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Gearbox Design for tight Space Constraints with simultaneous Cost Estimation

Efficient gearbox sizing including cost estimation with KISSsys, represented with practical examples of standard industry gearboxes, as well as precision- and micro-mechanics gearings.

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1 The first Phase in the Design Process

The first step in the development of a gearbox is, usually, the production of a principle sketch, either manually or using one already existing in a CAD Platform. Following, the essential transmission components (gears, shafts, bearings, etc.) are roughly estimated and then a first draft is built in the CAD. Here, emerge the first problems, for example, collisions or space problems for the bearings or shafts, which must be resolved by appropriate modifications. The handling of such changes in the 3D-CAD is rather costly and time-consuming.
With the modifications for individual elements, the gearbox loading conditions change and this requires new strength estimations. Because, until today, is not possible either to calculate the gearbox elements in the CAD Platform in an automatic and consistent way (or have the CAD program referring back to the geometry modifications carried out in the calculation program) this development step is iterative and time-consuming.
This is the reason why, still today, many engineers use a 2D-CAD Platform for this development phase in spite of the fact that collisions are then more difficult to spot.

2 The "KISSsys" Development Tool

The primary demand on the KISSsys program was to create a software tool, with which the calculations of individual machine elements could be interconnected. The goal was to display the power flow in a transmission system allowing the automatic interconnection of all relevant calculations. For instance, should the gear ratio in a stage of a multistage gearbox change, the speeds or torques of all other elements involved will also change. At the click of a button, KISSsys executes the rating of all elements in the system and clearly displays the essential results.

Additionally, KISSsys also allows a scaled 3D display of the transmission system. Producing the gearbox 3D arrangement in KISSsys is trivially simple: All elements' geometrical data are known from the calculations. For instance, the bearing calculation obtains from the bearing databases not only the load rating factors for the lifetime calculation but also, simultaneously, the geometry data that ought to be handed over to KISSsys. Thus, the 3D display runs 100% automatically in KISSsys. To establish a model in KISSsys, it is only necessary to define the shafts' relative spatial positions [1].
In KISSsys, the 3D Display service, which in the software development we consider as nice-to-have but not strategically necessary feature, proved itself to be extremely helpful for the

development of new drives. External boundary conditions can be pre-established as 3D solids (or read as SAT Files). The development of a gearbox principle sketch may now be directly executed in KISSsys. The concept, (for instance the number of the gear stages) must then be defined and subsequently modeled in KISSsys.

When planning transmission concepts, the safeties (or alternatively the lifetimes) of the individual components will be shown in real time, so that eventual weak points can be clearly identified. Using the KISSsoft sizing tools, the individual components can be very efficiently modified and optimized. The 3D Kernel permits the 3D display of the finest collisions. Iterations, as for example the change of a ratio distribution among individual stages in a multistage gearbox, will be carried out within few minutes. Once a satisfactory solution is found, the 3D concept can then be transferred to any CAD Platform via the STEP, SAT or IGES interface.

3 Space Boundary Conditions

The task of the design engineer becomes even more complex when a power drive must be integrated into predetermined close boundary conditions. These problems are very frequent in transmission technology, for instance in industrial special transmission drives, automotive and fine mechanics technology applications.
Since KISSsys administers the components of a driving stage and the appropriate calculations, it is possible to obtain suitable data by positioning the shafts. Logically, the distance between two shafts is given by the correspondent center distance resulting from the gear calculation. The shafts' relative position (or angle) may be either fixed (e.g., horizontal) or predetermined in a KISSsys model using simple mathematical formulae. With it, it is possible that, in case of a change of the center distance in a stage, the entire transmission stage will be automatically adjusted to pre-established space boundary conditions (see example in fig. 3).
In some cases, a transmission stage must also be integrated into an already existing casing. In such cases, KISSsys can read and display 3D drawings' data, in IGES- or STEP-format (Fig. 1). Collisions will be immediately detected during the sizing of the driving elements.

