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# Life-Cycle Cost Analysis for Filament Winding of Composite Structures

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# Life-Cycle Cost Analysis for Filament Winding of Composite Structures

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# Abstract

At the Institute of Composite Structures and Adaptive Systems in the German Aerospace Center facilities in Braunschweig a daily effort is made in the pursue of state-of-the-art lightweight and intelligent structure development. The growing demand for fiber reinforced polymers due to their strength-weight potential means an open door to an unexplored market for the composites manufacturing industry. The available manufacturing methods evolve continuously with the advancing material and process technologies. Therefore vast amplitude of analysis is required to better understand the implications of each new novelty for the industry in terms of environmental emission and manufacturing costs.

In this paper the total incurred costs for the manufacturing of composite structures by the filament winding process are evaluated. This process will be integrated in a computer based cost estimation tool to calculate the result and offer the capability to trace the cost source to its category and unit process within the complete manufacturing of a winded component. The comparison between manufacturing scenarios will aid decision makers to select a manufacturing system from the design stage. All approaches are to follow ISO standards in order to achieve an improved transparent performance. A subsequent intention is the reduction of skills for the end user to operate the tool.

# Table of Contents

# List of Figures

# List of Tables

# Useful definitions

**Life-Cycle**

in systems engineering, consecutive and interlinked stages of a product system, from raw material acquisition or generation from natural resources to final disposal.

**Product system**

collection of unit processes with elementary and product flows, performing one or more defined functions, and which models the life cycle of a product.

**Functional unit**

quantified performance of a product system for use as a reference unit.

**Reference flow**

measure of the outputs from processes in a given product system required to fulfil the function expressed by the functional unit.

**Unit process**

smallest element considered in the life cycle inventory analysis for which input and output data are quantified.

**Allocation**

partitioning the input or output flows of a process or a product system between the product system un-der study and one or more other product systems.

**Elementary flow**

material or energy entering the system being studied and drawn from the environment without previous human transformation, or material or energy leaving the system being studied that is released into the environment without subsequent human transformation.

**Concurrent Engineering (CE)**

a systematic approach to integrated product development that emphasizes the response to customer expectations. It embodies team values of co-operation, trust and sharing in such a manner that decision making is by consensus, involving all perspectives in parallel, from the beginning of the product life-cycle.

# 1. Introduction and Motivation

The pretext behind Sustainable Development is in concept much simpler than its development itself, whereas the consequences of not fulfilling such development will have very diverse and negative impacts in the future of human civilization as a whole. In many cases such detrimental effects won't be suffered by the ones who had the power to avoid them but by other beings with which we share an interdependent environment. The European aerospace industry has set very ambitious goals to overcome the challenges from emerging competitors but also to reach a state-of-the-art sustainable performance. "With its leading knowledge and manufacturing capability, the European aviation industry is in a position to define and shape a sustainable future" [1].

Sustainable Development (SD) as a term first appeared in the Brundtland Report in 1987 [2] then defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs", a call to counteract environmental impact of the industrial revolution demonstrated by the growing results from analysts [3]. Afterwards, the United Nations released in the Earth Summit at Rio de Janeiro in 1992 [4] a declaration of 27 principles with the intention to determine the target of the mankind future on the pillars of three interconnected frameworks to guarantee a Sustainable Development. These three are the Ecological, Economic and Social aspects.


*Figure 1: The three aspects of Sustainable Development*

When framing the aerospace industry in this target-oriented scenario it is commonly found that performed processes influencing any of the three aspects are evaluated in order to assess their impact and ultimately develop a solution with the mentioned sustainable goal. For example when an airline operating firm has to decide what part replacement is fitted to improve their aircraft fleet, the firm will be led to evaluate the part component as a function of not only its purchasing price, but also the in-service costs (ease of assembly, maintenance, fuel savings, i.e. Economic aspects), emissions to the environment (pollutants, noise, i.e. Ecological aspect), firm ethics and legal regulations (Human rights, political scenario, i.e. Social aspect). It is also observable in this example how the three SD aspects can be all related. Fuel consumption impacts the Economic and Ecological aspects, noise emissions the Ecological and Social, political scenarios can influence Economic and Social aspects.

The component from the previous example was evaluated in a fraction of its life-cycle (from purchasing of already manufactured part to its disposal), but a complete part life-cycle is defined by a cradle to the grave staged process, that is, from the raw material acquisition to

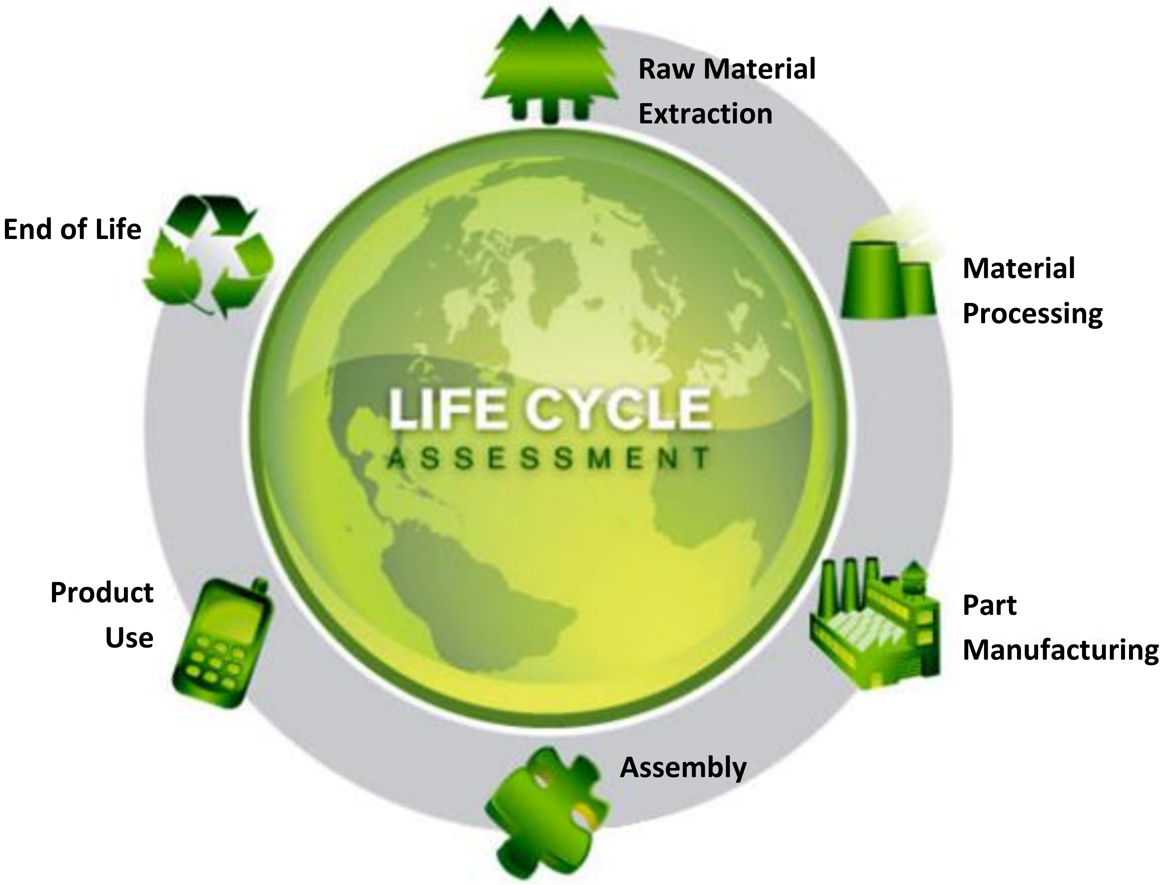



*Figure 2: Stages of a product Life-Cycle*

final disposal [5, p. 84]. For a product manufacturing process and especially for composite material products only the design and manufacturing stages are evaluated for their cost analysis [6]. These are key stages for the following life-cycle of the component because the design stage defines the characteristics of the composite product and it is during the manufacturing stage where the cost consequences of the design definitions are incurred. Cost allocation research on the military aerospace manufacturing industry reflects up to 70% of the total life cycle cost committed at the early design stage [7]. Designers are in a position to substantially reduce the life cycle cost of the products they design by giving due consideration to life cycle cost implications of their design decisions [8].

One of the many goals presented in the European Commission's vision for aviation, Flightpath 2050 [1], is the development of "Streamlined systems engineering, design, manufacturing, certification and upgrade processes to address complexity and significantly decrease development costs (including a 50% reduction in the cost of certification). A leading new generation of standards is created". One of the keys for Europe's global lead is the implementation of international standards, enabling market access and free, fair and open competition. This strategy will have a decisive role for the next decade's Fiber Reinforced Polymers (FRP) manufacturing industry in Europe. Market research firm *Lucintel* analyzed in 2012 the composite industry market opportunities [9] and estimated that the industry will reach a 7% CAGR (Compound Annual Growth Rate) by 2017, where the aerospace and wind energy segments would share a 15% and 14% of the global composite materials distribution. Developing nations overall take a strong role in the global composites production as they increase their participation in the global economy and will force stablished competitors to adapt innovative techniques. However, the high cost of materials and lack of competitive manufacturing processes will continue to be the limiting factors for future growth.

The reason why Filament Winding of Composite Structures was selected in this paper for the analysis of their manufacturing costs has its roots in an under-development project from the German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt, DLR). A computer based estimation tool has been developing in the institute of lightweight structures and adaptronics (Faserverbundlichtbau und Adaptroniks Institut) since 2014 with the purpose of analyzing the manufacturing cost and environmental impact of different manufacturing processes that take place in the DLR facilities of Braunschweig, Niedersachsen. Yet the existing process database and programmed simulations correspond to manufacturing processes such as the classical hand layup, different resin infusion techniques (RTM, injection molding, VARTM…), curing with heaters or Autoclave and assembly processes like positioning and machining to mention some examples. However other available manufacturing technologies like Filament Winding or Pultrusion are not yet implemented in the tool and require of extensive quantitative analysis, where a large database of accurate measurements is fundamental to reach precise estimations. "Besides the large increase in demand for FRP, filament winding has shown the largest growth in direct conversion over the last 10 years. The three major applications are self-contained breathing bottles (SCBA), compressed natural gas (CNG) tanks and industrial rollers. The largest new potential end use for filament wound CFRPs could be the manufacture of riser pipes, drill risers and choke and kill lines for the offshore oil industry" [10].

The interest of this theses is set on the intention for optimizing the costs incurred during the manufacturing of filament winded composite materials required to reach the competitive market, and it is therefore justifiable to exclude the Social aspect from its development as it is not affected within its Life-Cycle stages, considering that a FRP manufacturer will only perform value-added processes in a fraction of the entire Life-Cycle of the part, a Gate-to-Gate approach [11, p. 17]. Management decision makers will need to assess the possible solutions to transform the input pre-fabricated materials (fibers, resins…) and energy into a component or assembled components that satisfies the consumer requirements from a Sustainable Development perspective, in behalf of the future life-cycle stages being very sensitive to the early design stage.

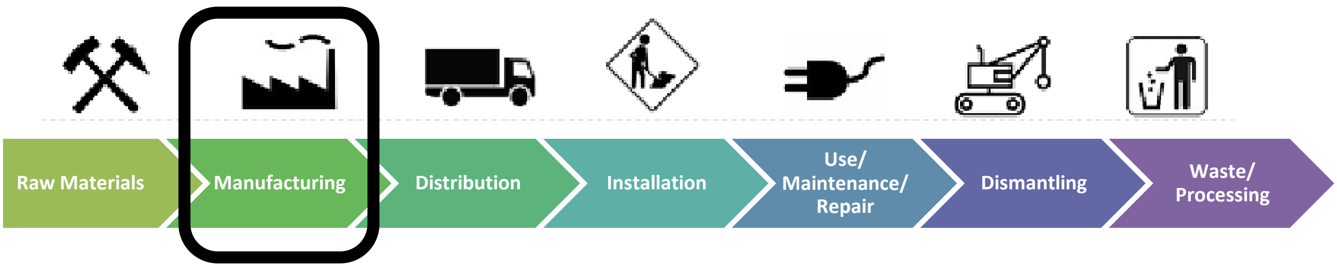



*Figure 3: Gate to Gate approach within the entire product Life-Cycle*

Further in this paper it will be discussed with detail why it is beneficial to evaluate two different performance indicators in product manufacturing (CO2 emissions and costs) in a single computer based assessment tool. Due to the advantages of analyzing similar boundary systems with a common framework, cost estimation procedures can rely on the same basis (scope, framework phases, assumptions) of environmental impact estimation, thus although the scope of the thesis lies on the manufacturing cost analysis, the ecological aspect will be briefly discussed.

# 2. State of the Art: LCCA for Composite Structure Manufacturing

The objective is to develop a cost estimating tool which can assess decision makers in the manufacturing industry to select the most cost effective processes to manufacture a FRC component from an early design stage. To reach a State-of-the-Art Sustainable Development used methodology and techniques are to be performed under ISO standards [12] thus ensuring the basis to build the estimation model that can achieve legitimate international requirements and avoiding the challenges presented to manufacturers due to the complexity and expertise required for formulating and solving assessment problems [13]. There are however other decision support tools which can also assess a possible solution to the ecologic impacts such as Design for Environment (DfE) or Extended Producer Responsibility (EPR), but the Life Cycle Assessment methodology (LCA) developed by the International Organization for Standardization (ISO) and introduced in the ISO 14000 family of standards already contains requirements and recommendations to ensure transparency when including both the ecological and economic impact analysis for comparing different results within an equivalent context of study. "There are a variety of potential further applications in private and public organizations. Other techniques, methods and tools (e.g. Life-Cycle Cost Analysis) do not indicate that they are based on the LCA technique as such, but that the life cycle approach, principles and framework can be beneficially applied" [12]. Although LCA has an Environmental perspective, the methodology it handles to analyze and evaluate the different inputs and outputs of a system can also be valuable to standardize the LCCA estimating tool. Consequently the LCA has to be well understood before introducing a direct application built upon it.

## 2.1. LCA

The increased interest in the developing of manufacturing methods to better understand and address the possible environmental impacts associated with manufactured and consumed products led to the creation of a technique for guiding decision-makers to evaluate the ecological performance and efficiency of available manufacturing processes for alternative scenarios, reducing the risks and costs of the development approaches [14]. The support tool presented in the ISO 14040 document, Life Cycle Assessment, can be defined as the "compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle" [15]. LCA can assist in identifying opportunities to improve the environmental performance of products at various points in their life cycle or the selection of relevant indicators of environmental performance [12]. Generally, the information developed in an LCA study can be used as part of a much more comprehensive decision process, taking in mind that comparing the results of different LCA studies is only possible if the assumptions and context of each study are equivalent. Changes or missing features at every level of detail of the system shall be reported, described and reasoned in order to enhance comparability and transparency.

#### 2.1.1. Phases of LCA

LCA is a systematic technique comprised of four phases and they will be the starting point for the development of the LCCA. These individual phases use the results of the other phases, an iterative approach that contributes to the comprehensiveness and consistency of the study and reported results. The four phases are named and illustrated in the following figure [12]:

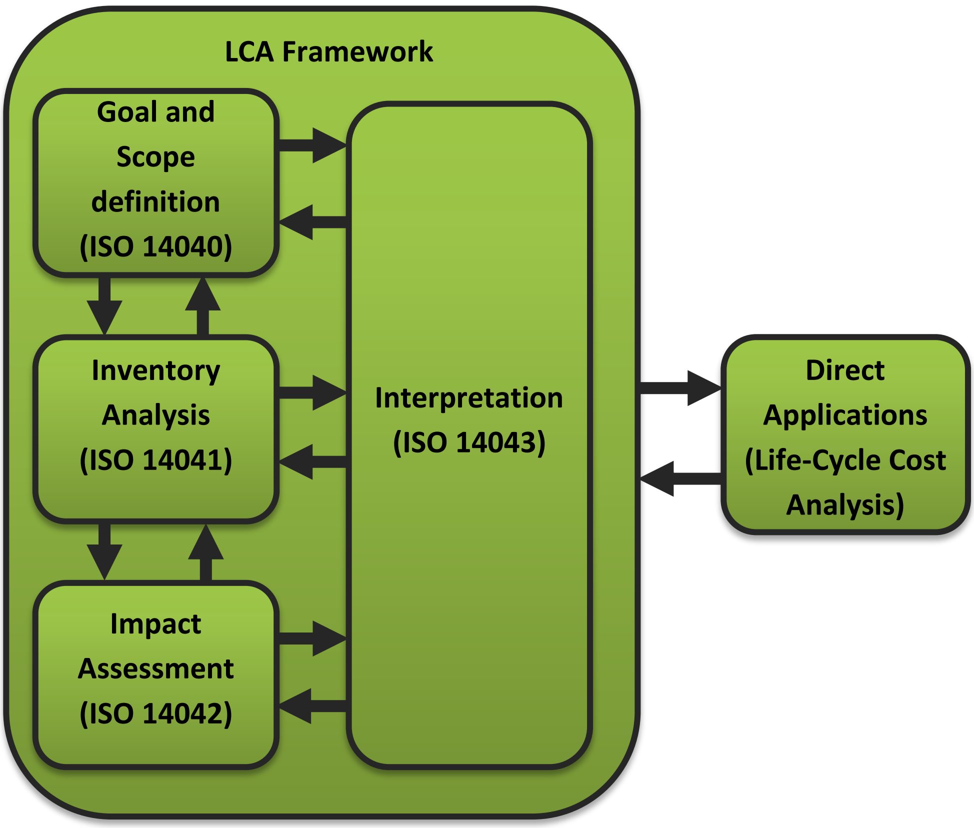



*Figure 4: Diagram illustrating the iterative relations between the framework phases of an LCA study*

The scope of a LCA depends on the product system and intended use of the study, defining also the system boundary and level of detail. A number of functions within the system (performance characteristics) are selected according to the intended goal and scope, and the quantification of these functions are defined by functional units, a key element of LCA that must be clearly understood. The primary purpose of a functional unit is to provide a reference to which inputs and outputs are related in mathematically normalized nomenclature. In other words, the functional unit is a measure of a function of the studied system. After having chosen the functional unit it is important to determine the reference flow in each product system. Ideally, the product system should be modelled in such a manner that inputs and outputs found at its boundary are elementary flows, where this system boundary defines the unit processes to be included in the system (the smallest elements considered in the life cycle inventory analysis for which input and output data are quantified) [16, p. 2.37].

