Manufacturing cost - a critical evaluation criteria for new developments in wind turbine drivetrain technologies

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Abstract. Innovation in the wind turbine’s drivetrain are mainly motivated by the goal to have better products. To have an improved final product, it should be analysed in a holistic manner over the drivetrains lifetime. One essential lifetime phase of a wind turbines drivetrain is the manufacturing phase, which is focused in this analysis. This paper presents a way to estimate manufacturing cost of wind turbine drivetrains at an early design phase. The approach is based on literature and expert interviews as well as their abstractions. The target audience are people involved in the development of new wind turbine drivetrain concepts. To customize the approach for their requirements, it is based on a minimum number of necessary input mainly geometric component specification. This approach is modular, scalable and applicable on to future drivetrain concepts. The used approach proves to be an effective way for estimating manufacturing costs of drivetrain components. A comparative analysis against a benchmark application, a 5 MW wind turbine’s drivetrain, confirms the accuracy of the presented approach. A case study dealing with two possible gearbox solutions with a power rating over 5 MW underlines the importance of taking manufacturing cost in consideration when thinking about new developments in wind turbine drivetrain technology.

1. Introduction
The results of the German onshore tenders from May 2018 with an average of 5.73 ct/kWh can be seen as an indicator for the electricity generation cost of wind onshore in Germany [1]. In 2018, the average day-ahead electricity price of 3.46 ct/kWh at the electricity exchange can be seen as the main revenue source for electricity provided by wind turbines [2]. Comparing average cost and revenue potential for one kilowatt hour electricity provided by wind turbines, strong discrepancies become visible. This indicates, that wind turbine technology is not economically viable without funding at its current state in Germany. Though it can be foreseen, that state subsidies for wind will be reduced onwards and abolished someday. This circumstance puts a lot of pressure on the entire wind turbine market. Mone et al. states, that 58 % of the investement cost for an exemplary onshore wind turbine is caused by the nacelle [3]. Reder detected, that roughly 84 % of the unplanned failures of his sample geared wind turbines are induced by nacelle components [4]. This puts the nacelle and especially the drivetrain into the focus of the analysis and forces the market to come up with new ideas and develop innovations. Decisions about introducing a new drivetrain generation have to be made in an early design stage. This stage is characterized by a high degree of uncertainty and complexity as well as an information deficit concerning the concepts characteristics. Nonetheless, it is a decision with a high influence on the company’s and wind technologies success in general. To have a better product in the end it should be analyzed over the drivetrains lifetime in a holistic manner as described in [5]. One essential lifetime
phase is the manufacturing phase, which is in focus of this analysis. It is estimated that 70-80% of the overall cost of a product is committed at the stage of design and conception and hence the manufacturing cost [6]. This estimate justifies the need for gaining feedback on manufacturing costs at the design stage of a wind turbine’s drivetrain to improve the technology.

This paper presents a way to estimate manufacturing cost of wind turbine drivetrains in an early design phase. It starts by presenting the object of reflection and the chosen approach in chapter 2. The following chapter 3 furthermore presents all underlying assumptions for representing the manufacturing processes of the analyzed drivetrain components. A comparative analysis against a benchmark application, a 5 MW wind turbine’s drivetrain in chapter 4 confirms the accuracy of the presented approach. Finally, in chapter 5 a gearbox concept comparison for an above 5 MW application proves the importance of manufacturing cost as a critical evaluation criterion. In chapter 6 the conclusion is drawn.