This considerably simplifies the work of adjusting the involved components.

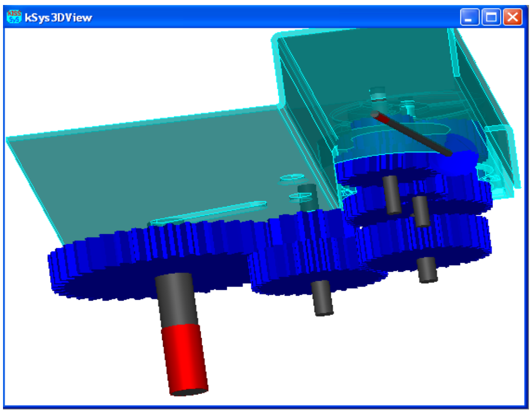


Figure 1: Multi-stage Transmission with Casing Parts. The Transmission Stages must exactly fit in the pre-established Casing. The Casing Data will be read in STEP-format and displayed in the KISSsys 3D Window.

4 Measuring Gearing for electric Motors

Fig. 2 shows an example of a micro technology application, with which quite particular assembly conditions ought to be taken into account. It concerns a motor feedback system to be fitted onto electric motors. The driving speed (up to 12000 rpm) will be reduced by means of two crossed helical (worm gear) stages and four spur gear stages. The mini magnets installed in the gear wheels produce incremental signals with a resolution of up to 2048 points per revolution. The device is designed for operating temperatures between -20 and +110 °C.

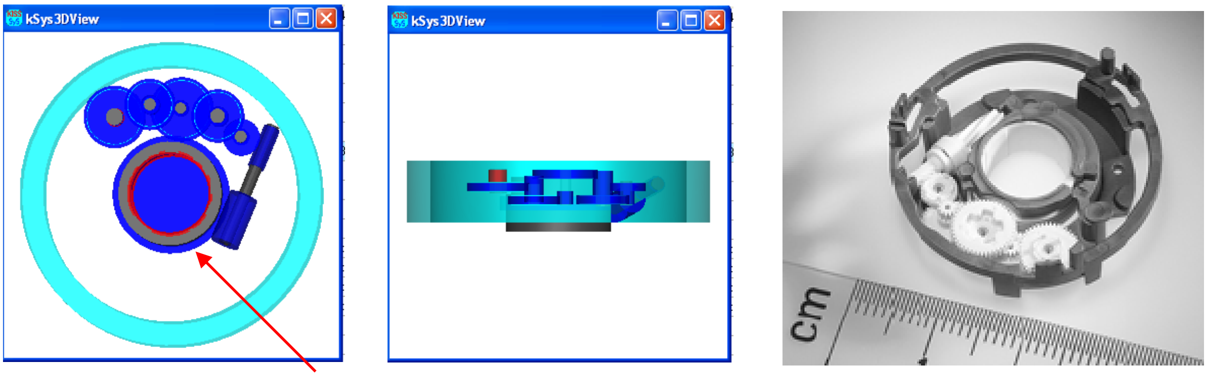


Figure 2: Measuring Device with a Combination of several Crossed Helical and Spur Gear Stages. The red Arrow marks the driving Worm with a tooth number of *Z*=1.

This gearing device is integrated into a ring mounted on a shaft. The worm gear, placed in the ring center with a bore hole corresponding to the shaft diameter, drives the following reduction stages. The more slowly-turning last gears are used for collecting the shaft speed and angular position of the shaft.

The ring outer dimensions (gearbox casing) are given. In order to use the place optimally, the shaft centers should be preferably as far away form the ring center as possible, but in such a way that the spur gears do not touch the casing's inner wall. The position of each following shaft (Fig. 3) can thus be defined. With this simple function in KISSsys, all system shafts will be optimally repositioned (space saving) in case of a center distance modification in a stage.

