LIFE CYCLE ASSESSMENT OF AN INTEGRATED UPPER SKIN WING BOX FOR NEXT GENERATION CIVIL TILTROTOR

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Abstract
The Next-Generation Civil Tiltrotor (NextGenCTR) will be one of the main flying demonstrators to be developed in the Clean Sky 2 Research Programme for the Fast Rotorcraft Innovative Aircraft Demonstrator Platform (IADP). Technology demonstration activities will be addressed to provide significant improvement with respect to current state-of-the-art Tiltrotors technologies. One of the key enabling feature of a civil Tiltrotor will be the advanced wing architecture having high level of integration able to minimize number of components, junctions and masses. Such optimization is mandatory to avoid the related structural weaknesses induced by its size, different operational configurations and unconventional/challenging flight conditions. Within Fast Rotorcraft (FRC) IADP Work Package 1, the T-WING project is aimed at developing, manufacturing, testing, and qualifying an Innovative Composite Wing for NextGenCTR. Specific T-WING new design and production techniques are fully relevant to the wider scope of Eco-Design Concept Implementation (FRC-IADP WP3) aiming to demonstrate the greening of rotorcraft production processes.
The Life Cycle Assessment (LCA) method defined for T-Wing complies with standard rules for assessing the environmental impact of the life cycle of a generic product (ISO 14040, 14044) from the extraction of raw materials, manufacturing and assembly processes (i.e. following a ‘cradle-to-gate’ approach). The use of such standards has been recognized as an effective way to assure a systemic and robust assessment. The standardized general rules drive a fruitful and effective approach to compare info, data collection criterions, data tracking methods and for result reporting. The life cycle inventory describes, in a detailed way, the wing box part characteristics, processes and the impact contributions referring to one single wing box with related air emissions, discharge in waters and soils through the full manufacturing process.
Preliminary LCA results, will be presented in order to identify, quantify, and evaluate environmental differences between a conventional structural concept and the innovative highly integrated upper skin wing box designed in the T-WING project.

1. INTRODUCTION

Tiltrotors are a class of vehicle that combines the advantages of aircraft (high cruise speed) and helicopters (Vertical Take-Off and Landing (VTOL) ability). Innovative and more effective passenger travel routes and emergency medical services are two good examples of such a platform.
Given the expected timeline from conceptualization to commercialisation of aerospace programs, key future technologies and innovations are today being developed within the European Union (EU) framework to further push forward the tiltrotor platform by Leonardo Helicopters Division (LHD) via its Next Generation Civil TiltRotor (NGCTR) Programme. This platform is part of the Clean Sky (CS2) programme that is co-financed by the EU and Industry under a Joint Technical Initiative (JTI) and is governed by a Joint Undertaking (JU) [1].

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Within this framework, Horizon 2020 (H2020) Clean Sky 2 FRC IADP NextGenCTR [2] will be dedicated to the design, manufacturing, and flying of an innovative Tiltrotor Technology Demonstrator (NGCTR-TD). Related flying demonstration activities, led by Leonardo Helicopters (LHD), will aim to validate its innovative architecture, and related key technologies.

The NGCTR-TD [2] is characterized by an advanced wing architecture (12 meters in span-wise direction), a fixed-engine installation with a split gearbox drivetrain in an efficient nacelle architecture, and an optimized V-tail configuration.

The advanced wing architecture is developed in co-operation with the T-WING consortium. It is classed as a Core Partner within the Clean Sky 2 programme and made up of Italian Aerospace Research Centre (CIRA) as Coordinator, Magnaghi Aeronautica, Salver, the Industrial Engineering Department of the "Federico II" University of Naples, Step Sud Mare engineering company, as well as IBK Innovation in Germany. The final objective of the project is to design and qualify the structure of the wing and moveable surfaces, involving design, manufacturing and ground tests up to flight [3], in compliance with the technical specification set by the Work Area Leader Leonardo Helicopters.

The main innovations related to the wing structure are the highly integrated composite concept and the presence of two moveable surfaces: a flaperon and a morphing flap.

Main driver for wing innovations is the impact on environmental emissions. Larger and clearer gains can be reached through the use of lighter airframes, which raise aircraft fuel efficiency, reducing emissions and lowering operating costs.

