Development of a Software Tool for Comprehensive Flight Performance and Mission Analysis of Hybrid-Electric Aircraft

Gilbert Tay
Technical University of Munich
Research Associate, Institute of Aircraft Design
85748 Garching, Germany
Gilbert.tay@tum.de

Paul Keller
Institute of Aircraft Design, Technical University of Munich
Graduate Student Researcher

Mirko Hornung
Institute of Aircraft Design, Technical University of Munich
Professor

ABSTRACT

This paper presents a software tool developed to comprehensively evaluate flight performance and mission analysis of hybrid-electric aircraft. The modelling incorporates conventional propulsion systems as well as an alternative electric propulsion system for flight performance and mission analysis. As part of the overall technology assessment of the Bavarian research project "PowerLab", which aims to develop a hybrid-electric flying platform, this tool is incorporated to assess the reference missions of the project concept. Further analysis on the impact of energy density variation on the transport efficiency using the developed tool was also performed. Finally we present an outlook into the integration of the tool in an overall aircraft fleet system dynamics model to estimate future fleet development for various future scenarios.

KEYWORDS: *Flight performance analysis, mission analysis, hybrid-electric propulsion*

NOMENCLATURE

a	- Acceleration	SEP	- Specific excess power
D	- Drag	T	- Thrust
g	- Gravity acceleration	TSFC	- Thrust specific fuel consumption
L	- Lift	v_{tas}	- True air speed
m	- Aircraft mass	w	- Energy density
MTOW	- Maximum take-off weight	μ	- Electric thrust fraction
OEI	- One engine inoperative	η	- Efficiency
Pel	- Electric power		
Q	- Power density		

1 INTRODUCTION

Prevailing efforts exploring the potential of hybrid-electric aircraft technology have found application potential for aircraft especially in the commuter category with a seat capacity of less than 20 seats [1] for very short trip distances. Thin-haul range capabilities in the United States have been described to be shorter than approximately 200 nautical miles [2, 3] or 370 kilometres. An analysis of OAG [4] data of the global aircraft fleet operations in 2014 showed, that the aircraft clusters [5] representing "commuter / regional turboprops" and "small propeller aircraft" operate over average trip distances of 360 km and 160 km respectively. The range limitation imposed by current commercial battery technology on electric aircraft, due to the relatively low energy density (<300 Wh/kg) [6] of such batteries, can be seen to be mitigated partially by the very short range requirements of thin-haul aircraft operations.

The Bavarian research project "PowerLab" aims to create a "competence centre […] for hybrid and fully electric aircraft", as well as to develop "core technologies for electrical propulsion systems for Turboprops […]" [7]. The application case within the project itself is a hybrid-electric propulsion system based on a Do-128-6x-platform with a MTOW of 4350 kg [7]. Depending on the mission, the passenger capacity of the hybrid-electric aircraft is estimated to be in the range of 3 to 10 passengers [7]. The modelling used for this paper adapts the concept of the project to model a slightly larger Do-228-platform.

As a part of the overall technology assessment of the "PowerLab" project, we have developed a tool to evaluate flight performance and mission analysis of hybrid-electric aircraft. The tool developed within this project was based on the 'Fuel Consumption and Emissions Calculation Tool (FCECT)', which is an "aircraft performance model being capable of simulating every flight operation […] on the global air transport network […]" [8]. The FCECT "primarily relies on the BADA (Base of Aircraft Data) aircraft performance model" [8, 9]. It is able to evaluate aircraft performance based on conventional propulsion systems with a fidelity level appropriate for the mentioned purpose. The tool developed here similarly relies on a modified BADA aircraft performance model for hybrid-electric propulsion systems.

There are a number of approaches to estimate the flight performance of conventional propelled aircraft. Most commonly the thrust specific fuel consumption (TSFC) is utilized. The TSFC is modelled based on primarily empirical data. This existing approach is, however, not valid for flight performance modelling of hybrid aircraft, since two propeller types, electric and fuel powered, are involved in thrust generation.

