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Weight assessment for a blended wing Body-Unmanned aerial vehicle implementing boundary layer ingestion

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Abstract. Boundary Layer Ingestion (BLI) has been studied extensively for implementation in Blended Wing Body (BWB) transport aircrafts, and it has been reported that BLI offers potential benefits mainly in terms of energy, improving the propulsive efficiency of a propulsion system and reducing the fuel consumption. This paper examines potential benefits of BLI related with a reduction on the Take-Off Gross Weight (TOGW) for a BWB-Unmanned Aerial Vehicle (UAV). It is discussed the methodology for weight estimation of a BWB-UAV through parametric models. To evaluate the benefits of BLI in terms of weight reduction, it has been taken into account the removal of pylons and the nacelle weight reduction when embedding nacelles into the airframe. The validation of the parametric models, and the case of study have been carried out for the aircraft NASA X-48B. The results show a reduction in TOGW between 8% and 19% when removing pylons and embedding nacelles into the airframe.

1. Introduction

The benefits of boundary layer ingestion (BLI) have been evaluated extensively with a special focus on Blended Wing Body (BWB) transport aircrafts. Most of previous studies about BLI for transport aircrafts have focussed mainly on design of inlets, reduction on fuel consumption, improvement of propulsive efficiency, ram and viscous drag reduction, aeroacoustics effects, and flow control at duct inlet. In 1998, Liebeck [1] introduces BLI in the design of a subsonic BWB transport aircraft, and the results show a reduction of 13% on thrust to weight ratio, and a reduction of 27% on fuel burned, compared to a conventional aircraft operating at the same conditions.

Rodriguez [2] performed a multidisciplinary design optimization (MDO) of BLI inlets, and estimated a reduction of 3.7% in fuel burn rate, and 2.3% in total drag coefficient. In 2004, a design optimization of a BWB subsonic transport was developed by Liebeck [3]; in his work, BLI was evaluated experimentally, simulating the boundary layer over a flat plate and testing different duct geometries. A. Plas [4] assessed the performance of a BLI propulsion system; to evaluate the benefits of BLI in terms of energy, Plas considered power saving coefficient as figure of merit. For the "Silent aircraft", Plas estimated a power saving between 3% and 4% when embedding nacelles into the BWB airframe [4].

Campbell [5] and Carter [6] designed and tested 2 scale models of a BWB aircraft: a clean wing BWB, and a BWB with BLI nacelles. These studies determined aerodynamic coefficients for both configurations and evaluated the Propulsor-Airframe Integration (PAI) through computational fluid dynamics (CFD) and wind tunnel experiments at high Reynolds numbers about 75 million and a Mach number of 0.85 [6].

Whilst, Hardin [7] estimated the fraction of viscous drag that could be ingested, and determined that BLI propulsors can reduce from 3% up to 5% the fuel burn rate, for BLI fractions between 10% and 12% (Drag ingested/ Total Drag). All the aforementioned works were conducted on baseline configurations of BWB transport aircrafts. The results from those works represents a quantifiable evidence of the benefits of BLI in terms of energy mainly. By now, the reduction of fuel burned, total drag coefficient, and the increment on range and propulsive efficiency are some of the performance benefits accrued from BLI.

For small UAVs, the incorporation of BWB and BLI have not been extensively documented, which is related to their military past and hence different design criteria for their development. In 2006, Berends and van Tooren [8] performed a MDO of a BWB-UAV; however, the focus of their work was the development of a multi-objective distributed optimization tool, and the aerodynamics of a BWB-UAV was used as case of study. Lee et al. [9] also carried out a MDO of the aerodynamics of a BWB Unmanned Combat Aerial Vehicle (UCAV). The figure of merit of their study was the aerodynamic efficiency. Chandrasekhara [10] assessed experimentally, in a wind tunnel, the aerodynamics of a UCAV (wingspan = 9 in). Jo et al. [11] evaluated, through numerical simulations, the aerodynamic characteristics of a BWB-UCAV (wingspan = 0.7 m). The same BWB-UCAV used by Jo [11], has been tested experimentally in a wind tunnel in Shim and Park's work [12]. These works have focussed on the aerodynamics characterization of BWB-UAVs and UCAVs; however, they neither address the propulsion system integration with the airframe, nor BLI integration features.