To achieve lighter airframe structures, the main design choice was to move towards carbon fibre reinforced plastics. Composites offer many advantages such as high specific strength, resistance to fatigue, improved manufacturability through part integration, which reduces part count and assembly times [12].

Main scope of Eco-Design Concept Implementation (FRC-IADP-WP3) was to assess global environmental impact of key tiltrotor technologies by means of Life-Cycle Assessment (LCA) tools.

As environmental issues become more relevant, the need to assess environmental performance from technological developments also arises for future aircrafts. For this reason, LCA method was selected for the assessment. It is a structured and internationally standardised methodological framework, which assesses the environmental impacts of a product over its life cycle [4].

The implementation of a such LCA approach is also the first step to fully quantifying the environmental effects of aircraft manufacture and forming a benchmark against which future improvements can be measured. This work aims to implement environmental assessment tools and to apply it to an industrial relevant use case, where the most significant innovations (the innovative scenario) are assessed against an established baseline scenario.

Figure 1 – Next Generation Civil TiltRotor (NGCTR).

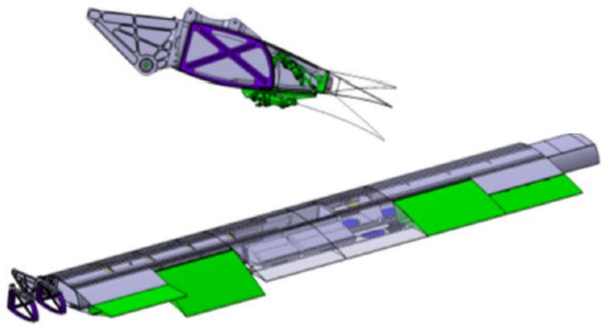

Figure 2 -- TWING Full wing assembly.

The study considers preliminary evaluations based on manufacturing trials of 5 metres upper skin highly integrated CFRP wing box. This innovative item is produced in autoclave and compared to multi-part assembly of CFRP upper skin wing sub-assembly. Key parameters affecting both scenarios are identified. LCA is carried out in parallel where impacts associated with each manufacturing process are quantified and dominant stages identified.

2. TECHNOLOGY SCENARIO

The wing design is very unique to the tiltrotor aircraft. It features characteristics and constraints which are very different from conventional fixed-wing aircraft and therefore it introduces specific challenges.

A key goal is to reduce complexity of the wing making it straight with no dihedral or sweep, and so providing easier assembly of the interconnecting shaft and eliminating the need for a mid-wing gearbox. The TD wing will use flaps much larger than those of any prior

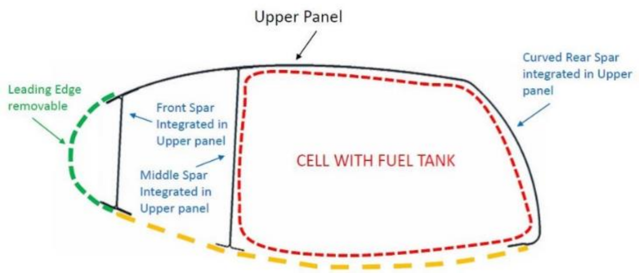

Figure 3 – TWING Integrated Upper Skin Wing box.

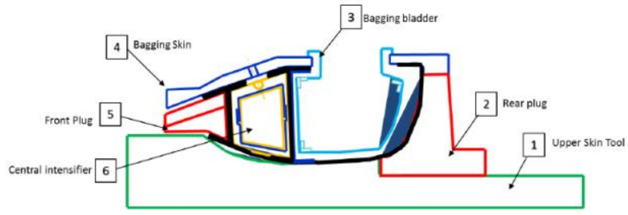

Figure 4 – TWING tool concept for innovative upper skin production system.

tiltrotor. These devices are required because of the fixed engine configuration and the higher download from rotors.

In addition, a quite important challenge will be to provide maximum wing aerodynamic efficiency in flight while taking into account all the required equipment and specific sub-systems functions to be maintained.

All these specific requirements will be fulfilled exploiting advanced structural architecture with lightweight composite materials, integration of major wing airframe sub-systems and intelligent manufacturing techniques.

In particular, the construction of the upper skin wing box is made of composite materials by means of an integrated co-curing process of the main structural elements [5]: spars (forward, middle, rear), stringers, and the leading edge.