Shaft 6 Center is defined by:

- **Distance** *a_56* **from Shaft 5 Center**
- **Distance** *dGi/2-Lmin-da2_p6/2* from Gearing Center (Shaft 1)

dGi	**Casing inner Diameter**
Lmin	**Minimum Distance, Tip Circle to Casing**
da2_p5	**Tip Circle output Gear, Gear Pair 5**
a_56	**Center Distance, Gear Pair 5**

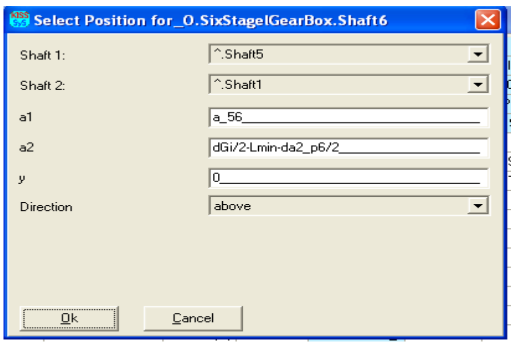


Figure 3: Shaft Positioning Example in KISSsys

Of utmost importance in measuring gearings is the positioning- and repetitive accuracy which will be determined by the summarized backlash and unevenness error of the gear stages. In the so called user window — one of the freely configurable and adjustable windows according to the model containing the most important features for the engineer using that model — the maximum and minimal total backlash is therefore displayed. The backlash of the individual stages can thus be optimized until the total result complies with the specifications.

An interesting peculiarity of the transmission concept discussed here ought still to be mentioned. The root circle diameter of the first gear (mounted on the main shaft) must be bigger than the motor shaft's diameter. The main shaft speed being already rather high (circa 12000 rpm), the speed in the first stage should not be further increased. Consequently, with a cylindrical gear pair execution, the pitch circle of the driven wheel must be bigger than the one of the driving wheel. However, this is not possible because of place restrictions. A good solution emerges by using a crossed helical gear pair. With crossed helical gears with a small gear ratio (for example 1:5), the driving wheel diameter (worm with *Z*=1) will be many times bigger than the driven wheel diameter (Fig, 4). For instance, a 1:5 gear ratio results in a pitch circle ratio of 11:1 which is exactly the desired solution.

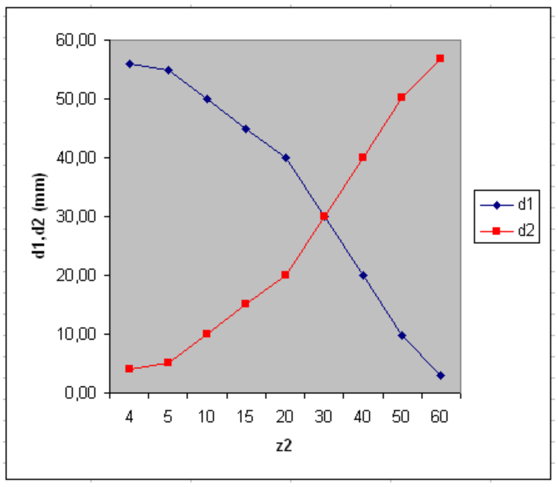


Figure 4: Pitch Circles *d1* (Wheel 1) and *d2*, (Wheel 2) of a Crossed Helical Gear mating with Z_1 = 1, Z_2 = 4 - 60; Shaft Center Distance = 30 mm, Normal Module = 1.0 mm.

