increasing. The optimal ascent acceleration corresponds to the maximum authorized value but it is possible to emphasize an optimal descent deceleration which is lower than the maximal authorized value.

Nevertheless, this tool can be significantly improved because some weak points are not taken into account. Especially, the following functionalities are planned to be integrated in the next steps of the development of the tool:

- Introduction of a transonic phase at a steady low altitude to be specified where the aircraft is accelerating at constant acceleration from Mach=0.85 to the Mach number corresponding to the cruise dynamic pressure
- Introduction of a supersonic ascent phase at constant acceleration and constant dynamic pressure corresponding to the cruise dynamic pressure
- Introduction of a descent phase at constant acceleration and constant dynamic pressure corresponding to the cruise dynamic pressure
- Introduction of $K_w(\tau)$ laws depending from the geometric topology of the aircraft
- Introduction of ISTR formula depending from level of heat fluxes and type of fuel
- Introduction of engine mass assessment corresponding to the maximum thrust during all the mission and not the thrust during cruise
- Sensitivity of the results, and especially optimal cruise Mach numbers, to the implemented laws of specific impulse

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