Under co-curing, the main objective is to induce solidification (or hardening) of a composite rolled section simultaneously to the adhesion of the latter to the CFRP material. In the co-curing, the resins of the composite laminated element of the fastening adhesives then harden simultaneously.

This technology provides the main advantage, compared to traditional constructions, to avoid connections of structural elements by means of riveting: a slow process retaining a considerable degree of accuracy and which however cannot implement a fully smooth external surface.

By referring to Figure 3, the innovative composite structural item consists of an upper skin made of laminated fabric and uni-directional CFRP materials implemented with a process of co-curing to CFRP front, middle and rear spars and to stringers. The whole assembly is inserted in an autoclave mounted on a dedicated tooling, inside thereof the resin of the carbon fibre hardens simultaneously.

The production system of these integrated structures provides the simultaneously construction, through dedicated tooling, of the outer upper skin, and of the inner structural elements (i.e. spars and stringers), as reported in Figure 4. This is implemented by means of combined system of stiff metal tools and flexible tools so as to guarantee the required compaction of the rolled sections made of carbon fibres and to allow the treatment in autoclave.

Once lay-up made of fabric and uni-directional CFRP materials are completed, the appropriate consumables are added on the main upper skin tool made in Invar (Figure 4). Rear and front plugs are used to position the main item into the tool, and the bagging skin for bladder is used for positioning and couplings between plugs and skin. The central intensifier and the bagging bladder is used to improve compaction between spars and the upper skin during the co-curing process.

3. GOAL AND SCOPE

The aim of this study is to assess the life cycle from cradle-to-gate of the innovative, highly integrated, composite wing box for NGCTR designed by TWING, quantifying its environmental impacts and mitigation benefits. The tool will assess the innovative wing box manufacturing technology in comparison to a conventional structural concept for the production of the same wing box in order to evaluate the accomplishable environmental benefits.

In the cradle-to-gate approach, the system life cycle will be considered from extraction of raw materials, to final manufacture and assembly.

The following manufacturing scenarios are considered in this study:

Scenario 1 – Innovative (TWING use case): upper skin highly integrated CFRP wing box prepeg hand layup composite by autoclave.

Scenario 2 – Baseline: wing box obtained by multi-part assembly of composite manufactured by prepeg hand layup and cured in autoclave.

