CoPropel

Composite material technology for next-generation Marine Vessel **Propel**lers

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Glossary

Abbreviation / acronym	Description
FEP	Freshwater eutrophication potential
FETP	Freshwater ecotoxicity potential
FFP	Fossil fuel potential
GWP	Global warming potential
HTPc	Human toxicity potential
LCA	Life cycle assessment
LCI	Life cycle inventory
METP	Marine ecotoxicity potential
NC machining	Numerical control machining
ODP	Ozone depletion potential
RTM	Resin transfer molding
TAP	Terrestrial acidification potential
TETP	Terrestrial ecotoxicity potential

1. Executive Summary

This report provides a detailed description of the work carried out under Task 6.6 of the CoPropel project. The main goal was to perform a life cycle assessment (LCA) of the manufacturing of a 5-blade novel marine propeller having composite blades. For this, the goals and scope of the LCA are first set along with assumptions made, the system boundary, and limitations. The analysis follows a cradle-to-gate approach where the study ends with the manufacturing of the propeller and does not include the use phase and end of life scenarios as these phases are not part of the scope of the current project.

All the partners in the project associated with the manufacturing process provided information on the energy and raw material inputs to the various subprocesses involved. This data was collected by Brunel and compiled to obtain the life cycle inventory (LCI). Next, the *LCA for Experts* software was used to create the model according to the processes and subprocesses involved in the manufacturing process. Four main overarching processes were studied: modelling and design, preliminary testing, assembly solutions, and manufacturing of the propeller. The data from the LCI were used to populate the model. The software processes the model and provides output in the form of selected impact indicators. Several indicators under the ReCiPe 2016 methodology covering various impact areas were used to investigate the impact that the novel propeller manufacturing process has. The indicators are reported in this study and can be used as a means to compare the process with existing manufacturing techniques. For ease of understanding, a functional reference unit of one propeller with 5 blades is considered.

After thorough analysis, a comparison is done between the LCA results of the current study with the manufacturing of a metal propeller. The investigation shows that the manufacturing of the composite blade has less impact on the environment compared to the manufacturing of a similar metal propeller. The indicators of the metal propeller manufacturing process are nearly 2.5 times the indicators of the manufacturing used in the current project. This serves to show the benefits of the methods used in CoPropel and encourages the shift towards using composite blades in marine propellers.

2. Deviations

The LCA analysis performed covers all the essential sections that were mentioned and discussed in prior meetings of the consortium as stipulated. The analysis includes a thorough study of the life cycle assessment of the composite propeller manufacturing and provides vital indicators concerning environmental and health impact areas. Using the available data, the results are compared with a metal propeller manufacturing process and conclusions are drawn. The models include the manufacturing steps from raw material extraction to final manufacturing of the propeller. Since the data for the use and disposal phases were not collected as part of this project, they were not considered and only the steps up to the manufacturing phase of the propellers were considered and compared.

3. LCA Methodology

Life cycle assessment (LCA) is a technique that addresses the environmental aspects and potential environmental impacts throughout the various stages of a product's life cycle from raw material acquisition to production, use, end-of-life treatment, recycling and final disposal. The methods and stages to be used while conducting an LCA are stipulated in ISO 14040 [1] and ISO 14044 [2]. There are four stages in an LCA analysis: goal and scope definition, inventory analysis, impact assessment, and interpretation of the results. These stages are shown graphically in Figure 1. This section describes the four sections and their individual contributions to the overall LCA study, as necessary for the current study: the design and manufacturing of a novel marine vessel propeller with composite blades.

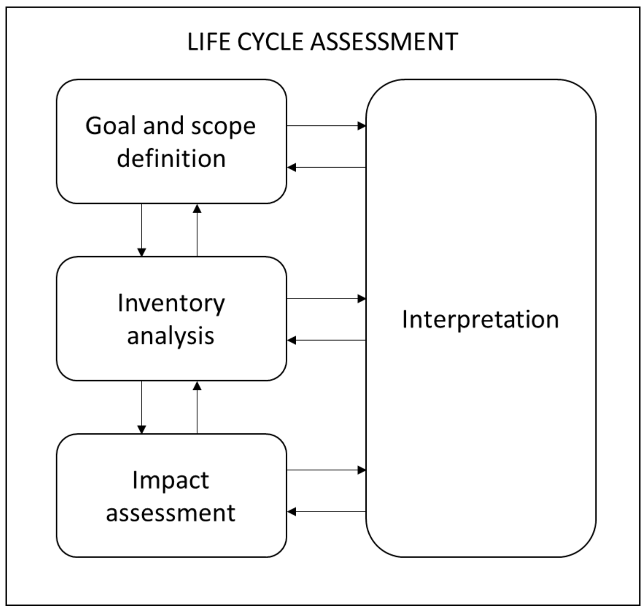

Figure 1: The stages in a life cycle assessment (LCA)

3.1. Goal and scope definition

The goal defines the intended end-purpose of and the reasons for performing an LCA. It also identifies the intended audience and how the results will be used in further comparative analysis and public dissemination.

The scope definition provides clarity on the actual system being studied and system boundary which indicates which stages (or unit processes) of the product's life cycle are included in the LCA. It also defines the functional unit, which is the reference unit for the product system, that can be used for comparative analysis. Other pieces of information such as the assumptions used, limitations, and requirements are also included in this stage.

3.2. Inventory analysis

This phase involves the collection and validation of data relevant to the various unit processes included in the LCA. This includes inputs to the various processes such as energy, raw materials, etc. and flows between the processes. The data is then categorized and it is ensured that they are quantified relative to the unit processes and functional units.

3.3. Impact assessment

This is the phase in which the actual LCA analysis occurs. It involves the selection of necessary impact categories and their indicators, assignment of the inputs and flows to the unit processes and calculation of the chosen impact indicators. The results are then compiled to be analysed and interpreted.

3.4. Interpretation

The interpretation phase involves a thorough study of the results of the impact assessment. This includes checking for consistency and completeness, identification of significant issues based on the results, and drawing conclusions based on the analysis. Limitations and recommendations can also be provided at this stage.

4. Implementation

This section describes the implementation of the LCA analysis of the design and manufacturing of a novel marine vessel propeller. This exercise involved the contributions of all the consortium partners involved in the design and manufacturing process of the project. BUL was involved in coordinating this task and performing the analysis.

The various stages of LCA described in the previous section (Section 4) are carried out in this project task. The details of the stages beginning with goal and scope definition up to impact assessment are provided in this section.

4.1. Goal and scope definition

The main goal of this life cycle assessment is to assess the environmental impact of the design and fabrication of a composite marine vessel propeller. The subsequent secondary aim is to use the LCA results to compare the environmental impact of the manufacturing of the composite propeller with that of a metal propeller manufactured by a conventional manufacturing method.

The primary target audiences of this study are the propeller manufacturers and end-users in the current project so that the viability of producing the novel composite propeller can be justified. This will involve comparing the impact of the novel propeller manufacturing to the manufacturing of existing metal propellers.

The subprocesses considered in the LCA are shown in Figure 2. They are divided into four groups: design, preliminary testing, assembly solutions and propeller manufacturing. This makes this analysis a cradle-to-gate assessment as it begins with the procurement of raw materials and ends with the manufacturing and assembly of the completed propeller. It does not include the use, end-of-life treatment, and recycling phases. This is because the main aim of this assessment is to assess the environmental impact of the manufacturing process of the novel propeller, and all subsequent stages are beyond the scope of the project.

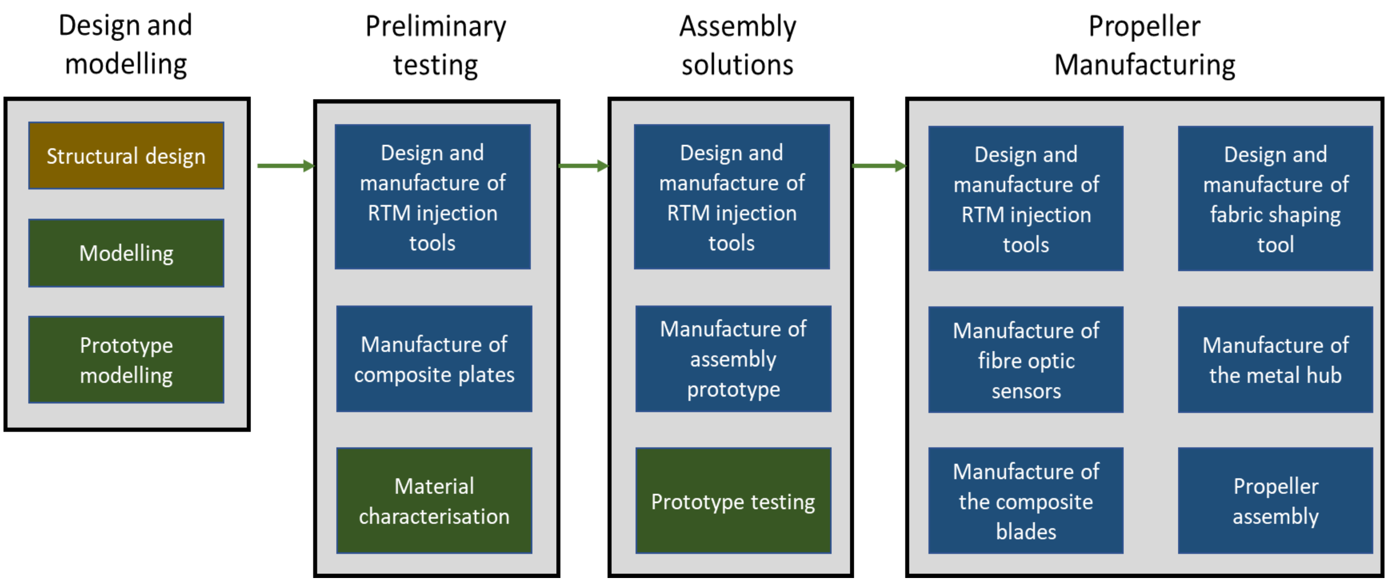

Figure 2: The various subprocesses included in the LCA model indicating the system boundary

As seen in Figure 2, the first stage in the process is the design and modelling of the proposed novel composite blade. The design of the assembly mechanism which links the composite blades to the metal hub is also considered. The next stage involves the preliminary testing of the composite to be used in the manufacturing of the blades. For this, composite plates are fabricated using resin transfer molding (RTM) and includes the design and manufacturing of the RTM tooling, manufacturing of the composite plates, and their testing and characterization. Next, the assembly solutions are designed and manufactured. The subprocesses in this step are the same as that of the previous preliminary testing step: design and manufacturing of the RTM tooling, manufacturing of the assembly prototype and prototype testing. The final and most important step is the manufacturing of the propeller. This step starts with the design and manufacturing of tooling required for RTM and fabric shaping. Next, the metal hub and the required number of composite blades are manufactured, and the entire propeller is assembled.