The Life-Cycle Inventory (LCI) identifies and quantifies input/output data with regard to the system being studied. It involves collection of the data and calculation procedures. Data can be classified throughout the system boundary as inputs (energy, raw material, auxiliary inputs), product (and co-product) and outputs (waste, emissions to air, discharges to water/soil). Calculation of data includes the validation of data collected, relating the data to a unit process and relating the data to the reference flow of the functional unit. The calculation of energy flows should take into account the different fuels and electricity sources used, as well as the efficiency of conversion and distribution of energy flow and the inputs and outputs associated with the generation and use of that energy flow [16, p. 3.491].

The purpose of the third phase, Life-Cycle Impact Assessment (LCIA), is to provide additional information to help assess a product system's LCI results so as to better understand their environmental significance, namely the potential human and ecological effects of energy, water, material usage and environmental releases identified in the inventory analysis. In general this process involves associating inventory data with specific environmental impact categories and category indicators [17].

Life Cycle Interpretation is the final phase of the LCA procedure in which the results of the LCI and LCIA and all choices and assumptions made during the course of the analysis are evaluated in terms of soundness and robustness, and overall conclusions are drawn. The interpretation should reflect the fact that the LCIA results are based on a relative approach, that they indicate potential environmental effects, and that they do not predict actual impacts on category endpoints. The main elements of the Interpretation phase are an evaluation of results (in terms of consistency and completeness), an analysis of results (for instance, in terms of robustness), and the formulation of the conclusions and recommendations for decision-makers, consistent with the goal and scope of the study [18].

## 2.2. LCCA

Although Economic and Social aspects and impacts are typically outside the scope of the LCA, it has been previously mentioned that the LCA technique can be modified to be applied as an assessment tool for cost estimation. Life-Cycle Cost Analysis is a systematic decision support tool that analyzes the cost effectiveness of the product system of a study. It evaluates the economic aspects within the product life-cycle by a set of cost associated indicators [19] resulting in the estimation of total incurred costs. The primary focus is to assess the competitiveness of their product's design and determine the sequences of processes to produce and assemble the constituent parts into a complete product in an early design stage where the decision-makers can develop the mentioned cost effectiveness of the product. On the other hand, not all are benefits. This methodology is usually cost and time consuming [20] and therefore one of the intentions in this paper is to develop an easy-to-use transparent method to support the effectiveness of the estimation procedure.

### 2.2.1. LCCA Framework

However, neither the internal nor external economic aspects of the decisions are within the scope of the developed LCA methodology, nor are they properly addressed by traditional LCA tools. Neither has the ISO 14040 series of standards addressed the integration of economic analysis within LCA [21]. There is the need to model the economic value of the inputs and outputs of a multifunctional product system, so that these values can be used as an allocation key [16, p. 3.687]. LCA and LCCA have major methodological differences, deriving from the fact that they are each designed to provide answers to very different questions. On the other hand they share common framework phases although they differ in the purpose and approach of each phase. In table 1 is illustrated the differences between the two methodologies at the common framework phases and their different category indicators implemented for each phase to quantify the goal by compiling miscellaneous results. The following evaluation will reflect the beneficial use of both decision-making tools when conducted through the same framework, leading to reason their integration in a unique computer based estimation tool, hence saving time and managing databanks in a transparent and efficient manner. In the future LCCA can be expected to become a standard addition to LCA applications [16, p. 1.9].

*Table 1: Comparison between the phases of LCA and LCCA studies from (18) and (20)*

| **Framework Phases** | Description of the compared Phases (The differences are written in bold) | |
|---|---|---|
| | **LCA** | **LCCA** |
| Goal and Scope Definition | Evaluating and/or comparing the life-cycle of functional unit(s) from **environmental perspectives** | Evaluating and/or comparing the life-cycle of functional unit(s) from **economic perspectives** |
| LCI | Observing the product system and measuring the elementary flows (as **physical units**) | Observing the product system and measuring the elementary flows (as **monetary units**) |
| LCIA | Determining (and comparing) the category indicator result Ex. **Kilograms of CO2-equivalents** per functional unit (s) , and identifying the category endpoints | Determining (and comparing) the category indicator result Ex. **€-equivalents** per functional unit (s) |
| Direct Applications | **Environmentally friendly** development applications | **Cost effectiveness** development applications |
| Interpretation | Evaluating the results and the framework from **environmental norms** | Evaluating the results and the framework from **economic norms** |

The two methods differ greatly in their flow scope. The LCCA includes only the cost flows described above. Some of the included cost flows may not be proportional or even dependent upon physical flows modelled in the LCA. The LCCA takes careful account of the timing of the cost flows, while LCA neglects flow timing. For properly and fully integrating meaningful economic analysis into LCA the economic costs cannot be treated like the other physical flows, it requires the addition of a time dimension to the modelling; the ability to introduce and work with variables that have no casual dependence upon inventory flows.

Another fundamental difference is the product life-cycle between LCA and LCCA. Given that the two decision support tools give answer to very different questions, the life-cycle of each one starts and ends at distinct points or stages in accordance to their particular goal and scope. Ideally, the LCCA investigates the cost of a system or product over its entire life span, that is, the already described ‘cradle to grave’ stages [22]. The level of breakdown and the cost categories considered will depend on the stage we want to use the model, the kind of information to be extracted from the model, the data available as input to the model and the product being designed. Life-Cycle Cost is the aggregate of all the costs incurred in the product's life, although it must be pointed out that there are differences between the cost issues that will be of interest to the person designing the product and the firm developing the product in a LCCA [8]. This concern about the cost issues of interest will be further discussed some lines below.

### 2.2.2. Gate-to-Gate data

It will be learned during the description of the data quality requirements for the LCA the importance of obtaining faithful, transparent and representative information for the further analysis of the product system, fairly giving reason for the data collection for being the most time-consuming step from any LCA study. However it can often occur, the practitioner faces the frustration of incomplete or missing information. Moreover, when focusing in gate-to-gate modules for the acquisition of information, these must be linked accordingly to the rest of the Life-Cycle: prefabricated materials enter the manufacturing stage and assembled components leave the assembly stage to enter the distribution stage. The information flows between stages are known as gate-to-gate data. For the generation of gate-to-gate data suitable for the manufacturing stage of composite structures the following state-of-the-art approach will be taken into practice:

1) Search and selection of process to be evaluated, with access to updated information.
2) Definition of the process to determine level of detail, also defining elementary flows in the process and their properties.
3) Mass balance between inputs and outputs of the boundary of the system.
4) Energy allocation. Besides rendering the amount of energy required to perform the process, the results of this stage can be used as the basis for the calculation of energy related emissions in the LCA study [6].

### 2.2.3. Cost Issues

In view of traditional manufacturing processes, when a frequent family of products is being evaluated to determine its cost, the application of an analogous estimation methodology can result in a relatively accurate estimation. On the other hand, when products and manufacturing processes are new, two issues in the Life-Cycle of the part cannot be determined by previous means. These are, firstly, the lack of previous information from the new manufacturing processes and secondly the performance costs after the final product production during its in-service use and until end-of-life [23]. Contrary to more traditional design of products, the integrated product development methodology of Concurrent Engineering (CE) considers three different coordinated and simultaneous product development cycles (product, process and logistic support) at every stage of the product's Life-Cycle involving all three perspectives in parallel [24].

This approach improves the design of a product, reduces costly design changes and time to market. It was already mentioned that the cumulative cost during the entire Life-Cycle of a component for the aerospace industry can rely heavily on the research and development stage. Therefore it needs to be evaluated to determine the sources and reasons with higher consequences on the Life-Cycle Cost. LCC can be divided into four distinctive phases:

- Research and development (incl. concept design) costs
- Production and construction costs
- Operations and maintenance costs
- Retirement and disposal costs [8]

Grading these phases for their contribution in the total aggregated manufacturing cost, it is indicated by numerous authors that 50-70% of the avoidable cost are committed within the conceptual design phase, especially when a small volume of concrete information about the project specifications is available [23]. Other difficulties of estimating at the early design phase include the accounting of changes in technology during the product development time and the quality of the estimation methodology (requirements, assumptions, risks…). Again, many authors agree that 70-80% of a product cost is inbuilt at the concept design phase and the modifications in the manufacturing process selection have a greater cost consequence the later they take place in the development cycle. Thus it is crucial to have access to accurate cost estimates for different scenarios at the early design stage even though the costs incurred are low during this first stage [25, p. 59]. The above figure depicts the explained consequences of concept phase cost commitment.

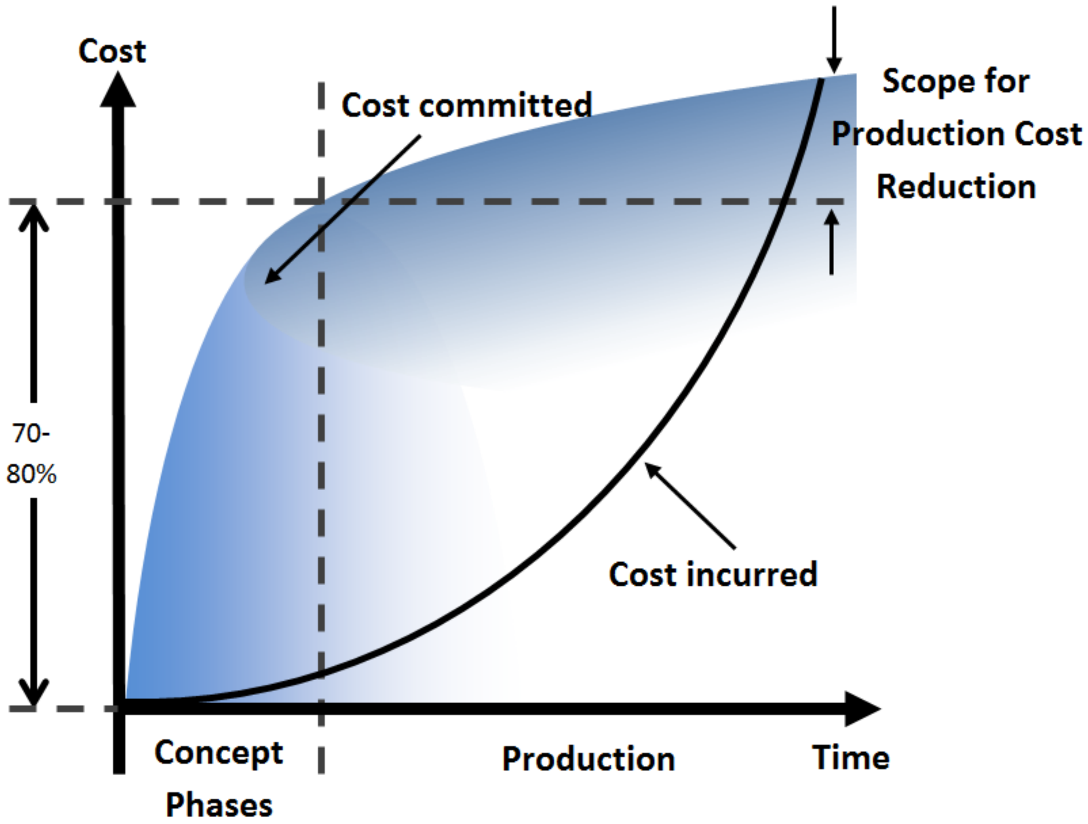



*Figure 5: Cost commitment curve (Rush and Rajkumar 2000)*

Research and development (first phase) may not be a cost category of interest for the designing and manufacturing process. This cost is not related to the actual design of the product but rather the industrial related activities including the research and development (R&D) and the early design stage [26], in other words, the manner in which resources are used to arrive at a design solution. The cost at the third stage, operations and maintenance, comprises consumer or user operations of the product and is therefore also considered to be beyond the goal of the thesis. Finally the retirement and disposal phase can be of mayor interest for the LCA, but its cost is not within the defined boundaries of the LCCA of this paper. Only production and construction costs are within the study of the thesis, while the rest of the stages are considered to be beyond the scope due to the already mentioned gate-to-gate approach on the product Life-Cycle.

The product manufacturing costs can be arranged into a cost breakdown structure. This cost breakdown structure is driven by the design of the particular product and must include all costs only once [27]. In the industry, some useful classifications facilitate this process in a number of ways:

1) As the activity level of the process is maturing, costs behave in a Variable, Fixed, Semi-fixed and Stepped-fixed fashion. Variable costs depend only on the production amount and are directly proportional to the level of activity while fixed costs are independent of the process itself and constant during its duration. For example the amount of matrix material required for each component and the rent of the facilities, respectively.
2) Traceability of expenses are classified depending on the ability to allocate them to each produced item. Direct costs are easily related to every individual piece and measurable at unit processes while indirect costs are not traceable and not involved with specific processes. For example the labor directly applied in producing parts and the various administration costs of the firm.
3) Some expenses occur only once while others are incurred as long as the production is taking place as expected. This concept must not be misplaced with variable or fixed costs, because a one-time expense can depend on whether the current batch production will be completed or not. Non-recurring costs usually include equipment and major tooling costs that are unlikely to occur in the normal course of the production and recurring costs are commonly direct material, direct labor, maintenance or indirect material [28]. The equipment and tooling set up labor for a batch production are hard to classify. They imply a necessary one-time expense regardless the number of pieces, and could be considered recurring when it is assumed to be constant in repeating scenarios and simultaneously considered a direct cost when proportionally allocated to each piece of the batch series. However, for the specific process of filament winding, it is never known beforehand how much time (and thus, cost) it takes to set up the filament winding equipment for a series of identical pieces, as will be explained in its corresponding chapter. Also this uncertainty does not vary when comparing several manufacturing scenarios that share the same equipment but can differ in the process methodology and performance parameters. Therefore, the set up cost for a filament winding manufacturing process will be considered non-recurring.

4) Another distinction can be made with a relative approach only when several design alternatives are available to the decision-makers. Classification of relevant and irrelevant costs can solve the problematic case from the previous point much easier: relevant costs are those associated with only one alternative but absent in the rest of them, and therefore all other costs are considered irrelevant. These differential costs represent valuable information for decision-makers [29].