As mentioned in [4,5,7]; BLI requires a deeper and broader analysis in aspects such as PAI, engines installation, flow control, inlet design, and mainly, it is required to analyse the effect of BLI in the performance of the whole aircraft, not only in the propulsion system.

This work examines, at a preliminary design stage, another potential benefit of BLI. Taking Take-Off Gross Weight (TOGW) as a figure of merit, a reduction assessment on TOGW for a BWB-UAV, implementing BLI, is presented. This works explores the integration of BLI for BWB-UAVs taking into account integration aspects such as the removal of pylons, nacelle embedding percentage, and propulsors location. In order to evaluate the benefits of BLI in terms of weight reduction, a parametric model for TOGW estimation for BWB-UAVs is also presented.

2. Weight estimation for a BWB – UAV integrating BLI

To estimate the weight for a BWB-UAV aircraft, a Class II method was used. As described by Roskam [13] and Elham [14], Class II method is based on empirical equations and is appropriate to be used at a preliminary design stage, when a weight breakdown and enough geometrical information for the aircraft in analysis is available [15].

2.1. BWB-UAV: weight breakdown

Weight breakdown is required to estimate aircraft weight using Class II method [13]. In this work, the following weight groups for a general baseline BWB-UAV have been considered:

2.2. Weight group 1: wtructural group

Structural group is integrated by: BWB-Wing, a generic landing gear, and control surfaces along the wing trailing edge.

BWB Wing: As mentioned in [16], the following parametric empirical equation, developed by Beltramo [17] is accurate for wing weight estimation at preliminary design stage. This equation has been used by Liebeck for the design of the BWB subsonic transport [3].

$$W_{Wing} = 4.24 \times I_W + 0.57 \times S_W \tag{1}$$

where:

$$I_W = \frac{n_{load} \times (AR)^{1.5} \times (ZFW/TOGW)^{0.5} \times (1+2\lambda) \times (TOGW/S_W) \times S_W^{1.5} \times (10^{-6})}{(t/c) \times (\cos \Lambda_{1/4}) \times (1+\lambda)} \tag{2}$$

In equation , n_{load} is the ultimate load factor, AR is the aspect ratio, λ is the taper ratio of the wing, S_W is the wing reference area, $\Lambda_{1/4}$ is the quarter chord sweep angle, t/c is the thickness to chord ratio, ZFW is the Zero Fuel Weight, and $TOGW$ is the Take-Off Gross Weight.

To estimate the wing weight, the BWB has been considered as a composition of small wing sections, as it is shown in figure 1 (a). Every wing section must be defined geometrically according to figure 1 (b). For every wing section, it is estimated the corresponding weight, and the total wing weight for a BWB (W_{BWB_Wing}) is defined as follows.

$$W_{BWB\_Wing} = \sum_{i=1}^{nws} W_i \qquad (3)$$

In equation , W_i is the weight of the wing section i, and nws is the number of wing sections of a BWB-UAV.
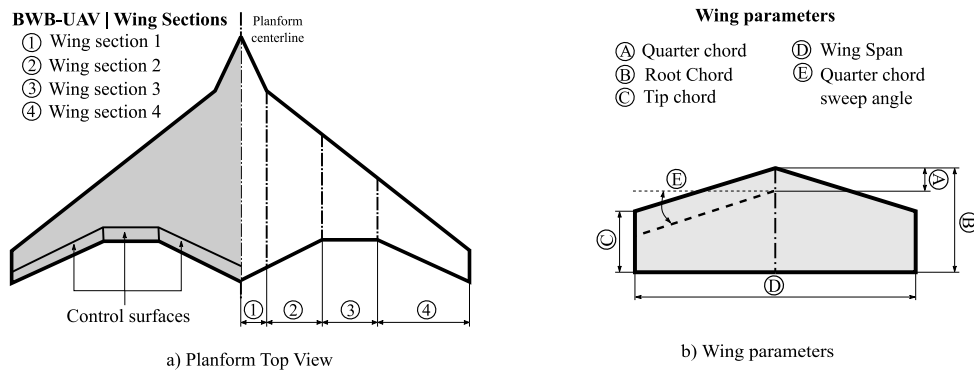

Figure 1. BWB geometrical description.

