KISSsoft Case Study on Gearing Optimization with the "Gearbox Variant Generator"

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When designing gears, the size, weight and manufacturing cost can be influenced to a great extent by both strategically splitting the overall reduction over the individual stages and by optimizing the geometric relationships. A newly developed tool, the KISSsoft "Gearbox Variant Generator" [1, 2], is able to automatically generate different gear variants, all of which have the same total reduction and performance, but have different numbers of stages and distribution of reduction across their stages. In addition, the generator systematically varies design parameters that are known to have a fundamental influence on gear size. These different drive variants are all sized exactly with gears, shafts and bearings that suit the torque to be transferred. Each of these different solutions is numbered sequentially and displayed as a 3D diagram to make the best solutions easy to identify.

The first two case studies, which used the Gearbox Variant Generator to analyze and optimize gears, are detailed below. Both cases involve gear units used in the mining industry: one with 12 MW nominal power and the second with 200 kW nominal power. The study revealed the quite astounding potential for saving both weight and costs.

Surface mining gear units from a manufacturer in the USA

In the USA, large gear units traditionally use double helical gearings made of heat treated steel (without surface hardening). These gear units are therefore larger and heavier than those made from case-hardened steel. However, because no hardening and grinding processes are involved, the manufacturing costs (in $/kg) are very low.

The case study concerns the cable drum drive used in a gigantic dragline (Figure 1) manufactured by the company Bucyrus International, Inc. The drum has a diameter of 3.5 m and is driven by 8 motors (4 on each side), each with 20.5 kNm torque. The 4 motors on each side are connected to each other by two reduction stages. A slower stage output gear is mounted on each side of the drum. This is driven by two pinions. Each of these pinions is in turn connected to the output gear of an input stage, each of which is driven by two motor pinions (Figure 2). An overall reduction of 35.5 results in a torque of 5.8 MNm (12.7 MW) on the drum. A picture of the drive configuration is shown in Figure 3.

In this analysis, only one drive train consisting of one motor with input and output stages will be considered. There is no real point in modifying the variant generator to the effective, less common drive configuration because it is possible to correctly reproduce the influence of the other motors in the calculation without any additional effort. Because the output gear on the input stage drives two pinions, it is simply a case of doubling the number of load cycles of the output gear. Furthermore – as the output stage pinion transfers double the amount of power – the application factor of the output stage, KA, is also doubled. And finally, to take the different numbers of individual parts into consideration when calculating the total weight and the manufacturing cost, the specific weight is also doubled or quadrupled accordingly. With these modifications, the existing 4-motor drive design can be represented as accurately and realistically as possible.

Figure 1 Surface mining dragline with the drives used in the analysis (photo BUCYRUS®, USA)