5 Industrial Gearbox Series for Cranes

Fig. 5 shows a quite different example. An integration gearbox series should be conceived for a series of cranes. The outer casing dimensions as well as the position of the drive and driven shafts are given and fixed. Aggravating the situation, there are four mounting bolts running through the casing. The gearbox should offer four different variations in the same casing with the same shaft ends, but different total reduction ratios: *i* = 85, 10, 130 and 170 (table 1). The maximum reduction, (*i* = 170), can be achieved by three spur gear stages with a reductions per stage between 5 and 8. Because of the fixed position of the drive and driven shafts in a three-stage gearbox, only the position of the first intermediate shaft the angle γ between the casing center axis and the shaft center distance of the first stage) may be predetermined. The position of the second intermediate shaft will be given by the center distance of stages 2 and 3. . This logic can be easily carried out into KISSsys. In the KISSsys model for the design of this gearbox, the angle γ is an input. The pre-determined constraints are entered in the KISSsys model (casing and cylinders in transparent color: Fig. 5) so that collisions will be immediately shown when sizing the individual parts.

In order to achieve pre-determined minimum safety conditions, despite of the close fit space constraints, the output stage with shaft and bearings is first designed. It turns out rather quickly that, by transmission ratios greater than 3.7, the driven gear tip circle will touch the casing wall. The output stage must, therefore, be designed for a reduction ratio unusually small for the high total transmission ratio. The sizing of the elements (gears, shafts and bearings) is carried out within few minutes because KISSsys uses KISSsoft sizing functions to calculate the gear stages and the shafts/bearings dimensions almost instantaneously.

Table 1: Lifting Gearing Specifications

Lifting Gearing Series	Unit	I	II	III	IV
Motor nominal Rating	kW	20	20	20	20
Total Transmission Ratio	:1	170	130	110	85
Driving Nominal Torque	kN	8 100	8 100	6 400	5 100
Driving radial Force	kN	53 125	53 125	42 521	33 220
Motor nominal Speed	rpm	2 840	2 840	2 840	2 840
Efficiency, each Stage		0.97	0.97	0.97	0.97
Service Life under nominal Load	h	800	800	1 600	1 600
Switched-on Time	%	50	40	40	40
Starts per Hour	c/h	300	240	240	240

Materials are pre-determined; in this case, for example, case hardened steel for the gears, since it is clearly obvious that, with another material, the gear diameters would become excessive. The calculated elements are directly shown in the 3D-display and can be changed by optimizing.

With big transmission ratios in gear stages, the problem often occurs that the pinion diameter is too small and the shaft diameter becomes thinner than reasonably acceptable. This problem is also immediately visible in the 3D-display. The transmission ratios of the first and second stages can therefore be optimally distributed. Should a collision of bearings in two neighboring shafts occur, the sizing functions will allow either to increase the corresponding center distance or modify the bearing type.

In order to keep total cost as low as possible, the design target for all four transmission ratio variants is, that the position of all the shafts remains the same (same casing), that always the same bearings are used (same casing machining) and, if possible, always the same gears are used in two of the three stages.

