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INFINITE

Aerospace composites digitally sensorized from manufacturing to end-of-life

D5.2
Life Cycle Analysis and Circularity Assessment (LCA)

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ABSTRACT / EXECUTIVE SUMMARY	
Abstract	This deliverable presents the life cycle assessment (LCA) and circularity evaluation of novel sensorised carbon fibre reinforced polymer (CFRP) panels developed in the INFINITE project. These panels integrate microwires (MWs) with Giant Magneto-Impedance (GMI) properties, enabling real-time monitoring during manufacturing and service life. The study compares the environmental performance of these sensorised CFRPs to conventional non-sensorised panels, using the Product Environmental Footprint (PEF) methodology. The LCA encompasses all life cycle stages—from raw materials to end-of-life—based on a functional unit of 1 m² of CFRP panel. Key results show that while the inclusion of MWs slightly increases environmental impacts during manufacturing, these are outweighed by substantial gains in process control and maintenance efficiency. Monitoring during manufacturing reduces material waste and defective output by up to 39%, lowering climate change impacts and improving resource circularity. During the use phase, early damage detection enabled by MWs reduces the frequency and severity of repairs, preventing panel replacements and reducing associated impacts by up to 96%. End-of-life scenarios integrate a pyrolysis-oxidation process for carbon fibre recovery, contributing to circularity through secondary material valorization. Overall, sensorised CFRPs achieve modest reductions in total life cycle environmental impacts—particularly in resource use and waste generation—depending on manufacturing efficiency. This analysis confirms the potential of embedded sensing technologies to not only enhance structural monitoring but also reduce the environmental footprint of high-performance composite materials, aligning with circular economy goals in the aerospace sector.
Keywords	INFINITE, life cycle assessment, circularity, end-of-life, recycling, pyrolysis, recycled carbon fibre, circular footprint formula, environmental impact, environmental footprint.

TABLE OF CONTENTS

1. INTRODUCTION

Although the main objective of any research project is to reach the defined technical objectives, it is necessary to monitor how these achievements affect the current sustainability of the equivalent situation that the project is expected to provide newer and better solutions.

At this point, the life cycle assessment methodology has achieved great recognition in the scientific community as it is able to assess quite precisely different environmental impact categories considering the complete life cycle of the product evaluated. This means that manufacturing, use and end-of-life stages of the product system will be assessed avoiding any mis-quantification due to impact from one stage to other.

The INFINITE project aims to develop a new technology based on the use of microwires with excellent magnetic properties, the Giant Magneto-Impedance (GMI), which can be used changes on the tensile of the microwire due to physical or thermal changes. Therefore, when introducing these MWs in CFRP products, as panels, the monitoring of this property can be used to determine if the CFRP panel has been modified somehow.

The results of the life cycle assessment carried out to assess the environmental improvements bring by this new technology compared to current conventional CFRP panels are collected in the following sections of this deliverable.

2. OBJETIVES

The main objective of the life cycle assessment carried out was to assess the environmental improvements brought by the incorporation of microwires to CFRP parts, to improve the monitoring of the manufacturing processes and of the maintenance process during the use stage of these parts.

To develop this assessment, two product systems will be compared. Firstly, the current system process, not implementing microwires, following current manufacturing procedures. Secondly, the INFINITE's product system, in which CFRP parts implement the microwires which will provide some magnetic properties that could be used to monitor the manufacturing processes, reducing defects, scrap generation and avoiding the generation of wastes, and to monitor the health and safety of the CFRP parts during the use stage, improving the efficiency of the maintenance operations, reducing waste generation, and avoiding consumption of virgin resources.

On the other hand, different CFRP manufacturing processes tested in the project could be compared in order to assess and compare their environmental behaviour.

To carry out the life cycle assessment, the product environmental footprint methodology developed and published in 2021 by the European Commission was followed. This methodology, based on ISO 14040 and ISO 14044 standards, sets the rules to make comparable life cycle assessments for a product according to homogenous method. It defines how to carry out each of the life cycle stages and which environmental impact categories have to be assessed (16 environmental impact categories and a single impact indicator, the environmental footprint, which is assessed after a normalization and weighting procedure that has been fully defined. Likewise, the methodology stablishes how to carry out the inventory and how to assess the quality of the data inventory, defining minimum quality requirements for the inventory in order to validate it.

In this assessment, all impact categories will be assessed but the focus will be put mainly on two of them:

- the climate change, and
- the environmental footprint,

as these categories could represent the easier understandable environmental impact categories.

3. SCOPE OF THE STUDY

3.1 FUNCTIONAL UNIT

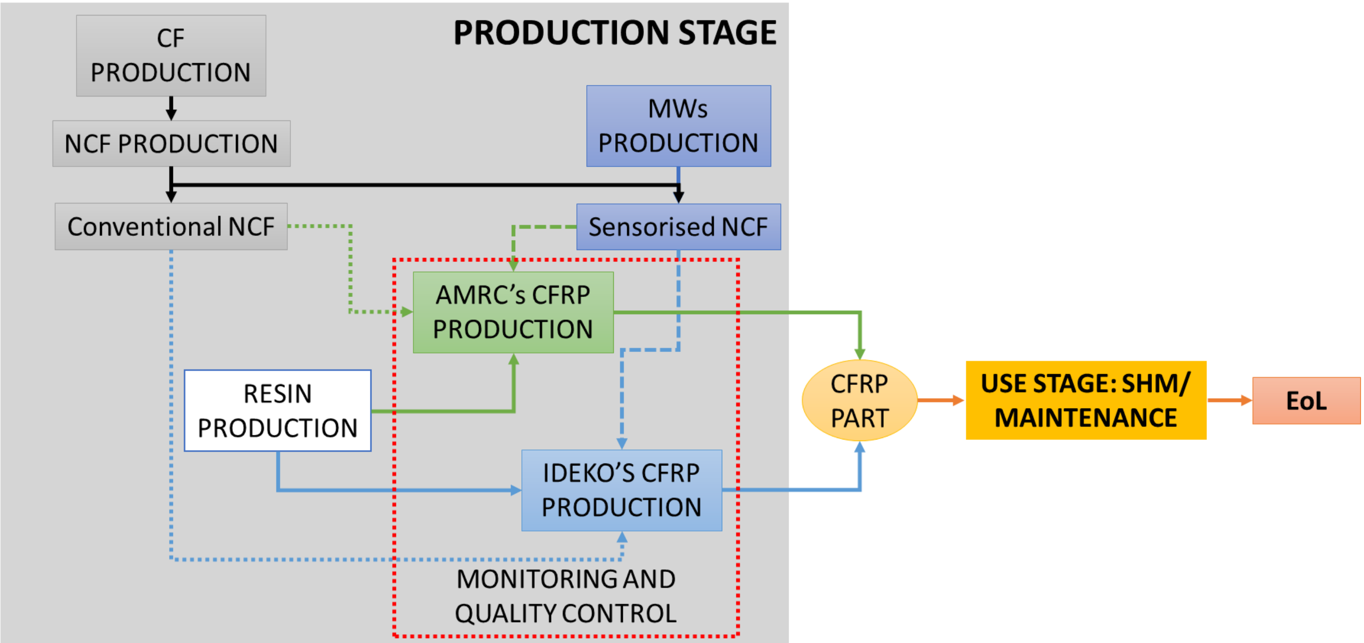
To make a fairly assessment of the potential environmental benefits and drawbacks brought by the sensorisation of the CFRP through incorporating the microwires in the NCF, it is necessary to define a functional unit that can be easily understood and for which the data inventory could be carried out for all manufacturing processes and all life cycle stages in both product systems: current non-sensorised CFRP and INFINITE's sensorised CFRP.

The functional unit defined was a 1 square meter of a CFRP flat panel.

3.2 SYSTEM BOUNDARIES

The scope of the study is a "from cradle to grave". This means that all life cycle stages will be considered, from raw materials production, CFRP manufacturing, use stage (considering the maintenance operations for the flat panel according to the air sector specifications) and end of life (considering current and INFINITE's practices).

In figure the system boundaries are shown for both product systems:



On the other hand, the assessment carried out is comparative, so some simplifications have been considered in order to make a better use of the available resources. This affects mainly to transport and distribution processes, as they are very dependant on the place where operations/processes are carried out and will provide not valuable information for the main objective of the study, to assess the environmental improvement provided by the use of the microwires in CFRP parts in the air sector.

Therefore, **the main manufacturing process** have considered:

- the microwires manufacturing, including the quality control of the produced MWs,
- the manufacturing of the NCF, without and with MWs,
- the manufacturing of the CFRP panels, for which we assessed three different manufacturing alternatives developed in the project:
  - Infusion process carried out by IDEKO

– Infusion process carried out by AMRC
– Double Diaphragm Forming carried out by AMRC

The manufacturing process/operation control without and with MWs has also been modelled and assessed. One of the advantages of implementing MWs in the manufacturing of CFRP products is the capability of these MWs of check the condition of the product manufacture during each operation/process involved, so any defect or damage on the product can be identified as soon as it occurs, not proceeding with the rest of operations/processes needed to finish the manufacturing process. This means a reduction in resources consumption and waste generated.

During the **use stage of the CFRP panel/products**, the MWs will be used to early identification of damages.

For the last decades the use of CFRP parts in aircraft construction has increased significantly due to the great advantages this type of materials brings compared to traditional materials as metal alloys like aluminium, steel and titanium, mainly related with weight reduction while keeping good mechanical and chemical properties.

On the other hand, aircraft sector is one of the most demanding sectors in terms of safety, therefore several periodic controls are performed during the lifespan of an aircraft focused on guaranteeing the airworthiness and safety of the plane and the crew and passengers' safety during the flight.

To carry out these controls each airplane has its own Aircraft Maintenance Program (AMP). This program describes the scheduled maintenance tasks and their prescribed frequency, which are necessary for the safe operation of the aircraft and maintaining its continuing airworthiness. The frequency of maintenance is typically determined based on parameters such as Flight Hours (FH), Flight Cycles (FC), calendar time, engine/APU hours/cycles, or engine/landing gear changes. There are two main reference AMP models, the European Union Aviation Safety Agency (EASA) and the Federal Aviation Administration (FAA).

Maintenance tasks are often grouped into a series of checks, commonly referred to as letter checks, which have increasing scope and are performed at defined intervals. A simplistic view is that A-Checks are performed in terms of months, C-Checks in years, and D-Checks in five-year periods (lustrums).