A few assumptions are made to facilitate the study. The number of composite blades that can be manufactured using a well-maintained injection mold set is limited only by market demand. The modelling, preliminary material testing and assembly prototype manufacturing needs to be done only once for every propeller type manufactured. The same propeller design can equip an identical boat fleet. In this study, a fleet size of 12 identical boats (as was the case for previous projects by the manufacturer LOIRETECH), each with two 5-blade propellers, is assumed. Together with spare blades, the number of blades that need to be manufactured can be approximated as 200. The steps that are non-recurring and need to be performed only once per production run are normalized with respect to this number.

Also, the functional reference unit in this LCA study is one propeller with 5 blades.

4.2. Inventory analysis

This step initially involves obtaining information on the subprocesses involved in the design and manufacturing process from the partners and the inputs and flows associated with each subprocess. A spreadsheet was distributed among the partners involved in the propeller manufacturing by BUL to gather the energy consumption and other data required for the LCA analysis. Next, the compilation of the information received through an inventory assessment was carried out. Upon receiving the data from the partners, it was analysed and compiled in a format suitable for use in the LCA software. In instances where the actual energy consumptions were not available, closest approximations were considered.

Table 1: Life cycle inventory (LCI) of the various subprocesses in the LCA (Gas and electricity usage)

Process	**Subprocess**	**Electricity usage** *kWh*	**Gas usage (Energy)** *kWh*	**Frequency of performing process**
Modelling and design	Structural design	17.25	-	Performed once per production run (i.e. per 200 blades)
	Modelling	0.16	-	
	Prototype modelling	0.58	-	
Preliminary testing	Design and manufacturing of RTM tools	94.92	4.69	
	Manufacturing of 5 composite plates	71.90	1.37	
	Mechanical characterisation	3.22	-	
Assembly solutions	Design and manufacturing of RTM tools	135.41	6.65	
	Manufacturing of assembly prototype	124.19	8.23	
	Prototype testing	2.09	-	
Propeller fabrication	Design and manufacturing of RTM tools	278.72	9.84	1 tool per production run (i.e. per 200 blades)
	Design and manufacturing of fabric shaping tools	222.21	8.68	
	Manufacturing of fibre optic sensors	0.1	-	1 set per propeller (i.e. per 5 blades)
	Manufacturing of metal hub	27.78	7.93	1 hub per propeller (i.e. per 5 blades)
	Manufacturing of 5 composite blades	4116.22	127.67	5 blades per propeller
	Propeller assembly	72.20	7.93	Performed once per propeller

Table 2: Life cycle inventory (LCI) of the various subprocesses in the LCA (Materials and equipment used)

Process	**Subprocess**	**Inputs**	**Category**
Modelling and design	Structural design	Computer	Equipment
		Designer	Labour
	Modelling	Computer	Equipment
		Designer	Labour
	Prototype modelling	Computer	Equipment

		Designer	Labour
Preliminary testing	Design and manufacturing of RTM tools	Aluminium blocks	Material
		Computer	Equipment
		Project manager	Labour
		Designer	Labour
		Numerical control (NC) machine	Equipment
		CAM manufacturing	Equipment
		Control equipment	Equipment
		Manual work	Labour
	Manufacturing of composite plates (5 nos.)	Fabric	Material
		Resin	Material
		Computer	Equipment
		Designer	Labour
		Oven	Equipment
		Injection molding system	Equipment
		Vacuum pump	Equipment
		Manual work	Labour
	Mechanical characterisation	Test equipment	Equipment
		Manual work	Labour
Assembly solutions	Design and manufacturing of RTM tools	Aluminium blocks	Material
		Computer	Equipment
		Project manager	Labour
		Designer	Labour
		NC machine	Equipment
		CAM manufacturing	Equipment
		Control equipment	Equipment
		Manual work	Labour
	Manufacturing of assembly prototype	Fabrics	Material
		Resin	Material
		Recycled sand	Material
		Computer	Equipment
		Project manager	Labour
		Designer	Labour
		Mineral printer	Equipment
		Vacuum pump	Equipment
		Pressurized water heating system	Equipment
		Oven	Equipment
		Injection molding system	Equipment
		Control equipment	Equipment

		Vacuum pump	Equipment
		Manual work	Labour
	Prototype testing	Test equipment	Equipment
		Operator	Labour
Propeller fabrication	Design and manufacturing of RTM tools	Aluminium blocks	Material
		Computer	Equipment
		Project manager	Labour
		Designer	Labour
		NC machine	Equipment
		CAM manufacturing	Equipment
		Control equipment	Equipment
		Vacuum pump	Equipment
		Water heating system	Equipment
		Manual work	Labour
	Design and manufacturing of fabric shaping tools	Wood blocks	Material
		Computer	Equipment
		Project manager	Labour
		Designer	Labour
		NC machine	Equipment
		CAM manufacturing	Equipment
		Oven	Equipment
		Control equipment	Equipment
		Vacuum pump	Equipment
		Manual work	Labour
	Manufacturing of fibre optic tools	Sensing fibres, sleeves and cords	Material
		Carbon powder	Material
		Epoxy resin	Material
		Manual work	Labour
	Manufacturing of metal hub	Cupro-aluminium alloy	Material
		Computer	Equipment
		Designer	Labour
		Control equipment	Equipment
		Manual work	Labour
	Manufacturing of 6 composite blades	Fabrics	Material
		Resin	Material
		Recycled sand	Material
		Computer	Equipment
		Project manager	Labour
		Designer	Labour
		Mineral printer	Equipment
		Oven	Equipment

		Injection molding system	Equipment
		Vacuum pump	Equipment
		Water heating system	Equipment
		Paint dryer	Equipment
		Control equipment	Equipment
		Ventilation system	Equipment
		Manual work	Labour
	Propeller assembly	Manual work	Labour

4.3. Impact assessment

This is the main step in the LCA process where the data obtained from the partners concerning the various subprocesses and flows is used to create a model in an LCA software and impact indicators are selected and set up.

4.3.1. Software used and definitions

The life cycle impact assessment is performed on *LCA for Experts*, which is an LCA software which provides means to model the various processes and subprocesses involved. A multi-cascade approach is used where the processes are divided into subprocesses which could be further subdivided where necessary. The four process groups are modelled in the software as **Plans** and the subprocesses are modelled as **Processes**. The software uses **Flows** to represent the inputs (energy and raw materials) to the various processes and the transfer of energy and materials between the various processes. An example of a **Plan** in the software is the Assembly solutions, whereas the subprocess Manufacturing of assembly prototype within assembly solutions is a **Process.** The subprocesses within this first-level process are modelled as second-level processes, for example, Electricity grid mix and Resin injection. Examples of a **Flow** would be the Epoxy resin which is the input to the resin injection process and Electricity which is the energy which is transferred between the Electricity grid mix and Resin injection processes.

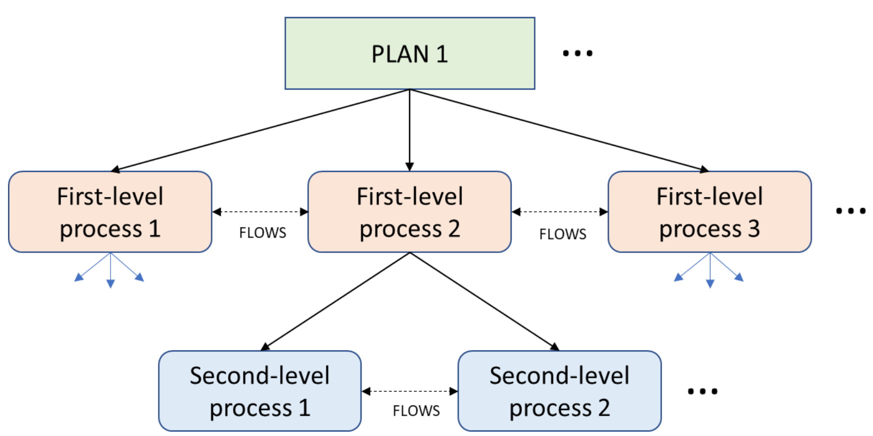

Figure 3: The multi-cascade approach used and its application in the ***LCA for Experts*** *software*

4.3.2. Modelling of the plans and processes

The four main plans and the first-level processes within them modelled in the *LCA for Experts* software are discussed in the following sections. Each of the first-level processes have secondary processes within them, energy and raw material inputs, and flows from other processes.