1.1 Flight Performance and Mission Analysis of Hybrid-Electric Aircraft

For the civil transport missions considered within this paper, the overall performance is computed solely via the travelled distance. Therefore, the flight dynamics is neglected as we consider a general approach to model the performance of hybrid aircraft. When a quasi-stationary flight condition is given, the performance of the aircraft can be calculated through the specific excess power, SEP, as follows:

$$SEP = \frac{T - D}{m \cdot g} v_{tas} \tag{1}$$

When the SEP is calculated, the potential gain in height or acceleration can be obtained directly with the following correlation:

$$SEP = \frac{dH}{dt} + \frac{v_{tas}}{g}\frac{dv_{tas}}{dt} \tag{2}$$

To fully gain all needed unknown quantities, one has to evaluate virtually static force equilibrium parallel and vertically to the flight path. For stationary flight conditions, the force equilibrium parallel to the flight direction is given as:

$$m \cdot a = T - D \tag{3}$$

Whereas the balance of forces perpendicular to the flight path is given as:

$$m \cdot g = L \tag{4}$$

This method of modelling the aircraft as a physical point mass in quasi-stationary flight conditions does not consider varying angles of attack, nor does it model dynamic effects during the flight, like manoeuvres or payload drops. In general, the omission of these aspects does not impede the results of overall evaluation of normal civil transport missions in the context of this paper.

1.2 Goals of the Paper

In this paper, a convenient approach for flight performance modelling of hybrid aircraft is introduced. It is especially designed with the fuel consumption in mind and the direct comparison of hybrid-electric aircraft to aircraft with conventional engines. A hybrid aircraft in this context is an aircraft, that uses conventional propellants and electric energy coming from batteries. Fuel cells are not considered in this paper for various reasons, partly due to unnecessary complexity. For various types of fuel cells, multiple consumption schemes for oxidizing and reducing agents have to be modelled for each aircraft type, similar to an engine performance modelling. An important design criteria for the development of this software tool, is the flexibility concerning the hybrid drive train concept. The ability to integrate the tool into the fleet model based primarily on conventional propulsion systems was also an important criterion. A general approach for modelling a wide variety of hybrid concepts is thus implemented.

1.3 Analysis of Various Hybrid-Electric Propulsion Concepts

We present three possible types of a hybrid drive train topology that could be applied. In the automotive industry, a common concept in use is the parallel hybrid drive [10]. For a given conventional drive train that is to be converted to a hybrid, this presents a relatively simple solution. A parallel hybrid concept is characterized by its two independent drive trains that are connected to the thrust generating element via mechanical connections, e.g. a gearbox. Both machines, the conventional and electric, can be controlled independently. This configuration makes it possible to withdraw different power levels from each machine: For example, supporting the conventional propulsion system with the electric drive train during take-off and climb. This enables the conventional propulsor to operate close to its design point during the highest power requirements. In contrast, during cruise or descent, electric assistance may not seem advantageous, since power demand is rather low or the propulsor is near its most efficient operating point anyway.
The second type of a possible hybrid configuration is the series hybrid [7,10]. The conventional fuel combustor is connected to a generator via a drive shaft. The electric propulsor is then driven by the output electricity of the generator, meaning that conventional fuel is the main energy resource. The direct mechanic coupling, meaning a fixed torque and revolution ratio, of combustor and generator results in a dependent design of both machines. In terms of system complexity, this concept is the most basic and simple one, but usually requires a new design of key components and may result in higher overall costs than a parallel hybrid system. Depending on prevailing flight conditions and power requirement, it may be possible to charge the batteries in flight. This type of hybrid concept is also known as the "range extender" in the automotive sector.
Lastly, there is the concept of the power split or series parallel hybrid [10]. It is a parallel hybrid in a strict sense, although is mentioned separately because of its flexibility. The conventional and electric machine have separate drive trains that are connected with a gearbox to the output shaft. In contrast to the parallel concept, the power split concept is able to distribute torque flux fully variably. In most use cases the electric motor is able to be used as a generator as well. This is achieved by using torque converters and "Ravigneaux" planetary gears.

2 METHODOLOGY

2.1 The Aircraft Performance Modelling Tool

As previously mentioned, the presented aircraft performance-modelling tool is currently only able to calculate the fuel consumption of conventionally propelled aircraft. This is done by calculating the TSFC depending on the three current mission phases, and a range of fuel flow coefficients that take height, speed and thrust requirements into account. Basis of this calculation is the Base of Aircraft Data (BADA) [9]. The TSFC is then multiplied with the prevailing thrust and consequently, the fuel mass flow is obtained. Fig. 1 shows the scheme of calculation implemented in the aircraft performance modelling tool.