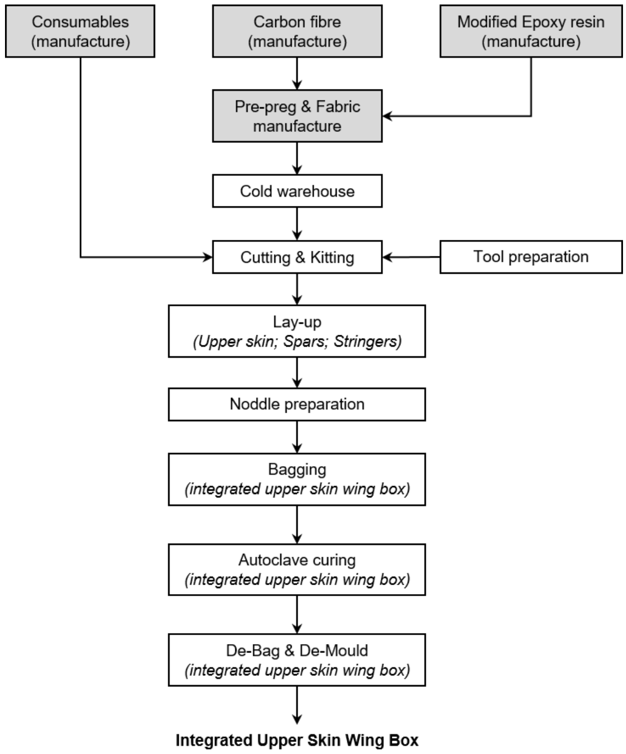

Figure 5 -- TWING Innovative Scenario: process flow

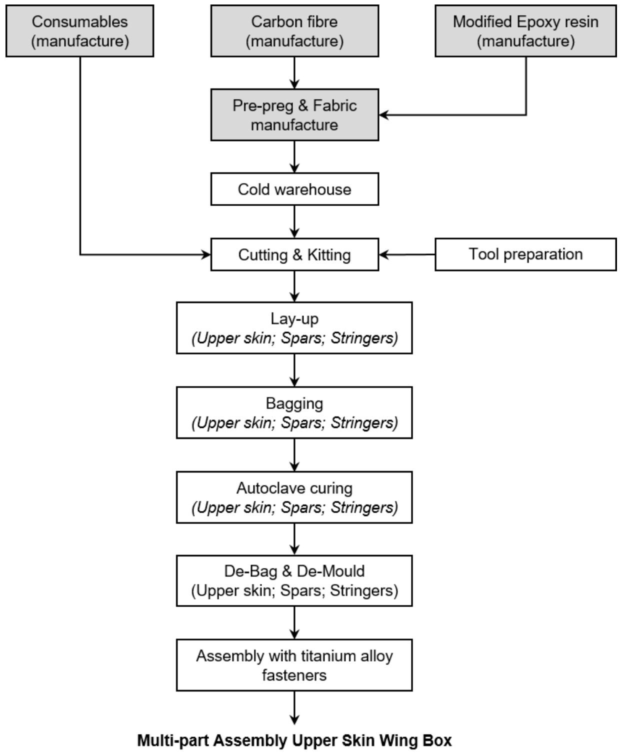

Figure 6 -- TWING Baseline Scenario: process flow

3.1. Scenario 1 – Innovative

The system diagram for scenario 1 is shown in Figure 5 and identifies all processes that are included in the assessment. Carbon fibre are manufactured, wounded into bobbins, and transported to the resin manufacturing site where prepregging occurs. The continuous fibres are unwound, spread, and combined with a hot melt epoxy modified resin and then packed with a protective fine and backing polypropylene paper. The uni-directional prepregs are then transported by truck to the site of production of the upper skin wing box. For the fabric, carbon fibres are then woven to a flat, two-dimensional textile structure.

At the manufacturing facility the sheet materials enter a preparation cell where an automated cutting machine is used to appropriately cut shaped plies and consumables. Energy use for the cutting machine are based on total time of machine use, and waste generated in the form of off-cuts represent 15% of initial material quantity. Once all materials have been cut, they are transferred to a lay-up cell. Lay-up is a labour intensive process requiring each ply to be applied to a mould face by hand. Laminate stack is prepared by hand for the main structural items: the upper skin, spars, and stringers. Once lay-up is completed the appropriate consumables for each structural item are added and the tool fully prepared.

In order to complete the part production, in the noddle preparation phase, UD tape stripes (45 mm) are cut, rolled and positioned in the cavity of the forming tool. After the installation of the compacting plate, the noddle is compacted by vacuum.

To ensure adequate compaction of the laminate, the TWING tool concept is arranged as described in Figure 4 with a central intensifier, plugs and bagging bladders. Various consumable materials are added to the laminate prior curing to facilitate adequate compaction of the structural items.

During the curing cycle, to ensure a satisfactory level of polymerisation is reached, temperature in the autoclave is regulated and pressure is applied.

3.2. Scenario 2 -- Baseline

The system diagram for scenario 2 is shown in Figure 6, and identifies all the processes steps included in the assessment. Carbon fibre materials (UD and fabric) are always considered for the structural items. Same consumable materials are assumed to be used for manufacturing each composite part: upper skin, spars, and stringers. For all structural items, laminate stack is prepared by hand and then cured in autoclave.

Total CFRP material weight used will be 6.2% higher than innovative scenario, and as main structural material titanium alloy fasteners have to be included for assembly of spars and stringers to the upper skin.

Total titanium alloy weight used for fastening is estimated to be equal to almost 12% of the gross weight of the innovative scenario.

The tool concept for the baseline configuration will have specific dedicated mould for each part in order to guarantee adequate quality and compaction of the laminate stack. Therefore, the total estimated consumable weight needed will be 141% higher compared to innovative scenario.

4. METHODOLOGY

LCA is an internationally standardised methodological framework used for estimating and assessing environmental impacts of the life cycle of a product or service [4]. It can be used to compare products and determine the most environmentally acceptable, or for improvement strategies, where a single product is evaluated in order to highlight environmental hotspots for improvements. LCA is therefore a useful decision support tool for the development of sustainable manufacturing practices. A set of standards defined by the International Standard Organization [4] provide a systematic procedure detailing how to conduct and interpret such a study and related main stages: (i) Goal definition and scope, (ii) Inventory analysis, (iii) Impact assessment, and (iv) Interpretation. ISO standards have been used to drive the methodological approach adopted in this study and the commercial available LCA software package SimaPro [6] has been used to perform the modelling.