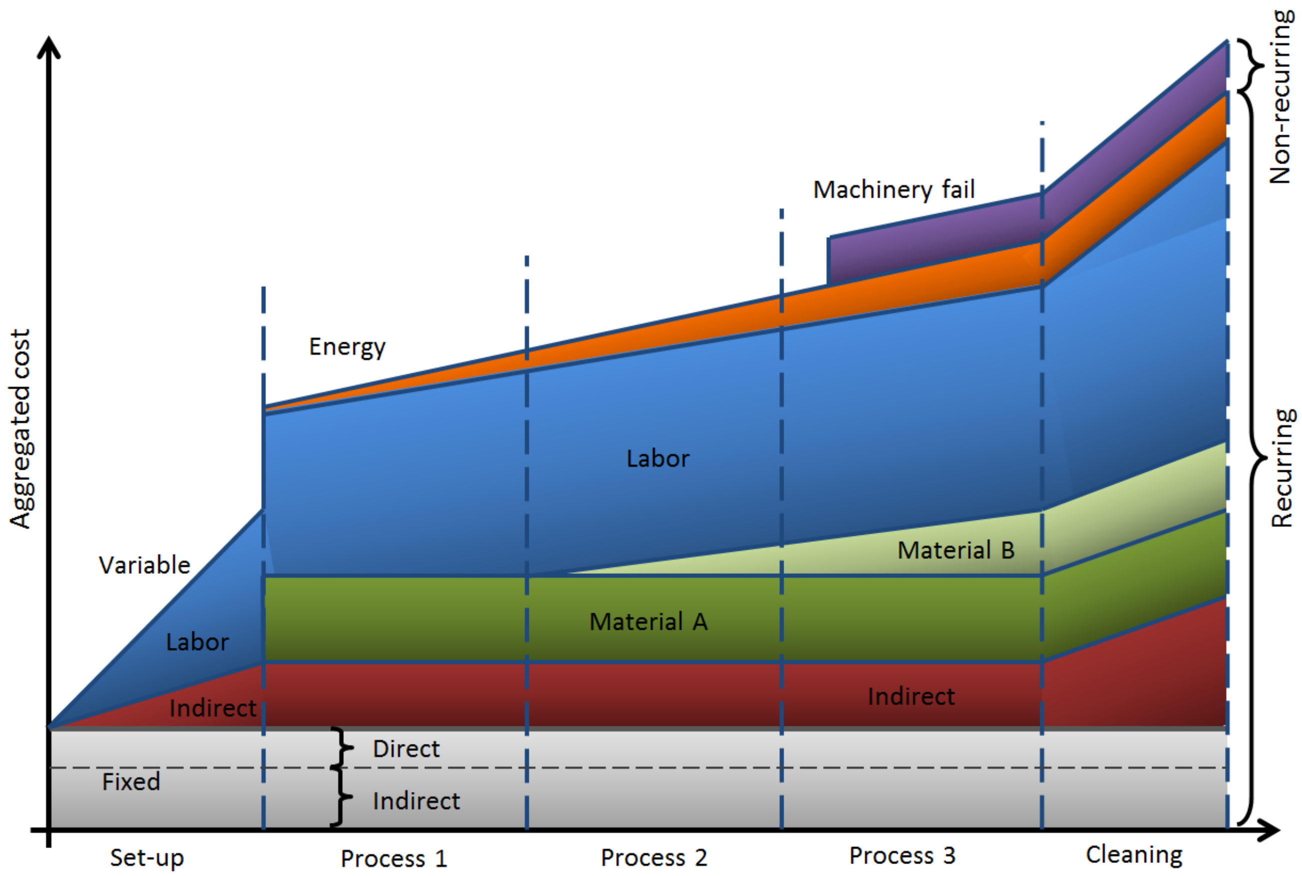



*Figure 6: Different cost classifications identified in the incurred costs of a generic case*

About cost allocation, it refers to the interpretation of cost and its categorization in order to obtain a reasonable distribution of those costs [30]. Direct costs can be promptly allocated according to their nature whereas indirect costs need to have their allocation base pre-defined. The increased use of automation in the manufacturing industry has significantly raised the relative importance of indirect over direct costs, e.g. direct labor costs become a smaller fraction of the aggregated cost [31]. Now overheads constitute a major share of total product cost. In order to accurately calculate these mentioned indirect costs it would be necessary to use another more realistic, detailed method. Fulfilling these requirements, a causal oriented methodology named Activity-Based Costing (ABC) can be adopted, for it assumes [32] that costs are caused by activities and that products consume those activities (namely, allocation).

In order to reach a state-of-the-art performance the causal approach to modelling is fundamental. Cowan and Rizzo [33] summarize the intentions that form the cornerstone of this approach: “those (intentions) that render the overall explanatory structure complete, and those that make it more nearly correct”. The entailment is an enhanced completeness which helps identifying what resources drive cost expenditures and moreover helps formulate guiding principles and useful rules. Another consequence of the greater insight and detail is the attribute of correctness, leading to a more robust modelling that is built on the correct causal relations and which gives a deeper understanding on the influence that concrete parameters can yield. Correctness will distinguish between a coincidence (possibly statistical) and result (causal) [27, p. 519].

After understanding and evaluating the elements from the different costs classifications, it can be regarded that only the direct and recurring manufacturing costs lie within the system boundary definition for the LCCA. A direct cost is an expenditure that can be broken down and allocated to specific items or causes while a recurring cost includes al expected expenses from the design of the manufacturing process of the component. Consequently, they are more easily identified and associated with an end product or project from the design stage.

However, although indirect costs cannot be identified specifically and consistently with an end objective [30], it will be later explained with the conclusion of this paper how the application of the ABC methodology could be beneficially practiced in order to allocate expenses from a relatively unpredictable process, where for the moment approximations based on experience are performed due the lack of interest for improved accuracy and traceability.

Non-recurring costs will have a place within the cost estimation tool in order to document and study the overheads arisen during the different undertaken activities.

## 2.3. LCC Methodology

From the three estimating models used in industry (parametric, analogous and detailed models) only the methodology of the detailed model matches the framework of the unit-process (activity) based product system, also achieving the most accurate cost estimates from all models. The detailed model, also referred to as Bottom-up estimating method [34], uses estimates of labor time and rates and also material quantities and prices to estimate the direct costs of a product or activity in a defined cost breakdown structure. It is the most time consuming and costly approach and requires a very detailed knowledge of the product and processes [8]. On the other hand, better understanding increases greatly the flexibility, usefulness, robustness, and accuracy of any engineering model.

Consequently the bottom-up approach relies on detailed engineering analysis and calculation to reach a precise estimate. Firstly it identifies and grades the component parts and tasks and secondly estimates these to fulfill an unbiased aggregation in order to produce the overall estimate. For this approach to be applied to any manufacturing system, the analyst would need detailed information from the component design and the system configuration as well as accounting information for all material, equipment and labor [35]. Some of the characteristics of the method are as follows:

- It is performed at a detailed level within the Work Breakdown Structure.
- Cost is estimated for basic tasks such as engineering design, tooling, fabrication of parts, manufacturing engineering and quality control.
- The cost of materials is estimated or obtained from the supplier.
- The approach requires detailed and accurate data and should be undertaken by an experienced engineer [27, p. 511].

To produce an estimate a Work Breakdown Structure (WBS) tree of the product is built and the total manufacturing cost is computed according to the information related to each elementary flow. Such structure defines tasks that can be completed independently of other tasks, facilitating resource allocation, assignment of responsibilities and measurement and control of the project.

An existing cost calculation model for the direct costs of production of composites will be adopted as the basic cost aggregation methodology. Developed by *Krolewski*, she represents the direct manufacturing cost as the addition of four cost categories:

$$C_{Direct} = C_E + C_L + C_M + C_T$$

$$C_E = Equipment\ depreciation, maintenance\ and\ operating\ cost$$

$$C_L = Labor\ cost$$

$$C_M = Material\ cost$$

$$C_T = Tooling\ cost$$

Regarding equipment depreciation, it will be assumed that the capital investment in equipment includes the purchasing value of the equipment and any auxiliary equipment and installation costs. The annual cost of maintenance can be estimated as a percentage of the capital investment in equipment. Labor costs are based on part cycle time, the learning curve and the degree of skill required [36]. Therefore, direct labor costs will depend on the time spent by the operator at a specific workstation to complete a task and must also be paid for idle time. Material costs are measured from their purchase price as a function of their quantity required for the given workstation. For example, carbon fiber prepeg layers can be measured by their area or, when purchased as a roll format, the length of roll required. The amount of waste produced by the original required material is taken into account but not discounted to the original price. Tool costs vary significantly with the size of the part and the production requirements.

Krowleski neglects in her methodology the equipment operating energy, which will be taken into account very carefully in our case. The energy required for the equipment to perform their task must be known, as well as the current cost of electricity in the available provider network and, of especially importance in the case of the LCA, the different sources of the energy for the evaluation of its sustainability.

## 2.4. Rundown of state-of-the-art underlining

After introducing several useful applications in the form of methodologies, tools and approaches, it can be noticed the presence of analogous definitions that partially give reason to why their cooperation contributes to their beneficial use. However this can lead to confusion and a misleading conception of the purpose of each of them. A brief reminder of the use of the noteworthy applications is clarified in the following table:

*Table 2: Characteristics and benefits of the employed applications*

| Application | Description | Given approach | Benefits |
|---|---|---|---|
| **LCA** | Technique to assess the potential environmental impacts associated with a product or service throughout its life cycle [37] | Using ISO standardized framework for LCCA | Standardization<br>Compatibility<br>Transparency |
| **LCCA** | Tool to determine the most cost-effective option among different competing alternatives to purchase, own, operate, maintain and, finally, dispose of an object or process [38] | Core of the study: improve its performance and quality of results for FRC manufacturing | Host of mentioned state-of-the-art methodologies |
| **Gate-to-gate focus** | Fraction of the total Life-Cycle (cradle-to-the-grave) evaluation | Manufacturing and assembly stages | Identifies process data to be collected for the LCI |
| **Cost classification** | For different cost performance definitions, the division of cost depending on its nature | Cost traceability and cost expectance (recurring) | Ability to allocate a cost to each produced item |
| **Activity-Based-Costing** | Approach to the costing and monitoring of activities which involves tracing resource consumption and costing final outputs [39] | Allocation of indirect costs | Solving the problem of traceability of indirect costs |
| **Bottom-up estimation** | Process of estimating individual schedule activities or costs and then aggregating these together to come up with a total estimate for the work package [40] | Selected cost estimation methodology | Accuracy<br>Robustness<br>Flexibility<br>Usefulness |
| **Work Breakdown Structure** | Deliverable-oriented decomposition of a project into smaller components. [41] | Aids the estimation methodology with allocation | Enhanced transparent allocation |
| **Krowleski's aggregation method** | Calculation methodology for the aggregation of direct costs for composites manufacturing | Addition of energy costs to calculate total direct costs estimates | Transparent calculation with simple relations for each resource |

Before adding a last column for drawbacks, it is noted that most of the used applications with their selected approaches share a one disadvantage: time consuming. The development of a state-of-the-art methodology comes to the price of time for every of the preferred improvements. Either in the form of accurate process data collection from the available processes, updating prices of materials and diverse rates from the different sources, proper translation of collected data into the corresponding category within the computerized database, programming of the calculations or maintaining a consistent reference system, every time consuming effort adds up to an improved performance of the cost estimation model.

Some achievements defining this state-of-the-art performance can be observed in the developed cost estimation model:

- The major effort is not directed uniquely towards estimating costs, but rather first developing a casual understanding that is a basis for that modelling
- Methodologies are based primarily on a causal truth and not a mechanistic approach
- Modelling is generic rather than product specific
- Costing is scientific based rather than experience

# 3. State of the Art: Composite Structure Manufacturing

It was mentioned with the introduction of the bottom-up estimation methodology the importance of a narrow comprehension and understanding of the selected unit processes. Without a deep understanding of the applied manufacturing techniques it can be difficult to perform an accurate cost estimation model [42]. Larger amounts of data are required in order to achieve higher levels of accuracy.

## 3.1. Composite Structures Theory

Fundamentally a composite material is one composed of at least two elements that combine synergistically to produce enhanced material properties, different than from those element properties by their own. Generally these elements involve the matrix and fiber materials, and in the case of Fiber Reinforced Polymers (most common and widely used in the aerospace industry) these materials use a polymer-based resin as the matrix and one of three fibers such as glass, carbon and aramid as the reinforcement [43]. When these materials are produced in fiber form they exhibit a higher tensile and compressive strength (closer to their theoretical mechanical properties), in other words, decreasing the material size to a fiber form will raise the practical “breaking point”. This phenomenon can be explained because the random surface flaws on the material are restricted to a smaller number of fibers, with the remainder exhibiting the material’s theoretical strength. Matrix materials like Epoxy resin usually have low normal strength but good adhesive shear strength [44, p. 34] and consequently when combined with reinforcing fibers it spreads the load applied to the composite material between each individual fiber. The best mechanical properties are given by the fiber material but still every individual fiber needs to be fully coated by the resin to perform optimally, resulting in a fiber to resin volume ratio determined by the manufacturing process. Among the polymer matrix composites, thermosetting resins are predominant over thermoplastic resins because the nature of the tying molecules (linkers) in the case of Epoxy or Polyester thermosetting resins is a chemical bond and thus the shape of a component cannot be changed by heating after their crosslinking or curing [44, p. 50].

Thermosetting resins have the disadvantage of starting to harden irreversible after their production. This process takes time, in the order of days or months at room temperature, and can be intervened by adding retarding molecules and inhibitors or lowering the storage temperature to enlarge their “Pot Life”, the amount of time the resin can be stored and remain useful after purchased, normally in large containers called drums. In a widely used manufacturing technique the liquid resin is applied to dry fibers and allowed to cure partially. The result is a viscous liquid (or flexible solid) due to the partially linked network, and thus offers an efficient handling when presented in a combined format with the fiber laminates called preimpregnated layers (prepegs). It is critical to assure the availability of resin on the surface of the fibers for both wet and prepeg processes [44, p. 48].

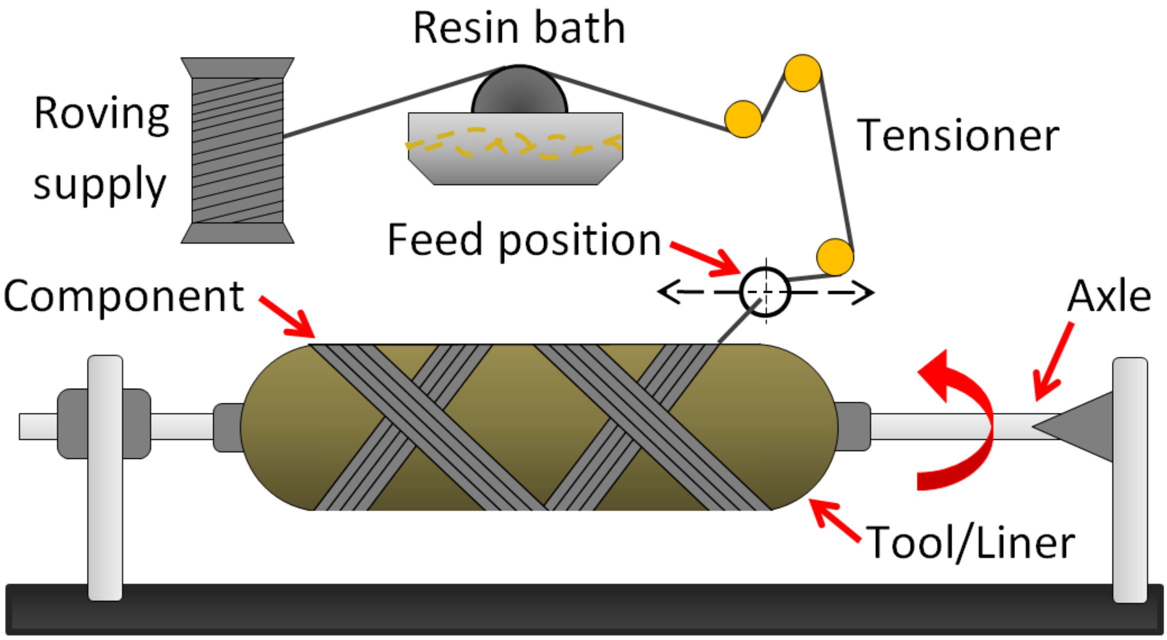
The orientation of the fibers in a composite is of ultimate importance since fibers show their higher mechanical strength along their lengths. During the design stage of a FRP it is crucial to understand the magnitude and direction of the loads expected to be applied to the part, culminating for many diverse applications in the use of overlaid laminates (unidirectional or woven fabrics) with a relative angle difference between the alignment of the fibers in each layer [43, p. 6]. In the case of the Filament Winding manufacturing process, a single unidirectional fabric band can produce different layer orientations over a same spot [45]. After the short introduction into FRP theory, the manufacturing process of filament winding will be described in detail.

## 3.2. Filament Winding of Composite Structures

The manufacturing method of filament winding was first introduced in 1947 by M. W. Kellog to produce a variety of spherical, conical and geodesic shaped components: structures such as pipes, drive shafts and vessels sizing from a few centimeters to two meters in diameter [46]. End closures can be incorporated into the winding to produce pressure vessels and storage tanks [44, p. 205].

The process of filament winding consists of wrapping continuous fiber bands over a rotating mandrel under controlled tension in a prescribed geometric path until the desired wall thickness is obtained. This path is described by the winding angle: the angle between the fibers and the axis of the mandrel [47]. It is controlled by the fiber feeding mechanism position and speed along the axial direction of the part and the rate of rotation of the mandrel [43], in other words, a carriage unit moves along the mandrel axis while this one rotates, generating with precision the calculated fiber path [45]. The fiber roving is pulled from a spool and may be impregnated in a resin bath before applied over the mandrel (wet winding) or it may be already preimpregnated with a thermosetting or thermoplastic resin (prepeg winding).