1. Plan 1 – Modelling and design

The first plan covers the initial design and modelling of the composite propeller blades and the assembly prototype as shown in Figure 4. This contains three processes covering the structural design and modelling tasks. The primary inputs are the electricity necessary to run the computers and workstations used to perform the modelling and the energy required to house the computers and personnel using them.

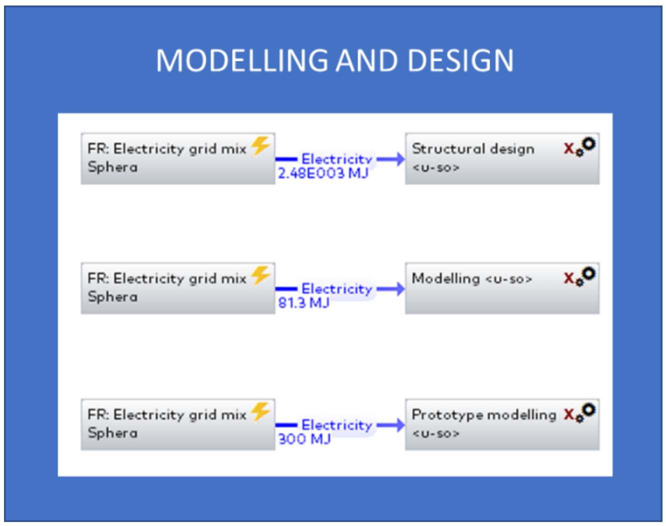

Figure 4: The first-level processes under the ***Modelling*** *plan as modelled in the software*

2. Plan 2 – Preliminary testing

This plan includes the manufacturing and testing of composite plates which provide the material characterization to be used in subsequent phases of the project. The plan, as modelled in the LCA software, is shown in Figure 5. In addition to the main processes, the plan also contains the transportation of the manufactured composite plates from the manufacturer to the testing facility as a separate process. The flows from one process to another are also modelled. For example, the output of the first process (design and manufacturing of RTM tools) is the manufactured RTM tool which is used as the input to the injection molding used in the second process (manufacturing of composite plates).

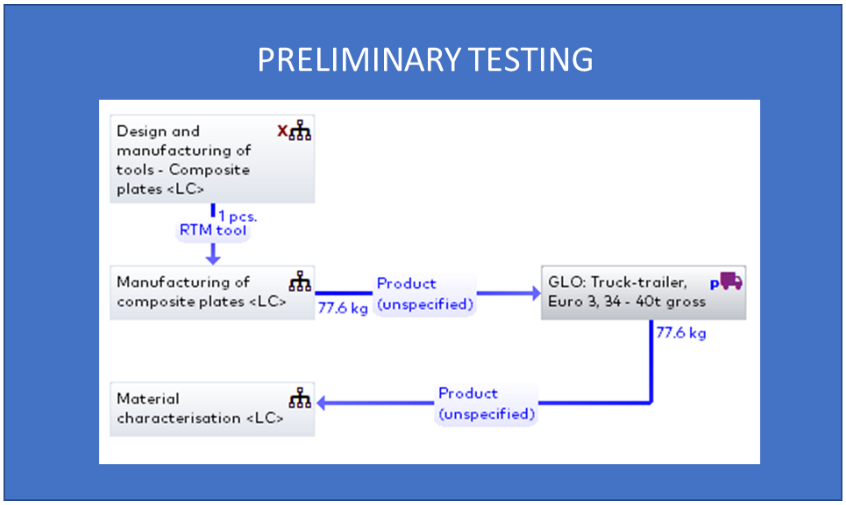

*Figure 5: The first-level processes under the **Preliminary testing** plan as modelled in the software*

The first process under this plan is the design and manufacturing of the RTM tools required to manufacture the composite plates. The model of the second-level processes under this main process is shown in Figure 6. It contains the main processes like tool design, material procurement, the various machining stages, inspection, and tool assembly. The model also contains the various energy inputs such as electricity and gas, and the raw material inputs and transportation required to procure the raw materials. The material flow (in this case, aluminium → RTM tool) along with the material waste at each processing stage is also modelled. This can be seen from the flows involved in one of the processes (rough machining) in Figure 7. As seen, the inputs are electricity, natural gas and aluminium and the output is the product which is the unfinished RTM tool. The quantities of the various flows are also mentioned.

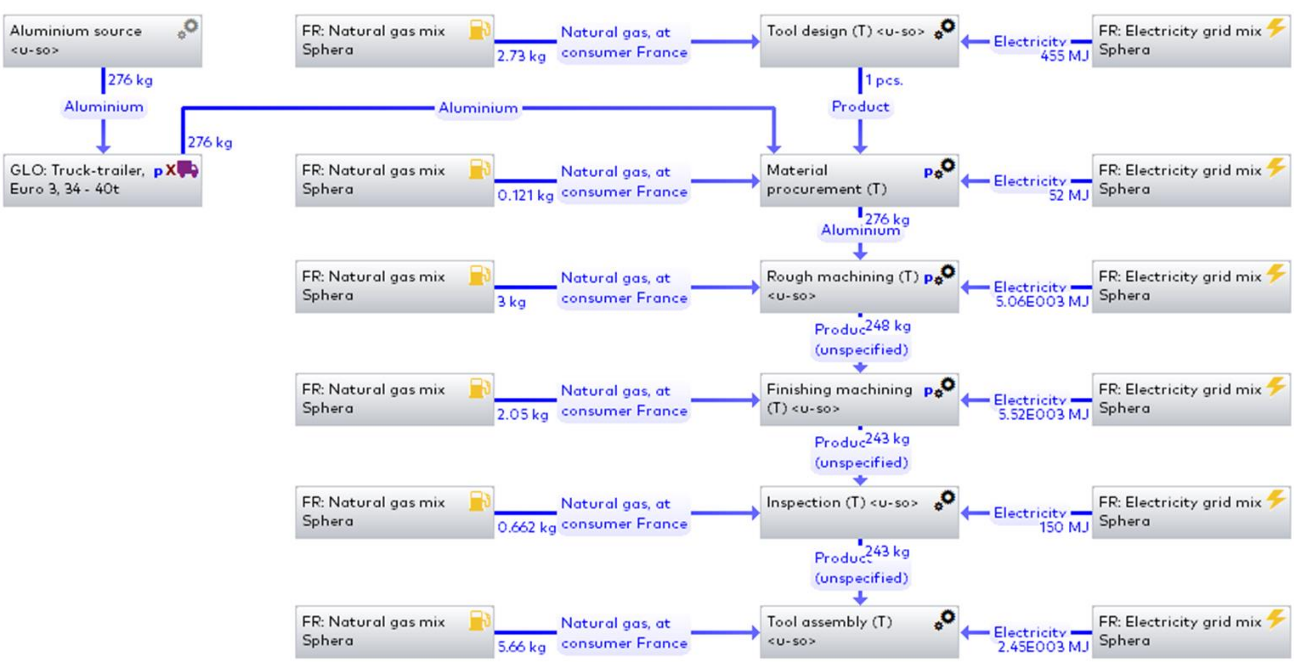

*Figure 6: The second-level processes under the **Design and manufacturing of RTM tools** process*

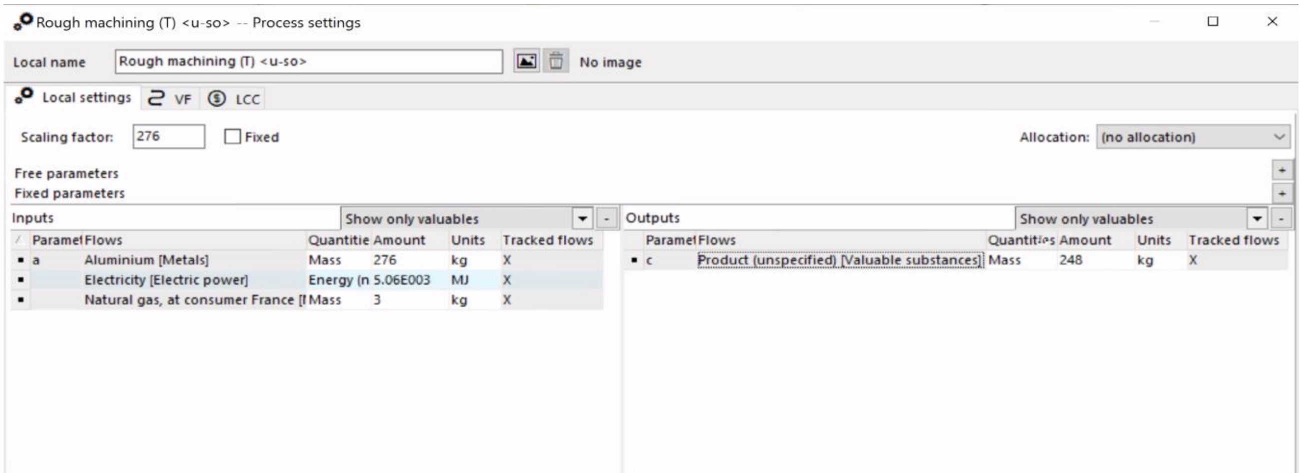

*Figure 7: The flows in the **Rough machining** second-level process*

The models of the other second-level processes in the preliminary testing process are similar to the process shown in Figure 6, and are given in Figure 8 and Figure 9. Although the specific processes are different, the inputs and flows are the same as the first process.