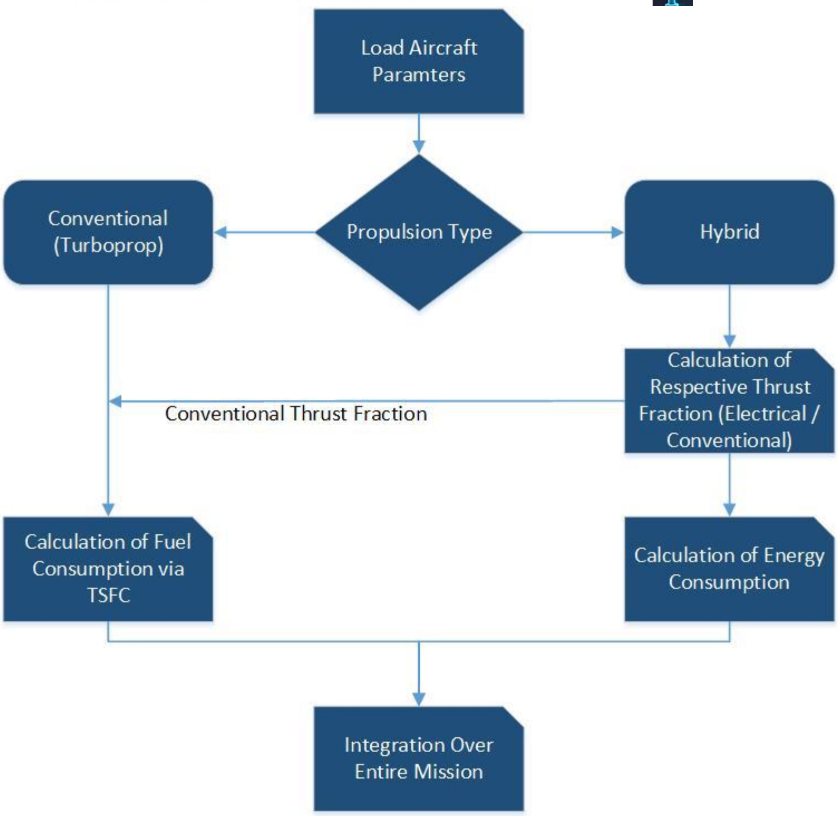

Figure 1: Scheme of calculation implemented in the aircraft performance modelling tool

2.2 Mission Analysis Tool Integration

Based on the functionality above, a new method is introduced to support the calculation and evaluation of hybrid aircraft. The main idea is to implement a new parameter, namely μ, which describes the hybridization of the concept. It is defined as:

$$\mu = \frac{T_{el}}{T_{total}} = \frac{T_{el}}{T_{el} + T_{conv}} \qquad (5)$$

In other words, it quantifies the thrust fraction generated from electric sources compared to the total thrust. It is assumed, that the thrust here is solely generated through accelerating air flow through a virtual propeller dissection with an infinitesimally small thickness. In order to calculate the electric power needed to provide the thrust, the following equation is used:

$$P_{el} = v_{TAS} \cdot T_{el} \qquad (6)$$

The total energy consumed by the electric drive train throughout the mission is given by integrating the power over the entire mission. Up to now, an ideal aircraft with no losses is considered. In order to be able to estimate the capacity of the electric energy storage system, the efficiency η is introduced. Both new parameters, μ and η, are split into three sections, representing the three main mission phases, in particular - taxi out, take off and climb, secondly, cruise and lastly, descent, landing and taxi in. The differentiation of parameters depending on the mission phase enables the modelling of different operational use cases of electric and conventional machines, as already described in section 1 and at the same time, enables the modelling of various operating points of the electric machines throughout the mission.

2.3 Application to a Hybrid-Electric STOL Utility Aircraft

In order to demonstrate the approach, a general STOL utility aircraft based on the Do-228-platform is modelled. This aircraft is modified to utilize a parallel hybrid system. The twin-engine, high wing and fixed landing gear design of the base aircraft remains, so that aerodynamic changes are negligibly small and only the changes in the powertrain are considered.