2. Approach

The approach offered by this paper for estimating the manufacturing cost of a wind turbine drivetrain in an early design phase is based on a bottom up cost estimation technique. Therefore, the drivetrain components are split up into their constituent parts. The components within the scope of this paper are: gearbox, generator, main shaft, main frame and the main bearing arrangement for currently available power ratings. The manufacturing cost for the constituent parts are estimated by breaking down the steps of manufacturing each of them and estimating the effort associated with completing each step. If literature does not supply sufficient information, simplified approaches are used. Estimations of the cost associated with completing each step are mainly performed by developing scalable formulas for the machining time and the cost per machining time for each manufacturing step. Initially, the required input for performing the machining time estimation included not only component specification but also a high number of process parameters that are typically known to manufacturing facilities or an experienced machinist. Since the target audience includes designers or engineers who might be less familiar with such process parameters the number of required inputs needed to be reduced to only component specification. This was performed by an extensive literature review as well as expert interviews to either assume average default values or calculate some of the process parameters based on component specification. Process parameters, which were most of the initial inputs could be excluded by making assumptions based on literature review, interviews, industry best practices, calculations of process parameters as well as eliminating inputs due to their low influences on the final estimate. The final required inputs only include component specifications. Initially, 123 input parameters were needed, with the presented approach this number could be reduced to 61 geometric inputs.

For estimating the cost per machining time, the following factors are considered:

- amortization cost
- interest cost
- maintenance cost
- room cost
- energy cost
- oil cost
- labour cost
- tool cost.

Several literature resources provided information about its constituent parts so that an estimated cost per hour can be calculated for each machining process. By multiplying the cost per machining with the machining time for each process step, the manufacturing costs for the wind turbine drivetrain components are estimated.

It is important to note that there exist major differences between various manufacturing facilities especially with respect to the machine tools and expertise of personnel available in each facility. Several formulas used to estimate the costs are based on survey data and so they represent averages. Therefore, it can also be possible to achieve lower costs than estimated with highly trained personnel using high-performance machinery or the opposite. Results of this model should be treated as an indicator and are valid for the assumptions which are going to be presented in the following chapter.
3. Model presentation

In this chapter, the underlying assumptions for calculating the machining times for each component process step are presented. First, the assumptions for the main shaft are presented. Some of which can also be applied to shafts within the gearbox and the low speed shaft. Then the main bearings, the gearbox and the generator follow. Finally, the assumptions for the machine carrier are presented. It should be kept in mind that these models are a first attempt based on publicly available data and therefore a poor database which will be extended whenever possible.

3.1 Main shaft

The manufacturing of the main shaft is split up in the following procedures (see Figure 1): Heating the ingot to forging temperature, forging and flange upsetting, forging heat treatment, sawing, turning, and drilling of the main shaft.

The heating time is estimated based on the shafts ingot diameter, a material coefficient and the arrangement of the shafts within the oven [7]. For estimating the ingots diameter, Greger’s relationship between the ingots weight and its dimensions is used [7]. According to literature, roughly 3 % of the material is lost during the forging process [8, 9]. Furthermore, a material removal of 7% of the mass of the final finished shaft during the upcoming turning and drilling processes is assumed. The cost of forging will be estimated via the material cost of the shaft under investigation. The material cost proportion of the total cost of hot steel forging can be estimated to be 50% [10] [11] [12]. Therefore, the cost of the forging process is estimated to equal the material cost of the forging. It is assumed, that the material of the main/highspeed shaft is low alloy AISI 4340 steel and the material of gear shafts is 17CrNiMo6 steel [13] [14].

After forging is performed, an annealing procedure is applied to release internal stresses in the forged workpiece [7]. For cooling down the workpiece to its annealing temperature a cooling rate of 10 °/h is assumed [7]. The holding time at the annealing temperature is estimated based on the workpiece diameter divided by 25 [7]. Based on Greger, cooling in a closed furnace at a rate of 12 °C/h until a temperature of 200 °C is assumed afterwards. After forging, there exist several alternate methods to trim the forged part to size [7]. The method assumed for adjusting the length of the forged part in this analysis is sawing. Sawing costs are estimated by the number of sawing operations, the diameter of the shaft and a specific sawing cost of 0.1 €/mm [15].