Typical maintenance check intervals include:

– A-Check: Typically performed every 1–2 months, or after 250–650 flight hours. It's usually done within one night and involves routine checks to ensure everything functions safely and efficiently. An equivalent A check for the A380 can be scheduled every 750 flight hours.
– B-Check: Typically performed every 3–5 months, or usually after every 1000 flight hours. This check is more extensive than an A-check and usually takes 0.5–1 day. For modern aircraft, the B-Check is disused, with its content absorbed by other checks.
– C-Check: Typically performed every 1–1.5 years. This check usually takes 1–2 weeks and requires the aircraft to be docked in a hangar for detailed inspections. An equivalent C check for the A380 can be scheduled every 24 months or 6,000 flight hours. A C-Check is considered heavy maintenance.
– D-Check: Typically performed every 4–10 years. This is a general overhaul that takes approximately 4–6 weeks and involves dismantling large parts of the aircraft for inspection and reassembly. For older aircraft like the Boeing 737, a D check might be done at 24,000 FH, while for the F27 it was every 18,000 FH, for the Boeing 727 around 8,000 FH, and for the DC9 also around 8,000 FH. A D-Check is also considered heavy maintenance.

There is a clear tendency to extend these maintenance intervals for newer aircraft programs. Structural inspections for the A380, for example, can be scheduled every 6 and 12 years.

Beyond these main checks, specific components have their own maintenance schedules, including scheduled tasks, Life Limited Parts (LLP) replacements, and overhauls, typically based on manufacturer's Instructions for Continued Airworthiness (ICA) and inputs from a Reliability Program. Preflight checks are also performed before each flight.

On the other hand, the framework for how these tasks are determined and performed is explained:

1. Maintenance Task Definition: Scheduled maintenance tasks for components and systems, which may include non-structural composite parts (e.g., panels, fairings, internal components), are derived from the Instructions for Continued Airworthiness (ICA), Component Maintenance Manuals (CMMs), Aircraft Maintenance Manuals (AMMs), and Reliability Program requirements. These tasks can include Cleaning (CLN), Lubrication (LUB), Servicing (SVC), Operational Checks (OPC), Functional Checks (FNC), Visual Checks (VCK), General Visual Inspections (GVI), Detailed Visual Inspections (DET), Special Detailed Inspections (SDI), Restoration (RST), Discard (DIS), among others. Nondestructive Evaluation/Inspection (NDE/NDI) is also a surveillance maintenance process used to check item integrity.
2. Check Interval and Scope: The A, B, C, and D checks provide the scheduled windows for performing these accumulated tasks.
3. Component Maintenance Locations: Maintenance on components, including those with composite parts, can be performed on-wing (while installed on the aircraft, often during Line or Base/Heavy checks) or off-wing (in a workshop). Off-wing maintenance is guided by CMMs and includes procedures for assembly/disassembly, cleaning, inspection, checking, repair, and limitations. On-wing maintenance procedures are found in the AMM.
4. Specific Component Programs: Certain complex systems or components, such as landing gear, powerplants (engines, APUs), and evacuation slides, have their own detailed maintenance programs and Life Limited Parts (LLPs) that integrate with the overall aircraft checks. Overhauls for engines and APUs, for instance, provide opportunities to perform maintenance tasks on their components, some of which may be composite.

Maintenance tasks for the systems and components are defined based on their specific characteristics and requirements (using documents like ICA, AMM, CMM, and processes like MSG-3). These tasks are then strategically allocated to the A, B, C, D, and other checks based on their required frequency, the access needed, and the overall maintenance concept adopted by the operator. Routine visual inspections might occur in A-checks, while more detailed inspections or component overhauls involving composite parts would likely be scheduled for the more extensive C or D checks or performed off-wing as part of a component maintenance program.

The main types of accidental damages that can occur in aircraft are painting peel off, oxidation, dent, wind erosion, hole, delamination and debond. According to literature, the distribution of occurrence of each of them is shown in Figure 1.

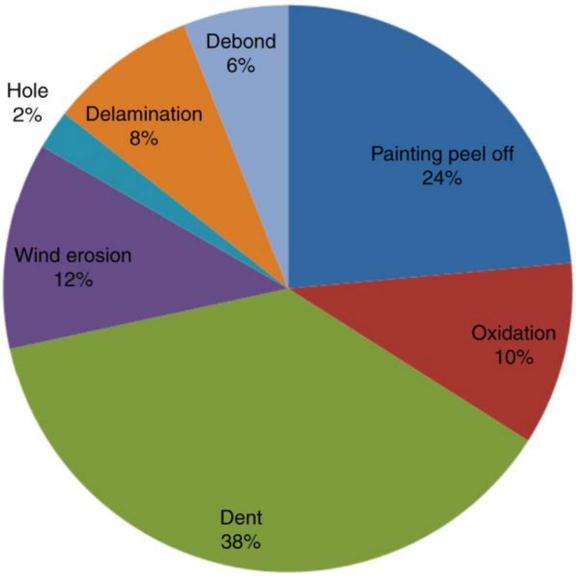


Figure 1: Damage category distribution

As it can be seen, dent damage is the most likely impact damage to happen in aircraft during the operative life of an airplane.

The primary repairing operations for composite aircraft parts are categorized into two main techniques: Bolted repair and Bonded repair. These repairs are performed as part of the overall maintenance program, often triggered by damage discovered during scheduled checks or unscheduled events like impact.

Here's a breakdown of the main composite repairing operations as described in the sources:

5. Overall Repair Process: When damage is identified in a composite structure, it is evaluated to determine a suitable maintenance activity. The general procedure involves damage identification, repair design, damage removal, patch or repair material selection, surface preparation (for bonding or curing), repair layup, curing (for bonded repairs), repair verification, and refinishing. All repairs must be conducted by approved organizations and personnel using approved processes, which are typically specified in manufacturer's approved repair manuals or follow drawings approved by the Regulatory Authority or a delegated design authority.
6. Main Repair Techniques:
   - Bolted Repair: This technique is described as being borrowed from conventional metal repair. It involves mechanical connections like riveting or bolting. Bolted repair is generally simple and quick. However, it changes the original shape and design of the structural component, which is considered structurally undesirable compared to bonded repair.
   - Bonded Repair: This technique is usually considered more reliable than bolted repair because it does not introduce holes, thereby reducing regional stress concentrations. Bonded repair encompasses several specific methods:
     - Patch Repair: This is listed as a type of bonded repair. It can be a quick and simple method, sometimes used for temporary repairs.
     - Scarf Repair: This is a type of bonded repair that involves tapering the damaged area and the repair patch to provide a straighter and stronger load path. This is considered a permanent repair and requires time and high skill.
       - Variations include Taper sanded and Step sanded methods.
     - Injection: This is another method listed under bonded repair.
7. Repair Context within Maintenance Checks: While the sources do not specify which particular composite repair operations (like a specific scarf repair on a particular panel) happen in an A-Check versus a C-Check, the repair process is triggered by the detection of damage. Damage is sought during inspections, and Non-Destructive Inspection (NDI) is often performed, especially during scheduled maintenance checks like C and D checks. If damage is found during these checks, or between them due to events like impact, the repair process is initiated following the damage assessment and repair tolerance criteria. For damage below a critical level, a basic cosmetic repair for protection or decoration might be applied. For damage beyond a critical level, temporary (like patch) or permanent (like scarf) structural repairs are initiated. If the damage is too severe, replacement may be more efficient than repair.

In essence, the main repairing operations for composite parts involve either mechanically fastening a repair (bolted/riveted) or adhesively bonding a repair (patch, scarf, injection). The choice of technique, and the specific procedures, depend on the damage type, location, severity, and the required outcome (cosmetic, temporary structural, or permanent structural repair). These operations are integrated into the aircraft's scheduled maintenance program, being performed when damage is identified during routine checks or other inspections.

Probability of Detection (POD) is the probability that a flaw of a particular size and location will be detected by a piece of NDT equipment. Quantifying the probability of detection is essential for damage tolerance assessments used to establish inspection intervals. The reviewed sources present data and models for POD based on the type of inspection and the characteristics of the damage (e.g., size, depth), rather than the specific check letter.

For the case of dent impact damages, the most likely damage to occur in the aircraft lifespan, the POD depends, on one side, in the size of the dent, which depends on to factors, dent's depth and dent's diameter, and in the other, on the inspection routine, a GVI or a DET. Figure 2 shows the relation between this factors in the case of dent impact damages.

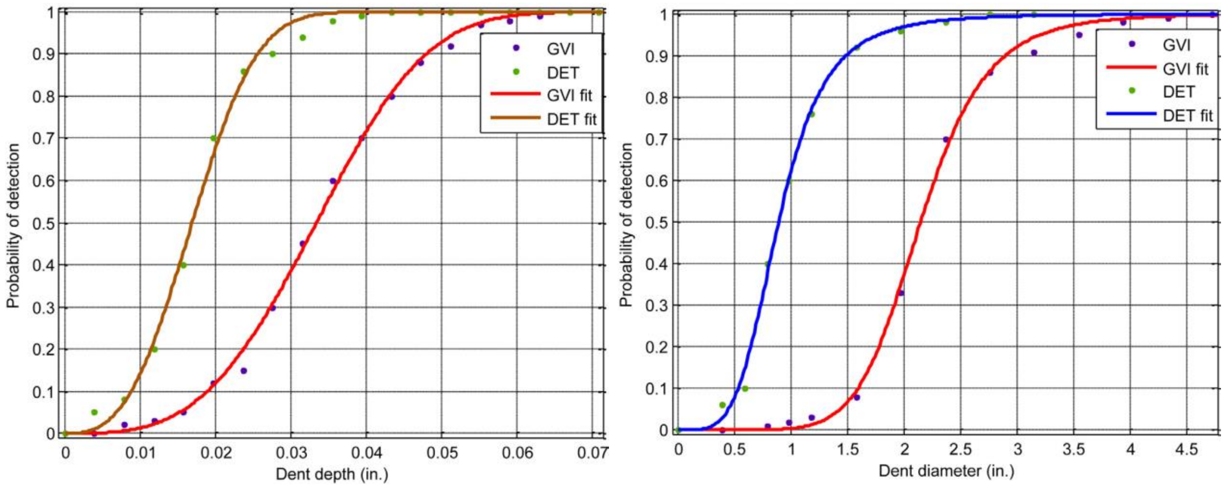


Figure 2: POD versus damage depth and diameter

On the other hand, the size of dents frecuency is shown in Figure 3.

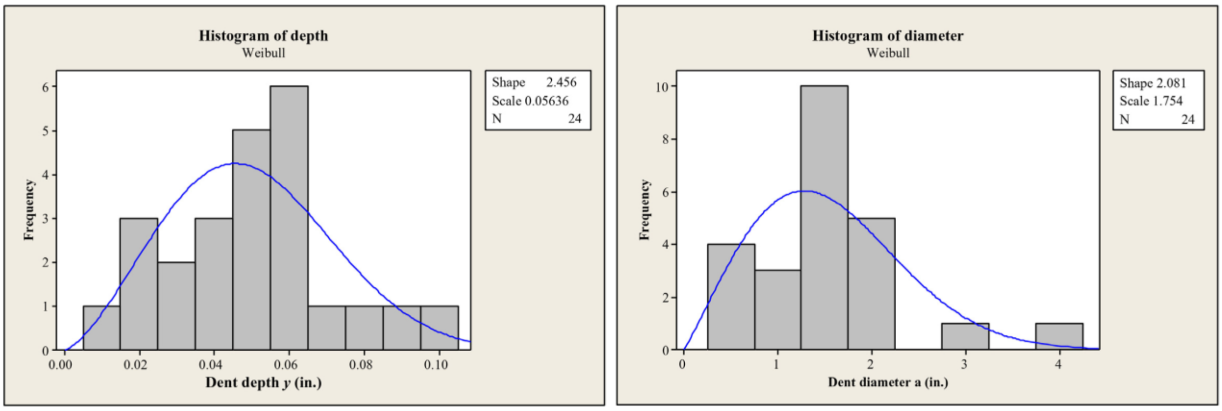


Figure 3: Damage depth and diameter distributions

With this information, in order to assess the improvements brought by the use of the microwires in CFRP panels during the life cycle of a CFRP panel installed in an airplane, we have define a realistic use stage scenario for a 1 sqm panel without and with MWs.