Landing gear: The weight of landing gear (W_{LG}) was estimated with equation , which was used by Ko [16] in a design optimization of a BWB aircraft.

$$W_{LG} = 0.0135 \times TOGW^{1.1} \qquad (4)$$

Control surfaces: Equation is used to estimate the weight of control surfaces (W_{CS}). This equation is presented in [18].

$$W_{CS} = 0.44 \times TOGW^{2/3} \qquad (5)$$

2.2.1. Weight group 2: Propulsion system, Fuel and fuel system
Engine, nacelle, pylon, fuel and fuel system are considered in this group. The following empirical equations are presented in Isikveren [19].

Engine: $\qquad\qquad\qquad W_{engine} = 0.0177 \times T_0^{1.0572} \qquad (6)$

Nacelle: $\qquad\qquad\qquad W_{nacelle} = 0.32775 \times W_{engine} \qquad (7)$

Pylon: $\qquad\qquad\qquad W_{pylon} = 0.574 \times W_{engine}^{0.736} \qquad (8)$

In equation (6), T_0 is the maximum sea level static thrust.

Fuel and fuel system: According to Kundu [20] fuel can be accounted as 20% of the $TOGW$. Whilst, Gundlach [21] mentions that fuel system can be estimated as 10% of the fuel weight.

2.2.2. Weight Group 3: Sub-systems

In this weight group; flight control system, electrical system, instrumentation, avionics, and electronics are included. Based on empirical equations developed by Roskam [13], equation presents a reduced expression to estimate weight for this group.

$$W_{Subsystems} = 0.055 \times TOGW \tag{9}$$

2.2.3. BWB-UAV Take-Off Gross Weight (TOGW) estimation

To estimate the TOGW for a BWB-UAV, considering the weight groups described above, it has been used the "Unity equation", equation , presented in Torenbeek [22].

$$TOGW = \frac{\sum_{i=1}^{n} W_{fix} i}{1 - \sum_{j=1}^{m} ((W_{var} j) / TOGW)} \tag{10}$$

In equation , W_{fix} groups the components whose weight does not depend on $TOGW$, and W_{var} groups the components whose weight does depend on $TOGW$. To solve equation , the secant numerical method has been used as in [21].

2.3. Boundary layer ingestion assessment in terms of weight.

To assess the benefits of BLI, TOGW has been taken as a figure of merit; however, the TOGW reduction for BLI configurations is related directly with the reduction on propulsion system weight when embedding nacelles into the airframe and removing pylons. The weight of a pylon-mounted propulsion unit is defined by equation .

$$W_{Prop\_Unit}^{No\text{-}BLI} = W_{engine} + W_{pylon} + W_{nacelle}^{No-BLI} \tag{11}$$

And the weight of a BLI propulsion unit can be accounted with equation , which includes the effects of removal of pylons and embedding nacelles into the airframe.

$$W_{Prop\_Unit}^{BLI} = W_{engine} + W_{nacelle}^{BLI} \tag{12}$$

The reduction on propulsion system weight, for BLI configurations due to nacelle embedding and removal of pylons, is characterized with equation . In this equation, ζ is the embedding percentage and represents the fraction of nacelle diameter that is embedded into the airframe, assuming a symmetrical nacelle. This assumption allows to relate directly the embedding percentage with a reduction in nacelle wetted area and hence nacelle weight.