The diameter of the forged shaft is assumed to be 3.5 % greater than the diameter of the finished shaft based on the assumed material removal during turning. This assumption is used to estimate the diameter of the unfinished shaft at the sawing stage to estimate sawing cost. Next process step is turning. Assumptions for estimating the turning time are based on Sandvik Coromants best practice machining time data for turning 34CrNiMo6 steel wind turbine main shafts [13]. In order to adapt to Coromant’s best practice the alloy of the steel had to be changed and is not equivalent to the assumptions for the prior process steps. It is assumed that both roughing and finishing are carried out. Tungsten carbide will be assumed to be the material of the tool used to perform the turning operation. Using standard turning process parameters by Ostwald and best practices by Sandvik Coromant, the feed and turning speed will be assumed to be 1.7 mm/revolution and 2500 mm/second for roughing, and 0.8 mm/revolution and 3500 mm/second for finishing, respectively [13] [16]. The best practice guideline by Sandvik Coromant for depths of cut of the wind turbine main shaft is 3-6 mm and 1-2 mm for rough and finish turning, respectively [13]. The depths of cut for rough and finish turning will therefore be assumed to be 4 and 1.5 mm. For limiting the number of required user input parameters of the cost estimation model, the volume of the material
removed during roughing and finishing will be assumed to be 5% and 1% of the volume of the finished shaft, respectively.

3.2 Main bearings
To estimate the cost of manufacturing the main bearings, a relationship between material and manufacturing costs is utilized. Industry sources estimate, that the total cost of producing the main bearing is split into 55% of manufacturing and 45% of the material cost. Where the bearing material can be assumed to be SAE 52100 chrome steel [17].

3.3 Gearbox
The main focus of the gearbox manufacturing estimation lies on the analysis of the manufacturing process of the gears. The first step is to identify the possible state-of-the-art gear arrangements, which are planetary and spur gears. Planetary gears consist out of the gear variants sun, ring and planet gear. Spur gear arrangements consist of two spur gears. These types can be broken down into two different designs of gears: exterior and interior gear. The difference between the geometry of the interior and exterior gears imposes a need for different manufacturing methods for the two gear types. Furthermore, certain requirements need to be fulfilled for manufacturing gears for wind turbines gearboxes: a high degree of accuracy for efficiency reasons, needed geometries need to be realizable and additionally the process needs to be economically feasible. Subsequently, the methods for manufacturing these gear variants are identified based on literature review and industry interviews [18] [19]. Blanks are the initial form of the gear before any teeth can be machined [18]. The envisaged cost estimation model will address the process of preparing a blank for teeth machining. This process involves two steps, sawing the blank to roughly reach the required dimension of the gear and then turning the gear to reach the required final dimensions and the needed surface finish.

As for the main shaft, sawing cost is estimated based on the shafts diameter and sawing cost of 0.1 €/mm [15]. The approach for estimating turning time is similar to that for main shafts. According to expert opinion obtained through interviews, the methods for manufacturing gears can be narrowed down into three sequences. The sequence of manufacturing the planet and spur gear is a combination of hobbing, case hardening and form grinding (see Figure 2 sequence a)). For sun gears, it is a combination of milling, case hardening, and form grinding (see Figure 2 sequence b)). For ring gears, it is a combination of milling and form grinding (see Figure 2 sequence c)). Case hardening is not needed as the ring gear has to withstand less torque compared to the other gears due to the concave-convex nature of its gears.

![Figure 2: Sequences for manufacturing gear teeth from a blank](image-url)
meshing with the planet gears. For estimating the hobbing time, a formula of Dudley is used [18]. Process parameters are estimated based on the following assumptions: due to accuracy reasons for every 30 gear teeth one hob thread is needed [18], hob diameter is estimated based on normal module and diametrical pitch [18], hob feed per revolution and speed are estimated based on the hob diameter, the hardness of 370 HV is assumed. Milling time can be estimated based on the number of gear teeth and their face width [15]. Case hardening is a process aimed at increasing the hardness of the surface zone of a gear to increase the capability of this area to withstand the high stresses in operation. The process consists mainly of a carburization, quenching, and tempering stage. The case depth is estimated based on the normal module of the gear [18]. The carburization time can then be estimated based on the case depth and the annealing temperature of the material [18]. The material is assumed to be 17CrNiMo6. It is assumed that the tempering time has the same duration as the carburization process for the sake of simplification. Quenching is neglected due to its short duration and low energy consumption. For finishing the gears, form grinding is used as it is possible to machine the high hardness. Grinding time can be estimated based on the number of gear teeth and their face width [15]. The time of dressing the grinding wheel is interpolated for different numbers of teeth, normal module and pitch [18]. Still the gears are not the only components which need to be manufactured for a finished gearbox. For simplicity reasons the manufacturing cost of the other components are assumed to be a percentage of the gears manufacturing cost. Based on a literature review and interviews of Spieß et al. the effort for manufacturing gearbox shafts can be assumed to 50 % of the manufacturing of gears, manufacturing the housing 200 %, vendor supplied items 75 % and the assembly 160 % [15].