The main advantage brought by the MWs is that they provide the possibility to check the state and health of the CFRP panels, easing the inspection of the panels during the use stage, when installed in the airplane and through its operative life, increasing the POD in early stages, like in check A operations, avoiding the substitution of these panels due to increased damage for late detection of the damages, by simple bonded repair operations.

The repairing process has been also included in the boundaries of the study and therefore assessed. This repairing operation consisted on the removal of the damaged area of the CFRP panel and the bonding of new prepared CFRP. This operation is very common on dent damages.

Finally, the end-of-life stage has been also considered for current situation, in which CFRP waste is mostly sent to landfill, and CFs recycling process studied and developed in the project, consisting on the combination of a pyrolysis process followed by an oxidation process, focused on the recovering of the carbon fibres used in the CFRP panel.

3.3 ENVIRONMENTAL IMPACT CATEGORIES

As it has been previously said, the environmental impact categories to be assessed are set by the followed methodology, the Product Environmental Footprint (PEF). Therefore, sixteen individual environmental impact categories will be assessed, as well as the single indicator environmental category, the Environmental Footprint (EF).

Table 1: Environmental impact categories assessed

Environmental impact categories	Units	Acronym
Acidification	mol H+ eq	AP
Climate change	kg CO2 eq	CC
Ecotoxicity, freshwater	CTUe	ET
Particulate matter	disease inc.	PM
Eutrophication, marine	kg N eq	EuMar
Eutrophication, freshwater	kg P eq	EuFW
Eutrophication, terrestrial	mol N eq	EUTer
Human toxicity, cancer	CTUh	HT-Cancer
Human toxicity, non-cancer	CTUh	HT-NCancer
Ionising radiation	kBq U-235 eq	IR
Land use	Pt	LU
Ozone depletion	kg CFC11 eq	OD
Photochemical ozone formation	kg NMVOC eq	POF
Resource use, fossils	MJ	RU-Fos
Resource use, minerals and metals	kg Sb eq	RU-MM
Water use	m3 depriv.	WU
Environmental Footprint	mPts	EF

Likewise, for the end-of-life stage the Circular Footprint Formula, defined in the environmental footprint methodology has been applied, allocating the impacts and benefits provided by the recycling process between the life cycle of the CFRP panel and the next life cycle in which rCF will be used.

Material

$$(1-R_1)E_V + R_1 \times \left(AE_{recycled} + (1-A)E_V \times \frac{Q_{Sin}}{Q_p}\right) + (1-A)R_2 \times \left(E_{recyclingEoL} - E_V^* \times \frac{Q_{Sout}}{Q_P}\right)$$

Energy

$$(1-B)R_3 \times (E_{ER} - LHV \times X_{ER,heat} \times E_{SE,heat} - LHV \times X_{ER,elec} \times E_{SE,elec})$$

Disposal

$$(1-R_2-R_3) \times E_D$$

In current and project assessment the values of the parameters considered in the CFF are shown in

Table 2.

Table 2: CFF parameters

Parameter	Current case	INFINITE case
R1	0	0
R2	0	1
R3	0	0
A	-	0,5
Qs/Qp	-	0,8

4. LIFE CYCLE INVENTORY ANALYSIS

Data inventory was carried out in a mixed way depending on the available information between the consortium members, as shown in Table 3:

Table 3: Life cycle inventory data providers

Life cycle stage	Process/Operation	Primary data	Secondary data	Provider
Manufacturing	NCF manufacturing		X	Literature review
Manufacturing	MWs manufacturing	X		UPV/EHU, TAMAC
Manufacturing	Infusion process	X		IDEKO
Manufacturing	Infusion process	X		AMRC
Manufacturing	Double diaphragm forming	X		AMRC
Manufacturing	Infusion Process monitoring	X	X	IDEKO, AMRC and literature review
Use stage	Control checks		X	Literature review
Use stage	Repairing operation	X		AEROFORM
End-of-life	Pyrolysis/oxidation process	X		GAIKER

Annex shows the results of the data inventory collection.

5. LIFE CYCLE IMPACT ASSESSMENT

Following the results of the life cycle assessment are shown for each life cycle stage and for the whole life cycle. The aim was to have clear information about the improvements achieved in the project with the implementation of the MWs compared to the current situation in which these MWs are not used in the manufacturing of CFRP panels.

Although results for all environmental impact categories is shown in Annex 2, in terms of making more easy to follow and read this deliverable, the assessment of the results will be based on two impact categories that can be better understood: the climate change and the environmental footprint.

Climate change has been recognised as one of the main environmental risks to the humankind and to our current way of life, and people is very aware of its importance, so its easy to understand its impact.

Environmental footprint represents the whole environmental impact considering the sixteen impact categories assessed by the EF methodology. The impact category is the results of a process of normalization and weighting of these categories in which the weights used for each impact category were agreed between an international panel of experts. When comparing the environmental impacts of different processes or scenarios, the EF single impact category ease the understanding and interpretation of results and therefore, it facilitates decision-making.

6. RESULTS

6.1 MANUFACTURING STAGE

Microwires manufacturing

The MWs manufacturing process consist of three operations:

- Metal alloy production,
- Microwire manufacturing, and
- Quality control.

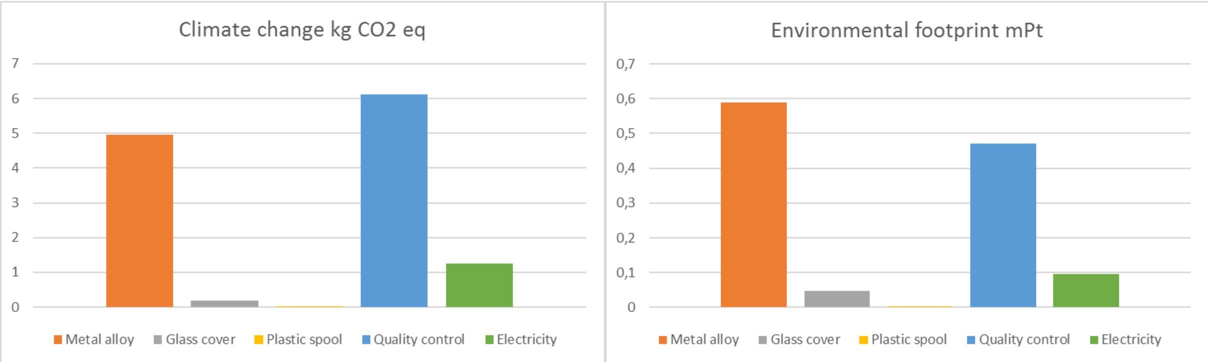


Figure 4: Environmental impacts in MWs manufacturing

As shown in Figure 4, the metal alloy production and the quality control check represent the most impacting processes in the manufacturing of the MWs.

Going deeper into the analysis, in Figure 5 it can be seen that most of the environmental impact are due to the electricity consumption, followed by the cobalt used in the metal alloy and by the glass coating of the MWs.

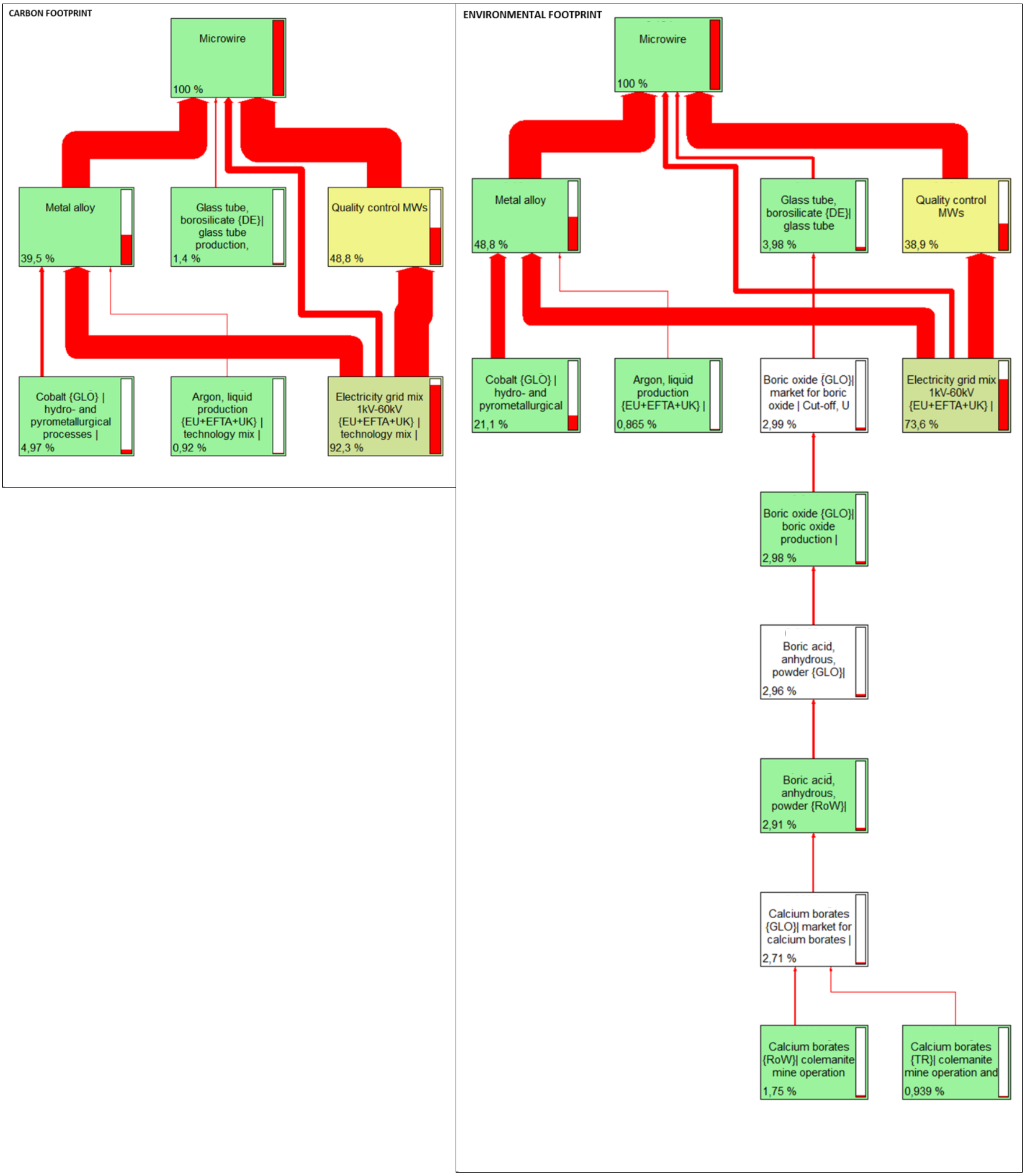


Figure 5: LCA tree assessment of the manufacturing process of MWs

IDEKO CFRP panel INFUSION manufacturing

The Infusion process carried out by Ideko consist of three operations:

1. Lamination
2. Preforming
3. Infusion

In the case of the non-sensorised CFRP panels, as shown in Figure 6 and Figure 7, the lamination is the operation with the higher contribution to carbon and environmental footprints, due to the use of the carbon fibre NCF, which contributes 56.3 % and 39.3% respectively to each impact category.