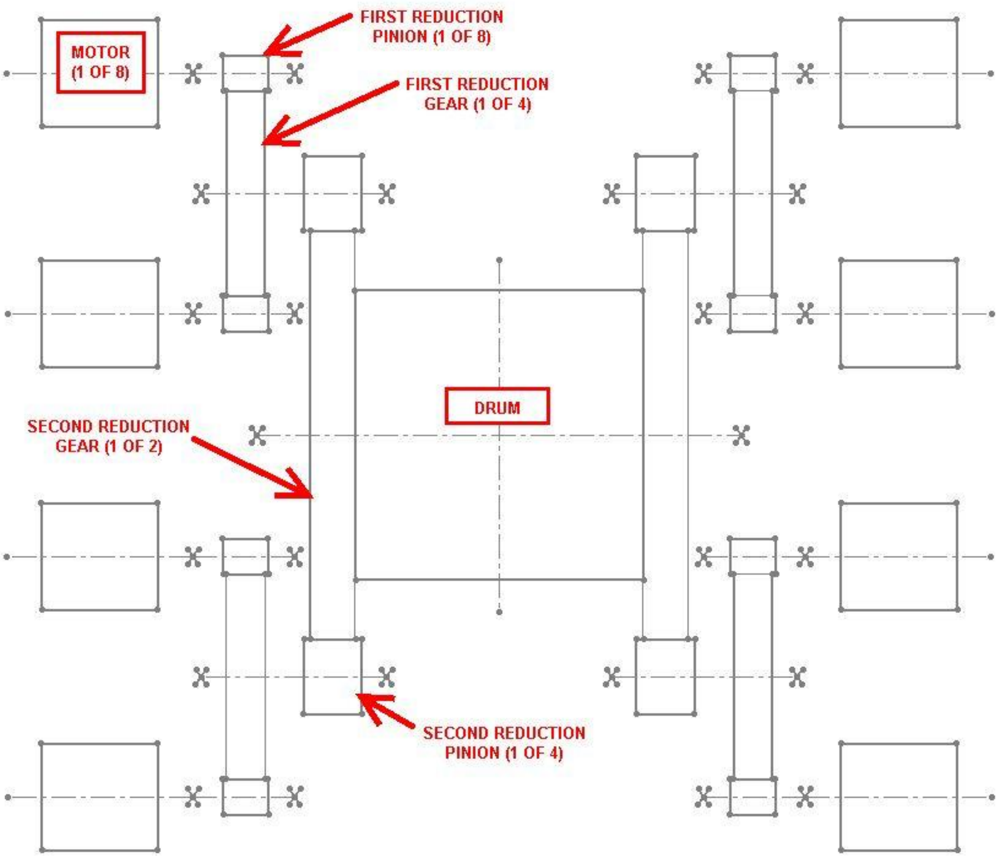

Figure 2 Machinery diagram

Figure 3 Drive configuration

In the first step, the current state of the drive unit is analyzed to determine its current strength. The bearing service life and the gearing safeties (bending and pitting) are of particular interest in this context. The purpose of this analysis is to define the safeties obtained from the mathematically weakest part. These define the minimum safeties for the drive variants that will then be sized.

The results of the analysis of the actual situation are given in Table 1. Here the weight was calculated using the same method as was used later to calculate the variants. The manufacturing costs shown here were each determined as $/kg prices using data provided by the manufacturer. This examination takes into account the costs for shafts, pinion shafts, gears and housing. Costs for the roller bearings have been omitted, because bearings of this size are not commonly available and no standard prices could be found for them.

	Input stage	Output stage	Gear unit
Torque	4 * 20.5 kNm	2,914 kNm	6.35 MW
Speed	730 rpm	20.76 rpm	
Reduction i	9.40	3.78	35.53
Safety Root SF	3.13	3.19	>= 3.13
Safety Flank SH	1.01	1.41	>= 1.01
Center distance a	1320.8 mm	2,489.2 mm	
Facewidth b*	394 mm	594 mm	
b/a	0.30	0.24	
Housing length X (approx.)			6,060 mm
Roller bearing service life			>= 68,000 h
Weight (approx.)			145,000 KG
Manufacturing costs (approx.)			471‘000 $

Table 1 Most important results of the analysis of the actual situation
* Facewidth b: Total width of the gear including intermediate groove (double helical gearing)

As requested by the customer, the variant analysis was performed with only two stages, although for an overall reduction of 35.5, a 3 stage variant would be well worth considering. The input stage reduction was varied in 10 steps: from 5.00 to 13.16 (and the drive correspondingly from 7.09 to 2.70). In addition, the program counted upwards from 0.15 to 0.40 in increments of 0.05 for each ratio variant. As a result, it calculated a total of 70 gear units.

Figure 4 shows the gear housing dimensions of the different variants. They vary greatly in length, from 5300 to 7500 mm on the X axis, and from 1030 to 2100 mm on the Y axis, and from 3280 to 5600 mm on the Z axis. Of even greater interest is the overall weight and manufacturing costs shown in Figure 3. The least heavy variants are those with i2=5.1 and with b/a=0.3. Those with the lowest manufacturing costs have i2=4.6 with b/a=0.25. The Figure clearly illustrates that the costs as a function of i2 and b/a show a fairly flat minimum, which varies within the range i2= 4.1 to 5.2 and b/a= 0.23 to 0.32.