Table 1: Specifications of the modified Do-228

	Span	Range	Empty Weight	MTOW	PL
STOL Aircraft	17 m	850 km	3740 kg	6400 kg	2200 kg

The basic specifications are given in Table 1. An average energy density of the whole aircraft of about $w_{\mathrm{MTOW}} = 17710\ \mathrm{J/kg}$ is assumed. The battery capacity of the system equals roughly 115 MJ. The value for the energy density is taken from the "PowerLab" hybrid aircraft preliminary design and is applied to this case. Furthermore, the baseline energy density for the batteries is assumed to be a conservative $w_{\mathrm{Bat}} = 100\ \mathrm{Wh\ /\ kg}$. A study of the variation of the battery energy density is conducted in the section 3.2 for variations up to 400 Wh/kg. With an appropriately scaled maximum take off weight, the battery mass is calculated as 320 kg. On top of the calculated battery mass, a fixed mass of 100 kg is added to take various controllers and wiring into consideration. Another mass-based preliminary design cycle is performed, but this time with the power of the electric machines as a design parameter. Again, the basis is the known hybrid-version of the "PowerLab" aircraft concept introduced at the very beginning. The overall MTOW based power density of the known design is given as $q_0 = 138\ \mathrm{W\ /\ kg}$, whereas the power density of a high performance electric machine for flight application at peak power is declared with $q_{\mathrm{el}} = 5000\ \mathrm{W\ /\ kg}$. Again, the necessary power for the electric machines is calculated using the scaled-up MTOW of the STOL aircraft together with the power density of the known hybrid concept. This calculation yields a total power of the electric machines of approximately $P_{\mathrm{el}} = 880\,\mathrm{kW}$. With the maximum power, the mass of the electric machines can be estimated with the use of the power density of the high performance electric motors. This renders a weight of approximately $m_{\mathrm{el}} = 176\,\mathrm{kg}$. The whole gain in empty weight is assumed to be the sum of the battery mass, electric machine mass and other masses including the controllers and wiring. This yields a total mass gain of $\Delta m_{\mathrm{el}} = 600\ \mathrm{kg}$. This amount is added to the empty weight and consequently substracted from the maximum payload mass.
Now the hybrid parameters μ and η are estimated. The nature of the electric thrust fraction μ is a solely operational one, since the electric machines are designed for emergency cases like OEI. Therefore, they are capable of providing 100% of the needed propulsion power. For the first design iteration, the electric thrust fraction μ is assumed to be 15% and electric thrust augmentation is only utilized during climb. At any other time, the electric machines are switched off. This also means that only the efficiency during climb has to be estimated. The estimation of the efficiency of the electric drive train requires certain assumptions. The first one is that the electric efficiency η represents the whole efficiency chain from battery to propulsor. Therefore, five major partial efficiencies are identified. Those are namely the efficiency of batteries, controller and wiring, mechanical efficiency, electric machines and the propeller efficiency.

Table 2: Partial and total efficiencies

η_{Bat}	η_{Ctrl}	η_{Mech}	η_{El}	η_{Prop}	η_{total}
90%	95%	98%	75%	70%	≈45%

An overview and the total efficiency is given in Table 2. The efficiencies were chosen conventionally based on best practices to reflect the current state of technology and augmented with data where possible [11, 12]. The estimated parameters as well as the reduced payload and increased empty weight are considered for the new, hybrid model based on the Do-228-platform.

3 RESULTS OF THE FLIGHT PERFORMANCE AND MISSION ANALYSIS TOOL

3.1 Results of a hybrid aircraft concept for reference missions

In order to validate and respectively test the new hybrid flight performance modelling, a comparison between conventional and hybrid aircraft is performed based on the performance calculation described in section 1. For the comparison a set of four characteristic reference missions are defined. Two payload levels are chosen, 500 kg and 1000 kg respectively, and two range capabilities, namely 500 km and 250 km. The range capabilities are chosen for realistic mission simulations for the thin-haul, commuter category type of operations.

