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INFINITE

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

D5.3

New sensor composites Life cycle cost analysis (LCC)

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Authors	Javier Rios, GAIKER
Responsible of the deliverable	Javier Ríos, GAIKER rios@gaiker.es
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ABSTRACT / EXECUTIVE SUMMARY	
Abstract	This report presents a life cycle cost (LCC) analysis of novel sensorised carbon fibre reinforced polymer (CFRP) panels developed within the INFINITE project. These panels incorporate microwires with relevant Giant Magneto-Impedance (GMI) properties, enabling real-time monitoring of manufacturing quality and in-service structural integrity. The LCC study compares the economic performance of these sensorised panels against conventional non-sensorised CFRP panels over their full life cycle—from raw material acquisition through manufacturing, use, and end-of-life. The analysis, based on ISO 15686-5:2017 standards, uses a functional unit of 1 m² of CFRP panel. Results indicate that sensorisation increases initial manufacturing costs due to the additional material and integration steps required for microwires. However, these upfront costs are offset during the use phase, where the embedded sensing capabilities reduce the need for intensive inspection, enable early damage detection, and lower repair and replacement costs—particularly relevant for dent-type impact damages common in aerospace applications. Additionally, end-of-life treatment using pyrolysis-oxidation for carbon fibre recovery introduces economic value by producing high-quality recycled fibres with market demand, further contributing to the overall cost efficiency of the sensorised solution. When viewed from a complete life cycle perspective, the sensorised CFRP panels demonstrate a net economic benefit. Despite higher manufacturing expenses, savings in maintenance and end-of-life recovery result in a reduced total cost of ownership. The findings support the adoption of embedded sensing technologies not only for operational advantages but also for lifecycle economic performance in aerospace composite applications.
Keywords	INFINITE, life cycle costing, cost, economic assessment.

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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 costing methodology has achieved great recognition in the scientific community as it is able to assess quite precisely different economic impact 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 costing carried out to assess the economic improvements bring by this new technology compared to current conventional CFRP panels are collected in the following sections of this deliverable.

2. OBJECTIVES

The main objective of the life cycle costing assessment carried out was to assess the economic 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 parts manufacturing processes tested in the project could be compared in order to assess and compare their economic impact, mainly in terms of costs from materials, investments in equipment, energy, waste management and manpower.

To carry out the life cycle costing assessment, the reference methodology was the ISO 15686-5:2017 (ISO/TC 59, 2017). This methodology sets the rules to make comparable life cycle costing assessments for a product according to homogenous method.

3. SCOPE OF THE STUDY

3.1 FUNCTIONAL UNIT

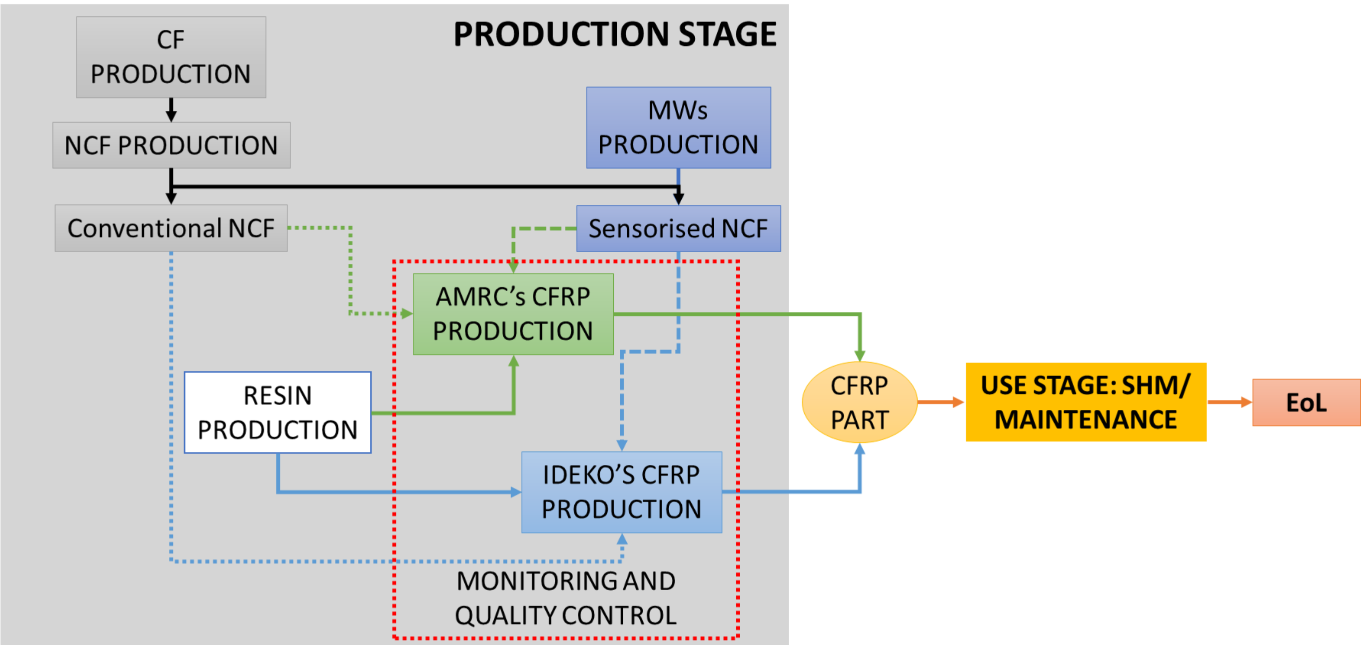
To make a fairly assessment of the potential economic benefits and drawbacks brought by the sensorization of the CFRP through incorporating the microwires in the NCF, it is necessary to define a functional unit that can be easily understood and for which the data inventory could be carried out for all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