3.4 Generator
Unlike the case with estimating the manufacturing costs of gears, estimation methods of the costs of the different processes of manufacturing electrical generators were not available in literature at the time of writing this paper. Therefore, a simpler approach is used here. Based on the table of VDI standard 2225 sheet 2 manufacturing cost is derived from the material cost [20]. The category chosen was three-phase-generator.

3.5 Main frame
The estimation model for the main frame will rely on estimates of the mass of the main frame. From Dandong Funding Engineering Machinery Co. LTD, a manufacturer specialized in castings and subsequent machining and processing, a cast steel price of 2.57 $/kg converted in 2.1957 €/kg for complex structures and casting weights between 1 – 50 kg casting unit weight was provided [21]. However, there exist other machining processes, such as milling and pocketing, which must be performed to the main frame in order to reach the final product [13]. Therefore, a factor of 1.79 will be multiplied by the main frame cost equations to account for these processes. This factor was obtained using an online casting total cost estimator by Dandong Funding Engineering Machinery Co., LTD [21]. The material of the casting was assumed to be ductile iron ASTM A536 60-40-18, and the manufacturing processes after casting consisted of machining and painting processes to protect against corrosion, package and sea fright as Dandong is a Chinese manufacturer.

4. Model validation
For validating the model average prices for the different drivetrain components in consideration are derived from literature sources and compared to the results the model provides. Unfortunately, literature does not deploy information about the prices on a component level. Therefore, a benchmark is compiled from several sources. EWEA provides a split of the turbine investment cost of the different components for the MM92 [22]. MM92 is a turbine with a three-stage gearbox, a three point suspension system and a doubly fed induction generator. The Danish Megavind project estimated the average division of Capex in % of the main components and subsystems in wind turbines [23]. Unfortunately, Megavind does not state what drivetrain configuration is evaluated. WindGuard states that the main investment cost for turbines in Germany in the range of 2 to 4 MW are in between of 1,380 and 980 €/kW [24]. These assumptions lead to the cost intervals displayed in Figure 3 for a 5 MW power rating. The power level of 5 MW is chosen, as literature provides valuable information for an example drivetrain at this power
range. Having a look onto Figure 3 especially for the gearbox, the investment cost can vary in a wide range. Still this figure accounts for the total investment cost for a component so takes also material cost and margin into account.

![Turbine component prices for a 5 MW power rating based on literature assumptions](image)

**Figure 3:** Turbine components investment cost for a 5 MW power rating based on literature assumptions

The model validation is mainly based on the information of a 5 MW high speed gearbox configuration with a four point suspension type designed by the national renewable energy laboratory (NREL) [25]. The gear specification (normal module, face width and number of teeth) from the 5 MW gearbox developed by NREL are used as an input to the model for the comparison [25]. The model calculates 105.150 € for the manufacturing of the gears of this gearbox configuration. In order to be able to compare this number to the prices in Figure 3 the gears manufacturing influence on the gearbox price needs to be assumed. Spieß states, that 14.6% of the gearbox price is entitled to the gears manufacturing [15]. This leads to a gearbox price of 720.205 € which seems reasonable comparing it to the benchmark in Figure 3.