$$W_{nacelle}^{BLI} = (1 - \zeta) \times W_{nacelle}^{No\_BLI} \tag{13}$$

Figure 2 (a) and 2 (b), show schematics representations of a pylon mounted nacelle and a BLI nacelle, respectively. Whilst in figure 2 (c), it is appreciated a detail view of an embedded nacelle and the fraction of embedding (ζ), which allows to model the nacelle weight reduction for BLI configurations using equation .
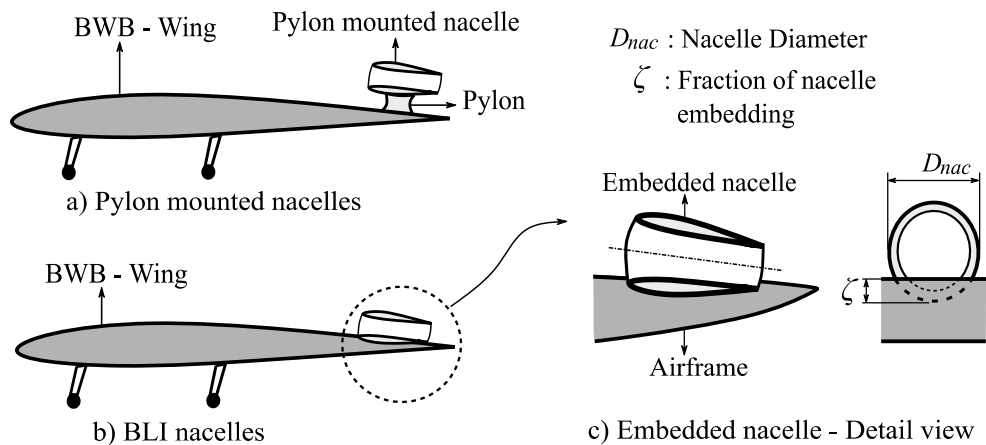
Figure 2. Nacelles configurations on a BWB-UAV [23].

3. Results and discussion

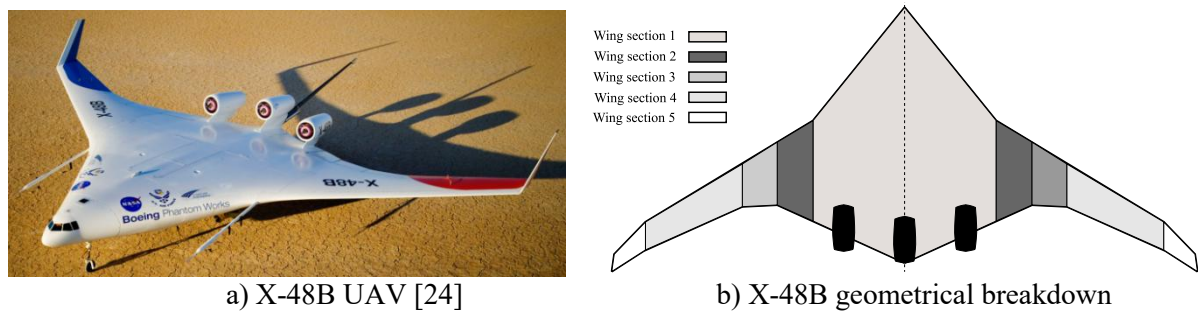a) X-48B UAV [24]   b) X-48B geometrical breakdown

Figure 3. NASA X-48B (8.5% scale model) [25].

The validation of the methodology and the case of study were carried out on the unmanned aircraft NASA X-48B BWB, figure 3 (a). Figure 3 (b) shows the geometrical breakdown in wing sections, which was used to estimate the BWB wing weight using equation (3). Table 1 presents the specifications of the NASA X-48B BWB-UAV.

Table 1. X-48B BWB-UAV specifications [26].

Parameter	Value
Wing span	6.22 (m)
Wing reference area	9.34 (m^2)
TOGW	227 (kg)
Maximum speed	60 (m/s)
Ceiling	3000 (m)
Endurance	40 (min)
Propulsion	3 JetCat P200 Turbojet
	0.23 kN thrusts each

To estimate the engine, nacelle and pylon weight, T_0 has been assumed to be equal to the maximum thrust provided by the three jet engines used by the X-48B aircraft. In this study, the engine weight remains constant for No BLI and BLI configurations. The propulsors are assumed to be distributed symmetrically rear of aircraft's centre of gravity on the BWB's centre body.

Table 2 presents the validation of the methodology used in this work, the actual value of TOGW, for the X-48B BWB, was taken from [26], and the actual weight of a JetCat P200 engine is given in [27]. To reduce the error incurred in TOGW estimation, it is required a more detailed weight breakdown to integrate some minor aircraft components that could have been passed over in this work.

Table 2. Validation results.