For a prepeg winding process the fiber requires previous softening in an oven or to be applied on a heated mandrel or liner. When winding is complete the part is prepared for curing. The




remaining fiber band is trimmed and the male mandrel is displaced into an oven or autoclave. This procedure prevails when the internal surface of the part is dimensionally critical, but in the case of being the outer surface dimensionally critical the part is generally transferred from the winding mandrel to a female tool for cure [48, p. 2.48].

In a third method, the fiber bands purchased free of resin that are typically resin-wetted during a wet winding process can also be added dry to the liner and the infusion process can be performed after the winding is complete and before the curing of the piece in an Autoclave (infusion here is not a process belonging to the filament winding technology). This method requires a further study on the ability for the inner fibers to be wetted with the resin for every new design, but can have some benefits like storing the resin-free winded component without the concerns of premature curing and is in some cases an overall time-saving solution. The filament feed mechanism operates at relatively lower speed when applying a resin bath than for a dry band, while a dry winding followed by a resin infusion process may be overall noticeably faster.

Besides accurate placement of the fiber bands on the mandrel or liner, the control of the tension in the fiber bands as they are being placed on the mandrel is of practical importance. The winding tension has a direct effect on the fiber volume fraction, fiber alignment and void content. Moreover, depending on the coordination between the rotational motion and the axial motion, different winding designs can be obtained: polar, helical, circuit and pattern, layer, hoop, longitudinal, and combination [44, p. 207].

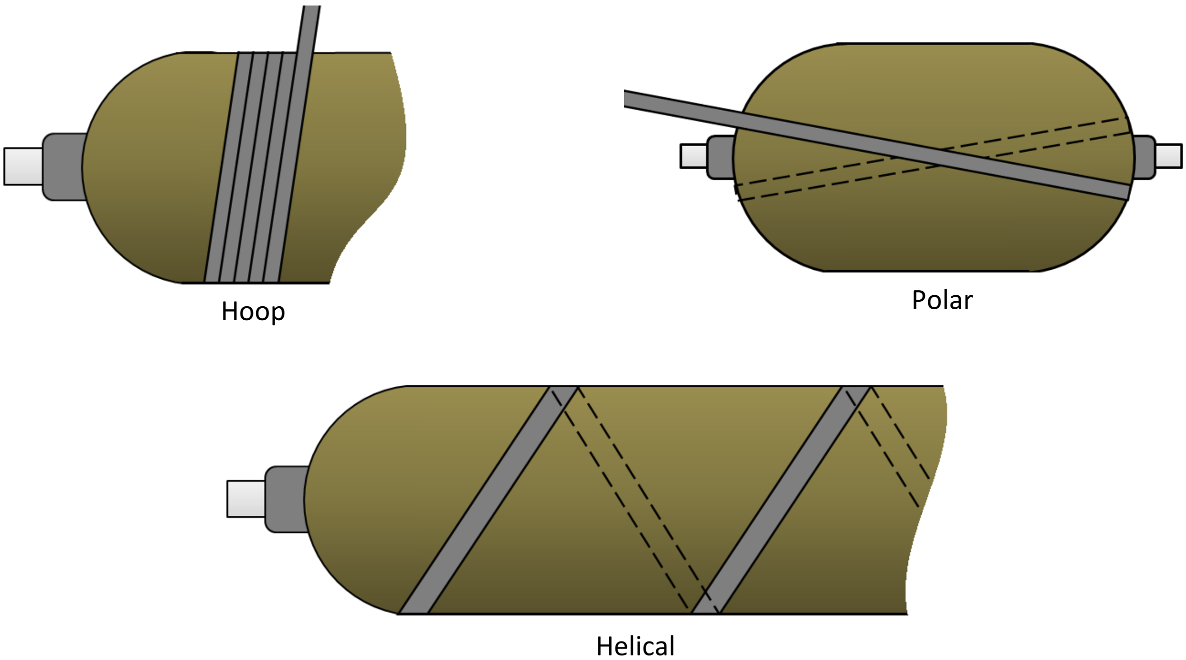



*Figure 8: Examples of winding designs: Hoop, Polar and Helical*

The set-up and preparation for a filament winding process can be very complicated because the position of the first band compromises the performance of the mandrel and directly affects the design definition [49]. The positioning of the first fiber band for the first ever-built component from a unique design is to be precisely determined after a trial and error process due to the unpredictable interactions between the fiber material, the liner, the feed tension, the feed speed and rotation speed. These can stretch the fiber band and aggravate the winding angle after a few rotations of the mandrel. In the DLR facilities there have been cases when 3 days of activity were required to determine the certain parameters for the mandrel and first band position to correctly manufacture the appointed design, and these parameters are saved and reused for the batch of identical components to manufacture. This implies that regardless of the number of pieces to be built, this first set-up time can never be precisely known beforehand, and thus the costs incurred during set-up are considered non-recurring.

### 3.3. Curing of Composite Structures

Curing is a term used in the chemical industry to refer to the cross-linking of the polymer chains present in synthetic resins (commonly with other chemical additives) and has the effect of hardening the material. It is an exothermic process initiated by the application of heat, after which the viscosity of the resin lowers until achieving vitrification [50]. The autoclave aids the resin consolidation and cure process and it is among the most sensitive between the production chain. It guarantees and regulates the proper bonding of the individual sections or layers of a composite structure and the capability to maintain the position of the fibers which will carry the loads and to prevent corrosion on the part [48, p. 2.52]. Substantially an Autoclave is a large pressure vessel with an integral heating capacity [44, p. 190] where the material to be cured is placed inside onto a tool providing the desired shaped of the cured material. Frequently vacuum is applied between the material and a sealed layer of bagging film against the mold such that the laminates are compressed through the thickness of the part wall [48, p. 2.52].

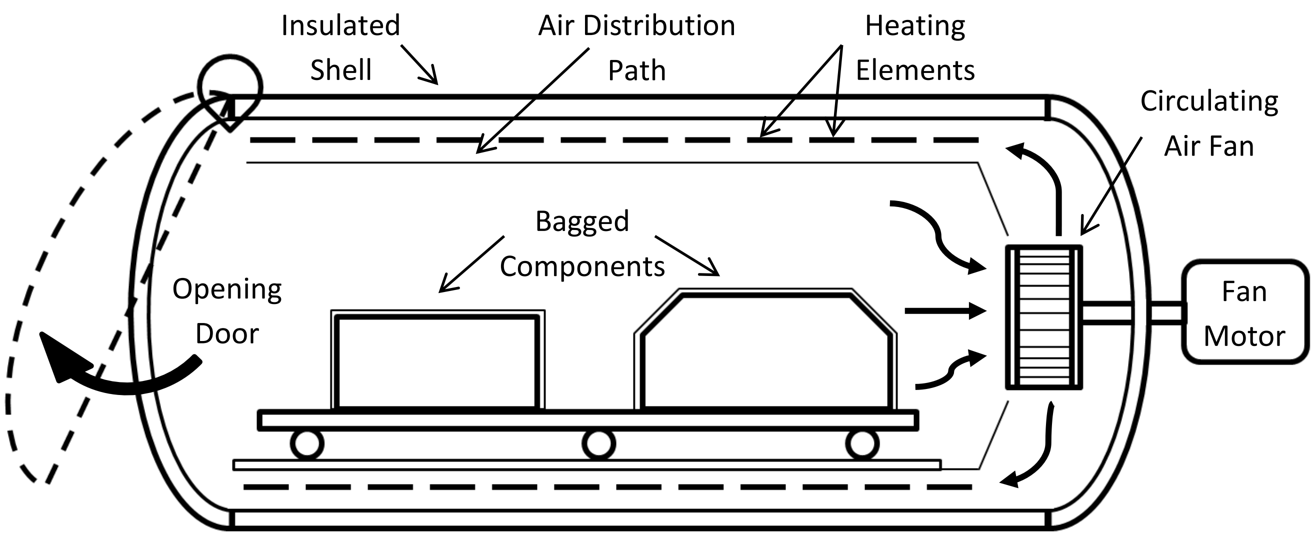



*Figure 9: Schematic representation of an Autoclave curing for Composite Structures*

As a thermosetting composite part is undergoing the chemical and morphological change associated during its curing, many simultaneous actions take place and some of them can be controlled directly or indirectly. These events include temperature, void formation, resin flow, degree and rate of cure or shifting of reinforcing fibers and may produce large changes in the properties of the cured composite [48, p. 2.52] and can be taken into account to develop a curing cycle [44, p. 189]. The curing cycle consists of a temperature cycle, pressure cycle and vacuum and it is typically comprised of two temperature holds. The first hold allows a time for the low viscosity resin to wet the fibers and discharge exceeding flow to the bleeders. During the second hold the crosslinking takes place.

## 3.4. Assembly of Filament Winded Composite Structures

The assembly of a filament winded composite structure is relatively simple for the case of pressure vessels. The orientation of the vessel will not affect its performance and therefore it is usually fixed in an optimal position with respect to the vehicle or room that bears the component. A piping system is then designed to circuit the gas in and out of the pressurized vessel.

For other designs such as flying wheels and driving shafts, where their designed mechanical performance is intended to be coupled with other components, the assembly is an important consideration from the design stage and it is studied and evaluated.

# 4. Goal, Scope and LCI

To achieve a higher level of manufacturing sustainability by improving energy and material efficiency for lower emissions and costs, manufacturing industries need systematic methodologies for formally describing, analyzing and optimizing sustainability performance metrics for manufacturing processes and systems [51]. Manufacturing processes must satisfy the engineering designer's imposed product mechanical properties, tolerances and life-cycle requirements (product profile requirements). Yet more than one method for manufacturing a part is regularly possible, and the lack of knowledge of the impacts for every different process and set-ups [52] has led to the development of a model-based decision guidance methodology based on LCCA. A key task to overcome is the reduction of the skills needed for analysis, modelling and programming, as well as a reduction in the diversity of manufacturing data management that lead to incompatibility between models.

## 4.1. Goal

The goal can be described as the development of a feasible cost estimation tool for composite material manufacturers, a model including a formulated problem with its associated manufacturing processes and process data, and a solving strategy to determine the cost optimization potential for the available manufacturing methods, minimizing the generally needed expertise for mathematical programming, software knowledge and underlying algorithm principles [13].

## 4.2. Scope

The Scope definition of an LCA establishes the main characteristics of the intended study [16, p. 2.31]. Quoting the ISO 14040 on the requirements of a scope definition, "The scope should be sufficiently well defined to ensure that the breadth, depth and detail of the study are compatible and sufficient to address the stated goal", and it shall thus include definitions for the product system, its functions, the functional unit, the system boundary, allocation procedures, data and data quality requirements and any assumptions or limitations [12]. However the iterative nature of the LCA technique will provide the possibility to modify the scope of the study in order to fit the original goal. This attribute will be discussed further with the LCI.

#### 4.2.1. System Process Definition

A product system can be defined by its primary functions and each of these functions can be considered differently for the intended LCCA study. In order to scale their functionality, functional units quantify the performance of the functions provided by the product system under study, and are a critical resource for selecting alternative product systems that fulfill the same functions [16, p. 2.37].

They consist of a task definition (example: soak $1\ m^2$ of the surface of a winded piece with 0,2 kg of resin), a measurable resource or product (example: time used for completion of the process), and its quantized value, called the reference flow, needed to fulfill the described task (example: 1 min). For every compared product system the reference flow of the functional unit describes a specific product flow for each system, reflecting the potential consequences of product alternatives on an equivalent basis. Therefore reference flows are used as a resource for selecting alternative product systems when these are treated as functionally equivalent (on the basis of the functional unit) and establish the starting point for the building of the product system models [53].

The reference flow is used to calculate the inputs and outputs of the system and it represents one way of obtaining the functional unit. Product systems are also subdivided into the set of the smallest portions where data can be collected, called unit processes. Unit processes are connected to one another by flows of intermediate products, also connected to other product systems by product flows and to the environment by elementary flows [54].

#### 4.2.2. System Boundary Definition

A few paragraphs above the goal was defined and it was already discussed how the support tool understands the life-cycle of the product only for the manufacturing and assembly stages of its entire life-cycle, a gate-to-gate approach. The system boundary defines the input processes to be included in the system to be modeled [54]. Within the functional unit of the case of study all the monetary flows will be considered as inputs or outputs of the system, although some of these elements do not have an influence on environmental impact categories for the LCA study per se. Elementary flows refer to matter, energy or time amounts entering or leaving the interface between the unit process and the environment or other product systems.

However, within the cost categories to be aggregated for an end estimation, for every product system there are several that have an undesirable effect when comparing between previously analysed manufacturing scenarios (non-recurring and indirect), and shall be considered within the cut-off criteria and excluded from the study [11]. Taking into account that only successful products are considered for the functional units and rejected products are not, regardless of the different scenarios for equivalent product systems, indirect costs will not vary [27].

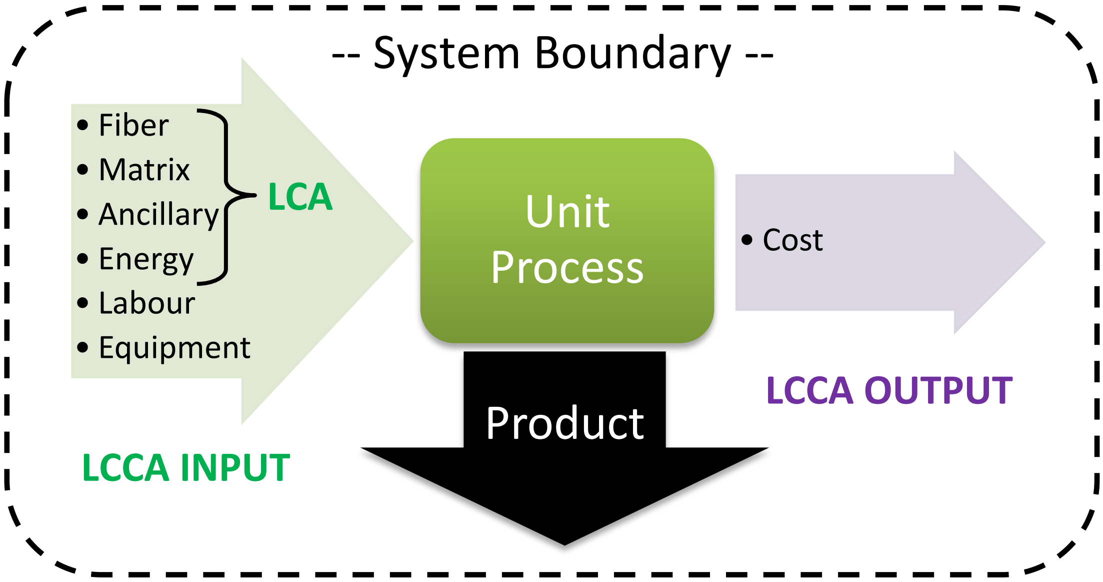



*Figure 10: Product system with inputs, outputs and boundary*

### 4.2.3. Data Requirements and Quality

Data quality will have a major influence on results for LCA models as it is the only resource for the calculation of these results. The step of data quality evaluation shall be given its importance in every LCA study and it must be kept in mind that quality requirements refer both to the reliability and validity of process data [16, p. 2.50]. When used to answer questions where the data has limited or no prospect it can yield erroneous results, even if the quality of the datasets is high. Several tools are available for checking the validity of the collected process data, like mass and energy balances and comparisons with data from other sources.

These data quality requirements shall be described in accordance with the goal and scope of the study and with the selected boundary system. They should also include the related unit processes data for the input elementary flows. Additionally a set of parameters shall be addressed by the data requirements to understand and document their origin: time-related coverage, geographical coverage and technological coverage. For example uncertainties in economic flows may increase with the length of time over which data should be collected. A similar consideration shall be given to the nature of the data to be collected, such as a specific sited source or public publication, and whether the data should be measured, estimated or calculated [54].

## 4.3. LCI

In the inventory analysis phase of an LCA the fundamental task is to record the required data for the product system defined by the system boundary in accordance to the goal and scope of the study. Also included in this context is the design of flow diagrams with unit processes, the collection of data for the system input and output flows, performing allocation steps for multifunctional processes and completing the final calculations through measuring or estimating the related parameters. The main result of the LCI is an inventory table containing the quantified flows from and to the environment with the unit process in terms of amounts of units for the different flows [16, p. 2.62].

LCI administers additional information related with data quality or aspects that cannot be treated as measurable or cannot be quantified, and can be especially useful at the Interpretation phase. Measurements of elementary flows from the product system and public sources represent the only available data whereas technical experts provide the knowledge to estimate the unavailable data [11]. Authorized technical experts are also responsible of describing each unit process and their starting and ending points. They document the manufacturing and assembly processes providing data about the unit process input elementary flows, intermediate flows between unit processes and the output product flow [42, p. 742].