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 economic improvement provided by the use of the microwires in CFRP parts in the air sector.

4. LIFE CYCLE INVENTORY

Data inventory was carried out in a mixed way depending on the available information between the consortium members, as shown in Table 1:

Table 1: 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. RESULTS

5.1 MANUFACTURING STAGE

In the framework of the project, apart from the manufacturing three different CFRP manufacturing processes have tested to evaluate if the presence of the microwires could affect somehow the manufacturing process and to check how these processes could be improved by this new technology.

Likewise, a life cycle costing has been carried out to assess how the use of microwires affect these manufacturing processes.

MICROWIRES MANUFACTURING PROCESS.

The first process assessed was the microwire manufacturing process. This process consists of three primary operations. The first one was the preparation of the metal alloy, in which the components of the alloy are melted and cooled in a specific proportion to provide the magnetic properties required. The second operation is the microwire manufacturing in which the melted alloy is converted into a wire with the desired diameter and rolled into spools. Finally, the last operation is the quality check, in which the microwire is subjected to different tests to check its magnetic properties and homogeneity.

The primary data was collected and provided by Tamac and UPV/EHU.

Table 2 shows the costs contribution by each operation carried out during the manufacturing process of the mocrowires, while Table 3 shows the cost distribution depending on the type of cost considered.

Table 2: MWs manufacturing cost structure by operation/process

Total cost per sqm CFRP	Metal Alloy Preparation	Microwire manufacturing	Quality control
0,55 €	0,28 €	0,11 €	0,15 €

Table 3: MWs manufacturing cost structure by type of cost

Total cost per sqm CFRP	Materials	Investment	Manpower	Energy
0,55 €	0,20 €	0,03 €	0,32 €	0,01 €

As shown in Figure 1, manpower cost represents more that 58% of the total costs. This is due to the fact that this manufacturing process is not automated and depends very much on manual work.

The metal alloy preparation accounts for more than 50% of the costs mainly due to the costs of the materials used, while in the case of the microwire manufacturing and the quality control costs they are driven by the manpower costs.

As result, the cost of manufacturing one meter of microwire is 0.55 €. This cost will be used in the assessments of the sensorised CFRP panels manufacturing processes.