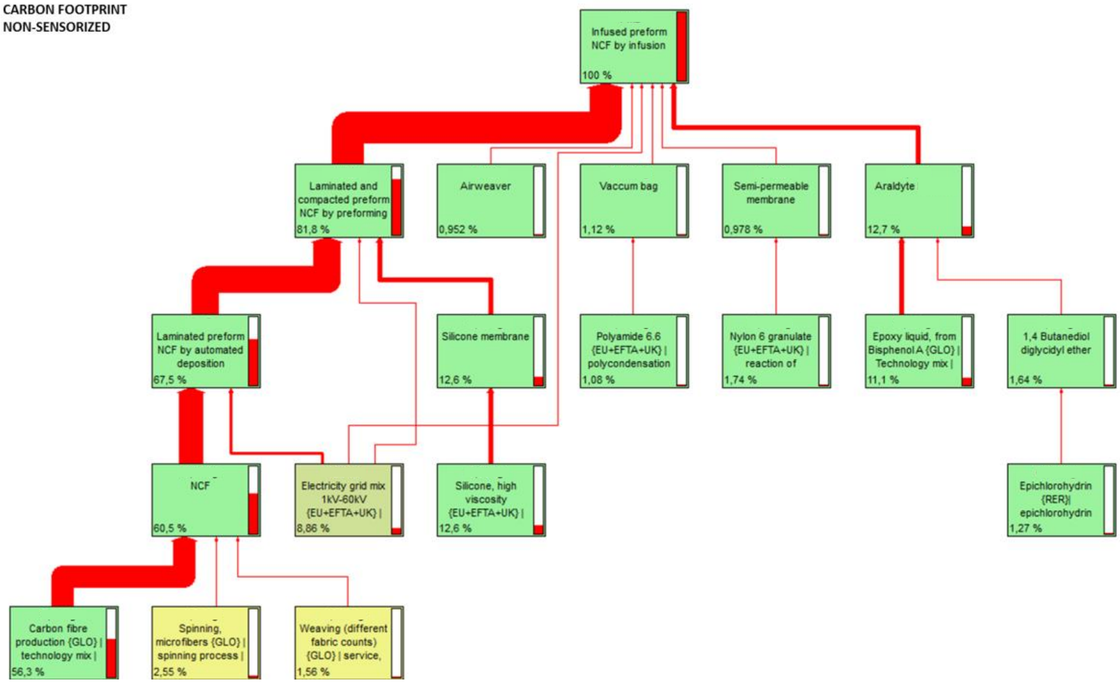


Figure 6: Results of the LCA tree assessment for carbon footprint of the Ideko's infusion manufacturing process of non-sensorised CFRP panels

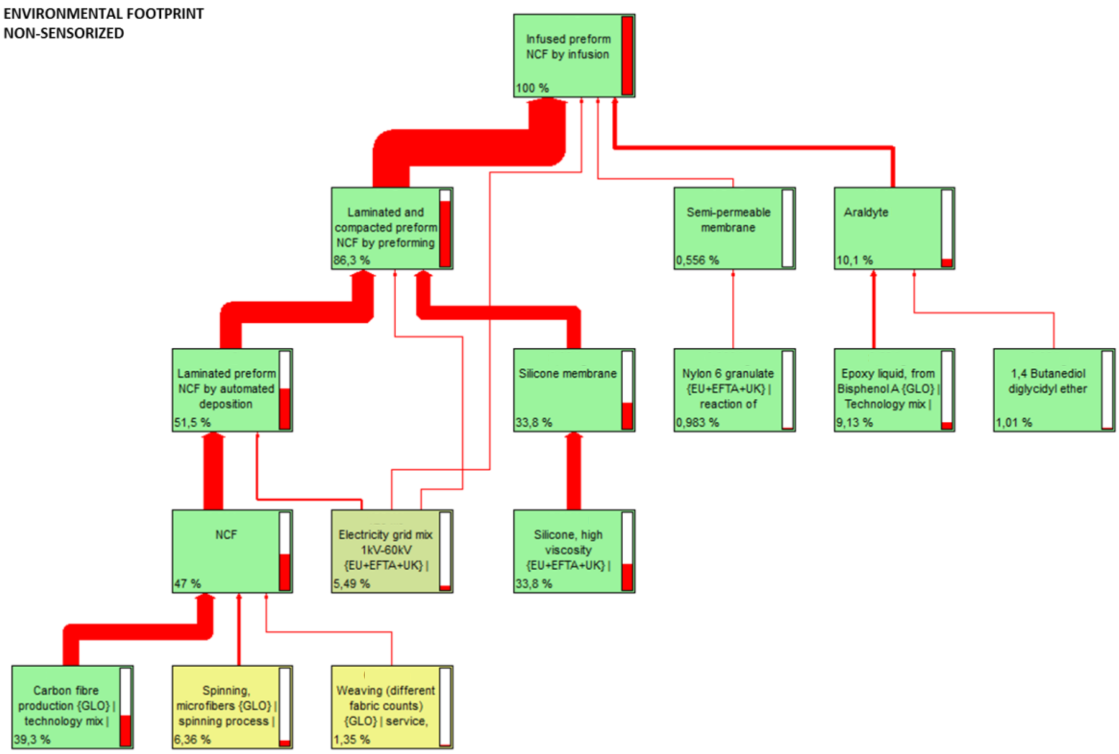


Figure 7: Results of the LCA tree assessment for environmental footprint of the Ideko's infusion manufacturing process of non-sensorised CFRP panels

In regard to the sensorised panels, Figure 8 and Figure 9 show that the NCF remains as the higher contributor to each impact category. In this case, the contribution of the MWs is low, but enough to increase the environmental impact on the manufacturing of the CFRP panels.

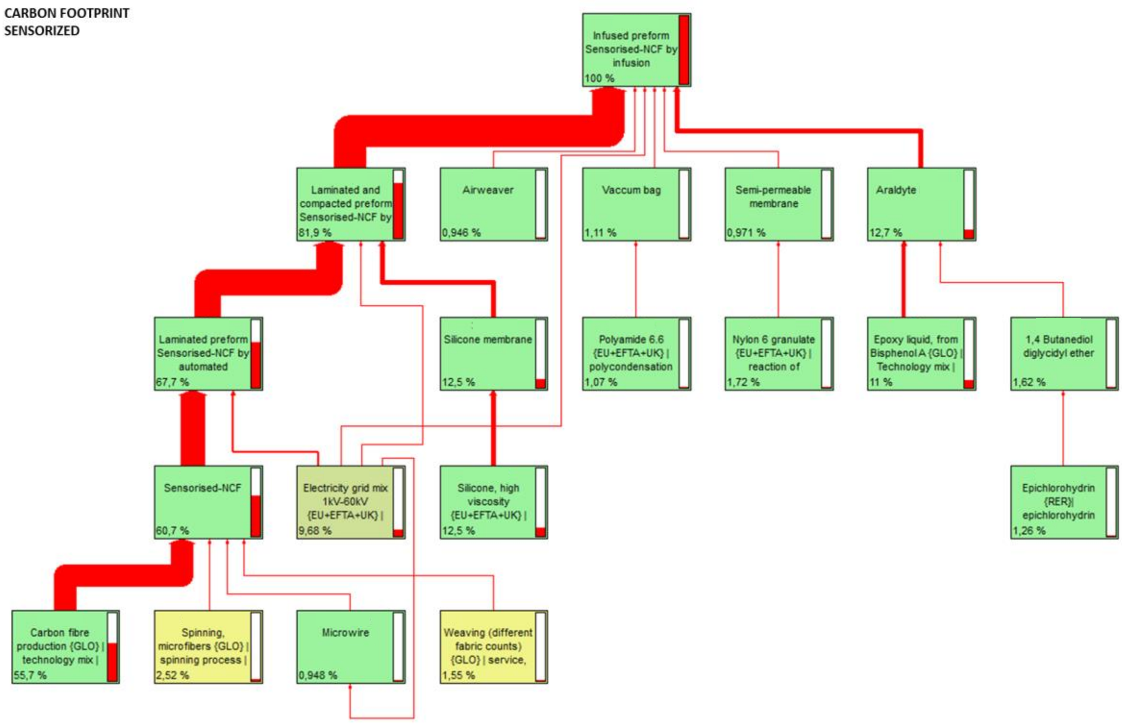


Figure 8: Results of the LCA tree assessment for carbon footprint of the Ideko's infusion manufacturing process of sensorised CFRP panels