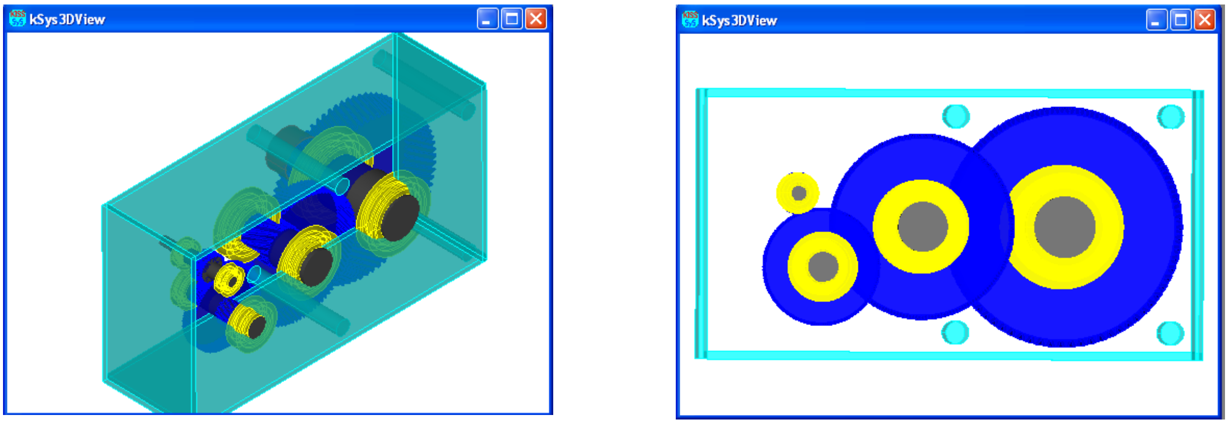


Figure 5: Crane Gearbox showing the Space Constraints, given Position of the driving and driven Shafts and 4 Through-drills (Tubes). The Display comes from the first KISSsys Release in 2001.

In order to achieve this, the optimal solution for the variant with maximum ratio is sought at first and, afterwards, the solution for the minimum total ratio.

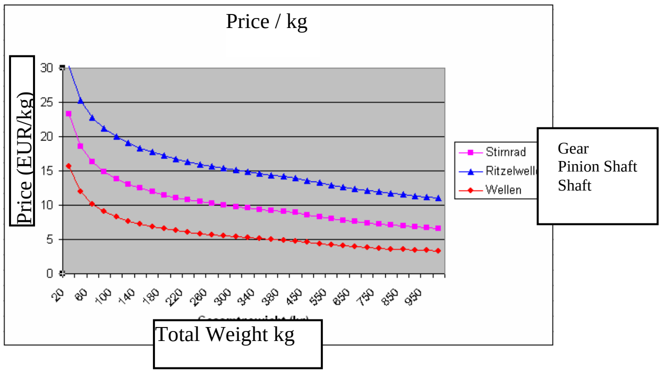
In comparison with the conventional gearbox design procedure, the time required in this case could be reduced by a good 65 %.

6 Costing

For customer gearbox design, it is desirable that the approximate dimensions could be determined in as short of notice as possible after establishing the requirements and the inherent feasibility basic acceptance. Immediately afterwards, or in parallel to it, the production costs must also be roughly estimated. To be able to hand over a serious offer for the gearbox manufacturing costs requires a considerable effort. Therefore, the availability of a solution to determine the weight and cost within a short period of time is extremely useful.

KISSsoft's calculation software includes many technically advanced tools for the quick and precise sizing of transmission system components. The use of these tools, available in the expert add-on tool KISSsys, allows the very fast design of complete gearboxes with a balanced service life calculation of all of its components. KISSsys-models for all usual systems such as 2- to 5-stage spur gears, bevel spur gears or planetary gear trains are available which permit the sizing of new gearboxes. With the specification of the desired minimum safeties for gears and shafts, as well as the mandatory service life for bearings, a precise sizing of the components can take place in few minutes. Because KISSsys can access all properties of the gearbox parts via KISSsoft, the weight of the individual parts or, for bearings the purchase prices in the database, is also available.

Some years ago, the L. Kissling company in Zurich, made an analysis of the manufacturing costs of typical gearbox parts, such as shafts, pinions and gears that clearly did show that, for classic gearbox parts within a certain area, a quite exact cost estimate can be done based upon the weight of the parts. At the same time, it must be stressed here that in companies active in special gearbox manufacturing, the typical batch size amounts to between 2 and 10 pieces. It turned out that the variation of the manufacturing costs (via post-calculation) of a same part by repeated manufacturing is approximately equal to the difference between the manufacturing costs of two different but similar parts of equal weight. Despite considerable scatter of the costs of individual production orders, a clear tendency between price and weight is detected after evaluation of the cost of hundred parts in the range of 20 to 2 000 kg (Fig. 6). The data here is based on cost for case carburized and grinded gears/pinion shafts.



Part Type	Price in EUR/kg , x = Weight in kg,
Spur Gear	Y = 60.9 * x-0.3206
Pinion Shafts	Y = 65.4 * x-0.2564
Shafts	Y = 52.0 * x-0.3985

Figure 6: Cost Function for classic Gearbox Parts depending upon the Weight.