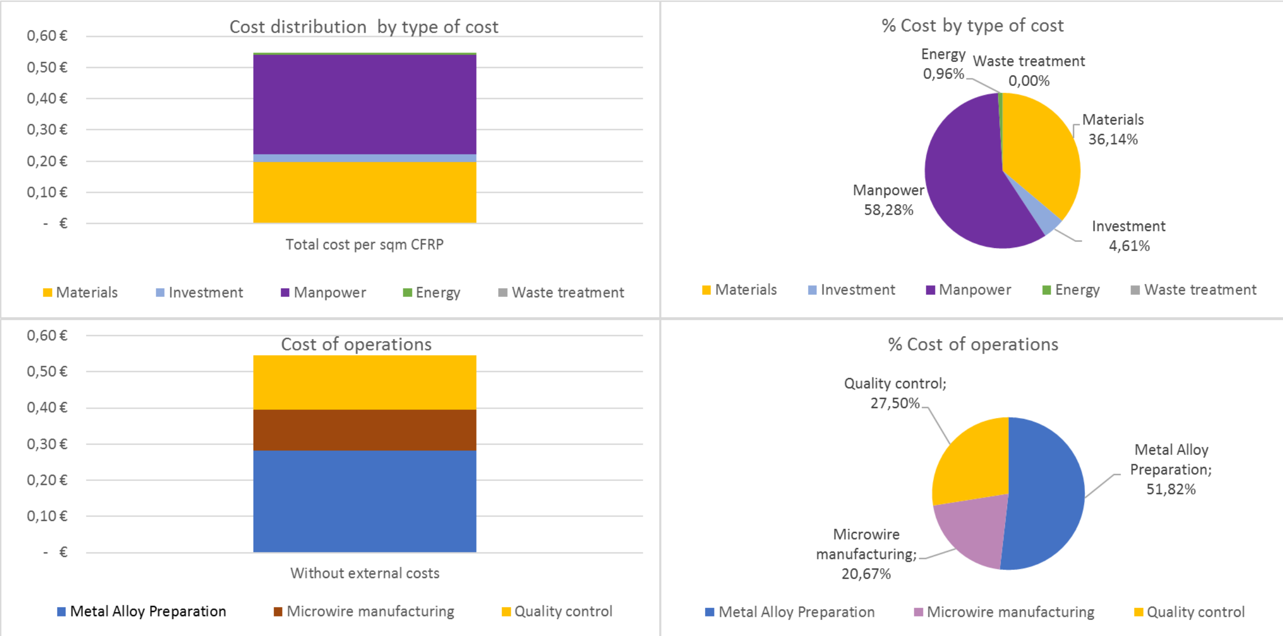


Figure 1: Results of the LCC of the microwires manufacturing process

CFRP PANELS MANUFACTURING PROCESSES.

The first CFRP manufacturing process assessed is the infusion process carried out by IDEKO. The primary data of the inventory was collected and provided by them.

In the case of the three CFRP panel manufacturing processes, both non-sensorised and sensorised panels manufacturing process were assessed to assess the impact of the use of the microwires in the manufacturing processes from the economic point of view.

Manufacturing process carried out by IDEKO: Infusion.

- *Non-sensorised panel*

The main difference between non-sensorised and sensorised CFRP panels is the presence of the MWs in the CF's NCF which accounts for an additional material cost but with no significative cost in the manufacturing of the NCF.

Table 4 shows the distribution of cost between the three operations carried out in this process. It is clear that the first operation, the automated deposition, accounts for more than 80% of the total costs. This is due to the costs of NCF, which is consumed in this operation (800,00€). On the other hand, cost of investment are also allocated to the automated deposition operation. On the other hand, manpower costs are allocated equally to automated deposition and infusion operations which account double than preforming.

Table 4: Infusion manufacturing of non- sensorised panels carried out by Ideko cost structure by operation/process

Total cost per sqm CFRP	Automated deposition	Preforming	Infusion
1.069,14 €	894,68 €	18,97 €	155,48 €

Table 5: Infusion manufacturing of non- sensorised panels carried out by Ideko cost structure by type of cost

Total cost per sqm CFRP	Materials	Investment	Manpower	Energy	Waste treatment
1.069,14 €	923,618 €	55,114 €	83,750 €	6,647 €	0,008 €

Finally, as Figure 2 shows, material costs contribute more than 86% to the total costs, while the automated deposition operation accounts for more than 83%.