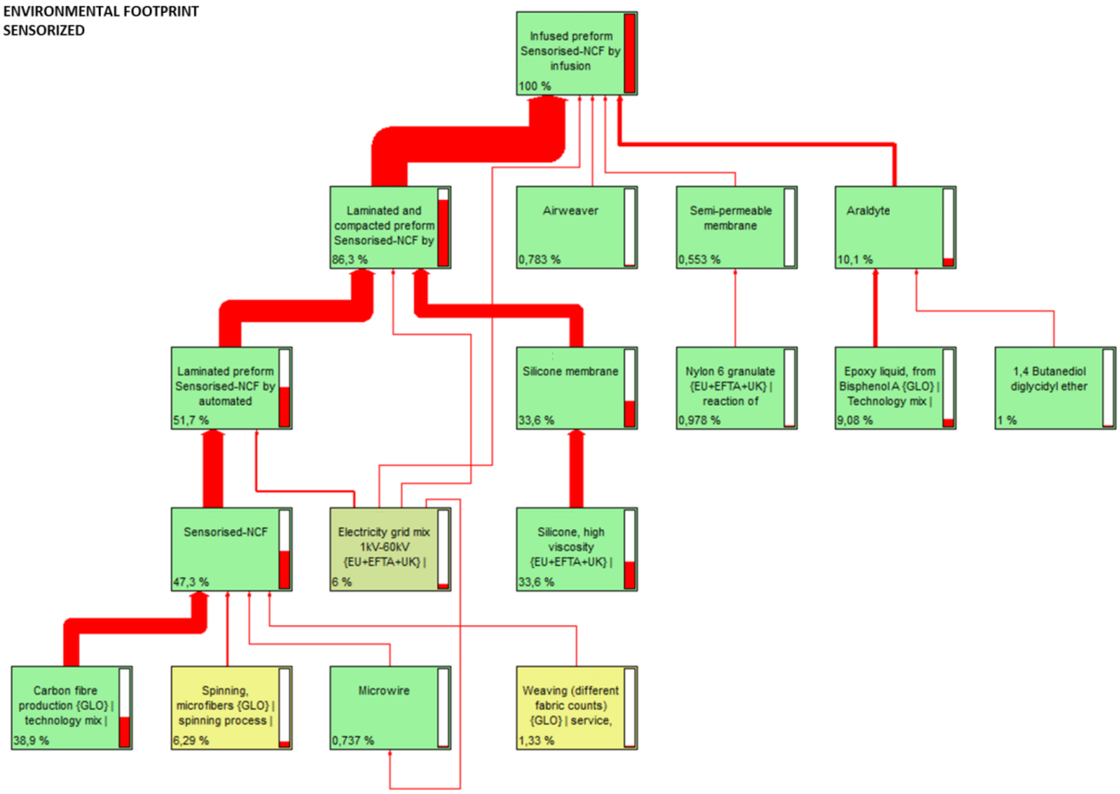


Figure 9: Results of the LCA tree assessment for carbon footprint of the Ideko's infusion manufacturing process of sensorised CFRP panels

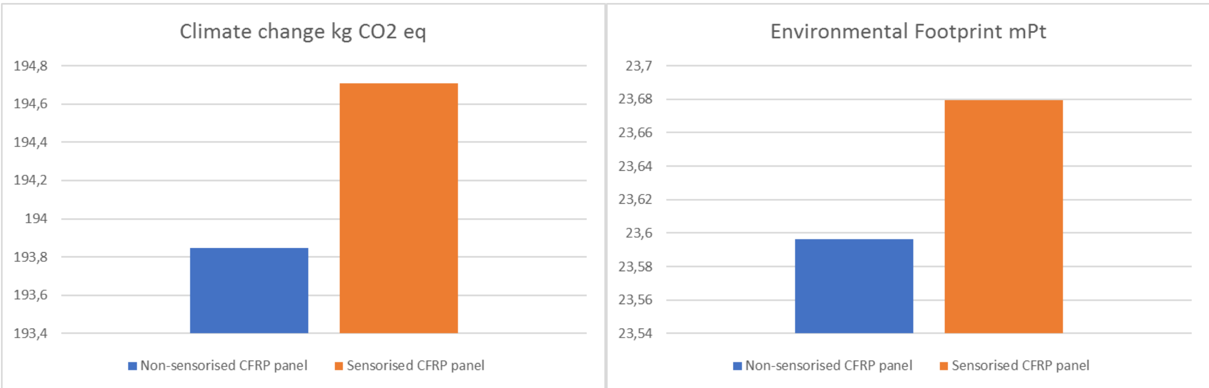


Figure 10: Environmental impact in IDEKO's infusion process

As shown in Figure 10, the manufacturing of the sensorised panels has a small higher environmental impact than current non-sensorised panels, mainly due to the presence of the MWs. Anyway the increase is very small, although it could be higher for CFRP panel's configurations with higher presence of MWs to improve the signal provided by MWs, which could be needed in some applications.

AMRC CFRP panel INFUSION manufacturing

In this case, the inventory provided was not split in different operations, but as a single step process.

As can be shown in Figure 11 and Figure 12, in the case of the non-sensorised panel the electricity consumption of the process is the main contributor to both carbon and environmental footprints, followed by the use on the carbon fibre NCF.

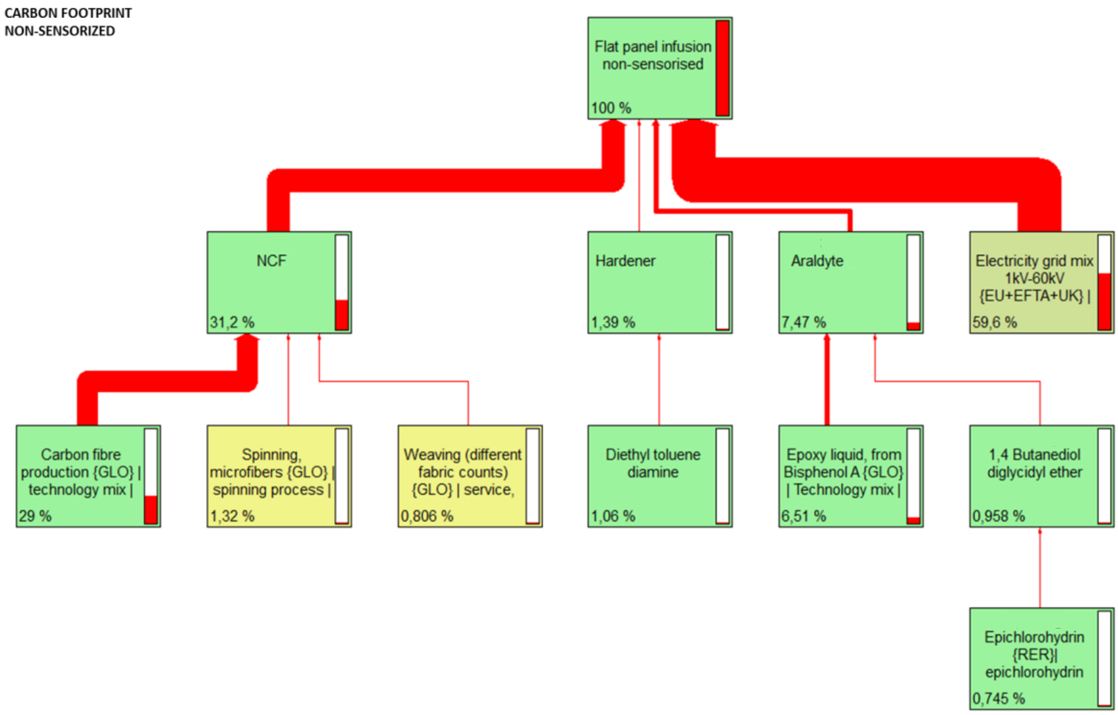


Figure 11: Results of the LCA tree assessment for carbon footprint of the AMRC's infusion manufacturing process of non-sensorised CFRP panels

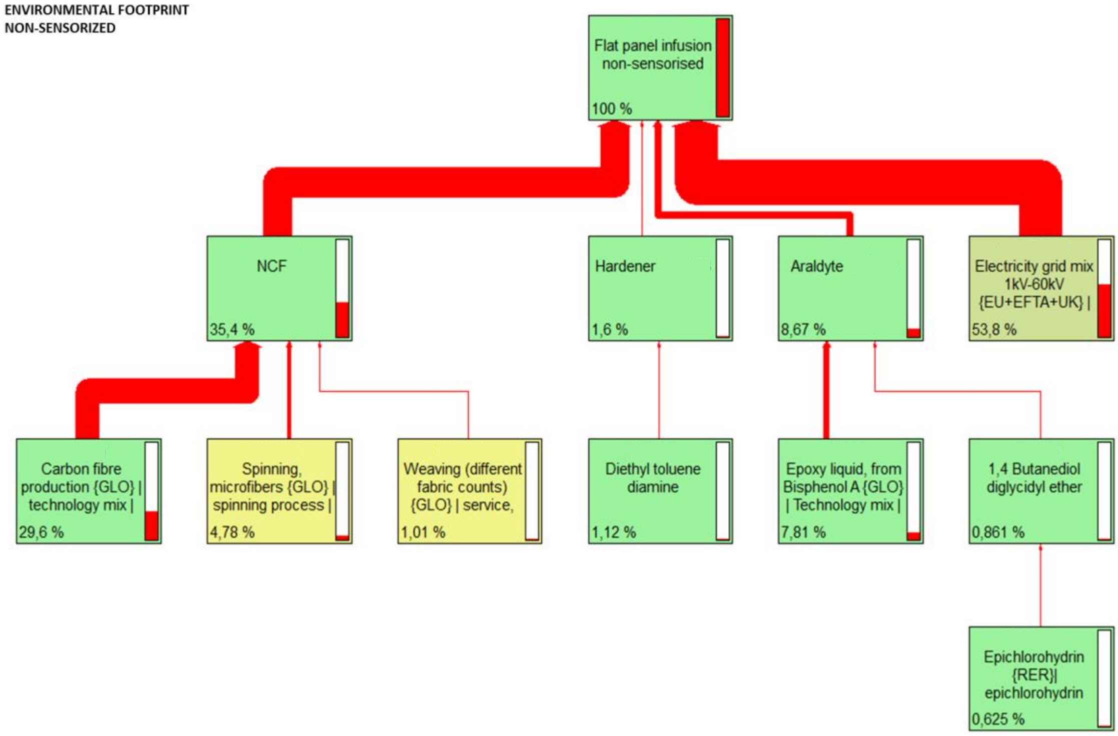


Figure 12: Results of the LCA tree assessment for environmental footprint of the AMRC's infusion manufacturing process of non-sensorised CFRP panels

In regard to the sensorised panel, the main contributors are the same, as shown in Figure 13 and Figure 14. The contribution of the MWs is quite low for both carbon and environmental footprints.