Parameter	Actual value (kg)	Estimated value (kg)	Error (%)
TOGW	227	218.5	3.74
Engine Weight	2.507	2.45	2.99

3.1. TOGW reduction due to BLI on NASA X-48B

To assess the TOGW reduction due to BLI on NASA X-48B, it was considered 3 BLI configurations with the following values of embedding fraction. $\zeta = 0$: This embedding fraction characterizes the removal of pylons. $\zeta = 0.5$ simulates a 50% of nacelle embedding, and $\zeta = 1.0$ represents the disappearance of nacelles and a fully embedded configuration, which would require to use special shaped ducts to ingest the airframe boundary layer as presented by Anabtawi [28]. Table 3 presents a comparison of the estimated TOGW for pylon-mounted nacelles and BLI configurations. The reduction on TOGW ($\Delta TOGW_{BLI}$) is in the range of 8% when removing pylons (0% BLI) and 19% for fully embedded configurations. When embedding nacelles, the propulsion system weight (W_{PS}) is reduced directly. However, the reduction on TOGW is not equal to the reduction on propulsion system weight (ΔW_{PS-BLI}), this is because the estimation of TOGW not only depends on propulsion system and the estimation of TOGW uses an iterative numerical method. TOGW reduction due to BLI is considerable and could be beneficial to improve cruise range, reduce fuel consumption, and other benefits in terms of aircraft performance.

Table 3. $TOGW$ and W_{PS} reduction due to BLI for NASA X-48B BWB-UAV.

Parameter	Pylon Mounted nacelles	$\zeta = 0$ 0% Embedded BLI	$\zeta = 0.5$ 50% Embedded BLI	$\zeta = 1.0$ 100% Embedded BLI
$TOGW$ (kg)	218.50[a]	200.47	187.35	175.09
$\Delta TOGW_{BLI}$ (%)	-	8.25	14.25	19.86
W_{PS} (kg)	24.61[b]	21.42	18.62	16.19
ΔW_{PS-BLI} (%)	-	12.96	24.33	34.17

[a] Reference value to evaluate the reduction on TOGW
[b] Reference value to evaluate the reduction on propulsion system weight.

3.2. Non-conventional propulsion system configurations assessment

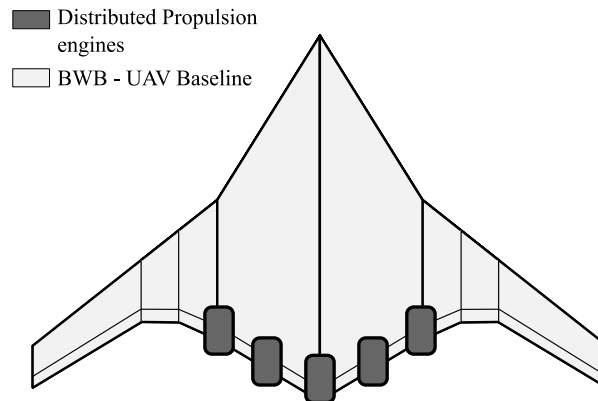*3.2.1. Distributed propulsion system configurations*

Figure 4. Distributed propulsion system configuration.

Additionally, the effect of increasing the number of engines on TOGW has been also evaluated. Figure 4 presents a non-conventional propulsion system with 5 propulsors distributed symmetrically on the BWB's centre body. To estimate engine, nacelle and pylon weight for distributed propulsion configurations, it was also assumed that T_0 is equal to the maximum thrust provided by the three engines used by the X-48B aircraft. This thrust has been divided for the number of propulsors, in analysis, to determine the required thrust from each engine. Figure 5 shows the benefits of BLI in terms of $TOGW$ and W_{PS} reduction, when increasing the number of propulsors.
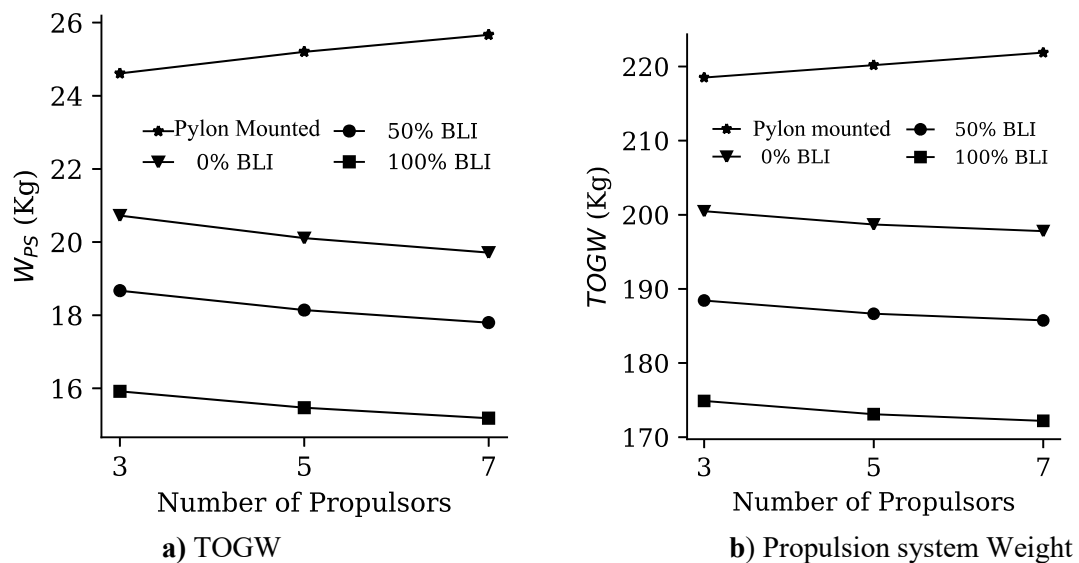