The 5 MW main shaft from NREL has a mass of 18,000 kg an average diameter of 1,000 mm is assumed [25]. A drawing of the main shaft was also used to indicate a length of approx. 3,500 mm. Using these specifications as input to the shafts program resulted in an estimated manufacturing cost of EUR 54.250 € and a material cost of 17.154 € leading to a total production cost of EUR 71.404. Which is much less than the literature review would estimate. Still the author assumes, that the main bearing price is included in the main shaft and needs to be added. Unfortunately, the main bearing arrangements weight is not stated in the source.

For calculating the machine carrier Fingersh’s cost and scaling model is used for estimating the mass of the machine carrier for a three-stage gearbox with a high speed generator [26]. To modify it to the assumptions from the NRELs 5 MW high speed gearbox configuration a rotor diameter of 126 m is assumed as Fingersh estimates the machine carrier weight based on the rotor diameter [25]. The models result state that this machine carrier leads to manufacturing cost of 111.003 € adding the material cost (1.5 €/kg cast iron [15]) leads to machine carrier investment cost of 140.659 € which is in the range of the cost calculated from the literature.
For the generator, the characteristics estimated by Sethuraman are used [27]. The 5 MW doubly fed induction generator has estimated material cost of 17.670 $ respectively 15.162 €. This leads to manufacturing costs of 35.259 € and total generator costs of 50.402 €. Compared to the number from Figure 3 the generator is too inexpensive.

All in all, the estimated costs are at the lower end of the benchmark but still within the range. Since the benchmark considers commercial products it also includes manufacturer’s margins, which are not included in the manufacturing cost estimation model. So the models results can be seen as minimum costs. Furthermore, one has to keep in mind, that the basis for the benchmark are historical data and might therefore be a bit conservative and possibly more expensive. Inflation has not been taken into account as the sources are not specific in the point of time where their data points have been enacted. Therefore, the results demonstrate that the cost estimation program is effective in fulfilling its objective. While the proximity of the respective benchmark varies, they are deemed satisfactory since the cost from which the benchmark is originated fluctuate depending on many external factors. As stated in the model presentation it should be kept in mind that these models are a first attempt based on publicly available data and therefore a poor database which will be extended whenever possible.

5. Model application

With the help of the presented model a case study for evaluating two gearbox configurations with a power rating of over five MW for manufacturing the gears is conducted. Gearbox one (I) is the 5 MW configuration provided by NREL, already used for the model validation [25]. Gearbox example two (II) has a power rating of 6.5 MW and is inspired by the gearbox used in REPower 6M [28]. Both gearboxes have an overall ratio of 96 - 97 and two planetary and one parallel stage. The 6.5 MW gearbox has four planets at the first and three at the second planetary stage [28]. The NREL gearbox has three planets at each planetary stage [25]. Figure 5 shows the calculated manufacturing cost for the gear designs with the help of the developed tool. Compared to the 105.150 € calculated for gearbox design I, design II is 30 % less expensive when taking the estimated manufacturing cost of the gears into account (73.329 €). In principle the cost distribution about the stages is comparable between these designs. For gearbox design II, the percentage share is 3 % higher for the first stage, than for design I.
Sources | (I) | NREL [25] | (II) | Berroth [28]  
--- | --- | --- | --- | ---  
**Stage 1**  
Ratio | 3.947 | 5.167 |  
Normal module | 45 | 25 |  
Face width | 491 | 560 |  
**Stage 2**  
Ratio | 6.167 | 6.522 |  
Normal module | 21 | 14 |  
Face width | 550 | 310 |  
**Stage 3**  
Ratio | 3.958 | 2.882 |  
Normal module | 14 | 11 |  
Face width | 360 | 250 |  

Table 1: Stage characteristics for the two gearboxes under investigation [25, 28]

For explaining the differences one has to have a deeper look on the gears design. Comparing the stage ratios of these configurations it becomes visible, that for design II a higher ratio in the first planetary stage compared to gearbox design I has been chosen see Table 1. Initially, the NREL approach also had several gearbox speed ratio options (see Table 2 [25]) and speed ratio option A being similar to the version chosen for gearbox II.