A systematic approach is suggested by the ISO with a series of operational steps to be followed. However one key aspect of the nature of the LCA methodology described by the ISO is the possibility of modifying the system boundary as a result of the continuous evaluation and interpretation within a same phase, in order to meet the original goal of the study [12].

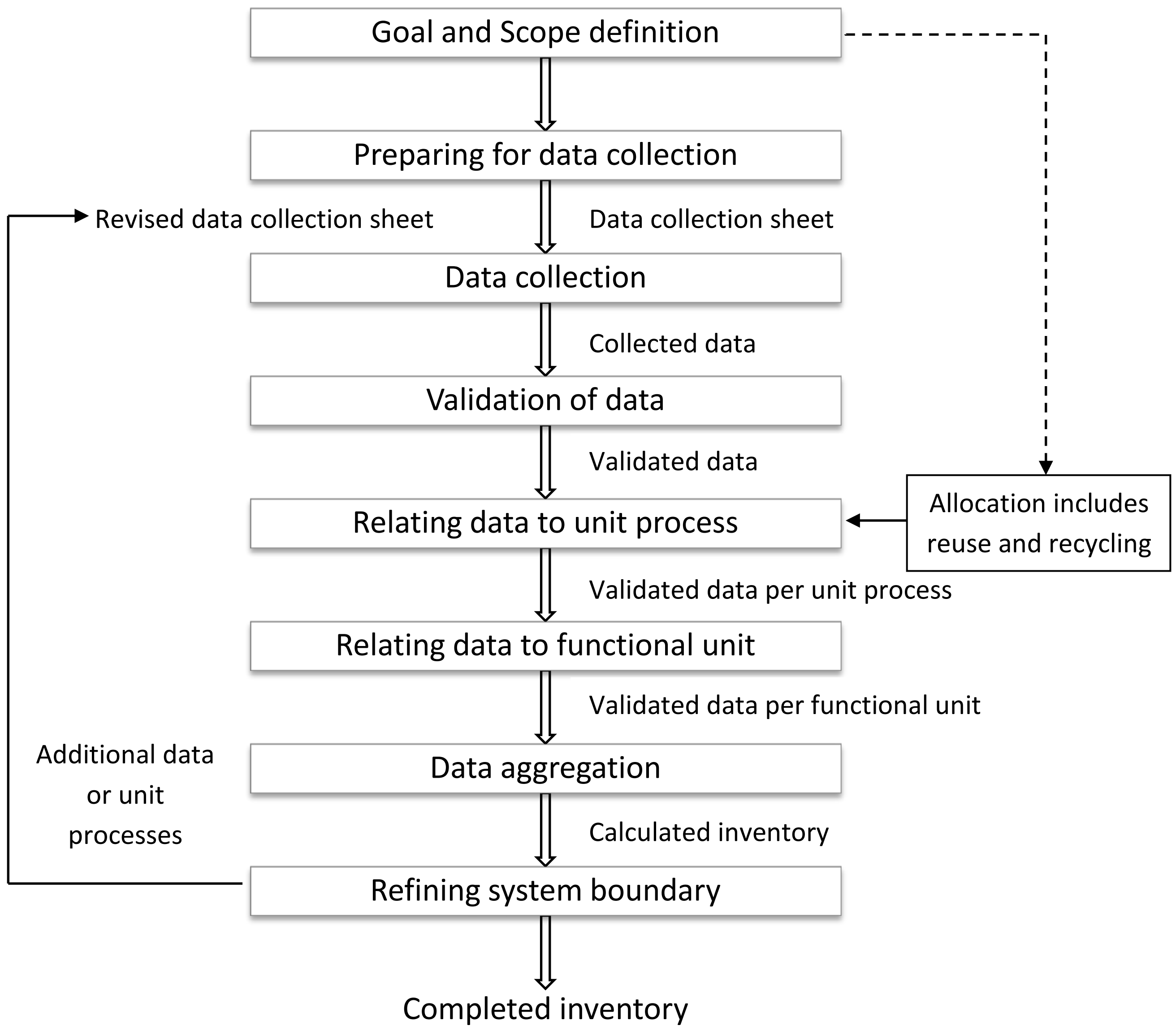



*Figure 11: Procedures in an LCA inventory analysis from ISO 14041*

### 4.3.1. Recording of Process Data

Among the considerations involved in the production processes that have an effect on composite part design and properties not all can be directly or indirectly measured. From a cost perspective the categories of interest include physical material amounts and prices, number and handling time of operators, total equipment energy used and timely cost rates for labor and energy [27, p. 175]. Many different elements play a monetary role at every unit process.

For the improvement of the existing cost estimation model by enlarging the processes database, the elementary flow parameters that belong solely to the filament winding process must be evaluated in order to develop a feasible system to record its process data. The following table displays all theoretically controllable parameters for the equipment, materials and operators of a filament winding process:

*Table 3: Direct controllable parameters found in a Filament Winding Process*

| | Parameter | Effect |
|---|---|---|
| Equipment parameter | Winding Tension | Consumed energy, process time |
| | Winding speed | Consumed energy, process time |
| | Mandrel heating | Consumed energy |
| Material parameter | Laminate band type | Material cost rate |
| | Number of layers | Fiber amount |
| | Laminate band width | Fiber amount |
| | Laminate band thickness | Fiber amount |
| | Resin type and amount | Resin cost rate and amount |
| | Hardener type and amount | Hardener cost rate and amount |
| | Mixing tools (one time use) | Diverse material amounts |
| | Liner mold | Material cost |
| Operator parameter | Set up | Process time, auxiliary materials |
| | Number of operators | Labor cost |
| | Safety and handling gear | Auxiliary materials |
| | Cutting and unmolding | Process time |
| | Cleaning | Process time, auxiliary materials, consumed energy |

In order to measure and quantify all the parameters that may have an impact as a cost category, we have developed in DLR Braunschweig a formalized spreadsheet as a template to record all the valuable data for the cost as well as for the environmental impact assessment, baptized “Process Data Sheet”. The objective is to include all the possible elementary flows at the different unit processes for every component, keeping an internal series of normalized references at every level of detail. A sample of the PDS with the integrated product flows for Filament Winding processes can be found in the attachments of this paper.

The benefits of these references are for example to easily locate elements between the Life Data Sheet (detailed description of the designed manufacturing system of a component handed to the operators) and the contents of the Process Data Sheet and easily translate the recorded values into de database. To enhance the pragmatic use of the method, it is handled in a hardcopy paper format and designed with enough space for calculations and unexpected changes to be recorded with a simple pen in a presently fashion during the course of a production process within the facilities. Tools like several stopwatches, an infrared camera (IR or thermal camera) and an electricity counter assist the analyst with the data collection task.

### 4.3.2. Relating data to Unit Processes

Normally the manufacturing of a component will require a specific chain of independent processes. These independent processes that complete the manufacturing or assembly of a component shall be associated with a unit process each. It is also possible to break down a manufacturing process into more than one unit process in order to internally standardize comparability between the available manufacturing methods (a wet filament winding process is treated as a preforming and infusion independent processes). The simplified interpretation of the manufacturing processes by one or a combination of unit processes is a key approach for the intended unbiased comparability. Eight defined unit processes are available as the standard rule to simulate the available composite manufacturing technologies (therefore eight categories in the Process Data Sheet). These are Preparing, Trimming, Preforming, Cutting, Infusion, Tempering, Demolding and Cleaning.

For the introduction of the three Filament Winding methods into the tool by means of the mentioned eight possible unit processes an evaluation is required to determine how to fragment these methods and allocate elementary flows. A consistent conclusion can be applied to how the Process Data Sheet is approached for the data collection.

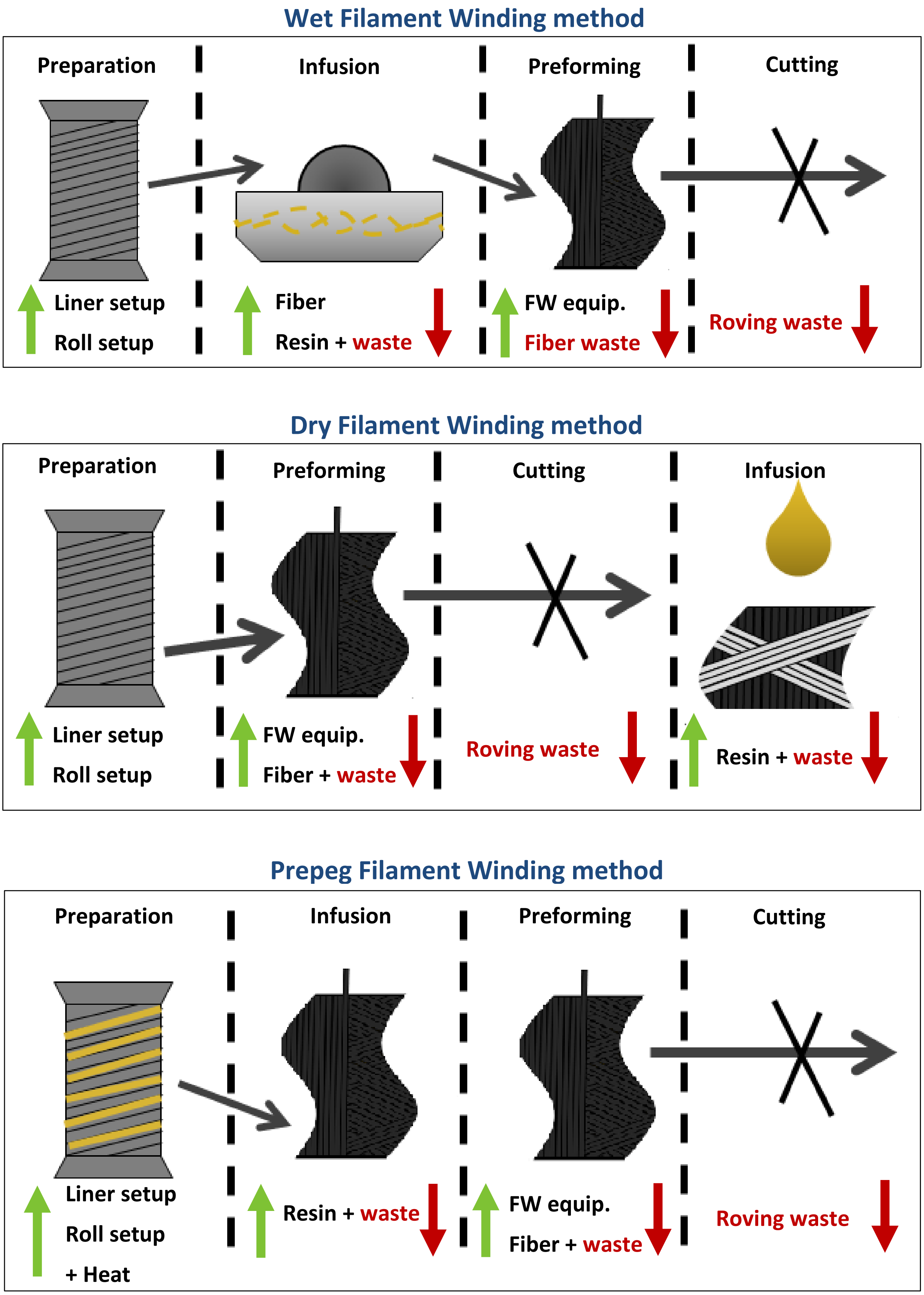



*Figure 12: Fragmentation of the three Filament Winding methods into unit processes*

In the previous figure a series of three diagrams represent schematically the wet, dry and prepeg filament winding techniques, fragmented into a combination from some of the defined possible unit processes before the curing of the component, or technically, the preparation for the curing unit process (infusion of a dry filament winded component does not belong to the filament winding technology). The biggest challenge here is to remain consistent with the accorded allocation of the elementary flows.

During the *Preparation* for all of three methods, process data from liner, fiber roll and equipment setup is collected. In the case of the wet FW method, *Infusion* is the next unit process and fiber and resin enter the boundary system. Also resin waste and all activities and their auxiliary materials related with the infusion are allocated here. *Preforming* will include the FW machinery system as input and the fiber waste which does not remain in the roving, plus the related activities and auxiliary materials. Finally *Cutting* determines how much fiber waste is found in the used roving.

After *Preparation*, *Preforming* is already the second unit process in a dry FW. It will be treated as for the wet method plus allocating the fiber input here. *Cutting* is treated identically as for the wet method. The *Infusion* of the component in this case will employ other technologies used for a variety of composite structures and it is already understood and decided that resin input and waste is allocated here, along with their activities and auxiliary materials.

For the prepeg method the pre-heating of the readily impregnated roving is also taken into account during *Preparation*. The *Infusion* and *Preforming* occur simultaneously. Infusion includes the input resin calculated from the resin volume ratio of the prepeg and its waste. Preforming includes the input and waste fiber. Like for the other two methods, the FW system machinery remains allocated to preforming. The *Cutting* is treated identically for all three methods.

*Table 4: product flow allocation to four defined unit processes for wet, dry and prepeg filament winding methods*

| | Preparation | Infusion | Preforming | Cutting |
|---|---|---|---|---|
| **Wet** | Liner setup<br>Roll setup<br>Resin bath setup<br>FW equip. setup | Fiber<br>Resin<br>Activities and aux<br>**Resin and aux** | FW system<br>Activities and aux<br>**Fiber and aux** | **Roll waste** |
| **Dry** | Liner setup<br>Roll setup<br>FW equip. setup | (not FW technology)<br>Resin<br>Activities and aux<br>**Resin and aux** | FW system<br>Fiber<br>Activities and aux<br>**Fiber and aux** | **Roll waste** |
| **Prepeg** | Liner setup<br>Roll setup<br>Prepeg heating<br>FW equip. setup | Resin<br>**Resin** | FW system<br>Fiber<br>Activities and aux<br>**Fiber and aux** | **Roll waste** |

In the above table the allocation of elementary flows for the three methods is illustrated. Regardless of the time sequence of the unit processes, the groups of elementary flows displayed can be identified with the FW method (rows) and to which of the defined unit processes they are allocated (columns). The product flows leaving the system boundary are represented in bold and red font, while the rest represent inputs.

### 4.3.3. Process database

The recording of process data will be usually translated or retrieved into large amounts of data in electronic form for its collection. As the sources of this information can differ in their architecture, a standard data format must be developed to achieve a comparable and consistent database [16]. A clear distinction is found between process data which will not necessarily vary in the recording of different unit processes and the process data which depend on the specific recording of a unit process. This separation will be designated Static and Dynamic data, respectively, and their characteristics will be taken into advantage.

Static data is normally given by the manufacturing company itself, material or electricity providers and typically consist of given labor rates, material prices and energy price rates.

Their sources must be correctly referenced and their values can be updated independently of the manufacturing activity level. On the other hand dynamic data must be measured for every analyzed unit process and therefore it will be unique for each manufactured component. Process time, for example, is considered a dynamic value. The two kinds of process data are originated at very distinct sources thus requiring different data collecting methods and are to be grouped separately within the process database, even though they can belong to a same category and allocated to a same input.

Prior to the LCCA of a composite structure all static data can be readily updated and allocated. After the dynamic process data is collected the results from the LCCA can be obtained. The advantage of introducing this separation in process data is the interaction between these two. If an elementary flow is recorded as dynamic data, then its associated static data is a characteristic of this elementary flow by relating this input to its output equivalent. A measured employee labor time required to fulfill a unit process (elementary flow) is associated with the company's given labor rate for this category of employee (rate relation) and multiplied together the outcome is a monetary result. Occasionally an elementary flow that is collected as dynamic data can be translated into static data when considered constant and independent, like equipment that consumes the same amount of energy per hour for repeated measurements (time is the new elementary flow to measure instead of energy).