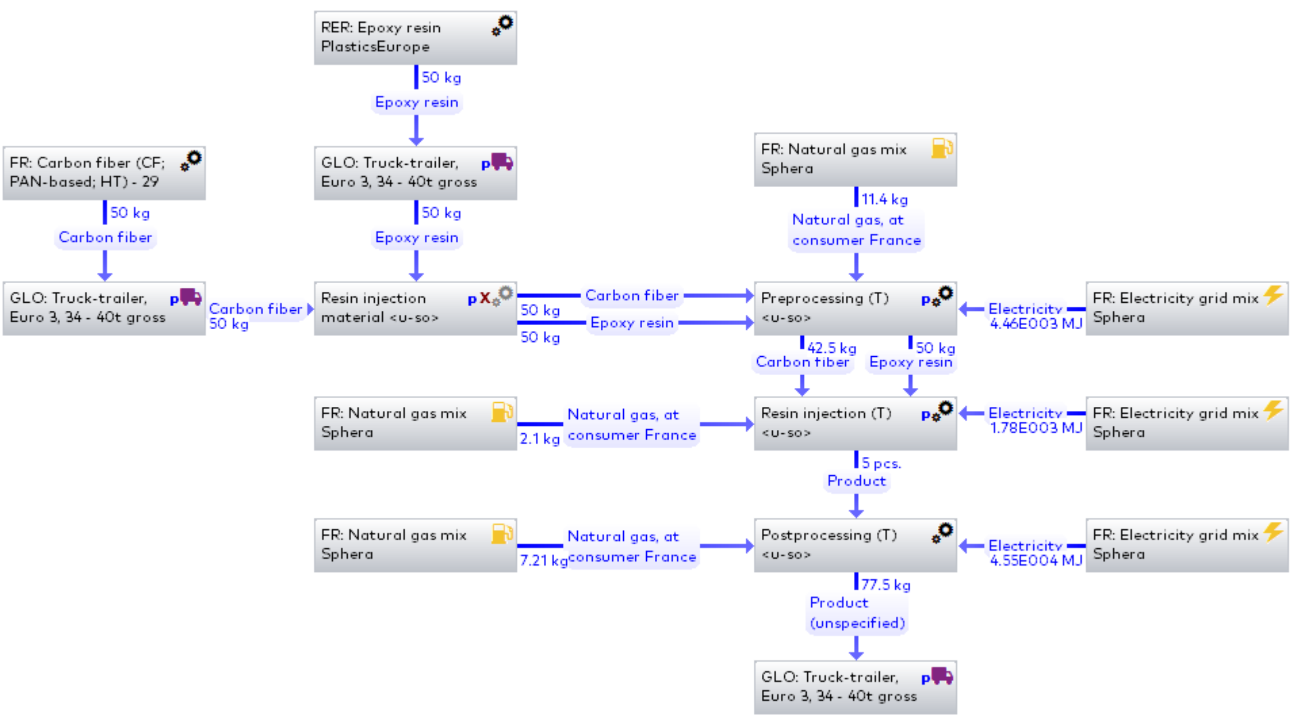

*Figure 8: The second-level processes under the **Manufacturing of the composite plates** process*

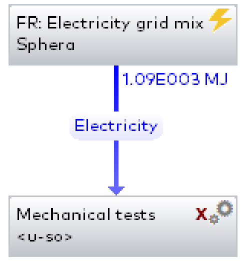

*Figure 9: The second-level processes under the **Material characterisation** process*

3. <u>Plan 3 – Assembly solutions</u>

The assembly solutions plan is quite similar to the preliminary testing plan. The only difference is the objective which in this plan is the design, manufacturing and testing of the assembly prototype. The model of this plan is shown in Figure 10. The second-level processes under the three main processes are shown in

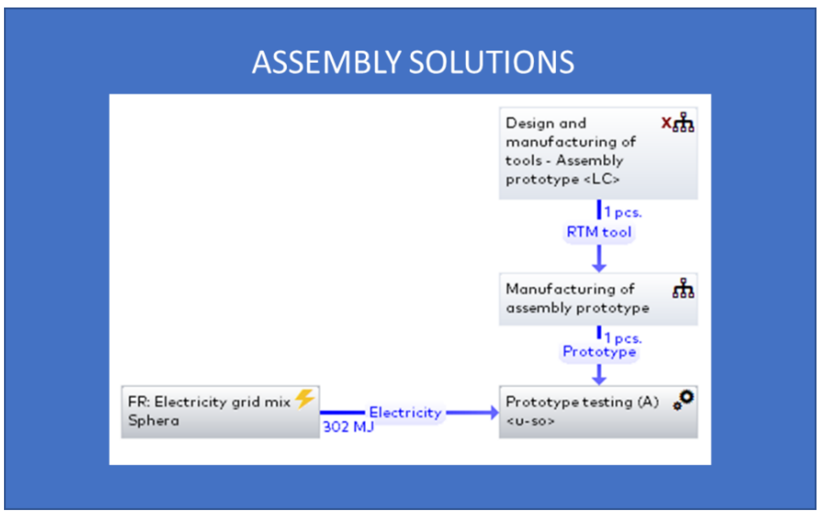

*Figure 10: The first-level processes under the **Assembly solutions** plan as modelled in the software*

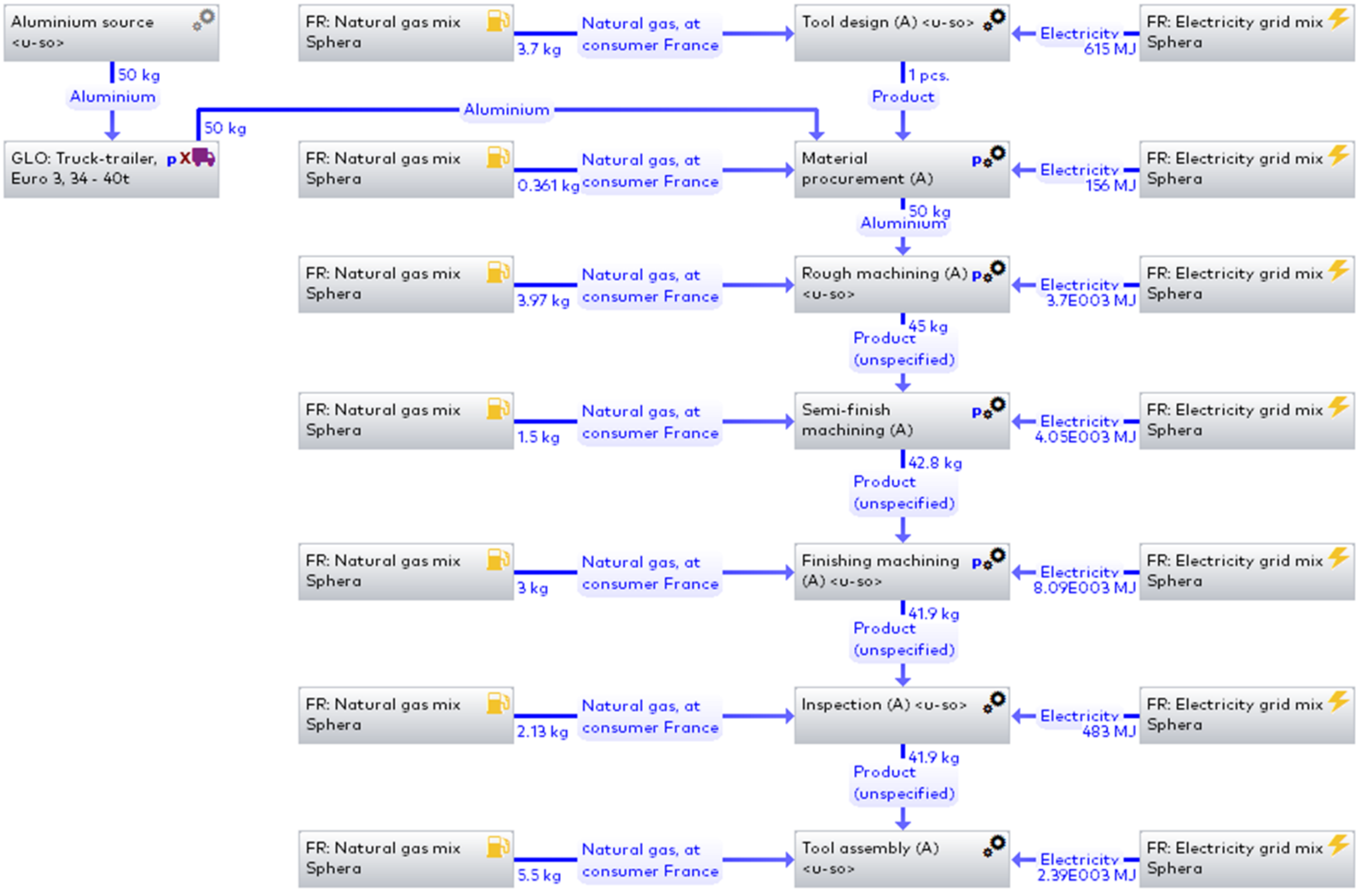

*Figure 11: The second-level processes under the **Design and manufacturing of RTM tools** process*