A cradle-to-gate assessment is carried out for the first two phases of the product system are studied: raw materials production, and manufacture.

Raw materials production for carbon fibre and modified epoxy resins are considered with their transportation and intermediate production steps, such as prepregging of the fibres. The manufacturing of consumable materials required for each manufacturing processes is also considered as well as their disposal after use, assumed to be by incineration. The manufacturing location of the upper skin is in Italy and the Italian average power mix is applied for all operations. All transportation is by standard load capacity lorry with distances from major materials supplier in Europe and calculating distance by road to a destination in south Italy.

5. LIFE-CYCLE INVENTORY

Raw materials production processes are modelled in the SimaPro. For the continuous carbon fibre, the process includes the production of the polyacrylonitrile (PAN) precursor and all relevant flows [7]: spinning, stabilization, carbonization, surface treatment and sizing. Main process data for prepreging and weaving was estimated as specified in literature [8]. The modified resin system was modelled starting from CFRP material safety datasheet composition as mixed of: epoxy resin, aniline, and thermoplastic resin. Starting from respective material safety datasheet, all consumable materials were modelled as specified in Table 1, where specific composition is retrieved from Ecoinvent Database v3.6 [9].

Energy consumption values for the autoclave were based on estimations obtained from supplier considering that autoclave uses a heat exchanger with an internal closed circuit with oil, and a radiator is installed to provide heat.

All production waste was assumed to be disposed through incineration with heat values from general plastic waste taken from Ecoinvent database [9].

Data quality of the created datasets and selected Ecoinvent datasets are verified by means of the pedigree matrix of Weidma [10], which defines reliability, completeness, temporal correlation, geographical and technological correlation.

Product	Materials and processes
Breather fabric	Nylon 6 {RER} Weaving, synthetic fibre {GLO}
Cleaning substance	Acetone, liquid {RER}
Peel ply	Nylon 6 {RER} Extrusion, plastic film {RER}
Vacuum bag foil	Nylon 6 {RER} Extrusion, plastic film {RER}
Vacuum sealant tape	Synthetic rubber {GLO} Extrusion, plastic film {RER}
Releasing agent	Naphtha {RER} 1-butanol {GLO}, Sulfuric acid.
Releasing film	Tetrafluoroethylene {GLO} Extrusion, plastic film {RER}

Figure 7 – Materials and processes selected from Ecoinvent [9] to model consumables

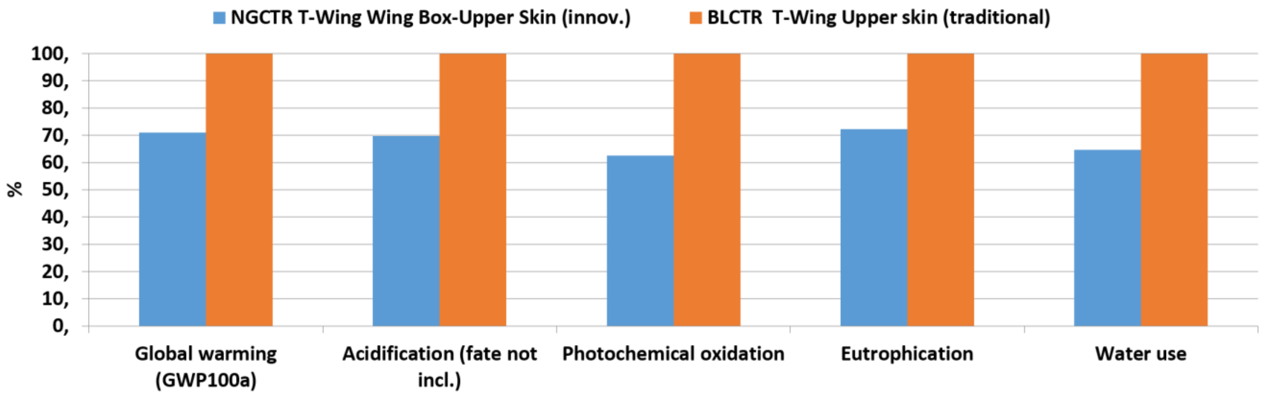

Figure 8 -- Comparing 1 p 'NGCTR T-Wing Wing Box-Upper Skin (innov.)' with 1 p 'BLCTR T-Wing Upper skin (traditional)'; Method: PCR 2019-09-06 V3.06 [21] / EU25 / Characterisation.