It is logical to expect that with a bigger series production prices must be somewhat more exactly differentiated because there, the scatter between repetition batches is clearly smaller.

With these data, the costs of the gearbox parts can be directly determined in the KISSsys model (Fig. 7). Additionally, the weight of the casing can be estimated from its outer dimensions if desired. The precision of the cost estimate clearly depends upon the quality of the used Weight/Cost function as can be seen, for example in Fig. 6. Obviously, this procedure cannot produce an exact price. However, experience shows that ─ even if the absolute statement cannot be accurate ─ this type of cost estimation is very good for the purpose of comparing cost of variants. Very often, however, it is a question of being able to decide very fast, whether a transmission system is more cost-favourable in two or three-stage implementation. Or, in precision mechanics, whether a transmission stage should be executed as a bevel/spur gear, crown/spur gear or a worm/spur gear combination.

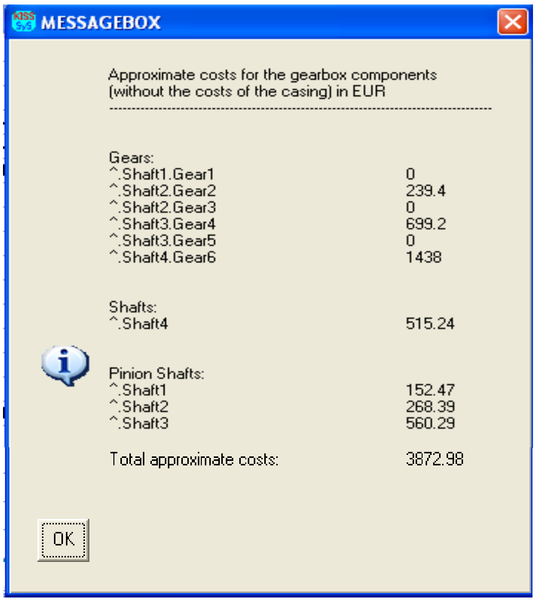


Figure 7: KISSsys Costing Results

7 Applying Cost Estimation to a 3-Stage Spur Gear Transmission

With multi-stage transmissions, the dimensions of the gearbox parts can drastically vary depending upon the distribution of the total transmission ratio by the individual stages. Fig. 8 shows a classic example of the influence of the reduction distribution onto the stages of a three-stage gearbox. From the literature, it is also known that it is more advantageous to have a somewhat smaller reduction at the output stage than at the input stage. However, the most cost-efficient reduction distribution depends upon too many factors that cannot be covered by a simple rule-of-thumb.