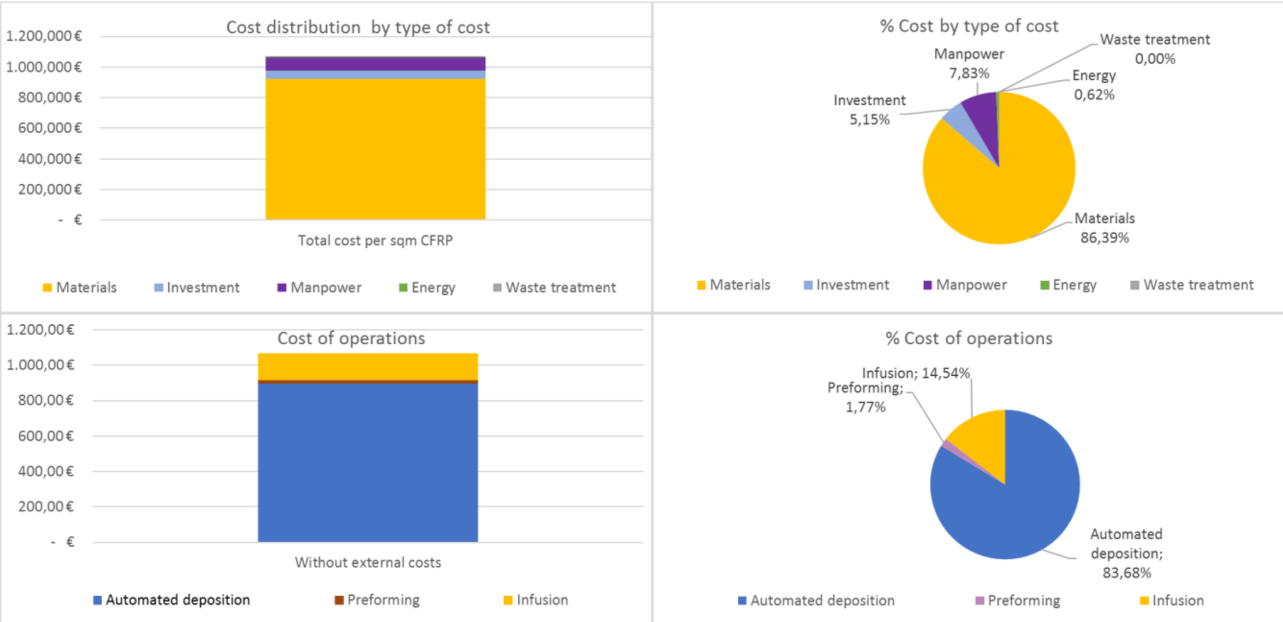


Figure 2: Results of the LCC of the infusion manufacturing of non- sensorised panels carried out by Ideko

- *Sensorised panel*

As expected, the cost structure is almost the same structure than that for the non-sensorised panels as there is no significant change in operations and equipment between both of them. The main change is due to the presence of the MWs in the configuration of the NCF but this has no impact on the development of the three operations. Therefore, as shown in Table 6 and Table 7, the cost of automated deposition in increased due to the cost of the MWs used in the NCF.

Table 6: Infusion manufacturing of sensorised panels carried out by Ideko cost structure by operation/process

Total cost per sqm CFRP	Automated deposition	Preforming	Infusion
1.123,19 €	948,74 €	18,97 €	155,48 €

Table 7: Infusion manufacturing of sensorised panels carried out by Ideko cost structure by type of cost

Total cost per sqm CFRP	Materials	Investment	Manpower	Energy	Waste treatment
1.123,19 €	977,675 €	55,114 €	83,750 €	6,647 €	0,008 €

In this case, as Figure 3 shows, material costs increase its contribution to total costs up to 87 %, while the automated deposition operation accounts for almost 84.50%.