6. IMPACT ASSESSMENT

The assessment of potential environmental impacts consists of aggregating inventory data, obtained through the inventory analysis by means of Life Cycle Impact Assessment (LCIA) methods shared by the scientific community [11]-[15]-[18].

The method considered for the calculation of the environmental impacts assessment is based on main indicators highlighted in the available Product Category Rules (PCR) in the aeronautic field for business jet [14]. The following environmental impact categories are reported:

- Emissions of greenhouse gases, expressed as the sum of global warming potential (GWP), 100 years, in carbon dioxide equivalents (kg CO2 eq.). Global warming potential category indicator is considered from the CML-IA baseline [16].
- Emissions of acidifying gases, expressed as the sum of acidification potential expresses in sulphur dioxide equivalents (kg SO2 eq.). Acidification potential (AP) category indicator is considered from the CML-IA non-baseline method [16].
- Emission of gases that contribute to the creation of ground-level ozone, “photochemical oxygen creation potential”, expressed as the sum of ozone-creating potential, in ethylene equivalents (kg C2H4 eq.). Photochemical oxidation potential (POCP) category indicator is considered from the CML-IA baseline method [16].
- Emission of substances to water contributing to oxygen depletion, “eutrophication”, expressed as phosphate (kg PO43- eq.). Eutrophication potential (EP) category indicator is considered from the CML-IA baseline method [16].
- Water scarcity potential, expressed in water stress index (WSI), m3 eq from the AWARE method [17].

The impact assessment was carried out with the commercial LCA software package SimaPro Software [6]. The characterization results are expressed as total result for each impact category indicators in Figure 8. Comparing innovative and baseline scenario, we have reductions higher than 25% for all main impact category indicators.

The dominant sources of emissions for both scenarios can be investigated with specific review of main process contribution for each category indicator. Assuming a cut-off equal to 3,8% of the total indicator results, all higher processes contributions are reported in Figure 9-13.

In Figure 9, for the GWP, the main contribution is related to the electricity and heat production for raw material production and then processing. The thermoplastic resin, available in the CFRP resin system, is the third contribution in absolute value for the GWP. Indeed, comparing the two scenarios, we have a reduction in GWP equal to 30% in the innovative wing box mostly because of the minor CFRP material (-6.2%) used.

In Figure 10, for the AP, the main contribution is similar to ones discussed for the GWP. In this case, acrylonitrile has a larger effect on the AP indicator.

In Figure 11, for the POCP indicator, results are mainly dependent from electricity production mix for the CFRP and titanium material. Indeed, comparing POCP indicators for the two scenarios, we have reductions equal to 37% in the innovative wing box mainly because of the titanium material used for fastening of the baseline multi-part assembly.

The EP is mainly affected by required electricity for raw materials production as per Figure 12.

Finally, the water use indicator is reported in Figure 13 where main contributors are related to electricity production for raw materials, process for acrylonitrile production, and production of high voltage electricity from hydropower plants mainly used in Italy during manufacturing activities of the upper skin.

Comparing water use indicator for the two scenarios, we have in the innovative scenario also a reduction mainly due to reduce use of ancillary materials as specified in associated processes contribution: nylon 6, synthetic rubber and extrusion plastic.