Table 3: Overview of reference missions

Abbreviation	Payload [kg]	Range [km]
10/50	1000	500
10/25	1000	250
05/50	500	500
05/25	500	250

The four reference missions represent specific combinations of the payload and range requirements, whereas the flight level is set at 10 000 ft. An overview over the reference missions is given in Table 3. The first number of the abbreviation represents the payload, the second indicates the range of the mission. Hence the abbreviation 10/50 stands for a payload of 1000 kg and a range capability of 500 km. All four missions are calculated for conventional and hybrid aircraft layout. It is to be noted here, that it is not the total fuel burn that is assessed, but the total energy consumed. The burnt fuel is converted to total energy with the average fuel value of kerosene of 46 MJ / kg [13]. The relative difference is then calculated by using the formula:

$$\Delta E_{\mathrm{rel}} = \frac{E_{\mathrm{tot,hyb}} - E_{\mathrm{tot,conv}}}{E_{\mathrm{tot,conv}}} \quad (7)$$

Using this convention, a gain in efficiency is represented with a negative algebraic sign, whereas a loss in efficiency is shown with a positive one. The results are given in Table 4.

Table 4: Results of mission calculation

Abbreviation	Aircraft Type	Fuel Burn [kg]	El. Energy [MJ]	Total Energy [MJ]	Difference [%]
10/50	Conventional	286	-	13156	1.51
	Hybrid	288	106	13354	
10/25	Conventional	161	-	7406	-0.46
	Hybrid	158	104	7372	
05/50	Conventional	279	-	12834	1.5
	Hybrid	281	101	13027	
05/25	Conventional	157	-	7222	0
	Hybrid	155	99	7229	

The results show that the hybrid configuration is less efficient on the missions with higher range requirements. This is due to the fact, that for missions with longer cruise phases, the higher empty mass impacts fuel economy negatively. For very short range missions, the time share of the climb mission phase is greater, enabling a greater possible efficiency gain. For missions with the highest electrical energy demand, a total of 106 MJ is used, whereas the batteries provide a capacity of 115 MJ. Only in one mission, on the shortest range does the hybrid configuration show a slight positive gain in efficiency.
It is to note that the absolute results of the calculation are to be handled with caution. The main goal of this paper is to develop a convenient way to model and implement a general hybrid aircraft for application in a low fidelity environment. A first model is introduced in order to test and verify the

calculations, but not to model in detail accurate approaches of a STOL utility aircraft. Nevertheless, the first mass based preliminary design cycle shows potential for further model refinement.

3.2 Impact due to variation of energy density on transport efficiency

In addition to the reference missions, an analysis was performed varying the energy density of the batteries from 100 Wh/kg to 400 Wh/kg. Table 5 shows the key parameters and results of the energy density variation. The calculation was repeated for all the reference missions with higher energy densities.
The values show that an increase in energy density of the batteries for missions with longer ranges with the same total energy capacity results in a decrease in the operating empty weight and consequently, an increase in the payload. This enables the transport efficiency to be improved for a range of 250 km from 4.4 kg of fuel per 100 passenger-kilometres to 3.7 kg of fuel per 100 passenger-kilometres. Fig. 2 shows the plot of transport efficiency against the various energy densities.

Table 5: Key parameters of the energy density variation

			Simulation eDo228				Conventional Do 228	
Energy Density [Wh/kg]	Payload-Factor [%]	Range [km]	Operating Empty Weight [kg]	Payload [kg]	Flight Altitude [ft]	Transport Efficiency [kg of fuel /(100 Pax-km)]	Operating Empty Weight [kg]	Payload [kg]
100	90	250	4335	1444	10.000	4.40	3740	1605
	85	500		1364	10.000	4.27		
200	90	250	4176	1588	10.000	3.99	3740	1764
	85	500		1500	10.000	3.88		
300	90	250	4123	1636	10.000	3.88	3740	1818
	85	500		1545	10.000	3.77		
400	90	250	4096	1660	10.000	3.71	3740	1844
	85	500		1568	10.000	3.71		