To perform the described task, the existing data collection and analysis software platforms were evaluated in the original development work on the cost and CO2 estimation tool by Herr Al-Lami [19]. Microsoft Excel was selected over the Statistical Package for the Social Sciences (SPSS) from IBM [55] and Statistical Analysis System (SAS) from SAS institute for advanced analytics [56] because of its acceptable abilities to perform the required tasks and the reduced price and user skills.

| Categor y | Sub-process | ID-No | Factor | Amount | Time | Unit | Energy | Unit | Cost/Unit | Recurring Cost | Non-recurring Cost |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | **Total** | | | | | | | **0,00 €** | **0,00 €** |
| | | | | | | | | | | | |
| | | | **Time** | **0:00 h** | | | | | | | |
| Time | General | 1001 | Process Time | | | h | - | - | - | - | - |
| | | | | | | | | | | | |
| | | | **Employees** | | | | | | | **0,00 €** | **0,00 €** |
| Labor | General | 2001 | MTB (Category 3 – E2-E8) | | | h | - | - | 80,40 €/h | 0,00 € | - |
| Labor | General | 2002 | Sc. MA (Category 2 – E9-E12) | | | h | - | - | 95,50 €/h | 0,00 € | - |
| Labor | General | 2003 | Project leader (Category 1 – E13-E15U) | | | h | - | - | 111,00 €/h | 0,00 € | - |
| Labor | General | 2004 | Student (Category 4 –HiWi) | | | h | - | - | 80,40 €/h | 0,00 € | - |
| | | | | | | | | | | | |
| | | | **Equipment & Tools** | | | | | | | **0,00 €** | **0,00 €** |
| Equipmer | Cutting | 4001 | Cutting Computer | | | h | | kWh | 0,08 €/kWh | 0,00 € | 0,00 € |
| Equipmer | Cutting | 4002 | Cutter Zünd | | | h | | kWh | 0,08 €/kWh | 0,00 € | 0,00 € |
| Equipmer | Cutting | 4003 | Locomachs Mold | | | h | | kWh | 0,08 €/kWh | 0,00 € | 0,00 € |
| Equipmer | Preformir | 4004 | Preform Ray | | | h | | kWh | 0,08 €/kWh | 0,00 € | 0,00 € |
| Equipmer | Preformir | 4005 | Iron Heater | | | h | | kWh | 0,08 €/kWh | 0,00 € | 0,00 € |
| Equipmer | General | 4006 | Hot air blower | | | h | | kWh | 0,08 €/kWh | 0,00 € | 0,00 € |
| Equipmer | Infusion | 4007 | Vacuum pump 1 | | | h | | kWh | 0,08 €/kWh | 0,00 € | 0,00 € |
| | | | | | | | | | | | |
| | | | **Fiber** | | | | | | | **0,00 €** | **0,00 €** |
| Fiber | Cutting | 6001 | CF-Gew HTA 5131:Style 796 | | | m² | - | - | 63,91 €/m² | 0,00 € | - |
| Fiber | Cutting | 6002 | Carbon NCF (HT) | | | m² | - | - | 49,00 €/m² | 0,00 € | - |
| Fiber | Cutting | 6003 | Carbon NCF (IMS) | | | m² | - | - | 88,20 €/m² | 0,00 € | - |
| Fiber | Cutting | 6004 | Carbon NCF (non cert) | | | m² | - | - | 36,54 €/m² | 0,00 € | - |
| Fiber | Cutting | 6005 | Carbon WF (non cert) | | | m² | - | - | 40,19 €/m² | 0,00 € | - |
| Fiber | Cutting | 6006 | E-Glass NCF | | | m² | - | - | 3,68 €/m² | 0,00 € | - |
| | | | | | | | | | | | |
| | | | **Resin** | | | | | | | **0,00 €** | **0,00 €** |
| Resin | Infusion | 7001 | EP, RTM-6 | | | kg | - | - | 40,00 €/kg | 0,00 € | - |
| Resin | Infusion | 7002 | Resin, EPS-601 | | | kg | - | - | 35,00 €/kg | 0,00 € | - |
| Resin | Infusion | 7003 | Resin, LY556 | | | kg | - | - | 7,00 €/kg | 0,00 € | - |
| Resin | Infusion | 7004 | EP, AV 118 | | | kg | - | - | 24,98 €/kg | 0,00 € | - |
| Resin | Infusion | 7005 | EP, AW 106 | | | kg | - | - | 19,25 €/kg | 0,00 € | - |
| Resin | Infusion | 7006 | EP, Pentapox R16 | | | kg | - | - | 13,25 €/kg | 0,00 € | - |

*Figure 13: Excel is the process database and analysis platform*

In the LCA database the relation between collected economic inputs and outputs (allocated incurred cost) are structured around the unit processes. Each group of related data values (dynamic and/or static) are conveniently assigned an internally standardized ID according to the nature of the elementary flow (fiber materials, machinery, employees, waste…) and each are carefully described and its source referenced to accomplish a transparent arrangement, facilitate and guide data entry and retrieval. The references are not shown in the above sample of the database but would be located on the same rows of the elements they relate to. Other static data entries needed for the calculation of non-recurring costs of equipment such as replacement cost for equipment, operating life, annual operating hours and maintenance costs are also related to each item when appropriate and each must be referenced with its source.

Most industrial processes are multifunctional. This implies that the output of a process is not composed solely by the desired product but rather more elements like intermediate or discarded material and thus providing more functions than the Scope and Goal definition are interested to investigate. However from the defined goal of this paper (aggregated cost result) all economic outputs are allocated per unit process of the product system under study and expressed in monetary currency (Euros). In contrast to LCA, LCCA has no component Impact Assessment, where the Impact Categories would have to be carefully related to the selected functions within the LCA scope [52].

# 5. The Cost Estimation Model

This modelling serves the purpose of representing the information and information flows in the selected composite structures manufacturing processes, by means of tools such as conceptual framework, mathematical models and simulation. The end goal of modelling is to understand the problems and recognize the constraints with the information and material flows and to seek optimal solutions for improving the overall performance of the system [57].

The realization of the cost estimation model is built upon the choices conducted after the diverse evaluations in the previous chapters. The methodology followed to achieve greater transparency and state-of-the-art performance in the analysis of the cost impact of filament winding of composite structures in the manufacturing stage of their Life-Cycle is the international standard family of ISO 14000. For the bottom-up cost allocation approach with a detailed Work Breakdown Structure, the cost aggregation calculation methodology that will be programmed is introduced by Krowleski, with the addition of considering the direct energy costs. The selected database and analysis software platform is Microsoft Excel, for it accomplishes the given task with a user-friendly and transparent interface.

Within the ISO requirements, further scope definitions were elucidated to complete a methodology that maintains the goal of determining the cost optimization potential for the manufacturing of filament winding composite structures. The series of identified unit processes constitute the inventory and relate the elementary flows (material amount, labour time…) to the output (cost) for the analysis of the given functional unit.

Moreover transparency and manageability within the tool are another objective to overcome. Following ISO requirements, a strong effort is made to maintain a reference of data sources and clearly note assumptions or exceptions in the LCI, but in order to understand the levels of manageability the particular operation of the developed software must be explained.

## 5.1. Cost Estimation Procedure

In order to bring to reality the described theoretical model an abstract line of reasoning is presented to better understand the procedures leading the software to the desired solution, i.e. the accurate estimation of traceable total manufacturing cost.

To begin the problem formulation the scope definitions shall be retrieved to identify the product system boundary and its unit processes, including the elementary flow categories for each (energy, time, rates…) as accorded internally by the eight defined unit processes. Now the modelling of the process can be conceived by relating mathematically the inputs and outputs at every unit process according to the data findings of the LCI.

Thereon the solving of the problem can take place by firstly obtaining the output of every unit process included in the selected product system and secondly aggregating these according to Krowleski's methodology. Within the software the different unit processes are referred to as "modules" and shall be analysed individually and aggregated to obtain their associated impact within the end result.

Finally the generated results can be visualized to trace the category or individual unit process (module) from which a cost was incurred.

## 5.2. Decision-Making Procedure

The role of the modules is fundamental for the decision making procedure. Every unique sequence of processes or modules that together reaches the desired end design of a component is called a "scenario". They virtually represent the manufacturing processes available for the designers. It is important to remember that modules (or a sequence of them) can only be considered equivalent to another when the product system they represent share a common boundary. Simple flow charts and fish-bone diagrams are useful practice to depict different available scenarios.

The problem formulation for the decision making procedure starts with the selection of previously assessed scenarios, including the traceability of their results like before mentioned. The definition of the reference flow is the basis of comparison between product systems that fulfill the same functions. Like explained in chapter 4.2.1, the reference flows recognize the

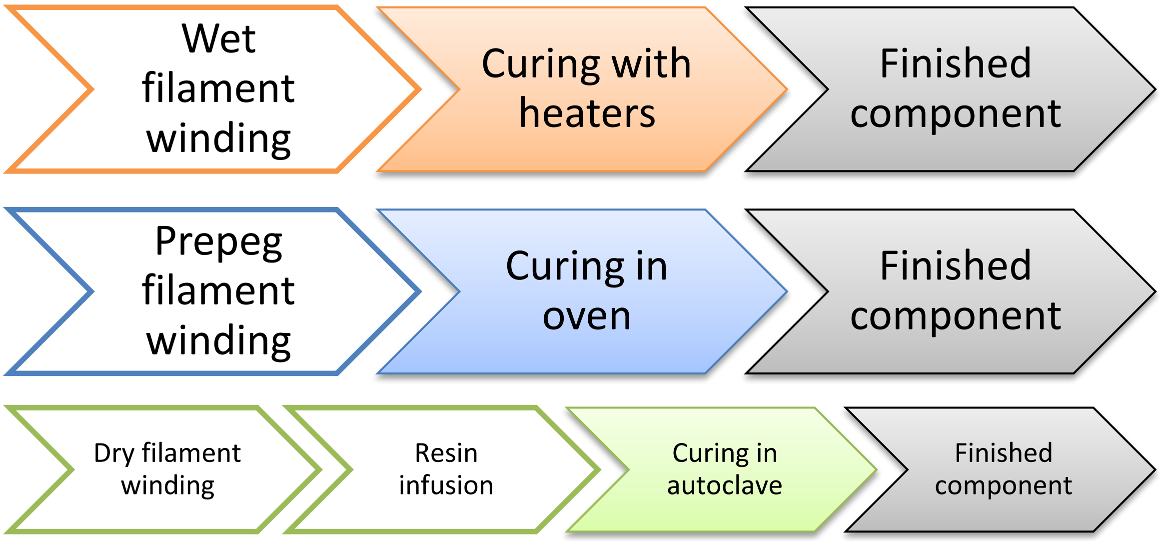



*Figure 14: three different scenarios for a filament winded composite structure*

product flows needed to complete a defined task for a given product system: another equivalent product system may have a different product flow that fulfills differently the task of the reference functional unit.

In the above diagram three different manufacturing possibilities reach the same finished component. It is important to remember that the various filament winding techniques are treated differently (but each consistently) with regard to the defined unit processes and the allocation of their elementary flows. In the diagram the processes indicated with white boxes represent an equivalent product system (each composed by different combinations of the defined unit processes) within the complete manufacturing process. The same occurs with the curing product systems indicated with filled boxes. This implies that the modules for the analysis of each scenario will have the same names as for other scenarios but may allocate elementary flows differently.

The cost estimation results from each scenario are then compared by their totals, by equivalent modules or by categories in the form of ratios and charts.

### 5.3. Programming of computerized model

The collection of process data comprises a database of unit processes. The act of quantitatively relating these processes to one another and include the reference flows to a variable of the functional unit needs to adopt a proper programmed calculation method. In the module files the calculations of an individual unit process can be easily accessed and will follow the explained causal approach, which concludes in very simple mathematical functions with its variables systematically found in the Excel cells for each category.

Each module file contains the dynamic process data associated with a unit process from the manufacturing chain of a specific component. However it also includes all the static processes data previously analyzed, for any kind of manufacturing process. The reasons for this are the benefits of using a uniform format for all modules, which have input entries for all the unit process. This means the analyst is presented with a template where to input the collected dynamic process data in the desired category. Obviously the entries left blank have a null effect in the calculations (as seen in Figure 13, p. 38). The calculation result from the set of linked and scaled unit processes is then aggregated following Krokleski’s method, also a simple summation function in Excel.

### 5.4. Software Structure and User Procedure

It was already explained how the process database is to be arranged, what procedures are to be followed to obtain the desired results and what methodologies are to be used to reach these results, every approach taking into account the goal and scope of the study. However to evaluate the manageability of the cost estimation tool this one needs to be broken down into its practical performance for the end user. Knowledge of mathematical programming, software knowledge and underlying algorithm principles are ideally not required skills for the user of this tool.

From a top-down approach, there will be a one Excel executable file performing aggregation calculations and displaying the results for a unique scenario. This scenario is normally composed by modules, which will be given another Excel file containing their process data. The series of module files that make a scenario are located in the same folder, with this folder found next to the first aggregation file. Every module runs the calculation of the unit processes they represent and aggregates their cost outputs with the ability to allocate the original unit process category from the end result. The aggregation file retrieves the results of each module when running the “Read Modules” function to aggregate their result for the complete scenario, without losing their category traceability plus now adding the possibility to allocate a cost to its source unit process. In other words, the aggregated cost incurred for a manufacturing scenario can be easily broken down into categories (energy, labor, materials…) and their source unit process from the production chain (cutting, curing, cleaning…). With the addition of more scenario folders containing their respective modules the aggregation file can read and differentiate all available scenarios and calculate their results individually.

Every module file must be referenced to its manufacturing project, the date of the undertaken process and which of the possible eight defined unit processes it represents.

## 5.5. Visualization of Results

The results of the cost estimation can be represented in form of charts and ratios. These aid in the tracing of incurred costs to their source unit process and category. Pie charts can illustrate the contribution of the included unit processes or input categories in the total estimated cost and bar charts can be displayed in the form of a bar per module, in this being identifiable the categories and their contribution to the module. A detailed description of the available charts representing the results of an LCCA is described with the results from the LCCA of the case of study (Chapter 6.1.4, p. 50).

For the comparison of scenarios pie charts would contain too much information, hard to easily illustrate the representative information. However each bar representing a module from the explained bar chart can be placed next to the rest of represented modules in for the different scenarios, like here shown for two scenarios:

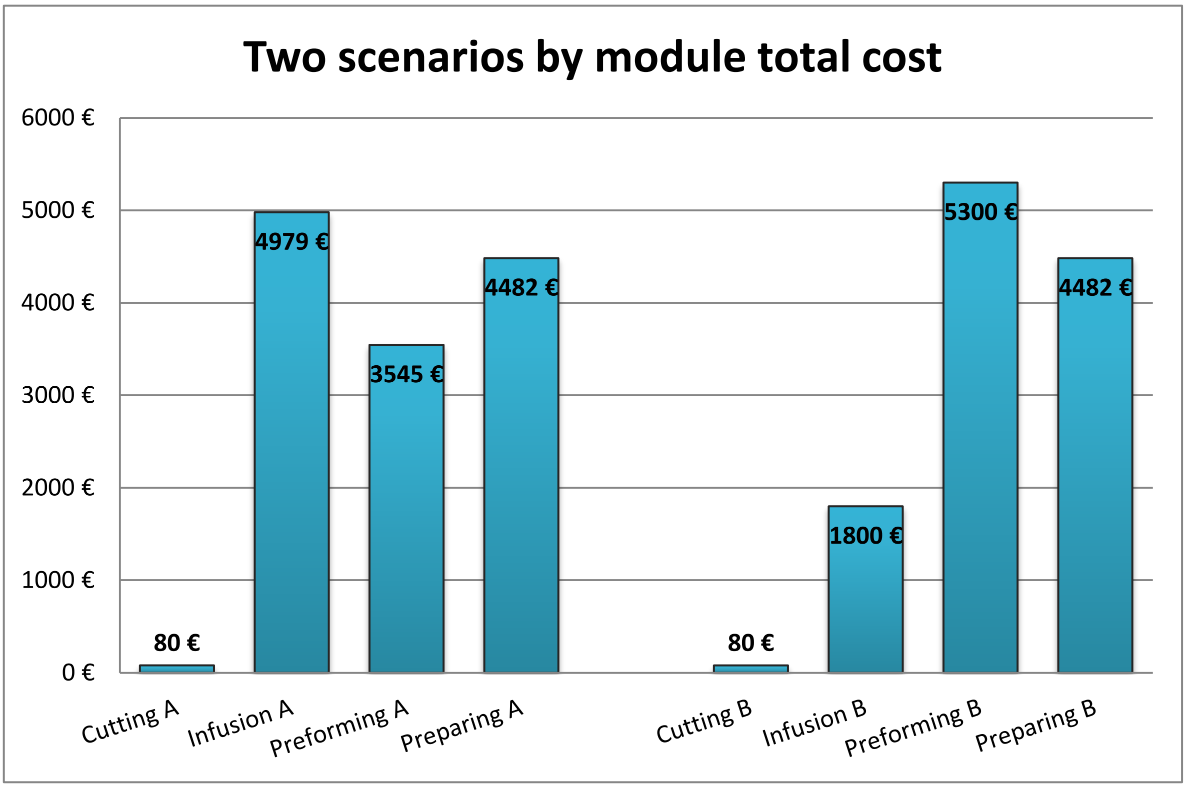



*Figure 15: Bar chart representing two different scenarios per module totals*

On the left hand side the illustrated bars represent the expenses allocated to the modules of the case of study, discussed in next chapter with detail. On the right hand side a simulated case for a dry filament winding and infusion processes is represented based on experience from an expert. In the second scenario the fiber is no more allocated in the infusion unit process but in the preforming, and the process time required for this dry FW preforming is considerable shorter, implying less employee and equipment costs in the unit process. Preparing and cutting remain equal for both scenarios.