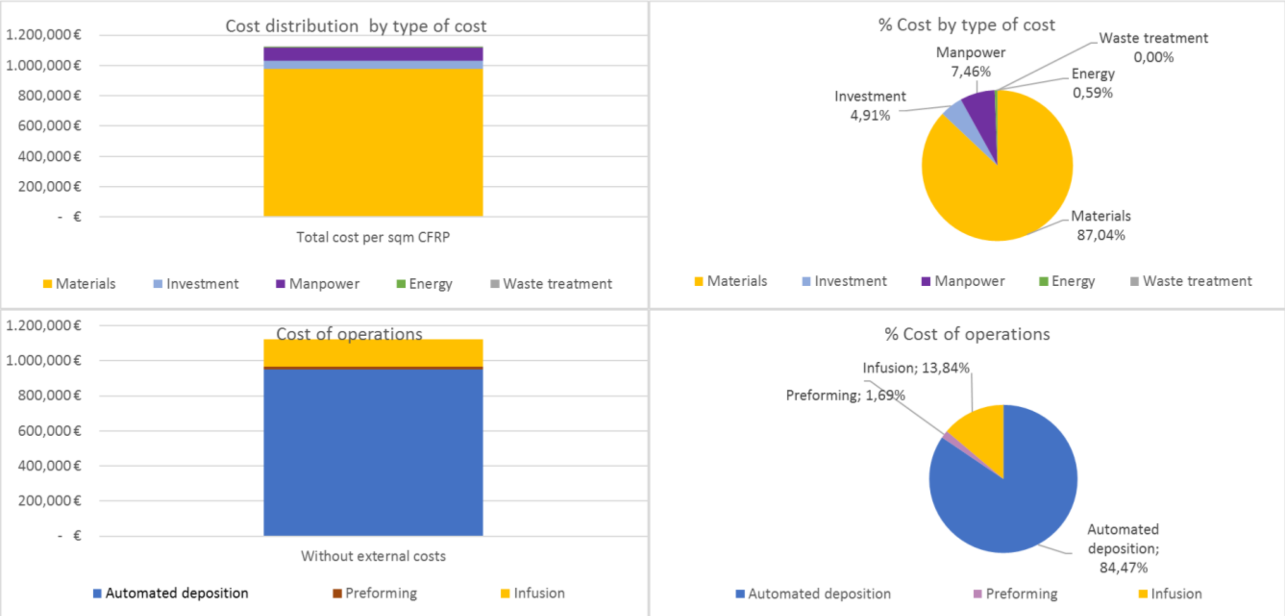


Figure 3: Results of the LCC of the infusion manufacturing of sensorised panels carried out by Ideko

When comparing the results obtained for non-sensorised and sensorised CFRP panels, the sensorised panels have a higher production cost, 54,05 €/sqm CFRP panel due to the cost of MWs.

Manufacturing process carried out by AMRC: Infusion.

- *Non-sensorised panel*

The data inventory was collected and provided by AMRC. In this case, the information was provided aggregated so all manufacturing process was carried out as a single operation: the flat panel infusion.

As Table 8 and Figure 4 show, cost are almost evenly distributed between materials, manpower and energy, representing 35,82%, 28,69% and 27,40%.

Table 8: Infusion manufacturing of non- sensorised panels carried out by AMRC cost structure by type of cost

Total cost per sqm CFRP	Materials	Investment	Manpower	Energy	Waste treatment
854,14 €	305,91 €	15,92 €	245,05 €	234,00 €	53,25 €

Figure 4: Results of the LCC of the infusion manufacturing of non- sensorised panels carried out by AMRC

- *Sensorised panel*

As in the case of the infusion process carried out by Ideko, the main change in cost structure is due to the use of the MWs but this presence has no impact in the performance of the manufacturing process, so no additional changes in cost structure occur as shown in Table 9 and Figure 5.

Table 9: Infusion manufacturing of sensorised panels carried out by AMRC cost structure by type of cost

Total cost per sqm CFRP	Materials	Investment	Manpower	Energy	Waste treatment
906,01 €	357,79 €	15,92 €	245,05 €	234,00 €	53,25 €

Figure 5: Results of the LCC of the infusion manufacturing of sensorised panels carried out by AMRC

When comparing the results obtained for non-sensorised and sensorised CFRP panels, the sensorised panels have a higher production cost, 51,87 €/sqm CFRP panel due to the cost of MWs.

Manufacturing process carried out by AMRC: Double Diaphragm Forming.

- *Non-sensorised panel*

The third and last CFRP manufacturing process tested was the Double Diaphragm Forming process (DDF) which is quite different from the two infusion processes. In this case, the inventory was carried out and provided by AMRC. As in the case of the infusion process carried out by AMRC, the data was provided aggregated as if the DDF process was carried out in a single operation.

Table 10 and Figure 6 show that manpower costs account for 56% of total costs, followed by the materials costs, almost 20%, and investment costs, nearly 14%.

Table 10: DDF manufacturing of non- sensorised panels carried out by AMRC cost structure by type of cost

Total cost per sqm CFRP	Materials	Investment	Manpower	Energy	Waste treatment
777,52 €	151,61 €	106,86 €	435,50 €	78,82 €	4,73 €

Figure 6: Results of the LCC of the DDF manufacturing of non- sensorised panels carried out by AMRC

- *Sensorised panel*

As for the other manufacturing processes, the use of MWs has no significant impact in the DDF manufacturing process, so, as Table 11 and Figure 7 shows, there is an increase in material costs due to the cost of MWs, increasing the contribution of material costs to almost 22% of total costs.