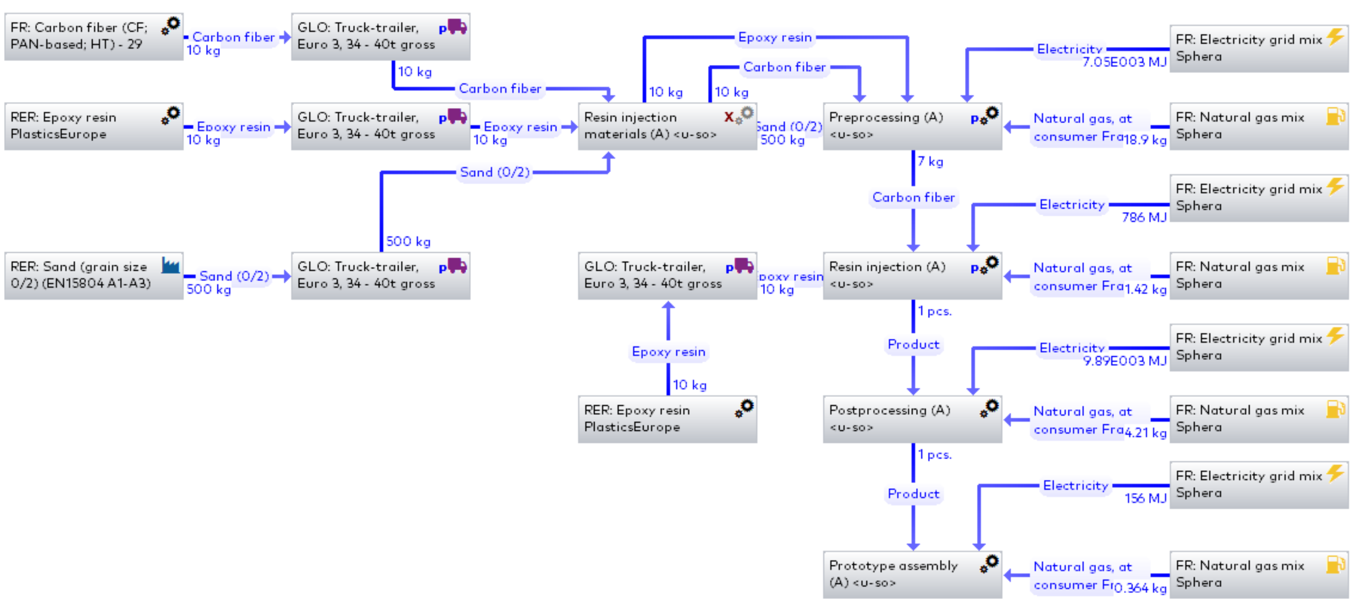

*Figure 12: The second-level processes under the **Manufacturing of assembly prototype** process*

4. Plan 4 – Propeller manufacturing

The final and most important plan is the manufacturing and assembly of the different parts in the designed novel propeller. The model is shown in Figure 13. The plan includes processes for the design and manufacturing of the different tooling necessary, manufacturing of the metal hub, and the manufacturing of the composite blades and final assembly of the propeller.

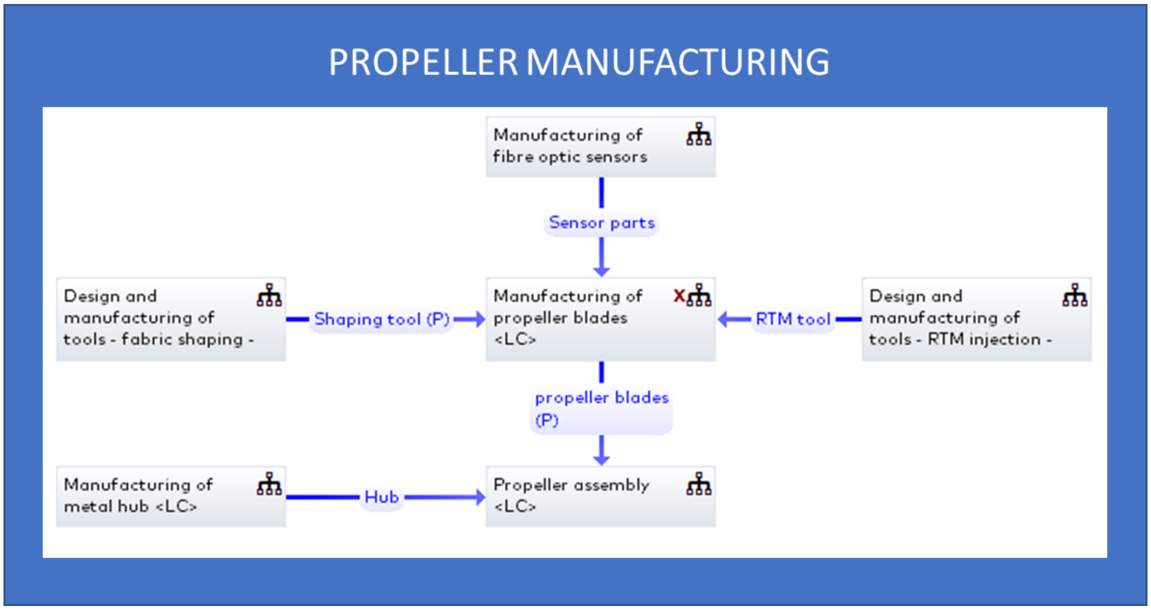

Figure 13: The first-level processes under the ***Propeller manufacturing*** *plan as modelled in the software*

The manufacturing of tooling contains two processes with their subprocesses. The models of these processes are shown in Figure 14 (RTM tools) and Figure 15 (fabric shaping tools).

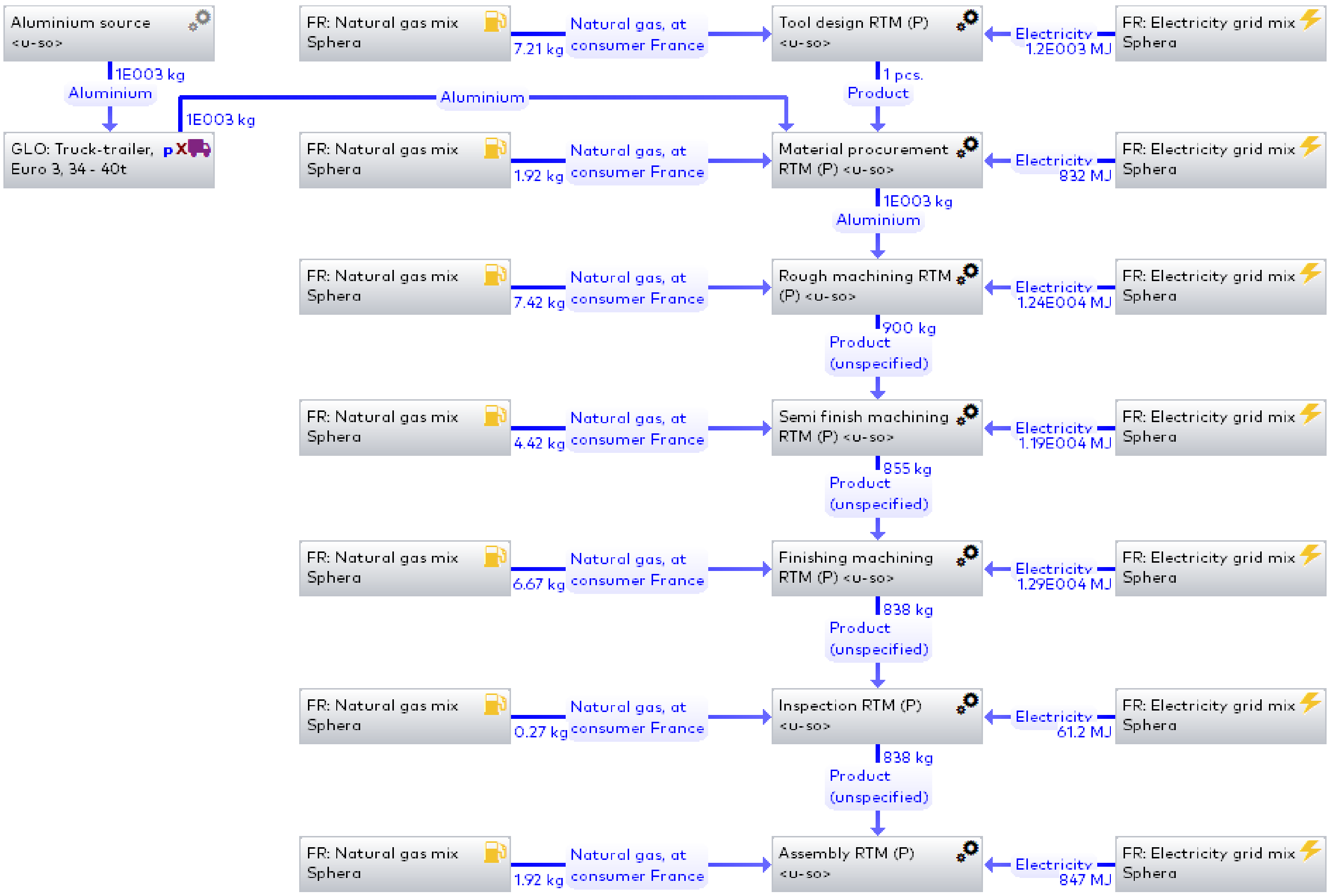

*Figure 14: The second-level processes under the **Design and manufacturing of tools – RTM** process*