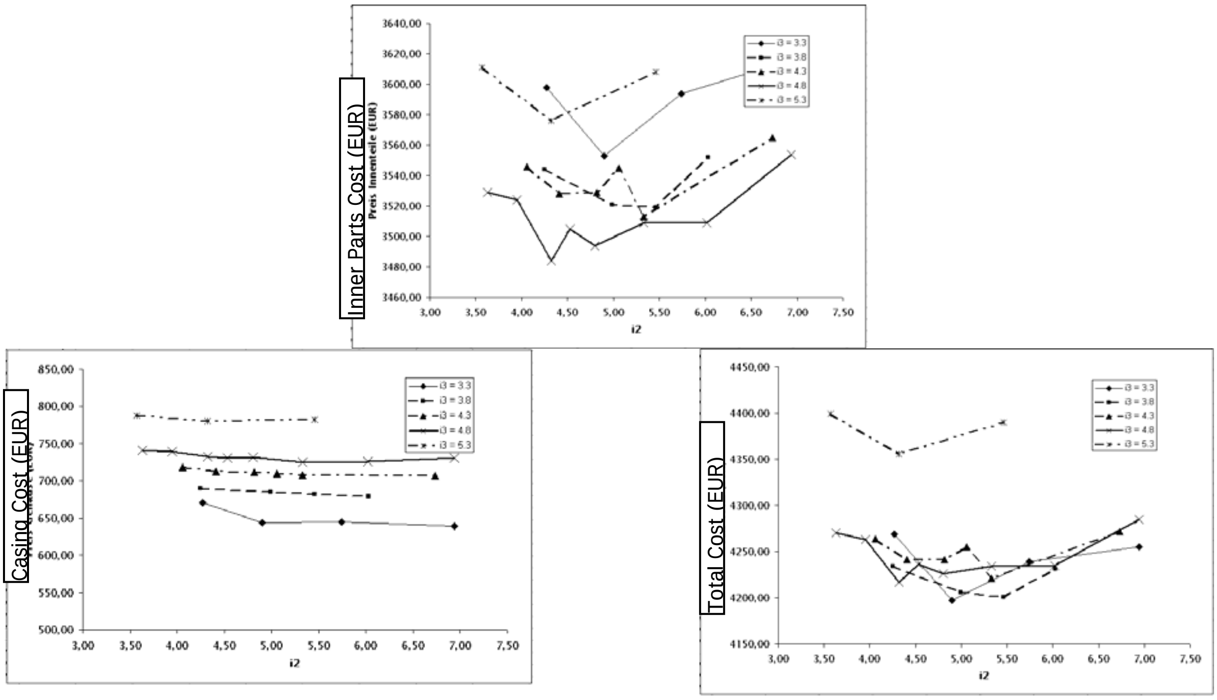


Figure 8: Cost of the inner Parts and total Cost (with Casing) for a Three-stage Helical gear gearbox depending upon the Transmission Distribution. Total Reduction *i* = 110; Driving Torque 25 kNm at 9 rpm (i_3: Reduction of the Driving Stage, i_2: Reduction of the intermediate Stage).

In the example of Fig. 8, with a total transmission ratio i_{tot} = 110 (average reduction per stage i_{stage} = 4.79) the lowest cost for the inner parts is achieved with a reduction on the output stage i_3 in the range of 4.30 to 4.80. However, the cost of the casing continuously decreases with a reduction of i_3. With it, the total cost stays practically invariable for an i_3 wide range between 3.30 and 4.80.

Since KISSsys, with its built-in program features, offers the possibility of automating model parameterization and calculation, it is even conceivable to run reduction variations with sizing and cost estimate autonomously and directly generate evaluations as shown in Fig. 8.

8 An Aid for Gearbox Design and Optimization

What KISSsys does, is what each design engineer does when designing gearboxes: based on power and speed data, determine the loads on the individual components and size them accordingly. Whoever uses calculation programs to design machine elements, must reflect on the logical way how the individual calculations should be embedded into a continuous gearbox design concept.

Already in 1990, at that time still as a DOS application, we have programmed a first prototype [2]. The calculation of the system took place in a batch procedure; it was time-consuming but absolutely usable. The main lesson from this exercise was that, in efficient system software the structure of the calculation programs for the individual components must be quite differently built; it needs, for instance, a clear separation between Input-Calculation-Results, things that are (almost) obvious today. At that time, efficient DLL-concepts were still early science fiction.

In the 90s, there were several different attempts, above all at some German University's, to develop software for the calculation of complete drive trains. In it, software with entirely usable concepts was developed for the flexible design of a drive train. The drive train could also be completely calculated. To do that, a set of self-made machine element calculation procedures was used, which, because of capacity reasons, were extremely simple. Had professional calculation software been integrated, this attempt would have no doubt been able to develop a commercially usable product.

Another attempt was pursued with the TBK calculation software. This gearbox calculation software, in DOS was, together with Hexagon and KISSsoft one of the most used commercial products to be employed by gearbox manufacturers in Germany. TBK permits the calculation of complete gearboxes, for instance, two- and three-stage spur wheel drives with gears and shafts. The disadvantage is that the gearbox structure being pre-determined and fixed programmed, the user itself cannot define it. The adaptation of the structure and also the embedding of specific evaluations by the user (according to demands) is thus not feasible. This massive limitation was the reason why this solution was not generally accepted by gearbox designers.