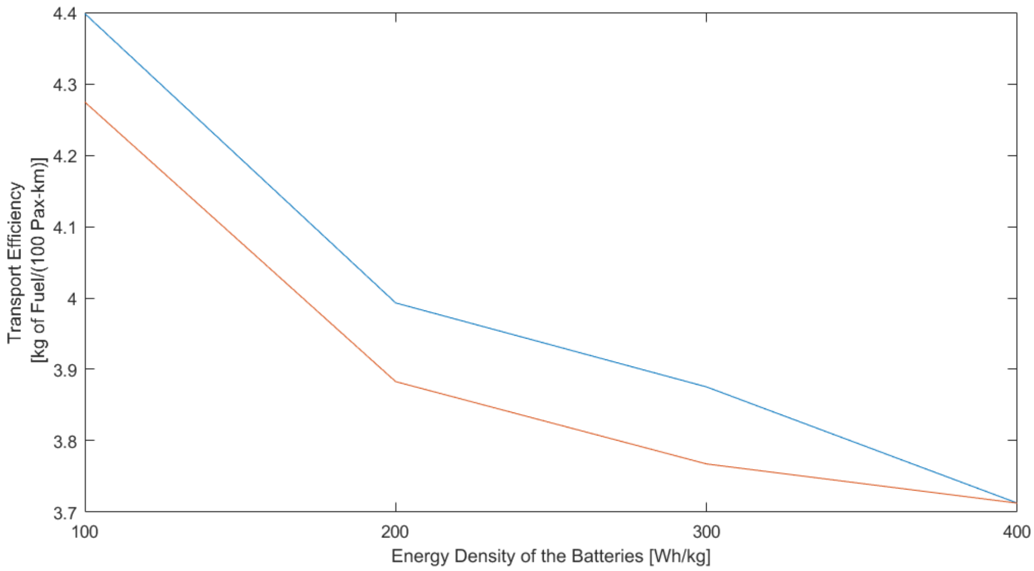

Figure 2: Transport efficiency with varying energy density of the batteries (Less is more efficient)

4 FUTURE APPLICATIONS OF THE SOFTWARE TOOL

Calculations of a relatively small STOL aircraft for a thin-haul commuter category type aircraft has been described in the sections above. However, on a global scale the impact of the introduction to the civil market of a hybrid aircraft in this class is negligibly small, due to the very small ranges, passenger capacity, and hence total transport performance in available seat kilometres. To have an impact on the civil aviation market, both parameters have to be increased. A possible category to scale the hybrid-electric concept is that of a regional turboprop and regional jet. We present here the steps and aspects in implementing the developed tool for integration in a global fleet development model.

4.1 Identification of Important Model Parameters

Important parameters and their influence on the model have to be evaluated initially. Crucial to the modelling are the empty and maximum take off weights. Consequently, the masses of the controller and wiring have to be examined carefully. In this approach, the masses of the bigger aircraft, the Do-228-platform are scaled accordingly with reference to the smaller baseline aircraft of a similar family, which is a Do-128-platform. However, the actual correlation between system power and wiring and controller mass is not confined linearly, especially if passive cooling is not sufficient and further constructive measures have to be implemented. Similar to the relationship between system power and masses, a possible connection between total battery capacity and controller mass has to be investigated. Depending on the concept and use cases of the hybrid aircraft, the charging and discharging control can mean a considerable amount of effort. With regards to the energy storage system, investigation is needed on how the increased empty weight has an impact on the payload. In this case, the masses of battery and electric machines are directly subtracted from the payload and added on the empty weight. For a more accurate approach, a combined investigation of gravimetric and volumetric energy density of the energy saving system has to be performed. Hence, analytically implying the importance of battery placement. In this paper, it is assumed that all the batteries are placed in the cargo compartment. This means that the amount of passengers able to be accommodated is not reduced, but only the maximum range. However, it is possible that the placement of all the battery stacks in the belly space would not suffice or even be ideal for certain configurations. In this case not only the range is reduced, but also the maximum passenger count.
Other very important design parameter are the electric thrust fraction μ and the electrical drive train efficiency η. It is easier to make a prediction of these parameters when more is known about the power topology concept. Extensive parameter studies are an imperative, if the drive train concept is not known or undefined in order to define certain operating optima.

4.2 Secondary Aspects

The main goal for the implementation of this method is to provide for a fast and comprehensive flight performance and mission analysis estimate of the fuel and energy consumption of a hybrid-electric aircraft concept. There are, however, other important factors that affect the direct operating costs and the total lifecycle costs of a hybrid aircraft. Besides fuel consumption, another important factor is the maintenance costs. The electric motors currently in use in the automotive sector indicate significant savings in maintenance costs. There are good justified reasons to assume a similar reduction in maintenance costs for the electric motors in aircraft. This assumption is only valid up to a certain power level that do not require exotic methods of cooling. Better methods have to be developed in order to calculate and estimate other cost components especially for larger (hybrid-) electric aircraft.

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