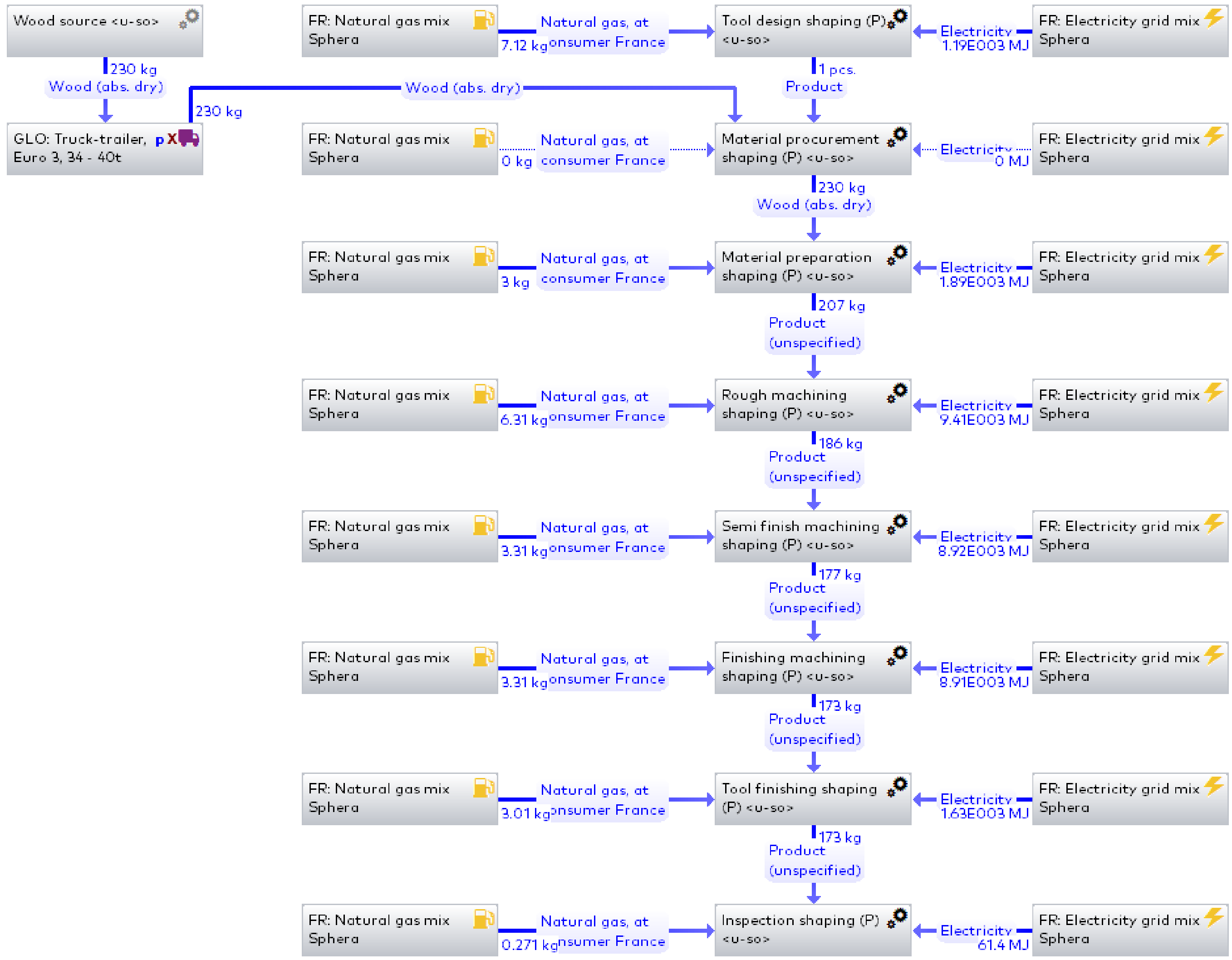

*Figure 15: The second-level processes under the **Design and manufacturing of tools – fabric shaping** process*

The fibre optic sensors are manufactured next, and the process is shown in Figure 16.

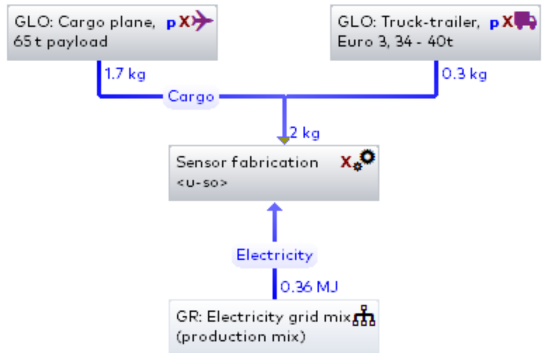

*Figure 16: The second-level processes under the **Manufacturing of fibre optic sensors** process*

The next process involves manufacturing of the metal hub and its subprocesses are shown in Figure 17. The next process involves the fabrication of the composite blades and finally assembling them, along with the hub, to obtain the final propeller as shown in Figure 18 and Figure 19, respectively.

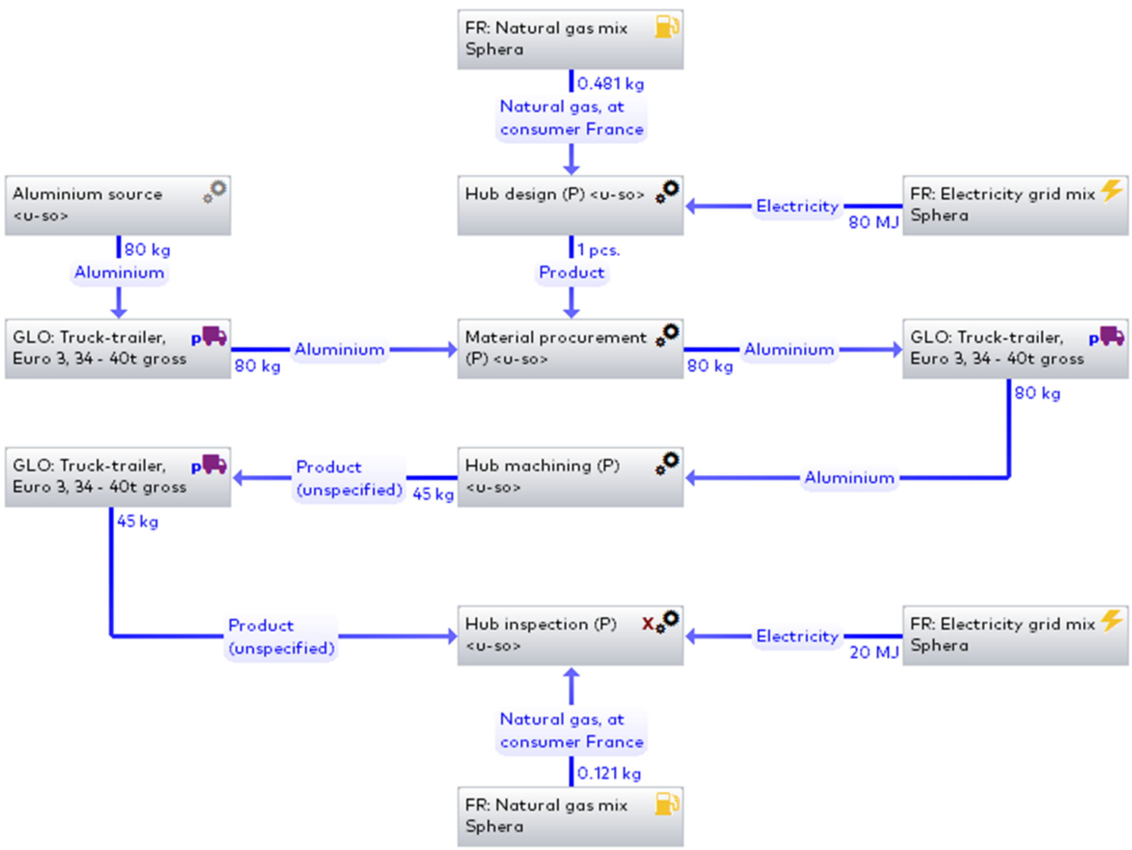

*Figure 17: The second-level processes under the **Manufacturing of metal hub** process*

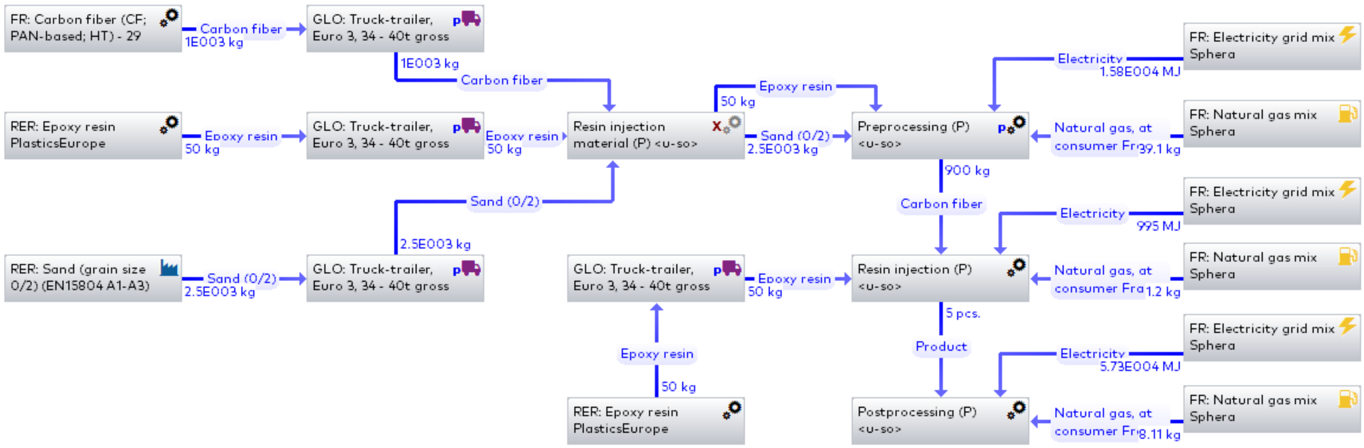

*Figure 18: The second-level processes under the **Manufacturing of propeller blades** process*

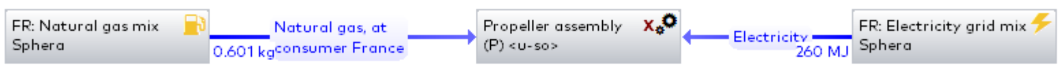

*Figure 19: The second-level processes under the **Propeller assembly** process*

4.3.3. Selection and set up of impact indicators

The next step in LCA modelling is to decide the impact indicators that will be used to assess the product being studied. The methodology used for the current study is ReCiPe2016, which provides the means to convert the life cycle inventories into a number of life cycle impact scores [3]. The impact areas covered in this methodology are human health, ecosystem quality and resource scarcity. Impact indicators and corresponding characterization factors are assigned to each impact category.