Decision-makers would have to consider the product quality, environmental impact categories and the total process time besides the assessed cost optimization.

# 6. Validation of Model

In order to check the cost estimation model for the accomplishment of its intended purpose and meeting the mentioned requirements and specifications [58] a case study is presented. The framework phases and the results from the LCCA are evaluated to ensure their reliability. The evaluation shall be performed using three techniques: completeness check, sensitivity check and consistency check [18].

## 6.1. Case of Study: Carbon and glass fiber pressure vessel

The selected component for the case of study is a filament winded pressure vessel designed for the containment of gas at 900 bar. To reach the application requirements with a low-weight solution, both glass fiber and carbon fiber bands are used, in two different winding layouts, polar and hoop, for each of the fiber materials. Overall, 24 independent windings are sequentially performed over the previous one, eventually repeating the material and layout. It is manufactured with the wet winding technique described before. In order to seal the vessel´s axial ends and serve as an assembly point, two aluminum head plates are attached to the inside of the polymer liner with a cylindrical gas pipe crossing to the exterior axis of the vessel. A first preparation process realizes the addition of each head plate to a half of the liner from its interior. Afterwards the two halves are assembled with silicon and mounted on the mandrel to start with the winding of the most inner fiber layer.

In the Life Data Sheet of the vessel the prescribed winding processes from the designed manufacturing system are enumerated along with the program to be run by the FW system, the employed materials (technical designation previously referenced) and winding pattern characteristics. A sample of this document can be found in the attachments of this paper.

*Figure 16: schematic evolution of the component of study*

Regardless of the process technique and sequence, the individual materials remaining in the finished pressure vessel as defined in the design are here enumerated and some can be found within a taken picture of the component during the winding process:

- 2 Aluminum circular head plates with cylinder in the axis of the vessel to serve as assembly point and gas piping (a)
- 2 polymer cylindrical halves to complete 1 liner
- Silicon to attach both liner halves after first attaching the aluminum ends
- Glass fiber band (to be used at different layers)
- Carbon fiber band (to be used at different layers) (b)
- Resin
- Hardener

The designated number and employee category of the operators to perform the activities:

- 1-2 MTB (Employee category 3)
- 1-2 Students (Employee category 4)

Further auxiliary materials are required:

- Hand gloves (c)
- Paper buckets for resin and hardener (d)
- Wooden spatulas for mixing resin with hardener (e)

The used equipment and tools:

- Filament winding system (f)
- Air outtake (g)

In the following picture taken during the manufacturing of the vessel some of the mentioned elements can be identified, several of which already left the system boundary as waste (on the floor):

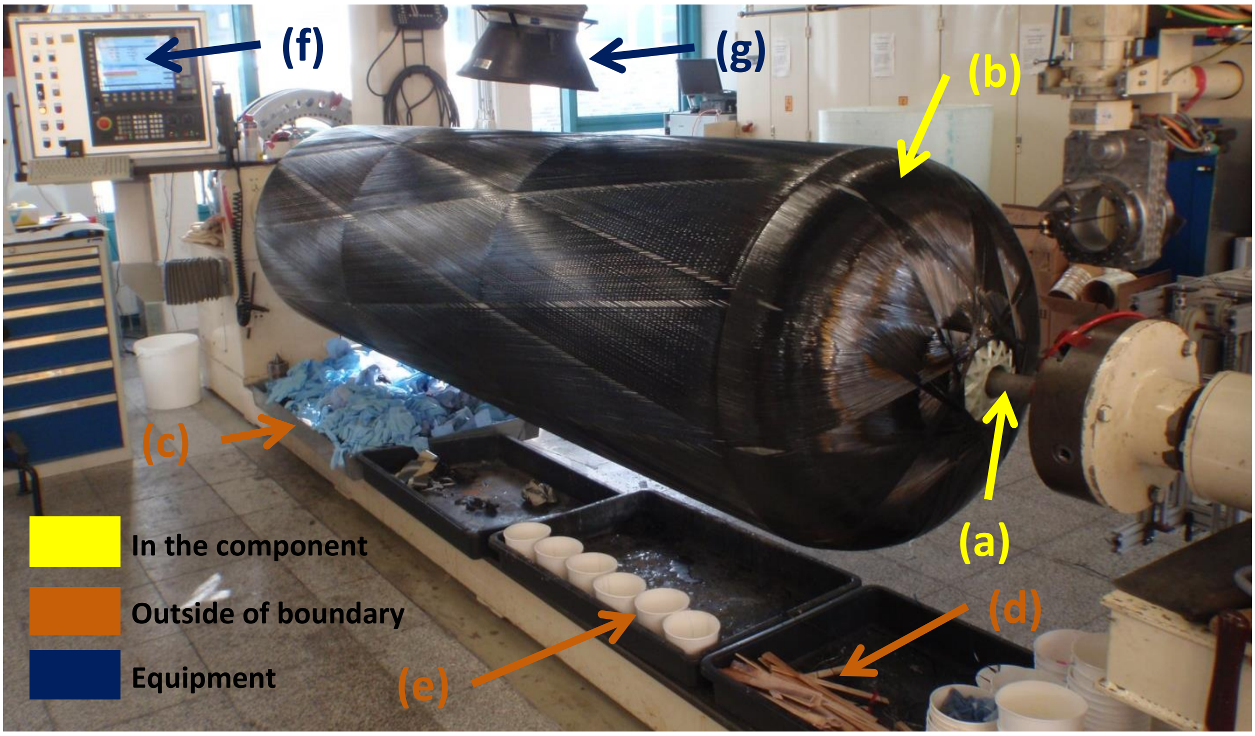



*Figure 17: Picture of the winded component before finishing stage 15 of 24*

#### 6.1.1. System Process and Boundary definition for the case of study

The unit processes identified in this study and the allocation of elementary flows correspond to the described approach given to a wet filament winding process in chapter 4.3.2. These are Preparing, Infusion, Preforming and Cutting. The curing of this vessel will be performed in a distant date from the deadline of this paper.

#### 6.1.2. Data Quality for the case of study

Regarding the time span for the measurement of the product flows for their analysis in this paper, a considerable short time of 3 months was used to collect the prices of the employed materials, labor and energy. The geographical coverage has a significant effect on the energy price and it is bounded to the available electrical network provider for the DLR Braunschweig facilities, thus limited to Germany´s area. Technological data resources are limited to the facility´s equipment and provide precise measurements, especially in the case of automated machines like the filament winding equipment since it can record the duration of specific processes. Another resourceful application is the use of a custom designed energy meter to which any electrical machinery device can be plugged acting as a bypass. These two resources are most useful for automated processes and raise a new question of whether the presence of the analyst or solely the recording from an infrared camera is decisive for the quality of the data.

This next snapshot of an IR camera recording performed on this component displays within its frame the entire vessel (a), most part of the feed mechanism (b), the turning mandrel (c) and the computer from the Filament Winded system (d). As the process is automated the motion of the mandrel is cyclic although other activities performed by the operators could be identified (e). These activities like adding resin for the resin bath require very short time and happen after long periods of time (20-30 min). Moreover the thermal performance is not of interest for this method where the fiber roving is not preimpregnated and the mandrel is not heated.

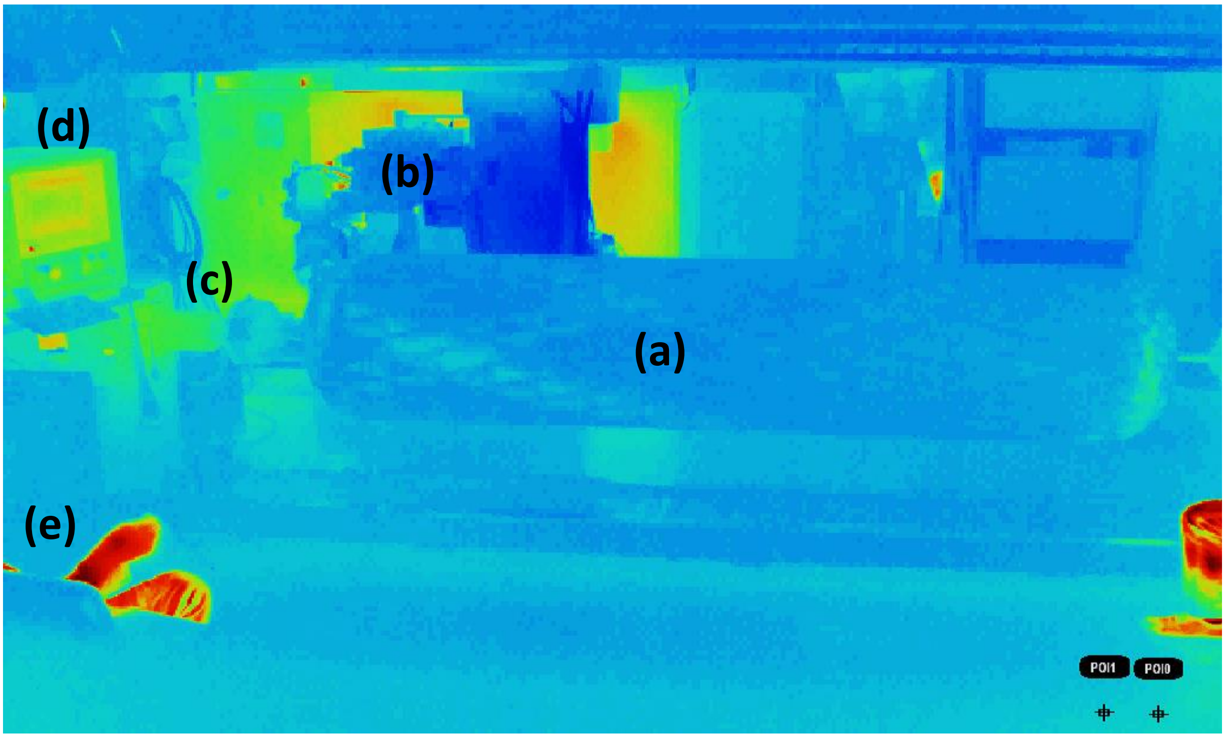



*Figure 18: Snapshot from an IR camera recording of a filament winding process*

The use of the IR camera data collection technique was needed to conclude that for such a process time of the component in question this method does not improve the quality of the data or the collection task compared to more traditional techniques like a stopwatch.

### 6.1.3. Data collection for the case of study

The data collection in practical terms was performed for the winding process of 6 of the 24 layers. A weighted average was obtained for the employment of fiber, resin, hardener, hand gloves, paper buckets, wooden sticks and process and labor times. Moreover, the resin remaining in the paper buckets, the cut fiber band during the preforming and the unfinished fiber roving that did not contain enough band length to perform another winding process (therefore useless) were measured for the interest of a waste analysis.

As it is the first time collecting data from a filament winding process, a first analysis from a few processes is performed in a draft paper in order to understand the peculiarities of data collection for this specific manufacturing process and thus smartly integrate it in the existing Process Data Sheet. In order to maintain the process traceability, every measurement is associated with one of the unit processes defined by the LCI for the manufacturing of the component (Chapter 4.3.2). Therefore for this case (wet FW) the addition of fiber will belong to the infusion unit process in the PDS, and it will have an analogous module in the cost estimation tool. A sample of the updated PDS can be found in the attachments of this paper.

### 6.1.4. Results for the case of study

The monetary output of the LCCA can be traced back to its category and source module. In order to understand the impact of specific elements, the numeric results are represented with pie and bar charts in relation to their source. Also ratios for the numeric representation of the contribution of each category or module to the total estimated cost can be calculated and are especially useful to quantitatively compare scenarios.

In the following chart the total incurred costs for the manufacturing of the component until the finishing of the winding process is represented by the contribution of each category. The core material includes the liner and inserts added during the first preparation step. Fiber accounts for both glass and carbon used roving allocated to the infusion unit process along with the resin. Employees were present in each unit process and they account for the greatest share of the incurred costs. Categories like mold and prepeg do not appear because they were not included product flows in this study.

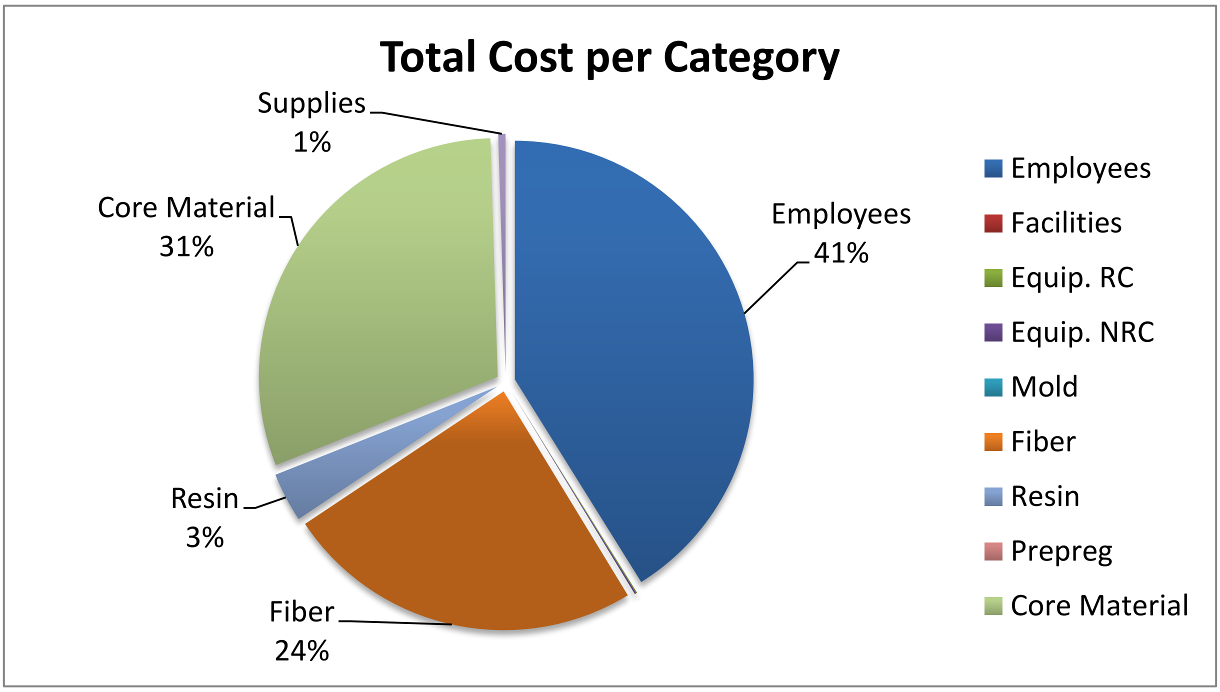



*Figure 19: Pie chart representing the contribution of each category to the results of the LCCA for the case of study*

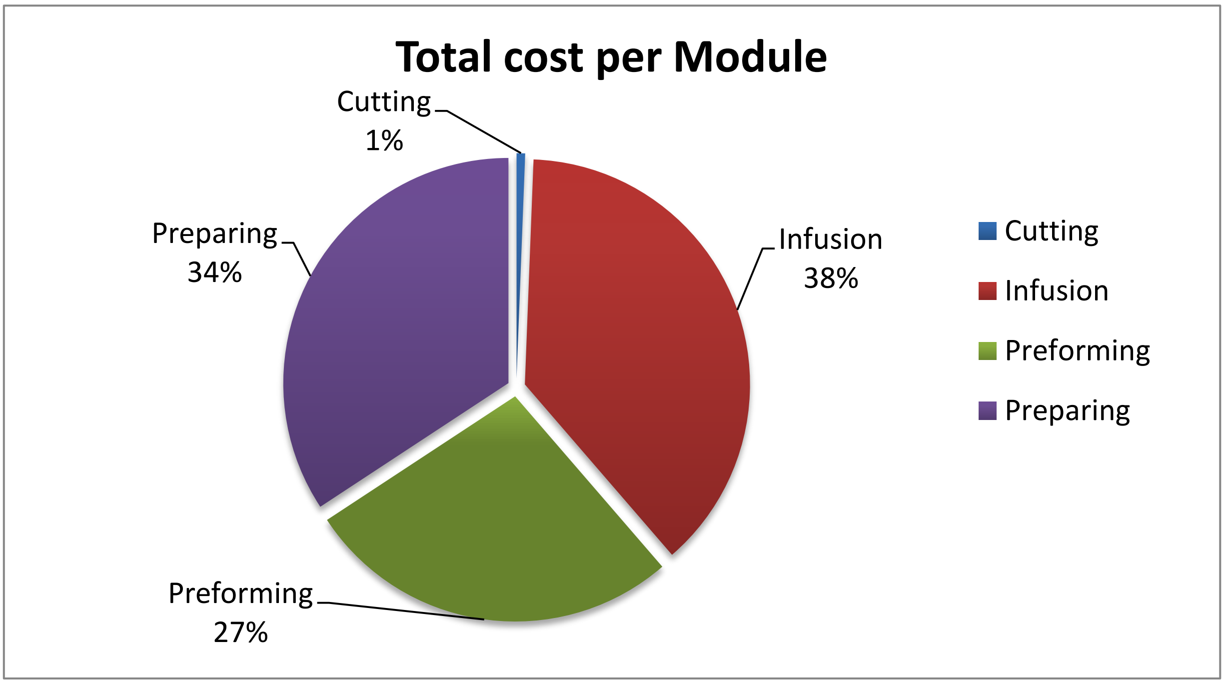



*Figure 20: Pie chart representing the contribution of each module to the results of the LCCA for the case of study*

In the lower figure from the previous page the representation of the contribution to the total incurred cost from each module is represented. The cutting accounts for a relatively small amount of expenses, as a result of not requiring materials and only a very short process time. During preforming there is no addition of materials like for the infusion and preparing unit processes, but it is where the filament winding system process time is allocated, including the required employees for its supervision and correct operation.