Comparing the least expensive variant (Table 2) with the status quo shows that costs could be reduced by 22%. Furthermore, the existing variant has a reduction distribution (i2=3.8), which lies below the optimum range, whereas the b/a values lie within the optimum range. In contrast, the existing variant does not have the best possible distribution of gear safeties. The output stage displays significantly higher safeties than the drive stages. This analysis shows that the current gear unit has been very well designed. When considering the considerable cost differences between the individual variants (Figure 5) the actual costs still lie within reasonable bounds. However, there is no question that a possible saving of over $100,000 is well worthwhile.

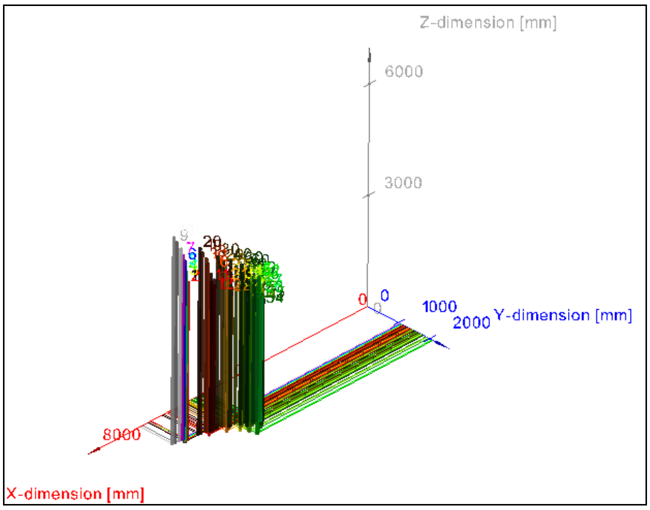

Figure 4 Housing dimensions (X, Y, Z) of the different variants

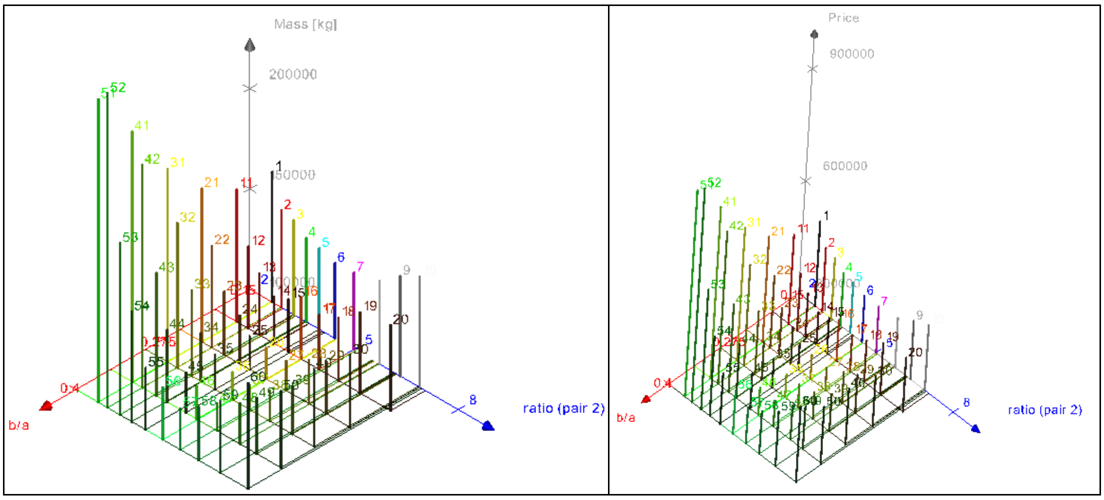

Figure 5 Weight and manufacturing costs depending on output stage reduction (i2) and the width/center distance ratio (b/a)

	Input stage	Output stage	Gear unit	Comparison with ACTUAL
Reduction i	7.70	4.61	35.53	
Safety Root SF	3.13	3.13	>= 3.13	
Safety Flank SH	1.01	1.01	>= 1.01	
Center distance a	1,296 mm	2,222 mm		
Facewidth b	325 mm	555 mm		
b/a	0.25	0.25		
Housing length X (ap-prox.)			5,900 mm	- 2.6%
Roller bearing service life			>= 68,000 h	
Weight (approx.)			116,000 kg	- 20.0%
Manufacturing costs (approx.)			367‘000 $	- 22.1%

Table 2 Most important results for the optimum variant

Gearing produced with hardened materials

It is well worth investigating whether a more cost effective solution could be achieved by using surface hardened materials. This would possibly involve the practical option of manufacturing the pinion shafts from case-hardened and ground steel, and the gears from heat treated (milled and nitrided) steel. The Gearbox Variant Generator can perform this type of analysis very quickly once the manufacturing costs are known. As a rough starting point for this analysis, we increased the costs for the pinion shafts (ground) by 100% and those for the gears (nitrided) by 50%.