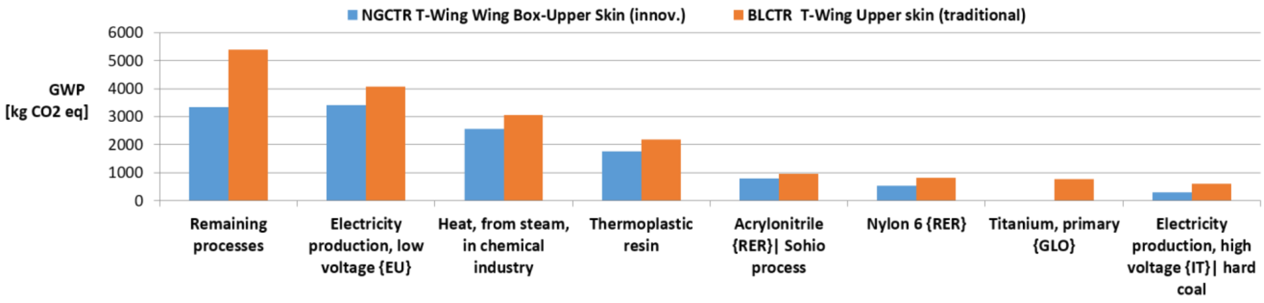

Figure 9 – Process contribution: Global Warming Potential (GWP). Method PCR [21], Characterization, Cut-off 3.8%.

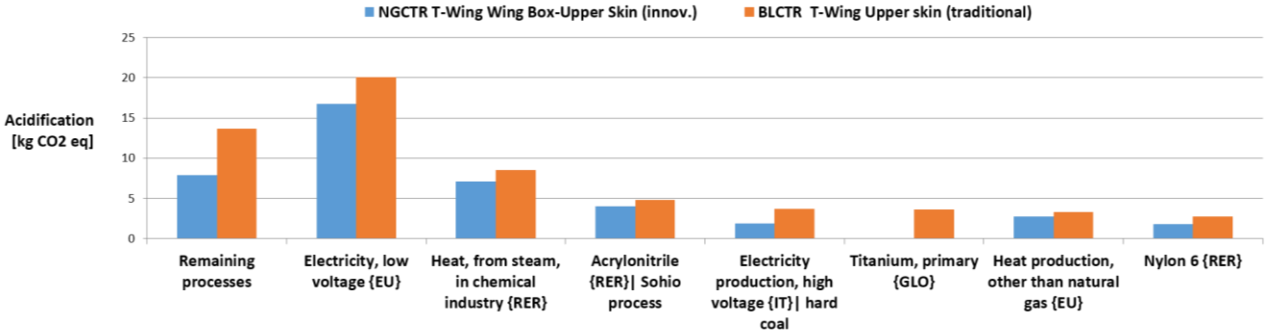

Figure 10 – Process contribution: acidification. Method PCR [21], Characterization, Cut-off 3.8%.

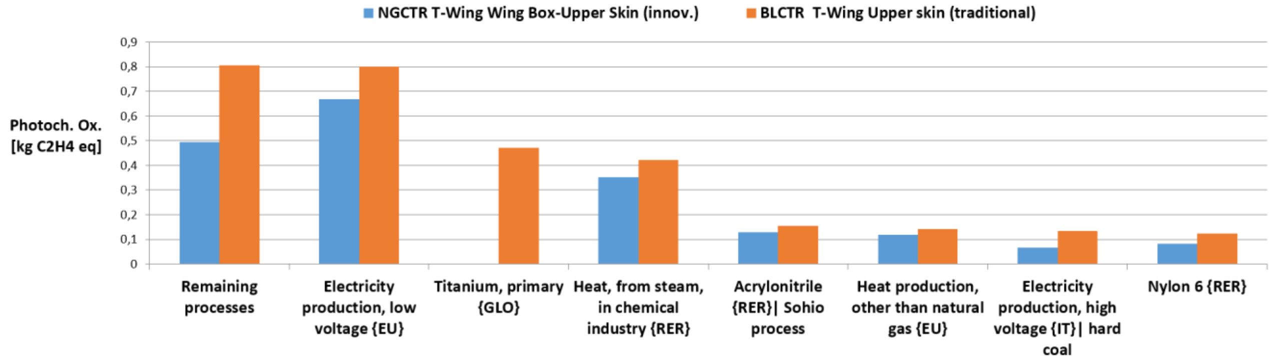

Figure 11 – Process contribution: photochemical oxidation. Method PCR [21], Characterization, Cut-off 3.8%.