Table 11: DDF manufacturing of sensorised panels carried out by AMRC cost structure by type of cost

Total cost per sqm CFRP	Materials	Investment	Manpower	Energy	Waste treatment
801,54 €	175,64 €	106,86 €	435,50 €	78,82 €	4,73 €

Figure 7: Results of the LCC of the DDF manufacturing of sensorised panels carried out by AMRC

When comparing the results obtained for non-sensorised and sensorised CFRP panels, the sensorised panels have a higher production cost, 24,02 €/sqm CFRP panel due to the cost of MWs.

5.2 USE STAGE

To compare the benefits of implementing the MWs technology in the CFRP panels, we have considered two different scenarios. As explained in deliverable 5.2, the MWs technology will bring the possibility of continuous monitoring of the health of the panels so early detection of defects and alterations of the CFRP panels will be possible.

This means that some of the most usual issues during the use stage could be repair instead of replacing the complete panel. Therefore, both maintenance operations have been modelled in order to assess the costing impacts.

Repairing process

During its use stage, the CFRP panels can suffer different issues that can be repair if detected early. For the aim of the study, we have assessed the most common issue which is dent damage. This type of damage can be repaired easily, avoiding the damage to increase the affected surface during time. For the purpose of the study, we have considered average dent damage usually not detected between aircraft D-checks during the use stage of the CFRP panels.

As Table 12 and Figure 8 show, more than 81% of the costs are material costs, while manpower costs accounts for less that 19%.

Table 12: Repairing process cost structure by type of cost

Total cost per sqm CFRP	Materials	Investment	Manpower	Energy	Waste treatment
12,10 €	9,837 €	0,014 €	2,233 €	0,020 €	0,0003 €

Figure 8: Results of the LCC of the repairing process of the CFRP panels during their use stage

Replacement of panel

Alternatively to the repairing operation, when dent damages are not detected early, the damage would increase with time, and when detected during D-checks, the panels will be replaced with new panels.

Table 13 and Figure 9 show that material costs contribute more than 86% to the total cost of the panel replacement process.

Table 13: Panel replacement process cost structure by type of cost

Total cost per sqm CFRP	Materials	Investment	Manpower	Energy	Waste treatment
14,26 €	12,31 €	0,73 €	1,12 €	0,09 €	0,00 €

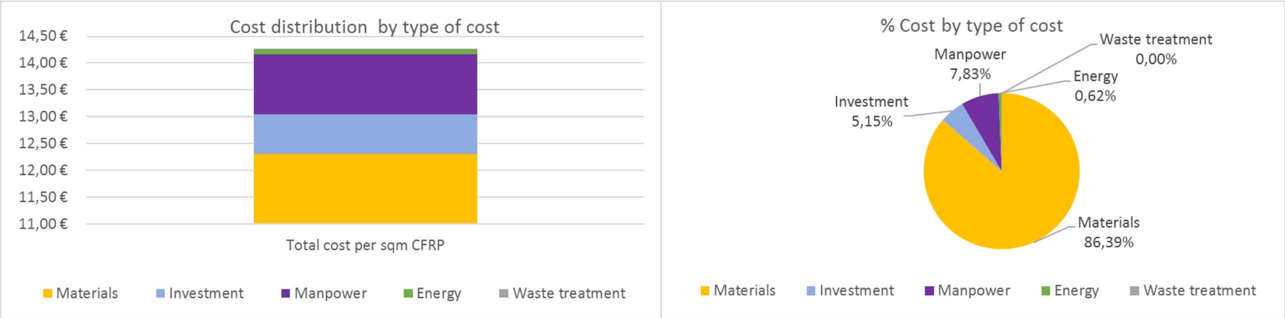


Figure 9: Results of the LCC of the panel replacement process of the CFRP panels during their use stage

5.3 END-OF-LIFE STAGE

In the end-of-life stage, two alternative scenarios have assessed.

The first one corresponds to the current situation of CFRP waste which are mainly sent to disposal. The average cost of waste disposal in Europe is 42,50 €/ton of waste.

The second scenario corresponds to the recycling process of the CFRP panels through the process tested and validated in the project to recover carbon fibres and MWs. The recycling process consist of a combination of pyrolysis and oxidation of the sensorised composite panels where CFs and MWs are recovered mixed, followed by a separation process using magnets.