	Input stage	Output stage	Gear unit	Comparison with ACTUAL
Reduction i	9.40	3.61	35.53	
Safety Root SF	3.20	3.23	>= 3.13	
Safety Flank SH	1.03	1.02	>= 1.01	
Center distance a	1,355 mm	2,048 mm		
Facewidth b	271 mm	409 mm		
b/a	0.20	0.20		
Housing length X (ap-			5,565 mm	- 8.2%

prox.)				
Roller bearing service life			>= 68,000 h	
Weight (approx.)			73,000 kg	- 49.6%
Manufacturing cost (approx.)			294‘000 $	- 37.5%

Table 3 Data for the optimum variant when surface-hardened materials are used

For experts, the results bring no surprises: in this variant, the weight of the gear unit can be reduced by 50%. According to the cost calculation the result is a reduction of 37.5% – or 20% in the case of the optimized gear unit made of heat treated steel (Table 2). In this context it should be noted that the assumed cost rates for this last analysis were estimated approximately and would need to be defined in more detail.

Mining gear units from a German manufacturer

The second case study involves a medium-sized gear unit (200 kW) manufactured by Bucyrus Europe GmbH for use in the mining industry and with a traditional European industrial gear box design. All the gears are made of case-hardened steel and the drive stage is ground.

The procedure for the analysis was carried out as shown in the example: The results of the analysis of the actual situation (where the variant was calculated with two stages) are shown in Table 4. The reduction of the drive stage was varied in 9 steps – from 1.20 to 3.4 (and the drive correspondingly from 6.00 to 2.2). In addition, b/a was varied from 0.10 to 0.90 in increments of 0.20 for each ratio variant. A total of 45 gear units were calculated. Manufacturing costs were defined using EUR/kg pricing data provided by the manufacturer.

	Input stage	Output stage	Gear unit
Torque	2.77 kNm	20.7 kNm	200 kW
Speed	662 rpm	88.6 rpm	
Reduction i	1.90	3.93	7.47
Safety Root SF	3.76	4.04	>= 3.76
Safety Flank SH	1.74	1.42	>= 1.42
Center distance a	307 mm	378 mm	
Facewidth b	95 mm	180 mm	
b/a	0.31	0.48	
Housing length X (approx.)			1,060 mm
Roller bearing service life			>= 68,500 h
Weight (approx.)			1,400 kg
Manufacturing costs (approx.)			EUR 23,000

Table 4 Most important results of the analysis of the actual situation

The results of the optimization process are shown in the figures that follow. It is obvious that there were significant differences in the external dimensions (Figure 6). This result from the Gearbox Variant Generator can be extremely useful if the new gear has to be installed in a specific space. The total weight and manufacturing costs displayed depending on b/a and i2 (Figure 7) also clearly illustrates that this design example – where the output stage is not ground – gives the optimum drive variants for b/a=0.3. The optimum b/a ratio is relatively small because, due to the non-ground output stage, the face load factor KHβ would increase significantly as the width increases and would therefore make this variant uneconomical. The ratio distribution between the stages gives good results if the output stage has a reduction in the range 2.0 to 3.0.