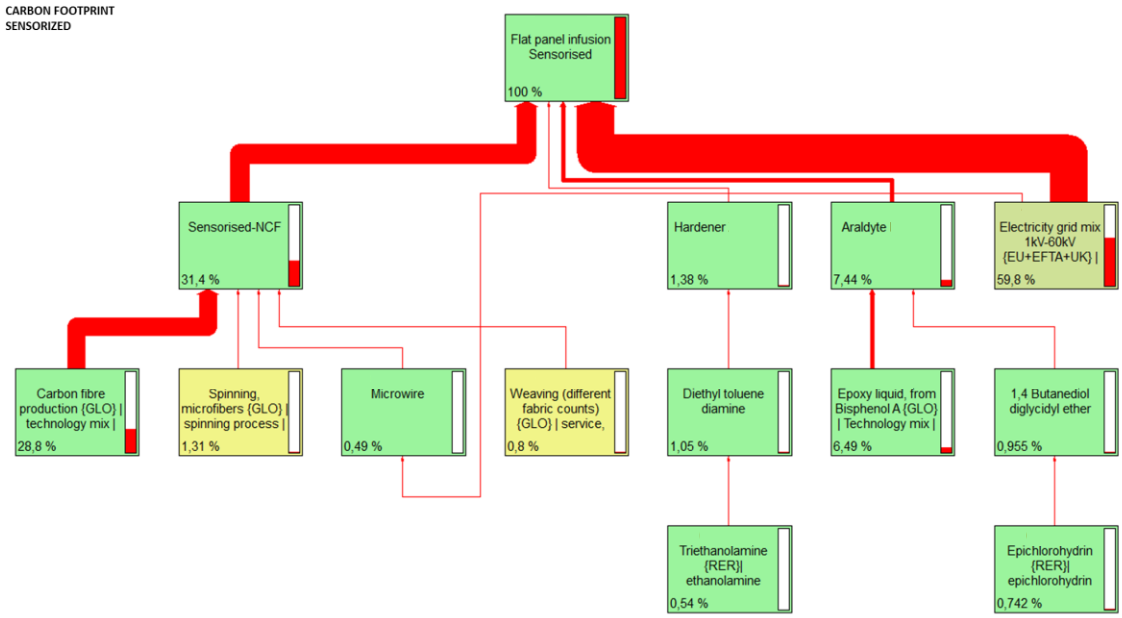


Figure 13: Results of the LCA tree assessment for carbon footprint of the AMRC's infusion manufacturing process of sensorised CFRP panels

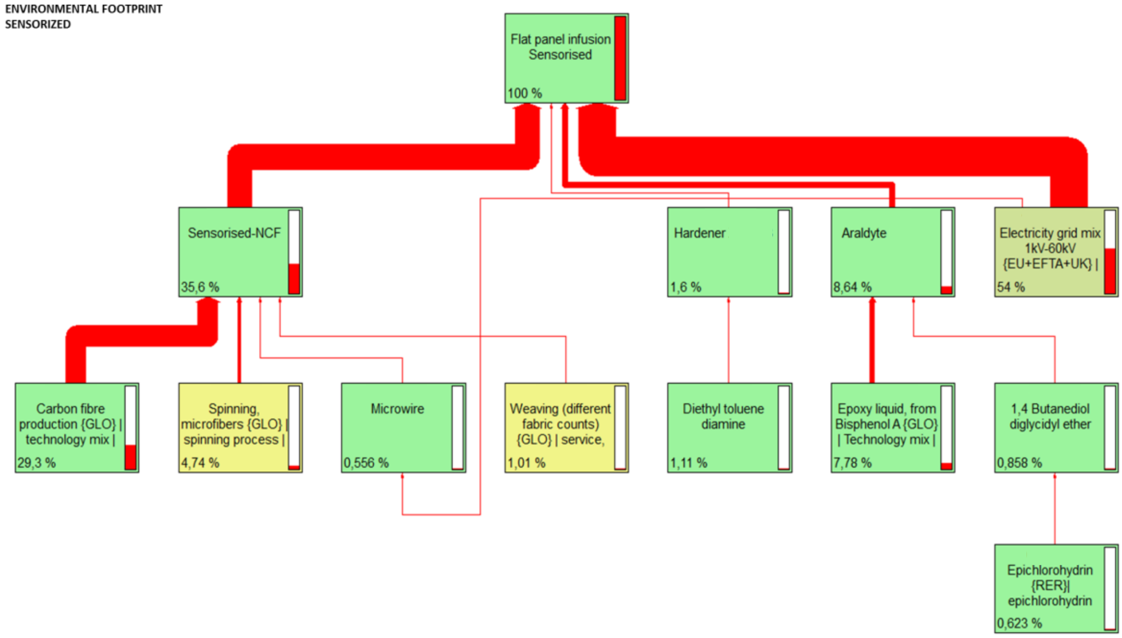


Figure 14: Results of the LCA tree assessment for environmental footprint of the AMRC's infusion manufacturing process of sensorised CFRP panels

The results are the same as in the case of IDEKO's infusion process. The sensorised panels have slightly higher environmental impacts than non-sensorised panels as shown in Figure 15.

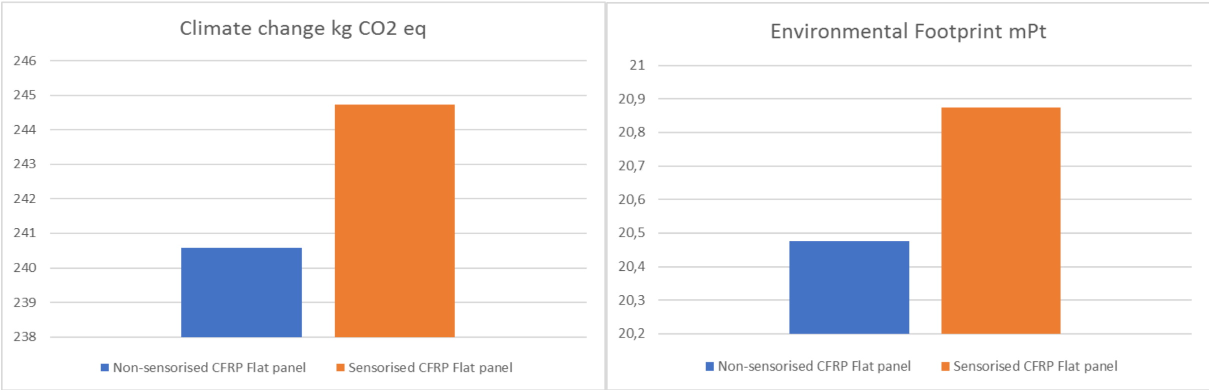


Figure 15: Environmental impact in AMRC's infusion process

AMRC CFRP panel Double Diaphragm Forming manufacturing

In this case, the inventory provided was not split in different operations, but as a single step process.

As can be shown in Figure 16 and Figure 17, in the case of the non-sensorised panel the electricity consumption of the process is the main contributor to both carbon and environmental footprints.

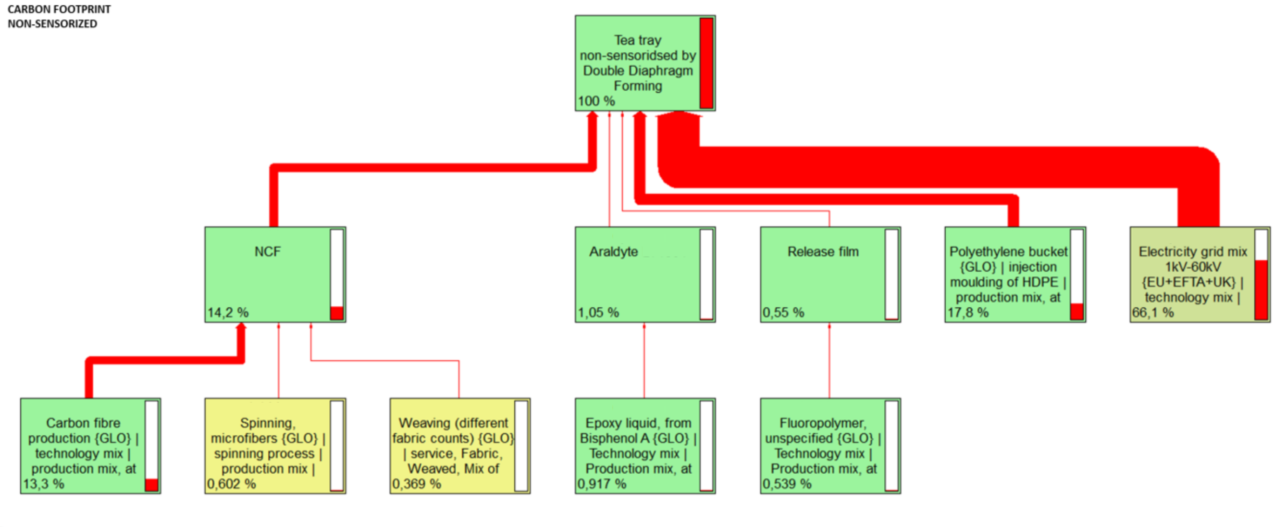


Figure 16: Results of the LCA tree assessment for carbon footprint of the AMRC's DDF manufacturing process of non-sensorised CFRP panels

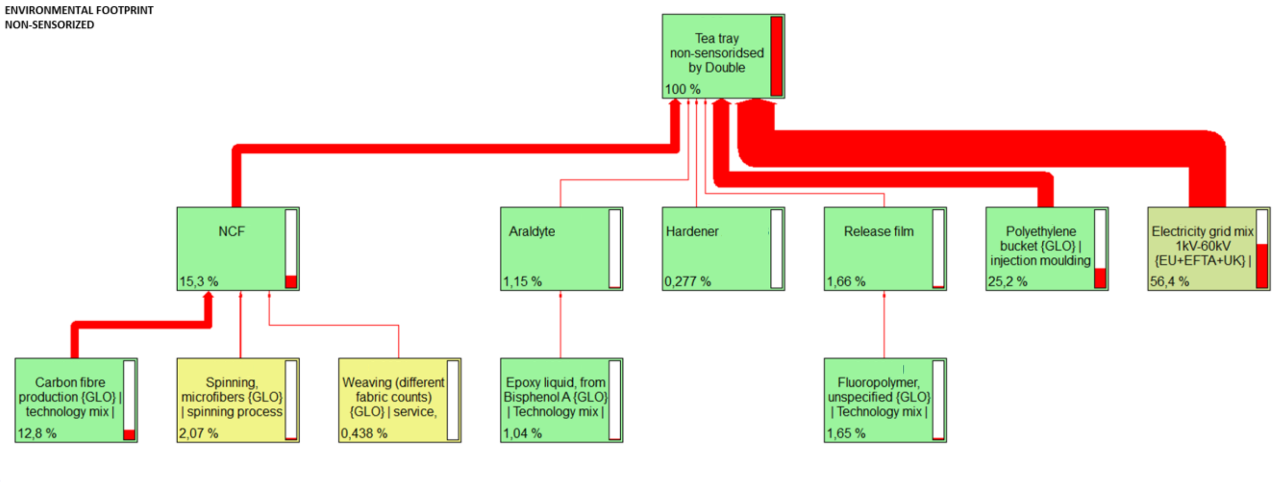


Figure 17: Results of the LCA tree assessment for environmental footprint of the AMRC's DDF manufacturing process of non-sensorised CFRP panels

In regard to the sensorised panel, the main contributors are the same, as shown in Figure 18 and Figure 19. The contribution of the MWs is quite low for both carbon and environmental footprints.