| a) TOGW | b) Propulsion system Weight |

Figure 5. $TOGW$ and W_{PS} reduction due to BLI and higher number of propulsors.

In figure 5 (a), it is observed that for BLI configurations, TOGW decreases when the number of propulsors increases, this is because for a higher number of propulsors, both engine and nacelle weight are reduced. However, the reduction in TOGW for BLI configurations, increasing the number of propulsors, is not so considerable. Now, for pylon-mounted configurations, increasing the number of propulsors increases TOGW due to pylons. Figure 5 (b) presents the same trend for the propulsion system weight, which shows that the main driver on TOGW is the propulsion system weight. Figure 6 shows the reduction on the wing weight for the X-48B when applying BLI and increasing the number of propulsors. Fuel weight, for the corresponding TOGW, also decreases with a higher number of propulsors for BLI propulsion systems. The reduction on wing and fuel weight is because the empirical relations used to estimate their weight depend directly on the TOGW, so if the TOGW increases, wing and fuel weight are increased proportionally.
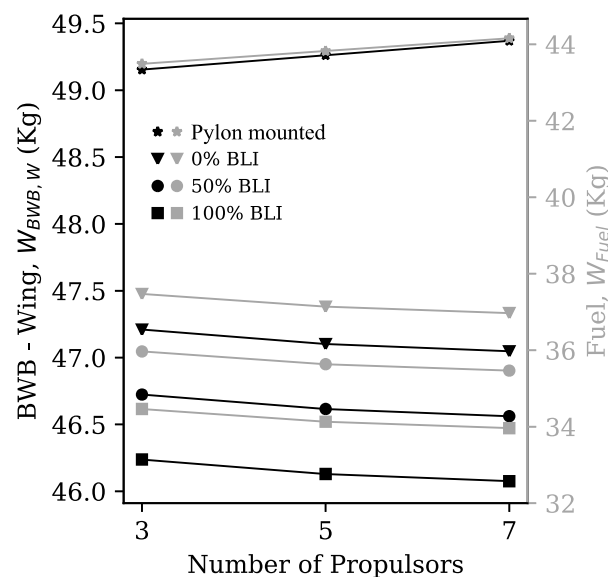
Figure 6. BWB wing and fuel weight reduction due to BLI and higher number of engines.

4. Conclusions

A weight assessment, at a preliminary design stage, for a BWB-UAV implementing BLI has been presented. TOGW has been taken as figure of merit and it has been determined that the implementation of BLI can reduce the TOGW between 8% and 19%. The reduction on TOGW due to BLI depends on how much a nacelle is embedded into the BWB airframe. TOGW decreases when the number of engines of a BLI propulsion system is increased; however the reduction is not so considerable. The reduction on TOGW due to BLI will improve range and endurance of a BWB-UAV, overcoming the current performance limitation, this makes more attractive and promotes the research of BWB-UAVs with BLI for civil applications, such as Site Specific Monitoring (SSM). Another benefit of BLI has been addressed, and the results obtained in this work encourages a more detailed research about the effect of TOGW reduction due to BLI, on aircraft performance, and propulsion-airframe integration.

Acknowledgements

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