The impact categories chosen in this study to investigate the impact of manufacturing of the designed novel propeller are tabulated in Table 3.

Table 3: Selected impact areas and corresponding indicators and characterization factors used in the LCA impact analysis

Impact category	Indicator	Characterisation factor	Unit
Climate change	Infrared radiative forcing increase	Global warming potential (GWP)	kg CO_2 eq to air
Ozone depletion	Stratospheric ozone decrease	Ozone depletion potential (ODP)	kg CF-11 eq to air
Terrestrial acidification	Proton increase in natural soils	Terrestrial acidification potential (TAP)	kg SO_2 eq to air
Freshwater eutrophication	Phosphorus increase in freshwater	Freshwater eutrophication potential (FEP)	kg P eq to freshwater
Human toxicity: cancer	Risk increase of cancer disease incidence	Human toxicity potential (HTPc)	kg 1,4-DCB eq to urban air

Terrestrial ecotoxicity	Hazard-weighted increase in natural soils	Terrestrial ecotoxicity potential (TETP)	kg 1,4-DCB eq to industrial soil
Freshwater ecotoxicity	Hazard-weighted increase in freshwaters	Freshwater ecotoxicity potential (FETP)	kg 1,4-DCB eq to freshwater
Marine ecotoxicity	Hazard-weighted increase in marine water	Marine ecotoxicity potential (METP)	kg 1,4-DCB eq to marine water
Fossil resource scarcity	Upper heating value	Fossil fuel potential (FFP)	kg oil eq

5. Results

5.1. LCA results and interpretation

The results of the LCA are obtained directly from the software. As mentioned above, various indicators from the ReCiPe 2016 methodology were studied. The software provides both graphical depictions and tabulated results which can be extracted and further analysed. An example of the graphical representation of the results as obtained from the software is shown in Figure 20.

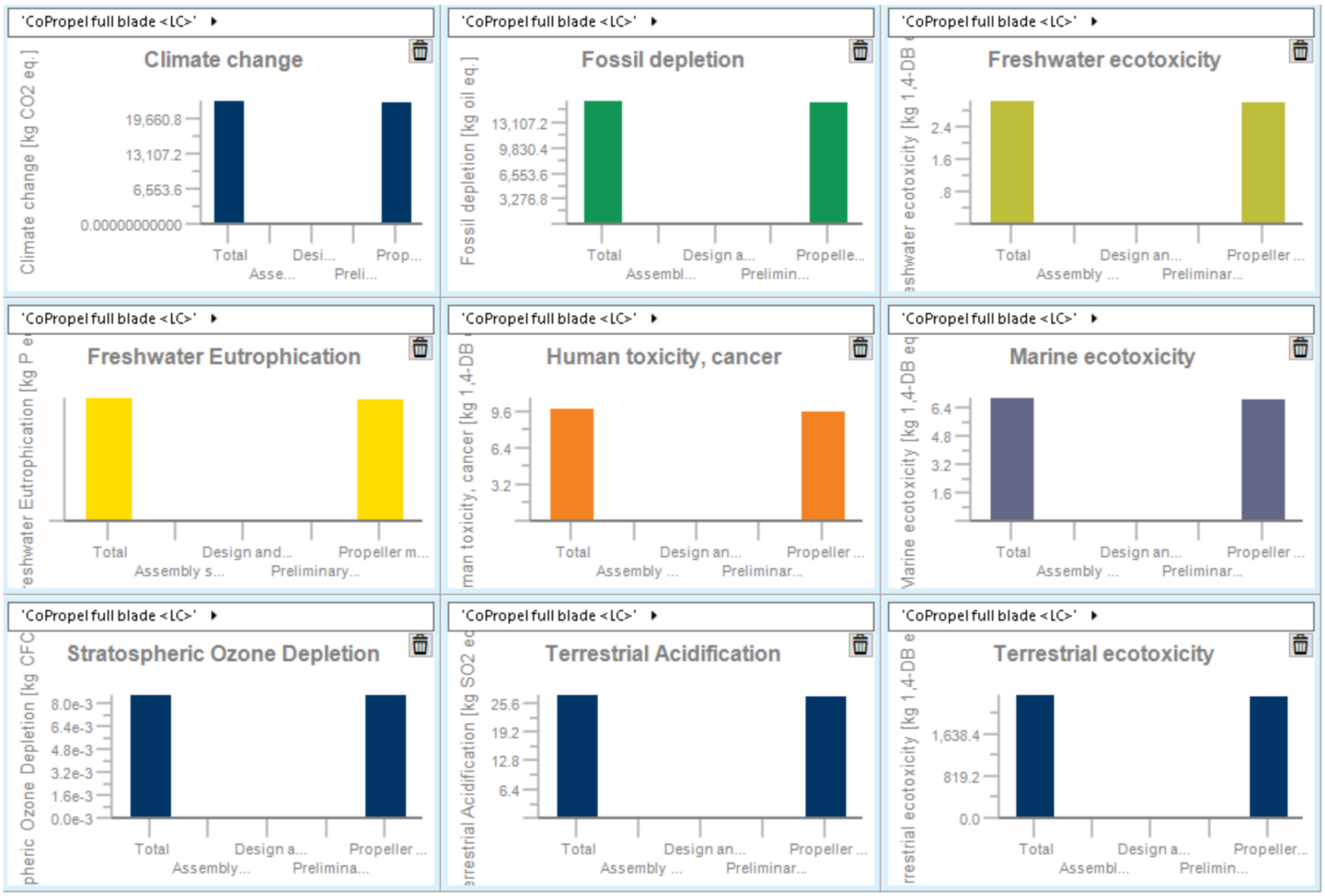

Figure 20: The results of the LCA as directly obtained from the software

The detailed tabulated results are further studied. Table 4 provides a summary of the values of the characterisation factors of the different impact areas studied. Upon performing a hotspot analysis, in all cases, propeller manufacturing has the maximum environmental and adverse human impact. This stage includes the fabrication of the molds to be used, manufacturing of the composite blades and final assembly of the propeller. This is followed in terms of maximum environmental and adverse human impact by the preliminary testing, then assembly solutions and finally the initial design and modelling stage. A graphical comparison of the global warming potential (GWP), which represents the climate change impact area, is shown in Figure 21.

Table 4: The values of the impact indicators studied for different phases of the propeller manufacturing process

Characterisation factor	Unit	Design & modelling	Preliminary testing	Assembly solutions	Propeller manufacturing	TOTAL
Global warming potential (GWP)	kg CO_2 eq	1.52	130.17	41.85	22832.89	**23006.42**
Ozone depletion potential (ODP)	kg CF-11 eq	5.95E-07	3.21E-05	1.15E-05	8.49E-03	**8.53E-03**
Terrestrial acidification potential (TAP)	kg SO_2 eq	2.23E-03	2.90E-01	8.25E-02	26.99	**27.37**
Freshwater eutrophication potential (FEP)	kg P eq	8.01E-06	4.62E-04	2.05E-04	4.77E-02	**4.84E-02**
Human toxicity potential (HTPc)	kg 1,4-DCB eq	2.26E-03	1.09E-01	4.04E-02	9.60	**9.75**
Terrestrial ecotoxicity potential (TETP)	kg 1,4-DCB eq	0.44	28.97	9.57	2369.29	**2408.27**
Freshwater ecotoxicity potential (FETP)	kg 1,4-DCB eq	6.23E-04	2.18E-02	9.65E-03	2.98	**3.02E+00**
Marine ecotoxicity potential (METP)	kg 1,4-DCB eq	1.17E-03	5.72E-02	2.11E-02	6.84	**6.92**
Fossil fuel potential (FFP)	kg oil eq	3.69	122.06	57.52	15822.03	**16005.29**

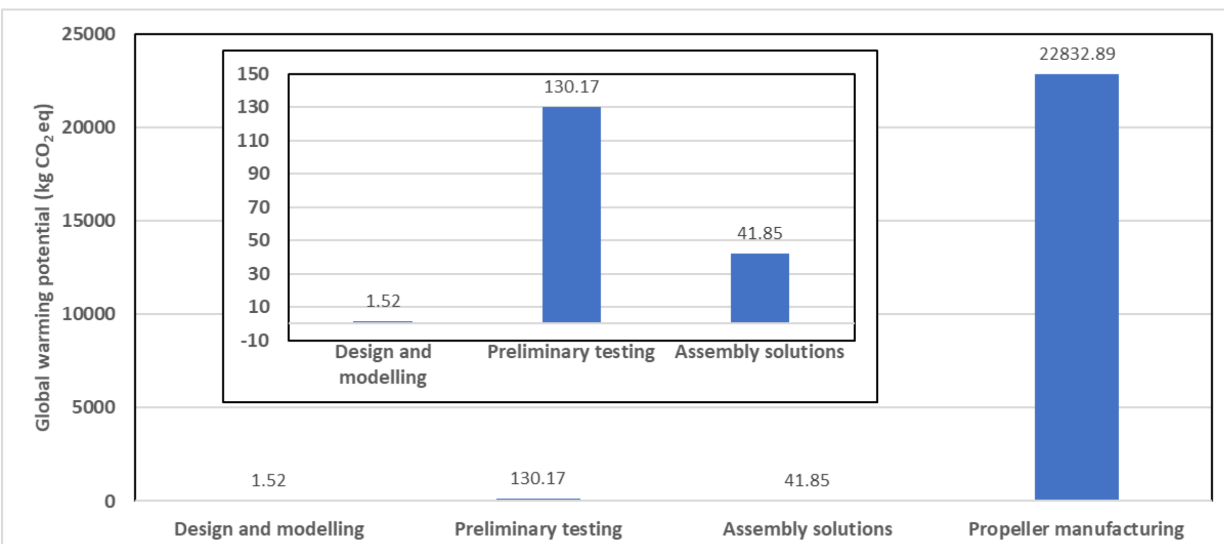

Figure 21: Comparison between the global warming potential (GWP) impact between the different phases of the propeller manufacturing process