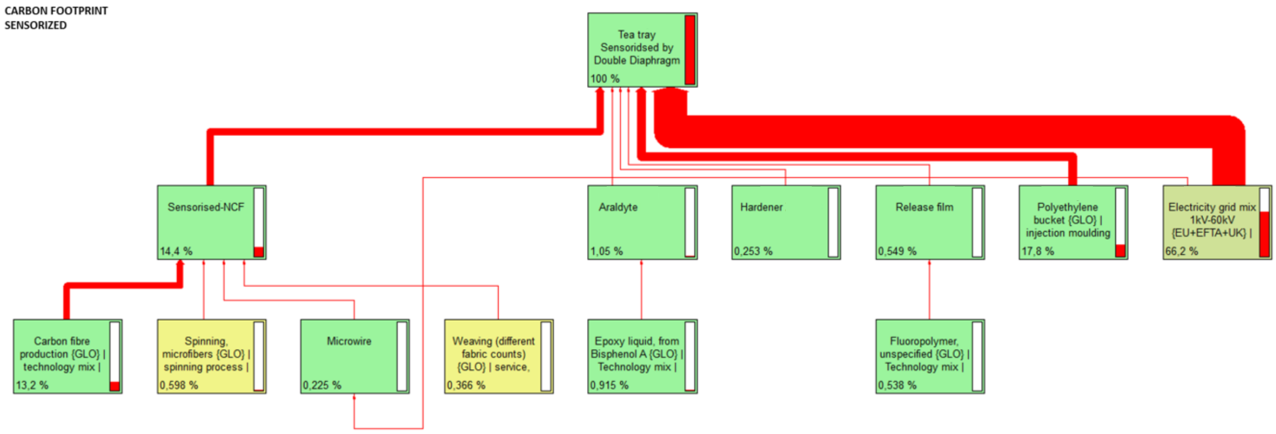


Figure 18: Results of the LCA tree assessment for carbon footprint of the AMRC's DDF manufacturing process of sensorised CFRP panels

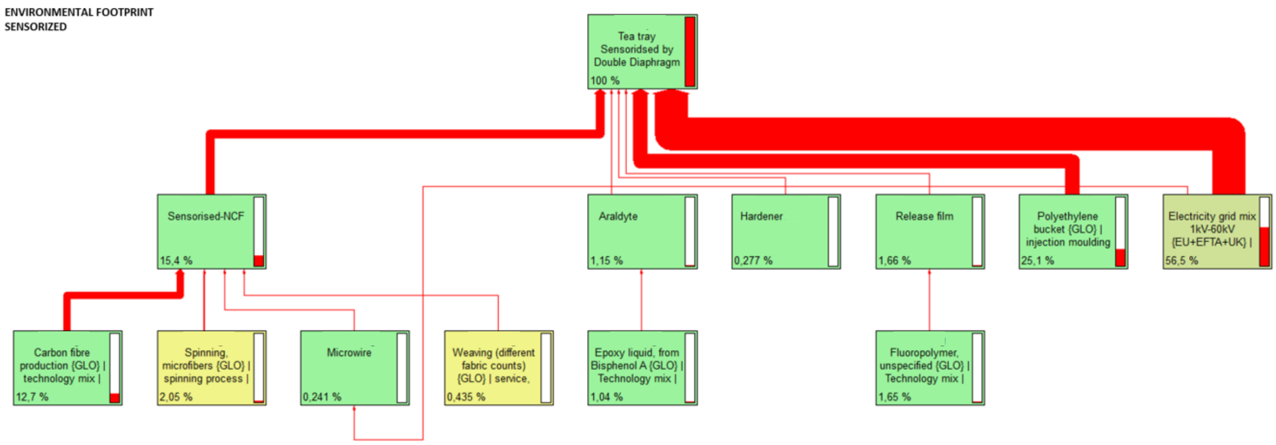


Figure 19: Results of the LCA tree assessment for environmental footprint of the AMRC's DDF manufacturing process of sensorised CFRP panels

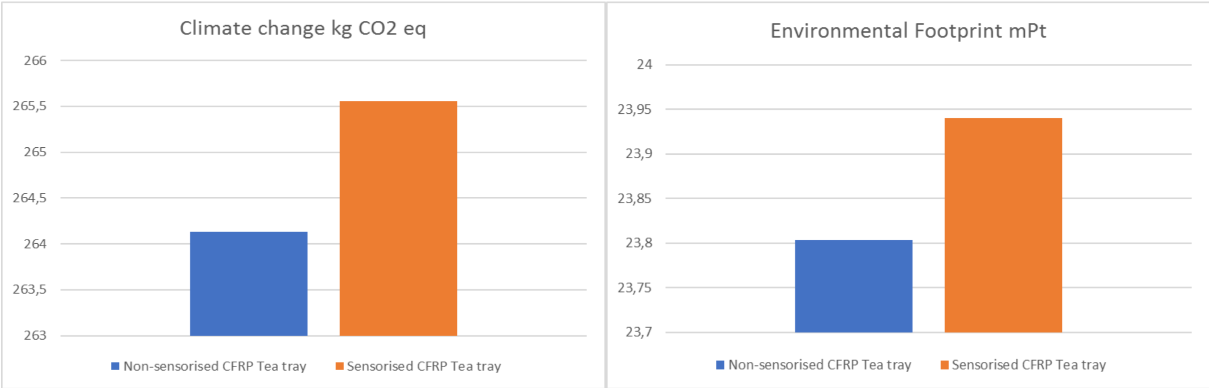


Figure 20: Environmental impacts in DDP process

The same situation happens with the DDF process when comparing non-sensorised vs sensorised panel manufacturing, as shown in Figure 20.

Comparison between CFRP panel manufacturing processes

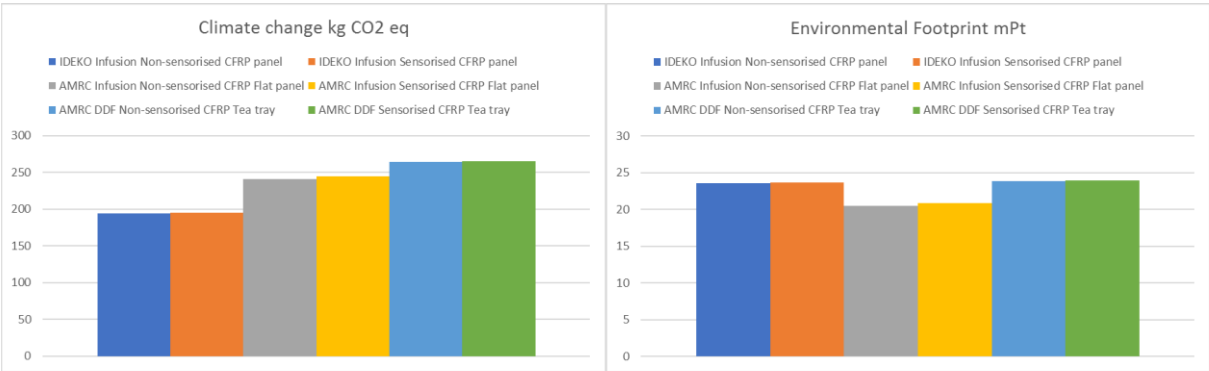


Figure 21: Environmental impacts in manufacturing process

As shown in Figure 21, the results are not conclusive. Depending on the impact category assessed, a manufacturing process is better than the others or not. In regard to the climate change and environmental footprint categories, infusion processes show lower emissions than DDF process.

MANUFACTURING MONITORING PROCESS

When making use of the magnetic intrinsic property of the MWs, to monitor the state of the CFRP panels during the operations carried out in the infusion manufacturing process carried out by IDEKO, the quantity of resources and waste generated is reduced significantly, as shown in table, where two different scenarios have been considered.

Table 4: Manufacturing monitoring scenarios

		Scenario 1: 10% defective			**Scenario 2: 25% defective**		
		Current case	INFINITE case	Reduction	Current case	INFINITE case	Reduction
Material Resources consumption	[kg]	143.384	137.666	3,99%	172.058	154.903	9,97%
Energy resources consumption	[kWh]	389	383	1,50%	467	449	3,75%
Waste generation	[kg]	15.943	15.036	5,69%	19.131	16.409	14,23%
Weight defective pieces	[kg]	8.401	5.136	38,86%	25.201	15.407	38,86%
1 sqm CFRP Panels manufactured		10.000	10.000		10.000	10.000	

In the first scenario it was considered a 10% defective panels manufactured, while in the second scenario it was a 25%, as these are common figures for the infusion process. In current situation, defective products are identified at the end of the manufacturing process and these products are managed as a CFRP waste. Likewise, the resources needed in each operation of the manufacturing process have been consumed, and associated wastes generated and managed. In the INFINITE case, each panel is control through the presence of the MWs, so early identification of defects is possible, avoiding sending the defective product to the next manufacturing operation, with the corresponding resource saving and waste generation.

Figure shows the results obtained.

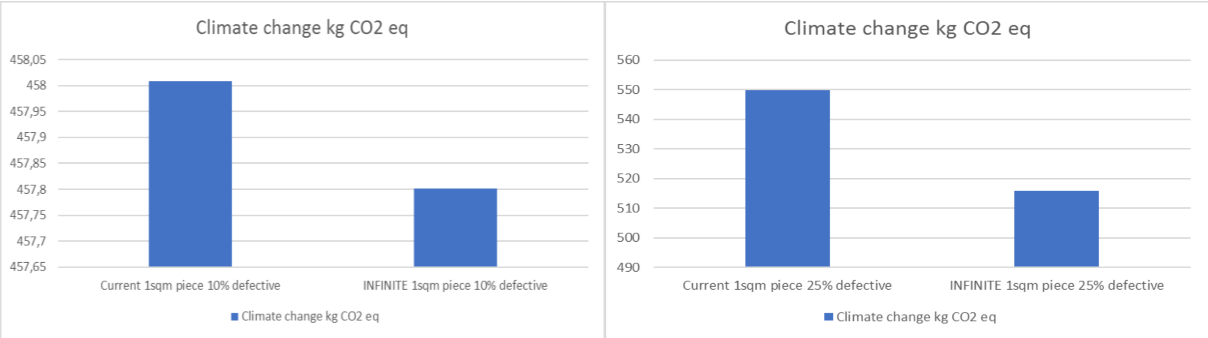


Figure 22: Environmental impacts in manufacturing process moniotoring

As shown in Figure 22, there is a significant reduction on both impact categories when manufacturing sensorised panels.

The improvements are not only at environmental impact level, but also in terms of circularity as there is:

- between 4 and 10% reduction in material resources consumed,
- between 1,5 and 3,75% reduction in energy consumption,
- between 5,7 and 14,2% reduction in process waste generated, and
- around 38,9% reduction in defective waste generated.

6.2 USE STAGE

To assess the environmental impact for current and INFINITE cases during the use case, it has been considered the control checks carried out during the complete life cycle of an average commercial airplane. Only control and repairing operations related with dent type impact damages have been considered as this is the most common impact damage happening. Likewise, we have considered in the current case only repairing operations of those dent damages with POD lower than 70% during GVIs which finally result in panel substitution due to not being able to early detect them, increasing the damage on the CFRP panel. In the INFINITE case, these dent damages can be identified earlier and therefore the repairing operations are simpler and smaller like the one developed in the project.