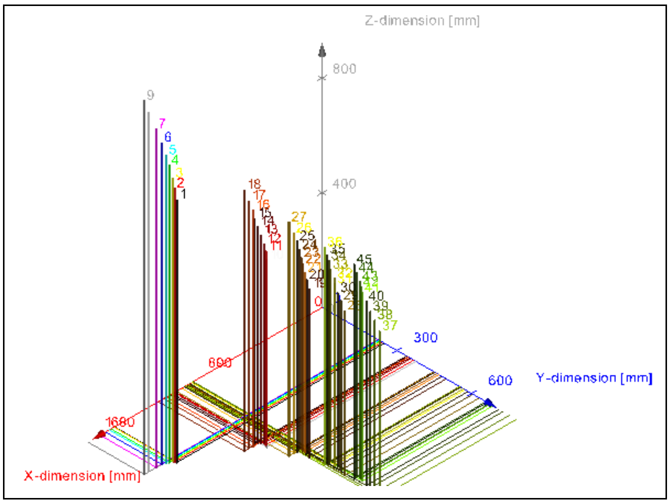

Figure 6 Housing dimensions (X, Y, Z) of the different variants

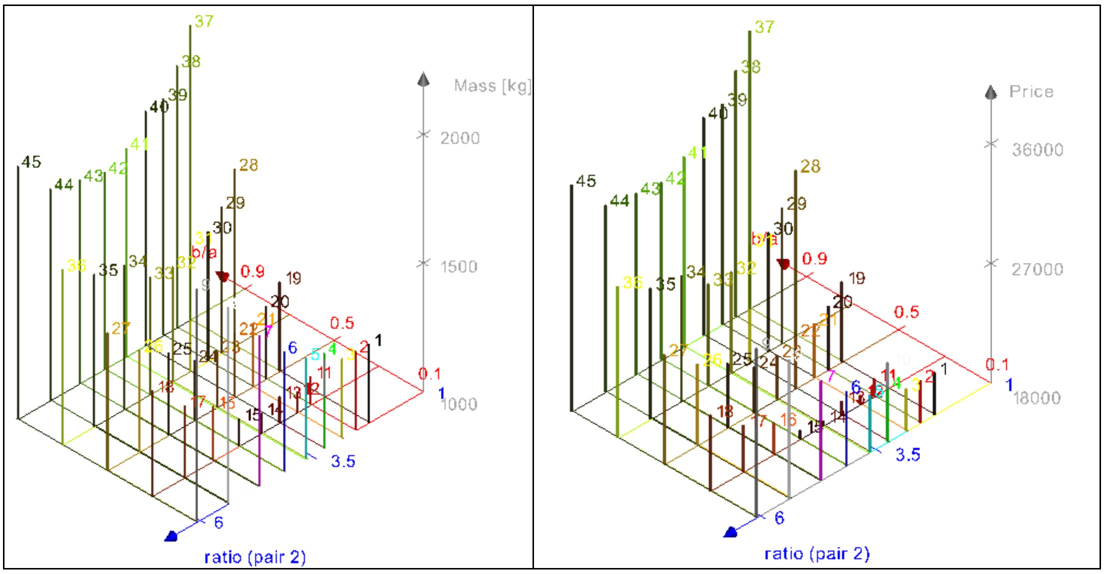

Figure 7 Weight and manufacturing cost (EUR) depending on the reduction of the output stage (i2) and of the width/center distance (b/a) ratio

A second calculation run was performed to analyze the optimum range of solutions in greater detail: The reduction of the drive stage was varied in 5 steps from 1.81 to 3.0 (and the drive correspondingly from 4.11 to 2.48). In this instance, b/a was increased for each ratio variant from 0.18 to 0.42 in increments of 0.04. This analysis calculated a total of 35 gear units whose results are shown in Figure 8.

Contrary to expectations, the second run did not find a significantly better solution. The best solution with regard to weight was found in the first calculation run at b/a=0.3 and i2=3.64, which gave a weight of 1077 kg. In the second run, the optimum weight at b/a=0.26 and i2=2.82 was 1073 kg. The differences in manufacturing costs were also not very great. In the second run they were only reduced from EUR 18360 to EUR 18302, a reduction of only 0.3%. The range that contains drive variants with minimum costs is obviously scarcely affected by smaller changes to the output reduction or the b/a ratio. This situation is also very obvious in Figure 6. It is beneficial to recognize this fact, which can then be applied if it is intended to create different reduction systems in the same gear housing, while keeping costs down.