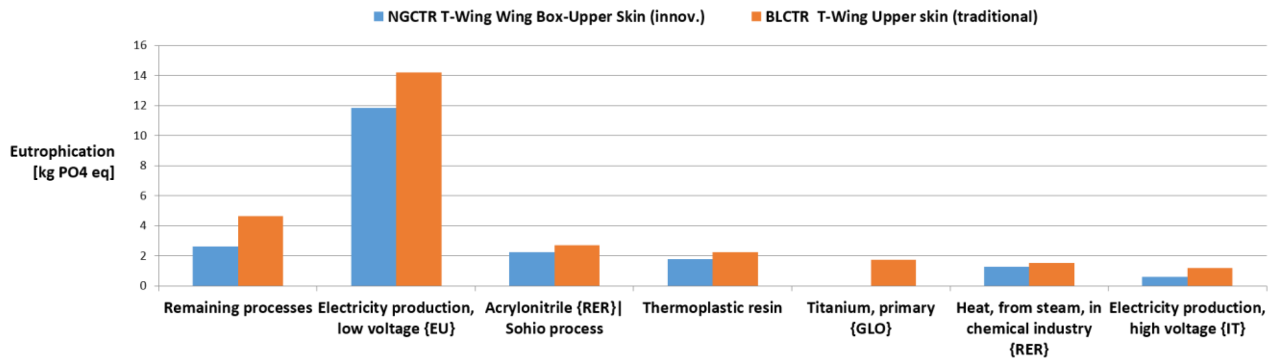

Figure 12 – Process contribution: Eutrophication. Method PCR [21], Characterization, Cut-off 3.8%.

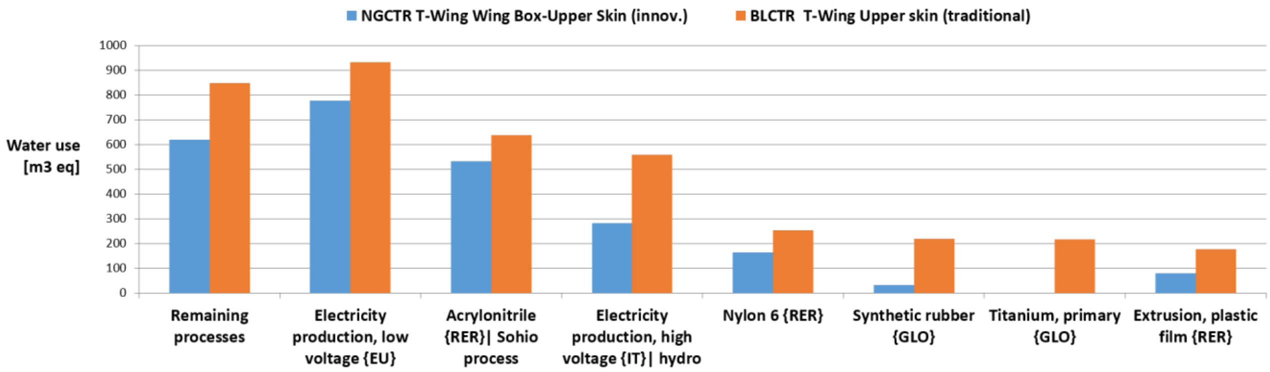

Figure 13 – Process contribution: Water Use. Method PCR [21], Characterization, Cut-off 3.8%.

7. CONCLUSIONS

As tiltrotors are a class of promising vehicle for different transport missions, the Next Generation Civil Tiltrotor (NGCTR) platform is currently under development within the EU Clean Sky Programme. Several key technologies will be validated during the research program with a flying Technology Demonstrator (TD).

The integrated wing architecture, developed by TWING, is one of the most innovative and industrially relevant sub-systems designed, manufactured and ground tested up to the flight for the NGCTR. The technology has been introduced with the related features for part manufacturing, as well as for the developed system.

In this study, a specific LCA methodology was implemented to assess environmental “cradle-to-gate” performance. Two scenarios were considered in the study. Main differences between them are related to:

- Integration of main structural items.
- Total CFRP used (6.2% higher in the innovative scenario).
- Titanium alloy used for fastening main structural items.
- Reduced amount of ancillary and consumable materials used in the production for the innovative scenario.

Materials, in particular carbon fibres, have the highest impact on environmental burdens of the wing box. Using less CFRP materials through the integrated wing box architecture has shown a reduction of all main category indicators.

Assessing specific process contribution for each category indicators was useful to identify main environmental drivers and to quantify main gains obtained in the innovative scenario.

8. ACKNOWLEDGEMENTS

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