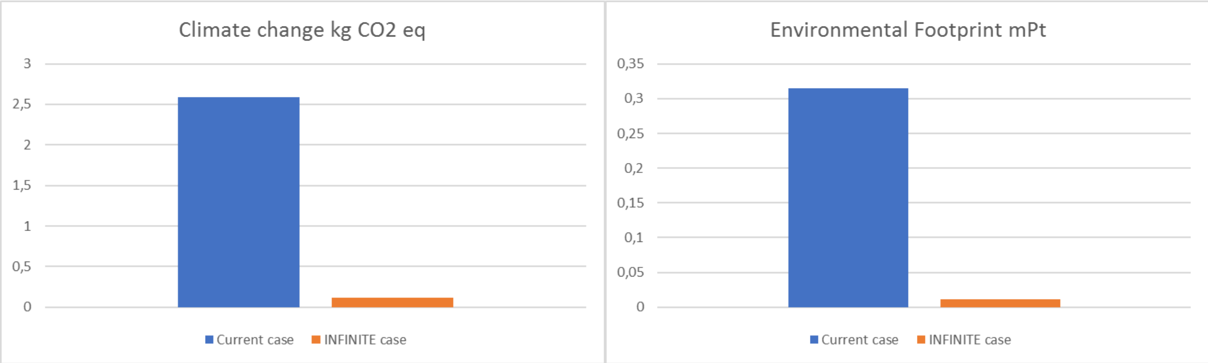


Figure 23: Environmental Impacts in use stage

As shown in Figure 23, there is a significant reduction on environmental impact, around 96%.

6.3 COMPLETE LIFE CYCLE

As previously mentioned, to compare the environmental impacts of the current and INFINITE cases, all life cycle stages have been considered as described, including the end-of-life stage.

For scenario of 10% of defective pieces during the manufacturing stage of the panels, most of the environmental impacts come from the manufacturing stage, as shown in Figure 24. The impacts on this stage are a little bit counterbalanced in the INFINITE case, due to the recycling of CFs.

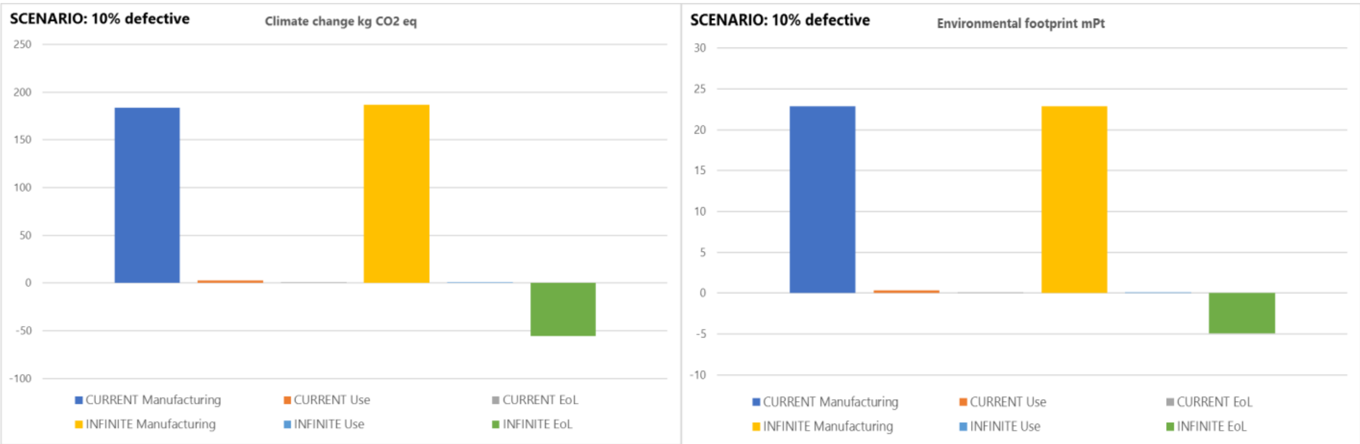


Figure 24: LCA results completed LC for scenario 10% defectives in manufacturing stage

The results for scenario 10% defective panels in the complete life cycle of the CFRP panels are shown in Figure 25.

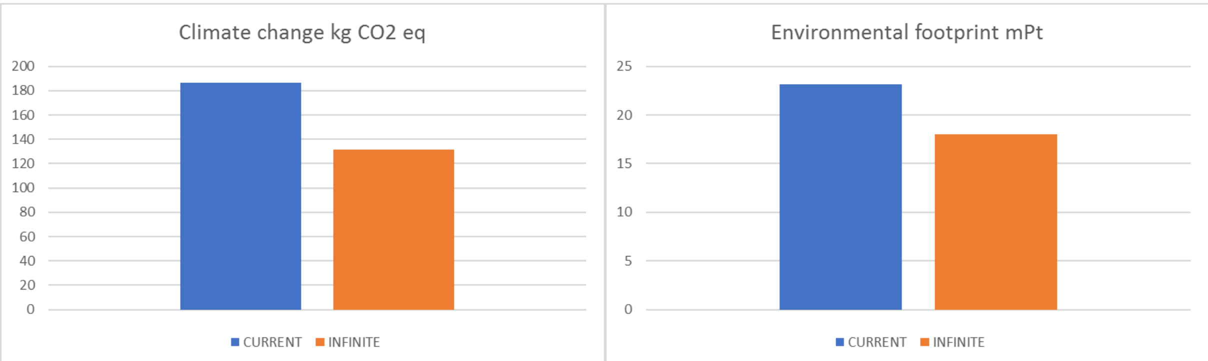


Figure 25: Environmental impact in complete life cycle in scenario 10% defectives

As it can be seen, there is a decrease in the climate change impact category, a 29,66%. On the other hand, the environmental footprint in the complete life cycle is reduced around 22,37%.

For scenario of 25% of defective pieces during the manufacturing stage of the panels, again, most of the environmental impacts come from the manufacturing stage as shown in Figure 26. The impacts on this stage are a little bit counterbalanced in the INFINITE case, due to the recycling of CFs.

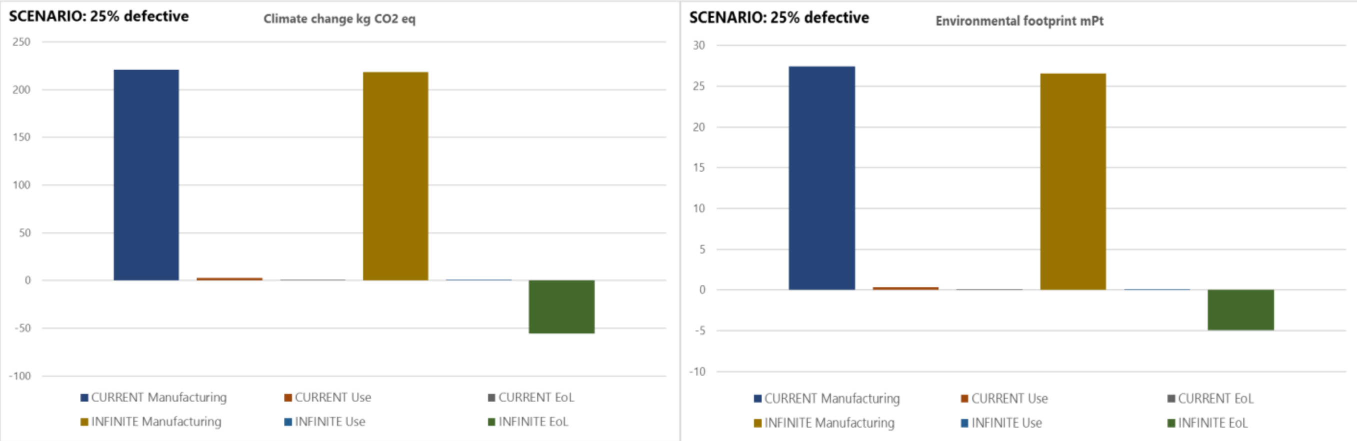


Figure 26: LCA results completed LC for scenario 25% defectives in manufacturing stage

On the other hand, the results for scenario 25% defective panels in the complete life cycle of the CFRP panels are shown in Figure 27. In this scenario for both impact categories the use of sensorised CFRP panels will improve current situation.

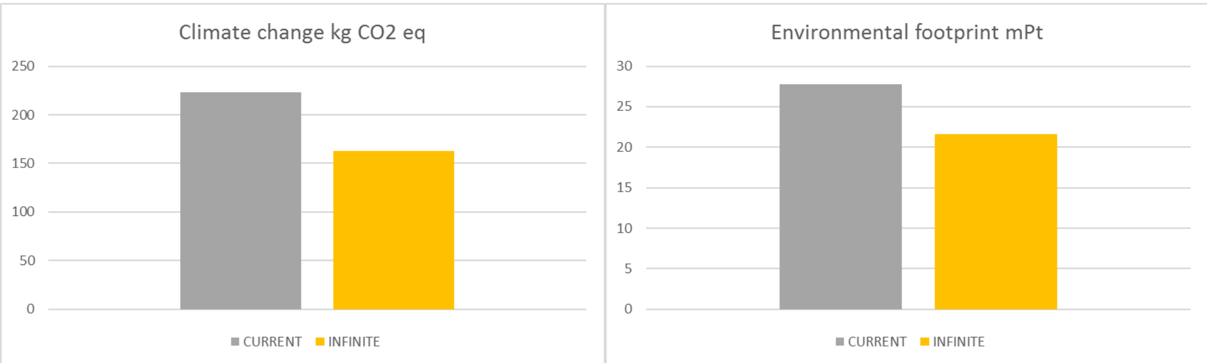


Figure 27: Environmental impact in complete life cycle in scenario 25% defectives

As it can be seen, there is a decrease in the climate change impact category, a 27,14%. On the other hand, the environmental footprint in the complete life cycle is reduced around 22,04%.

7. CONCLUSIONS

The main conclusions after carrying out the life cycle assessment of the new sensorised CFRP panels compared to current non-sensorised CFRP panels are listed following:

1. The introduction of microwires on the manufacturing of CFRP panels will generally increase the environmental impact of the CFRP panels compared to current non-sensorised panels. This is due to the environmental impacts generated in the manufacturing process of the MWs. Therefore, a balance should be met between number of MWs introduced in the CFRP panel and the signal provided by the MWs, trying to reduce as much as possible the number of MWs whenever they keep providing a good quality signal for process monitoring and panel health monitoring.
2. There are no significant differences between the three manufacturing processes assessed during the project. In fact, these differences are more related with the configuration of the panels, than with the manufacturing process itself.
3. The use of the MWs to monitor the manufacturing process will bring big environmental benefits. Not only in terms of environmental impacts, but also in terms of circularity: material resources use, energy resources use, process waste generated and waste defective panels.
4. Despite the benefits brought by monitoring the manufacturing process, the efficiency of the manufacturing operations carried out in each manufacturing process has influence in the scale of the benefits. For lower efficient processes, the benefit will be higher than for more efficient processes.
5. The use of the MWs to monitor the health of the sensorised panels during the use stage will reduce the environmental impacts compared to non-sensorised panels. This is due to the early damage detection which will require small repair operations.
6. The environmental impact of the complete life cycle is very much influenced by the manufacturing stage. This has to do with the fact that CFRP panels are passive elements of aircraft (non-energy consumers during the use stage). And, at this regard the benefit will be closely related with the efficiency of the manufacturing process: the lower the efficiency, the higher the environmental benefit.