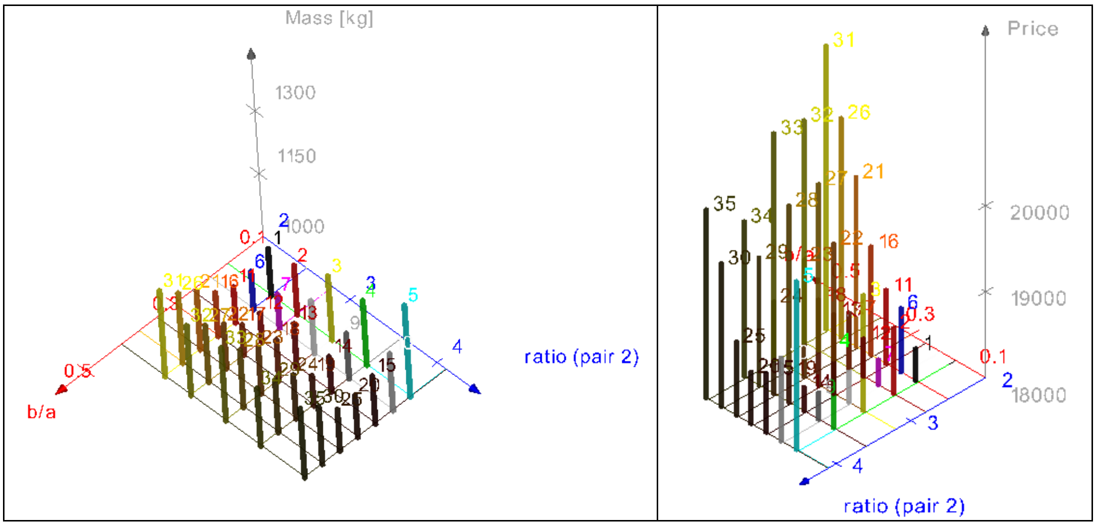

Figure 8 Weight and manufacturing cost (EUR) after more detailed breakdown of the reduction interval and the b/a interval

	Input stage	Output stage	Gear unit	Comparison with ACTUAL
Reduction i	2.05	3.60	7.47	
Safety Root SF	4.26	3.88	>= 3.76	
Safety Flank SH	1.42	1.44	>= 1.42	
Center distance a	276.2 mm	441.0 mm		
Facewidth b	71.8 mm	114.0 mm		
b/a	0.26	0.26		
Housing length X (ap-prox.)			1,259 mm	+ 16%
Roller bearing service life			>= 68,500 h	
Weight (approx.)			1,073 kg	- 23 %
Manufacturing costs (approx.)			EUR 18,302	- 20 %

Table 5 Most important results for the optimum variant

Comparing the least expensive variant (Table 5) with the status quo shows that costs could be reduced by 20%. The actual variant has a reduction distribution which almost lies in the optimum range, whereas the b/a values lie a little above it. In our opinion, the current gear unit has been fairly very well designed, even if a possible saving of 20% could be achieved, and should therefo-re be taken into consideration.

Conclusions

Two very different gear unit variants from mining applications were investigated with the Gearbox Variant Generator. In both cases, an analysis of the status quo was performed, to determine the effective strength values and safety factors for the gear units. Then, a large number of gear units with the same strength values, but with differing reduction distribution due to different stages and b/a parameter, were designed.

In both cases the study showed that the gear units were definitely well designed for their intended purpose: Compare to the range of possible solutions, the current actual design lies in the "green" zone. Nevertheless, the study showed that, in both cases, costs could be reduced by 20% if the best possible solution were adopted.

In both cases, KISSsoft's Gearbox Variant Generator has proved its effectiveness: without this tool it would have been impossible to perform these studies so quickly, even with the most sophisticated software.

[1] : Kissling, U.: Optimierungsprozedur zum Auslegen von Stirnradgetrieben nach Gewicht, Kosten und Wirkungsgrad, Zeitschrift ‚Konstruktion', 2011, Heft 3.

[2] : Kissling, U; Kivelä, R.: Automatic Optimization Procedure of a complete Gearbox for weight, efficiency, costs and dimensional restrictions; International Conference on Gears; VDI Bericht 2108.2; 2010; ISBN 978-3-18-092108-2.