| Option      | A                      | B                      | C                      | D                      |
|-------------|------------------------|------------------------|------------------------|------------------------|
| First stage | 1:5.1944 (3p)          | 1:3.9549 (3p)          | 1:3.8322 (4p)          | 1:3.9502 (3p)          |
| Second stage| 1:6.2257 (3p)          | 1:6.1695 (3p)          | 1:6.2367 (3p)          | 1:6.1262 (4p)          |
| Third stage | 1:3.0000               | 1.3.9754               | 1:4.0586               | 1:4.0083               |
| Total dry weight (x1000 kg) | 53.69 | 48.82 | 43.98 | 47.30 |

Table 2: Gearbox speed ratio options for gearbox type (I) [25]

Due to the chosen weight optimization approach Nejad decided to use option B which is 9 % lighter than option A. Nevertheless, the advantage of high ratios in the first stage is, that lower torque is transferred to the subsequent stages which can therefore be designed less massive. Comparing normal module and face width of the gears of the second and third stage reflects this relation. Comparing the face width of both designs, gearbox design I is 44 % longer on the second stage and 31 % on the third stage. Gearbox design I normal module is furthermore 33% larger on the second stage and 21 % on the third stage. Keeping in mind that the geometric input for the estimation model is the number of teeth, the normal module and the face width of the respective stages, this can be an explanation for the higher cost estimation for gearbox design II.

One has to keep in mind the limitations of this simple estimation approach. Up to now process application limits due to geometry or weight are not implemented. Furthermore, the same hourly rate for all possible workpiece dimensions is used. For the future not only, the duration but also the hourly rate of the process steps needs to be adjusted to the workpiece dimensions. For the presented example manufacturing accuracy between a planetary stage of three and four planets is assumed to be the same. In reality, higher accuracy standards need to be fulfilled for planetary stages with four planets. No quantity discount due to common parts and therefore a higher utilization of the manufacturing factory is implemented. This might be interesting for evaluating high speed concepts with a standardization strategy like the RapidWind concept [29].

Still this result shows, that a weight optimization approach for the gearbox might not always lead to the best design in terms of manufacturing. It furthermore indicates, that manufacturing cost can be a critical evaluation criterion for new developments in wind turbine drivetrain technologies. Obviously there exists a trade-off between weight optimization and manufacturing efforts minimization in this design.
decision. Further analysis should take the most important implications drivetrain weight can have on its lifetime into account e.g. material, transportation, installation and the operational phase. Comparing the weight optimization approach against the goal to have a better manufacturability will therefore lead to improved products. This is an essential goal of the authors for the future [5].

![Comparison of cost for manufacturing gears for two different gearbox configurations](image)

Figure 5: Comparison of cost for manufacturing gears for two different gearbox configurations [25, 28]

This case study has a strong focus on the manufacturing cost of different gearbox configurations. At the current model status, presented in Chapter 3 it can be enrolled on the main shaft in the same level of detail. For the generator, analysis on this level of detail is not possible at the moment. Still this component with its high influence on the drivetrains overall cost and its high influence on the drivetrain design especially on the gearbox aims for detailed analysis. Same treatment for the main bearing arrangement. This isn’t as expensive as the generator thus industry sources estimate that 55 % of the components price account for manufacturing. This fact represents a good motivation for detailed manufacturing cost analysis especially as there exist several different suspension and bearing types.

6. Conclusion
This paper builds awareness to take manufacturing cost/implications into account at an early design stage of wind turbine drivetrains, as it is crucial when aiming for superior concepts. It furthermore offers a validated approach to estimate manufacturing costs of wind turbines drivetrain components at an early design stage phase. This way bottlenecks of current wind turbine drivetrain concepts with respect to manufacturing costs become visible paving the way for innovation and improvement of wind turbines. It furthermore offers an opportunity to evaluate the trade-off between weight optimization and manufacturability. Still, it should be kept in mind that these models are a first attempt based on publicly available data and therefore a database which will be extended whenever possible. A similar approach can also be applied to further lifecycle steps of the wind turbines drivetrain, which is planned by the authors.

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