A combination of the two traceable cost sources (category and module) can be represented using a bar chart. In the following figure it is clearly distinguished the impact of a cost category in the modules, and where each is allocated:

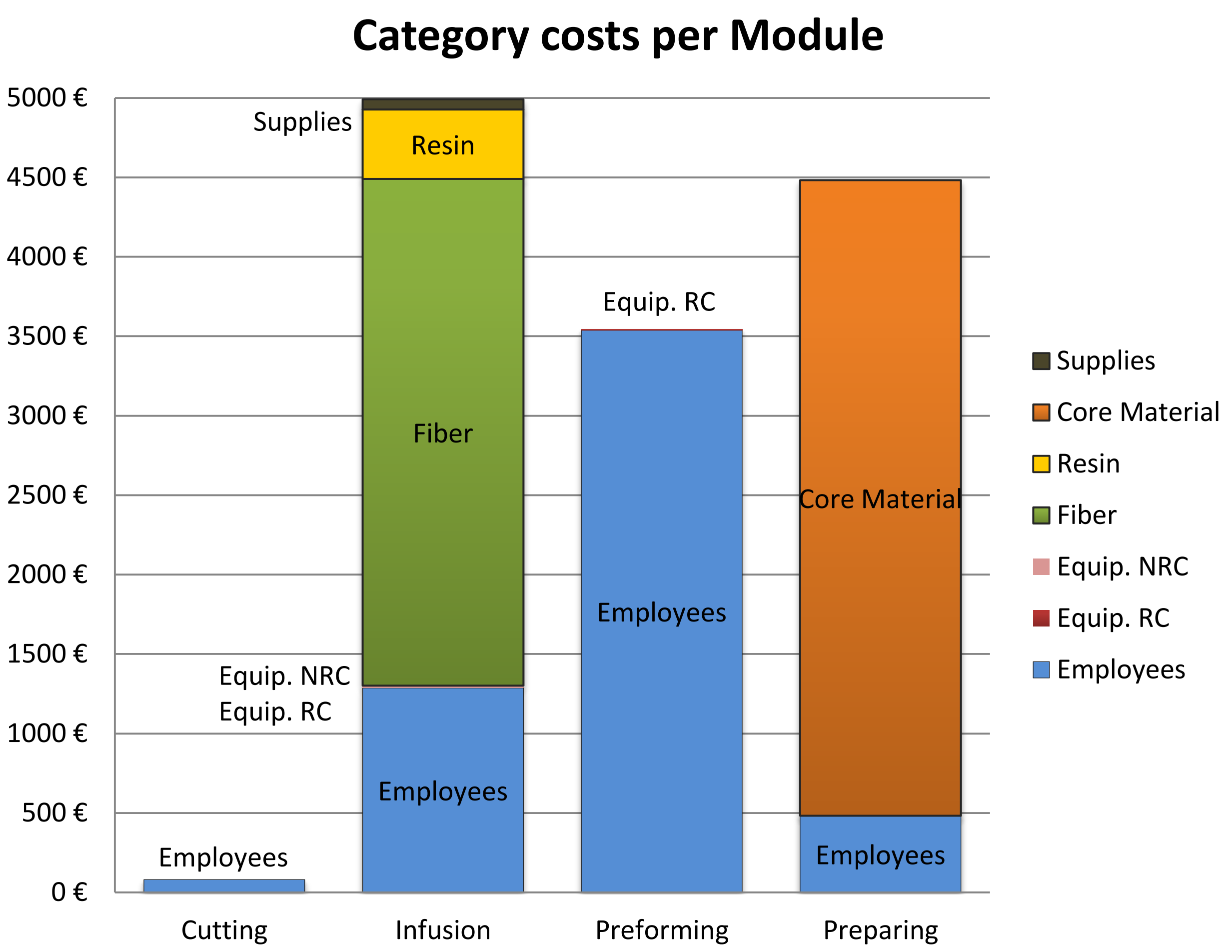



*Figure 21: Bar chart representing the contribution of each category to each module from the results of the LCCA for the case of study*

## 6.2. Completeness Check

"The objective of the completeness check is to ensure that all relevant information and data needed for the interpretation is available and complete. If any relevant information is missing or incomplete, the necessity of such information for satisfying the goal and scope of the study or LCI shall be considered" [18].

In the process database all information needed for the calculation of the LCCA results was either collected from the filament winding process or acquired from the product providers. However for other processes it may be found that in the LCI a required data for a unit process is not available, and thus shall be noted and revisited, alternatively adjusting the scope and goal definition.

## 6.3. Sensitivity Check

For the sensitivity check the reliability of the final results and conclusion is assessed by evaluating the data allocation and calculation methods and whether they are affected by uncertainties in the data [18]. The uncertainty is already controlled during the LCI phase and its analysis is considered beyond the goal of this paper.

A first consideration is given to the goal and scope of the study to determine the level of detail required in the sensitivity check. To accomplish the sensitivity check the results of each phase within the framework are evaluated, reviewed by experts and compared with associated results from available external and internal studies. The lack of previous LCCA studies on this specific manufacturing process implies a difficulty at the time of finding other comparable studies. Moreover when the goal of the study is supporting a comparative assertion, differences between alternative studies may only be found with a detailed sensitivity analysis. Existing differences may not be identified or quantified due to data and method uncertainties being related with poor sensitivity in the study results.

## 6.4. Consistency Check

“The objective of the consistency check is to determine whether the assumptions, methods and data are consistent with the goal and scope” [18]. The following checklist will evaluate the approached given for the goal scope of this study:

- Data considered in the gate-to-gate approach maintains its quality along the product system and is consistent with the goal and scope of the study.
- Regional and temporal boundaries are defined and limited and show no differences along the product system.
- Allocation rules and system boundaries have been applied to the product system as defined in the scope of the study.

# 7. Conclusions

A state-of-the-art cost estimation tool was developed to reach precise results in order to give decision-makers a more realistic framework where to implement the desired changes within the manufacturing of composite structure scenarios. The most noticeable drawback which builds up with the addition of state-of-the-art methods is the time consumption required for the collection of process data. However with a better understanding of every individual process, practical approaches can be developed to improve the efficiency of the data collection itself as well as the successful translation of these data into the electronic database without losing the reliability of the results. On the other hand, the addition of state-of-the-art methodologies does not require increasingly intricate software for the database or analysis, and can be performed by well-known and user friendly platforms like MS Excel.

In the future it can be expected that the most challenging aspects found in the performance of the LCI will be reasonably dealt with by transparency approaches such us integrating the valuable LCA and LCCA information to a service or product by its provider [6]. Simulations with the cost estimation tool could be performed with this LCA and LCCA readily information in order to assess the selection of products and their providers.

Another concern regarding cost traceability was found during the first fiber band placement in the filament winding setup for a series of identical components. It was mentioned that this process is so far considered indirect and non-recurring for its nature. From the design of the manufacturing system it is not possible to determine the process time required to perform this crucial task, and like learned with the case study, the employee costs can become a greater share of the expenses when a larger process time is employed. The available methods to allocate indirect costs include the described Activity-Based Costing (ABC), a causal methodology built upon the idea of activities entailing costs and products consuming these activities [32]. Therefore the analyst would have to collect the unpredictable process data related to the activity of determining the parameters required to correctly place the first fiber band and include it in the LCI. However while its non-recurring nature will remain, its allocation would mean a new source for its analysis.

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# 9. Attachments

DLR LDS - Wickelkörper

Version 1.0
Datum
Seite 8 von 11

## 4.2 Ablage der Lagen und Ausrichtung

| Lfd. Nr. | Lage | Material | Durchmesser | Programm | Status |
|---|---|---|---|---|---|
| 1 | 1-2 | Glas | 49 | 800_L1_Glas_49 | ✓ |
| 2 | 3-6 | Glas | Ringwicklung | 800_L1_Ring_3_6 | ✓ |
| 3 | 7-8 | CFK | 260 | 800_L1_C_260 | ✓ |
| 4 | 9-12 | CFK | Ringwicklung | 800_L1_Ring_9_12 | ✓ |
| 5 | 13-14 | CFK | 140 | 800_L1_C_140 | ✓ |
| 6 | 15-18 | CFK | Ringwicklung | 800_L1_Ring_15_18 | ✓ |
| 7 | 19-20 | Glas | 86 | 800_L1_Glas_86 | ✓ |
| 8 | 21-24 | Glas | Ringwicklung | 800_L1_Ring_21_24 | ✓ |
| 9 | 25-26 | CFK | 260 | 800_L1_C_260 | ✓ |
| 10 | 27-30 | CFK | Ringwicklung | 800_L1_Ring_27_30 | ✓ |
| 11 | 31-32 | CFK | 140 | 800_L1_C_140 | ✓ |
| 12 | 33-36 | CFK | Ringwicklung | 800_L1_Ring_33_36 | ✓ |
| 13 | 37-38 | Glas | 49 | 800_L1_Glas_49 | ✓ |
| 14 | 39-42 | Glas | Ringwicklung | 800_L1_Ring_39_42 | ✓ |
| 15 | 43-44 | CFK | 260 | 800_L1_C_260 | ✓ |
| 16 | 45-48 | CFK | Ringwicklung | 800_L1_Ring_45_48 | ✓ |
| 17 | 49-50 | CFK | 140 | 800_L1_C_140 | ✓ |
| 18 | 51-54 | CFK | Ringwicklung | 800_L1_Ring_51_54 | ✓ |
| 19 | 55-56 | Glas | 86 | 800_L1_Glas_86 | ✓ |
| 20 | 57-60 | Glas | Ringwicklung | 800_L1_Ring_57_60 | ✓ |
| 21 | 61-62 | CFK | 260 | 800_L1_C_260 | ✓ |
| ~~22~~ | ~~63-66~~ | ~~CFK~~ | ~~Ringwicklung~~ | ~~800_L1_Ring_63_66~~ | — |
| ~~23~~ | ~~67-68~~ | ~~CFK~~ | ~~140~~ | ~~800_L1_C_140~~ | — |
| ~~24~~ | ~~69-72~~ | ~~CFK~~ | ~~Ringwicklung~~ | ~~800_L1_Ring_69_72~~ | — |

*Figure 22: Sample of Life Data Sheet of the case of study handed to the operators with the 24 layers and manufacturing characteristics*

Process Data Sheet (PDS) v001

Fertigung

4- Materialien

| | | |
|---|---|---|
| Die Materialien sind in dem LDS eingegeben | Ja ☐ Nein ☐ | falls nein, bitte folgendes ausfüllen |

Bitte die entsprechende Materialien auswählen (falls mehrere Materialien bitte Zahlen eingeben z. B. *1 ,2 ,...)*

**4.2- Matrix**

| 4.2.1 Harz / MatrixSystem | | | | 4.2.2 Härter | |
|---|---|---|---|---|---|
| Araldit SV 556 (ID-7044) | ☐ | EPS-601 (ID-7002) | ☐ | HV 953 U (ID-7024) | ☐ |
| EP, Araldit LY 564 (ID-7045) | ☐ | Ethylacetat, 864 Ethylac,Reins (ID-7013) | ☐ | HY 2404 (ID-7028) | ☐ |
| EP, Araldit SV 410 (ID-7010) | ☐ | | | HY 5003-1 (ID-7030) | ☐ |
| EP, AV 118 (ID-7004) | ☐ | HexPly 8552 (ID-7048) | ☐ | HY 917 (ID-7029) | ☐ |
| EP, AW 106 (ID-7005) | ☐ | LY556 (ID-7003) | ☐ | Klebeharzhärter 135 (ID-7041) | ☐ |
| EP, L 20 (ID-7007) | ☐ | Polyisocyanoat, BlendurVP KU 3-4516 (ID-7015) | ☐ | Klebeharzhärter 137 GF (ID-7042) | ☐ |
| EP, LY 556 (ID-7003) | ☐ | Polyisocyanoat, BlendurVP KU 3-4520 (ID-7016) | ☐ | Scotch-Weld 9323 (ID-7049) | ☐ |
| EP, LY3007 T 1.5 (ID-7011) | ☐ | | | SICOMIN SD8822 (ID-7032) | ☐ |
| EP, Pentapox R16 (ID-7006) | ☐ | UP-Harz, Oldopal P6L (ID-7017) | ☐ | SL (ID-7026) | ☐ |
| EP, RTM-6 (ID-7001) | ☐ | UP-Harz, Palatal A 430-01 (ID-7018) | ☐ | T3 (ID-7031) | ☐ |
| EP, SICOMIN SR8100 (ID-7022) | ☐ | Vernetzer, VN A 2 blau (ID-7019) | ☐ | **4.2.3 Beschleuniger** | |
| EP, SR 1710 Injection (ID-7046) | ☐ | Vernetzer, VNC 5 (ID-7021) | ☐ | CA-12 (ID-7033) | ☐ |
| | | **4.2.2 Härter** | | | |
| Vernetzer, VN A 3 (ID-7020) | ☐ | 113 Larominersatz (ID-7025) | ☐ | Co-B (ID-7034) | ☐ |
| EP, SR 811 (ID-7047) | ☐ | H 91 (ID-7023) | ☐ | DY 070 (ID-7035) | ☐ |
| EP, X 257 (ID-7012) | ☐ | HT 976 (ID-7027) | ☐ | DY 5054 (ID-7036) | ☐ |
| EPIKOTE™ System 600 (ID-7043) | ☐ | Arodur 22962 (ID-7050) | ☐ | Loctite BZ9130 AERO Henkel (ID-7052) | ☐ |

| Sonstige: bitte eingeben | Menge (kg) | Abfälle (kg) | Preis (€) |
|---|---|---|---|
| *4.2.1 Harz / MatrixSystem* ☐<br>*4.2.2 Härter* ☐<br>*4.2.3 Beschleuniger* ☐ | | | |

12 FG-Prozessbewertung DLR-FA-FVT

*Figure 23: Matrix material PDS entries for the defined infusion unit process*

Process Data Sheet (PDS) v001
Fertigung

DLR

**Teilprozess: Preforming**

| | | | |
|---|---|---|---|
| Teilprozessinhalte (Fertigung) | 2_Preforming: (Anlagen, Arbeit, Hilfsstoffe ….) geschnittene Faser preforming | | |
| *Datum:* | | *MA:* | |
| *Teilprozessdauer (min) (ID-1001) :* | | | |
| *Kategorien* | | | |
| 1-Beschäftigte | Zahl | Dauer (min) | |
| MTB (Kategorie 3 – E2-E8) (ID-2001) | | | |
| Wiss. MA (Kategorie 2 – E9-E12) (ID-2002) | | | |
| Projektleiter (Kategorie 1 – E13-E15U) (ID-2003) | | | |
| Student/HiWi (ID-2004) | | | |
| *Sonstige:Gehalt €/Std.* | | | |

| 2- Räume | Zeit (min) | Raumnummmer |
|---|---|---|
| Labor, klimatisiert (ID-3001) | | |
| Labor, nicht klimatisiert (ID-3002) | | |

| 3- Anlagen & Werkzeug | Zeit (min) | Energie (kW) |
|---|---|---|
| Bügeleisen (ID-4005) | | |
| Heißluftföhn (ID-4006) | | |
| Preform-Heizstrahler (ID-4004) | | |
| Staubsauger (ID-4030) | | |
| wkz.ink.Standardwkz. (ID-4014) | | |
| Cutter mit Vakuum (ID-4031) | | |
| Cutter ohne Vakuum (ID-4002) | | |
| Vakuumpumpe (ID-4007) | | |
| Abluft (ID-4010) | | |
| Filament Winding System (ID- 4022) | | |
| *Werkzeug (Mold)(ID-40xx)* | | *welches Projekt:* |

3 FG-Prozessbewertung DLR-FA-FVT

*Figure 24: Employee, room and equipment PDS entries for the defined preforming unit process*