Within the propeller fabrication stage, which has the most adverse negative impact, the GWP values of the different subprocesses and their proportions are shown in Table 5. Nearly all the impact is from the manufacturing of the 5 composite blades. Each of the remaining processes only contribute to 1% to 2% of the total. This is justified since the tools are manufactured for multiple blade manufacturing sets (in this case, 1 tool per 200 blades). The same trend is seen in the preliminary testing stage where most of the environmental impact is from the manufacturing of the composite plates.

*Table 5: The values of GWP for the processes under the **Propeller manufacturing** plan*

Process	GWP	%
	kg CO_2 eq	
Design and manufacturing of RTM tools	230.98	1.01
Design and manufacturing of fabric shaping tools	17.86	0.08
Manufacturing of fibre optic sensors	2.37	0.01
Manufacturing of metal hub	3.13	0.01
Manufacturing of composite blades (5 nos.)	22549.54	98.76
Propeller assembly	29.02	0.13

5.2. Comparison with fabrication of metal propeller

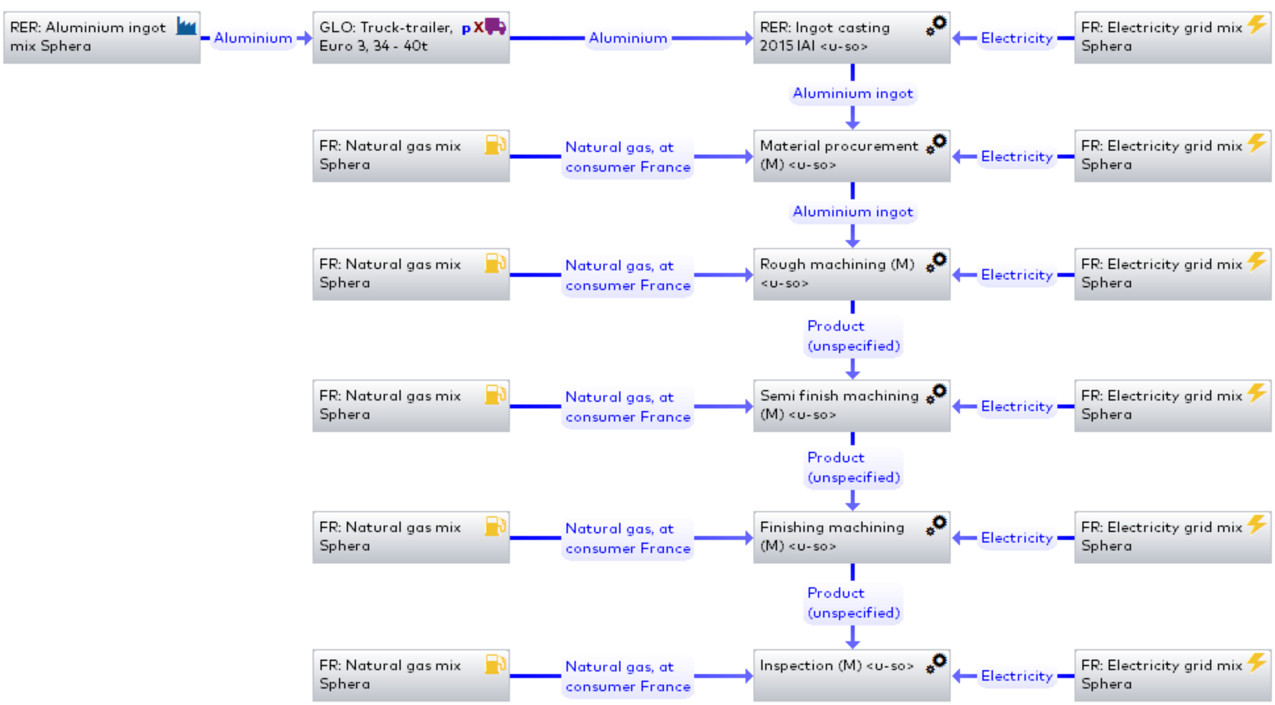

*Figure 22: The subprocesses involved in the **Manufacturing of the metal propeller** process*

The model as used in the software to analyse the metal propeller manufacturing impact is shown in Figure 22. A few assumptions are made to make the comparison easier:

- The manufacturing of the hub is not considered as both the metal and composite propellers use the same type of metal hub. Also, the manufacturing and integration of the sensors in the composite propeller manufacturing is not considered as the same is not required for metal propellers.
- The functional unit for both composite and metal cases is *one propeller consisting of 5 blades.*

- The subprocesses considered for metal propeller manufacturing are the casting to obtain the initial material, metal propeller machining process and inspection.
- Since the manufacturing of the metal blade was not within the scope of the current project, obtaining the exact energy and raw material inputs was not possible. Thus, the inputs of the metal propeller manufacturing case are obtained from the tooling data of the composite blade manufacturing process.

The model was analysed and the values of the indicators are obtained. The impact indicators mentioned previously are used to compare the environmental impact of the manufacturing of the novel propeller with the fabrication of a conventional metal propeller. The results are tabulated in Table 6. In most of the indicators, the impact of manufacturing of the composite propeller is significantly lower than that of the metal propeller. The driving factor for this reduction is the fact that machining, which is one of the processes with a large environmental impact, needs to be performed lesser for the composite propeller manufacturing as part of the tooling manufacturing, whereas in the metal propeller manufacturing, the entire propeller, consisting of five blades, needs to be machined. This is energy intensive and results in more environmental impact. The largest benefits are seen in the terrestrial acidification and ecotoxicity potentials and human toxicity potential (cancer) with nearly 80% reduction in impact indicator values. The global warming potential reduces by half. This shows that the manufacturing of composite propellers is more sustainable and environmentally and human health friendly compared to the manufacturing of metal propellers.

Table 6: Comparison of impact indicators between the manufacturing of the composite and metal propellers (5 blades each)

Indicator	Unit	Metal propeller manufacturing	Composite propeller manufacturing	% change
Global warming potential (GWP)	kg CO_2 eq	45980.21	23006.42	-50%
Ozone depletion potential (ODP)	kg CF-11 eq	7.65E-03	8.53E-03	12%
Terrestrial acidification potential (TAP)	kg SO_2 eq	143.96	27.37	-81%
Freshwater eutrophication potential (FEP)	kg P eq	3.91E-02	4.84E-02	24%
Human toxicity potential (HTPc)	kg 1,4-DCB eq	39.72	9.75	-75%
Terrestrial ecotoxicity potential (TETP)	kg 1,4-DCB eq	12502.61	2408.27	-81%
Freshwater ecotoxicity potential (FETP)	kg 1,4-DCB eq	4.77	3.02E+00	-37%
Marine ecotoxicity potential (METP)	kg 1,4-DCB eq	19.65	6.92	-65%
Fossil fuel potential (FFP)	kg oil eq	22452.51	16005.29	-29%

6. Conclusions

In this study, a thorough LCA analysis is performed on the manufacturing steps of the novel marine propellers in CoPropel consisting of composite blades. Several indicators in different impact areas from the ReCiPe 2016 methodology are used to quantify the environmental impact. The indicators show that most of the impact is from the manufacturing of the composite blades using injection molding. The low values in the other stages are because of the assumption that the initial design and testing stages need to be performed only once per production run, which in this case is assumed to be the production of 200 blades, which is in line with observations from previous projects by LOIRETECH. The results obtained are then used to compare the sustainability of the manufacturing process used for the propellers with composite blades to the manufacturing of a metal propeller using conventional machining methods. The comparison shows that the method and propeller used in CoPropel is much more sustainable to manufacture than a metal propeller manufactured by conventional manufacturing method. Most of the impact indicators involved in the manufacturing of the composite propeller are significantly less than those in the manufacturing of a metal propeller. While the global warming potential (GWP) reduces by nearly half, some indicators such as terrestrial acidification and ecotoxicity potentials and human toxicity potential (cancer) show nearly 80% reduction in values for the composite propeller manufacturing. This is significant as it means that the manufacturing of the novel composite as proposed by the CoPropel project is much more sustainable compared to the manufacturing of metal propellers using conventional methods.

Due to the data used in the LCA study being directly obtained from the partners and it being actual energy and raw material input data, the results obtained can be readily used to perform further, more complex analysis of the next stages in the propeller life cycle such as the use phase and the end-of-life scenarios. The comparison with the metal propeller manufacturing process shows the sustainability of the method used in the CoPropel project and the advantage of using a composite propeller compared to a metal one. This will encourage further study in the area and will provide an incentive to use marine propellers with composite blades which are also much lighter (nearly half in terms of weight) compared to conventional metal propellers.

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