A similar problem occurred with several big German gearbox manufacturers. One of them, world market leader in the area of gear motors, has since years an impressive calculation solution for the complete calculation of gearboxes. For the calculation of machine elements, FVA programs such as STplus and own software are embedded. In this solution, the gearbox structure is also rigidly pre-determined. Subsidiary companies' demands for variations, for instance for planet stages, could not be met in due course. This led to the fact that KISSsys is now, since only three years, used in all companies of the group.

Romax Software offers another solution developed in England by a bearing specialist. With Romax, the user can configure, calculate and visualize transmission systems in 3D. Next to KISSsys, Romax is today the only software that can carry out strength calculations for complete gearbox stages. With exception of bearings, the strength calculations are rather modest, especially also for the corresponding documentation. Presumably, together with the high price, this is the main reason why Romax is not so much widespread. However, contrary to KISSsys, gearbox oscillations and vibrations may be calculated. This is the reason why KISSsys and Romax are both frequently used in the same company. Whereas KISSsys will be used for service life and strength calculation with load spectra (including with position shifting).

World-wide, KISSsys is the leading product for the strength calculation of complete transmission drives. The two main reasons for it are:

- KISSsys uses KISSsoft for the strength calculation, a software that is the recognized leader in the area of gear calculation and optimization.

- KISSsys is an extremely flexible tool. With a built-in interpreter language, all possible transmission stage variations can be modeled.

Empirically established figures with KISSsys in development departments of several companies show a 5-fold reduction of development times for new transmission concepts. This high efficiency increase (factor 5) in the gearbox design is an empirically established figure from one of the first KISSsys user, the Getrag company that uses this software since 2001.

Last but not least, the documentation- and administration overhead is considerably reduced using KISSsys. As long as the calculations are individually executed and filed, the gearbox verification always consists in dozens of documents and files from quite a number of development phases. If months or years after the conclusion of a project questions must be answered or changes introduced, so often begins the time-consuming search for the last state of affairs. This task completely disappears with KISSsys since the last stand is stored in the model and all elements are extensively documented. In the sense of a PDM concept, the gearbox sizing is automatically administered. In the field of engineering this is a useful and timesaving matter; when, for example, the customer for whom we developed the measuring gear transmission calls (see Fig. 1), we will have the gearbox in the most current condition within 30 seconds and can start answering questions.

9 End remarks

With the software tool “KISSsys”, the development process can be considerably accelerated. In KISSsys, the gearbox concept is displayed to scale in 3D. However, the data of the elements (such as gear diameter and width) are not an input as in a CAD, but come directly from the strength calculation of the correspondent component. KISSsys is directly superimposed on the KISSsoft machine element software. The force transmitting elements are sized in KISSsoft. The data of individual elements, relevant for the gearbox, are automatically transmitted to KISSsys and are processed there where both the power flows and 3D displays are continuously updated. Through the logic interconnection of the existing data in a KISSsys model — without any manual manipulation — the gearbox 3D model is continuously being updated and collisions immediately made visible.

The work with this tool is shown in several examples. Since it is possible to access the attributes of individual elements, as, for example, it is also possible to perform production cost estimates.

A historic and current contemplation of the available tools for the strength calculation of driving trains shows, that KISSsys is the leading product today. Empirically established figures with this tool, from research and development departments of different companies, have reduced the developing times for new driving concepts by a factor of 5.

[1] Kissling, U., Raabe, M., Dinner, H.P. (2004) *Evaluating Gearbox Design Concepts*, 3rd International CTI Symposium, Berlin, 2004.
[2] Kissling, U. (1990) *Vom Berechnungsprogramm zum intergrierten kompletten Konstruktionsmittel*, Antriebstechnik 29, Nr. 1, 1990.