In this case, recycled carbon fibres are a market valued material. The market value has been estimated considering its quality properties compared to the virgin carbon fibres and the market demand for this product. Therefore, a market value of 23,68 €/kg has been considered.

As Table 14 and Figure 10 show, the value of the recycled CFs compensates the costs of the recycling process making it profitable according to current market situation.

Table 14: Recycling process cost structure by type of cost

Total cost per sqm CFRP	Materials	Investment	Manpower	Energy	Waste treatment
- 98,11 €	- 113,80 €	0,13 €	2,03 €	13,53 €	- €

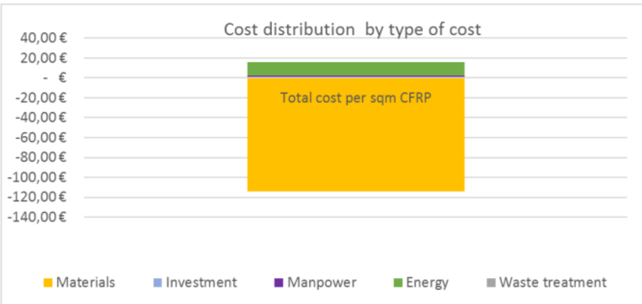


Figure 10: Results of the LCC of the recycling process of sensorised CFRP panels

5.4 COMPLETE LIFE CYCLE

Finally, to assess the cost impacts considering the complete life cycle of the non-sensorised CFRP panels (current scenario) and the sensorised ones (project scenario), all life cycle stages were put together and compared.

Table 15: Non-sensorised and sensorised CFRP panels cost structure by life cycle stage

	Manufacturing stage	Use stage	End-of-life stage	Total cost per sqm CFRP
Non-sensorised panel	1.069,14 €	14,26 €	0,32 €	**1.083,71 €**
Sensorised panel	1.123,19 €	12,10 €	- 98,11 €	**1.037,18 €**

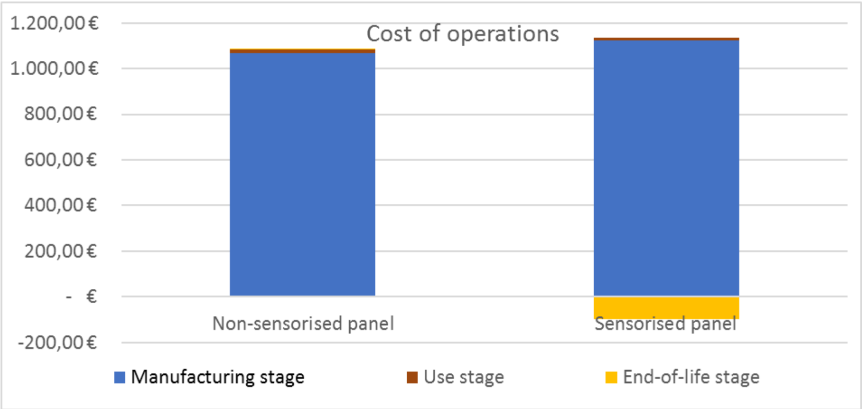


Figure 11: Results of the LCC for non-sensorised and sensorised CFRP panels

As shown in Table 15 and Figure 11, although the manufacturing costs of the CFRP panels are higher for the sensorised panels due to the use of the MWs, these costs are balance with the cost reduction during the use and end-of-life stage, mainly due to the value of the recycled carbon fibres obtained after the pyrolysis-oxidation process.

If the recycling process is not carried out, economic benefits will not be realized from the life cycle perspective. Despite this, it should be taken into account that the use of the sensorised panels would bring additional intangible benefits, such as improved safer air transportation operations as a consequence of early repair operations of the CFRP panels.

6. CONCLUSIONS

The main conclusions after carrying out the life cycle costing 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 increase the manufacturing costs of the CFRP panels.
2. During the use stage, the costs of maintenance during the lifespan of the airplane will be decreased due to the advantage brought by the health monitoring capability the technology provides, being able to detect damages on the CFRP panels earlier, and therefore providing most efficient repairing solutions.
3. The recycling of the carbon fibre contained in the CFRP at the end-of-life through pyrolysis-oxidation process will be beneficial as this is a very valued recycled material with high price in the market, making recycling process profitable.
4. Considering the complete life cycle of an airplane, the analysis shows that the cost of the CFRP panel will be reduced by the implementation of the MWs technology.