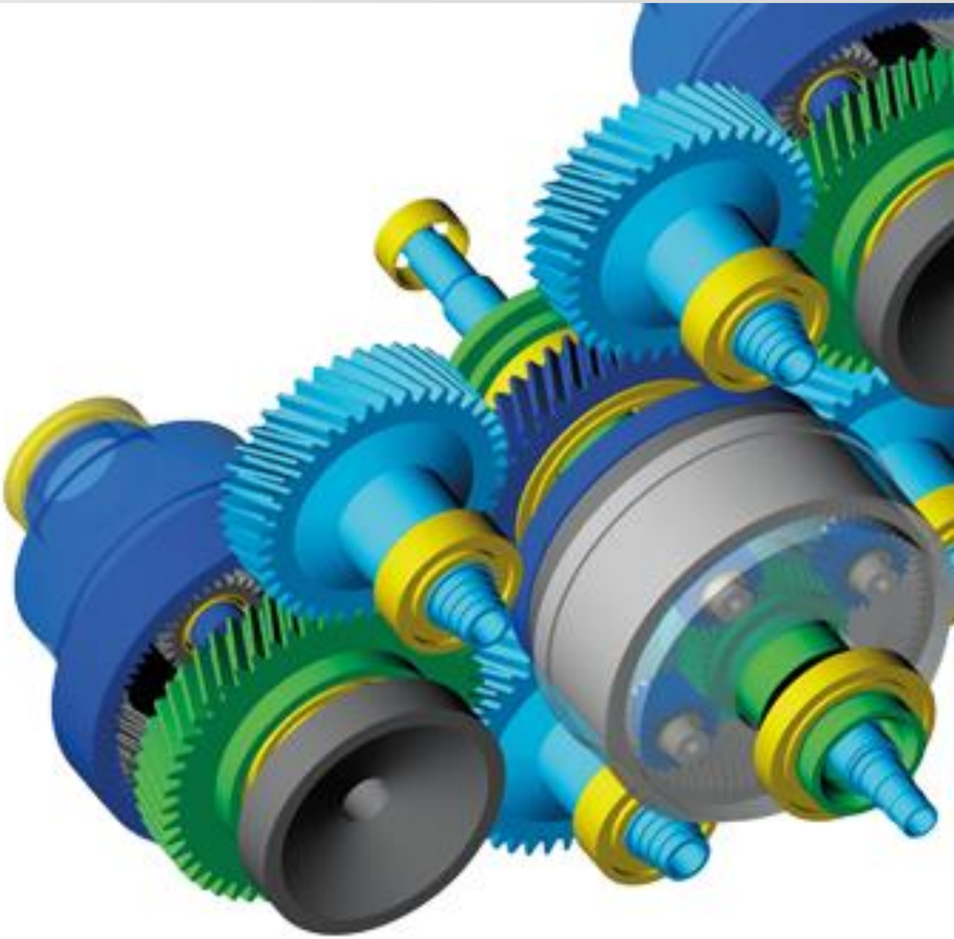
Design of bevel and hypoid gears with integration to manufacturing



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Lyon Villeurbanne FRANCE

KISSsoft

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- Design calculation by ISO standard
- Cutting methods and hard finishing processes
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- Connection of design and manufacturing
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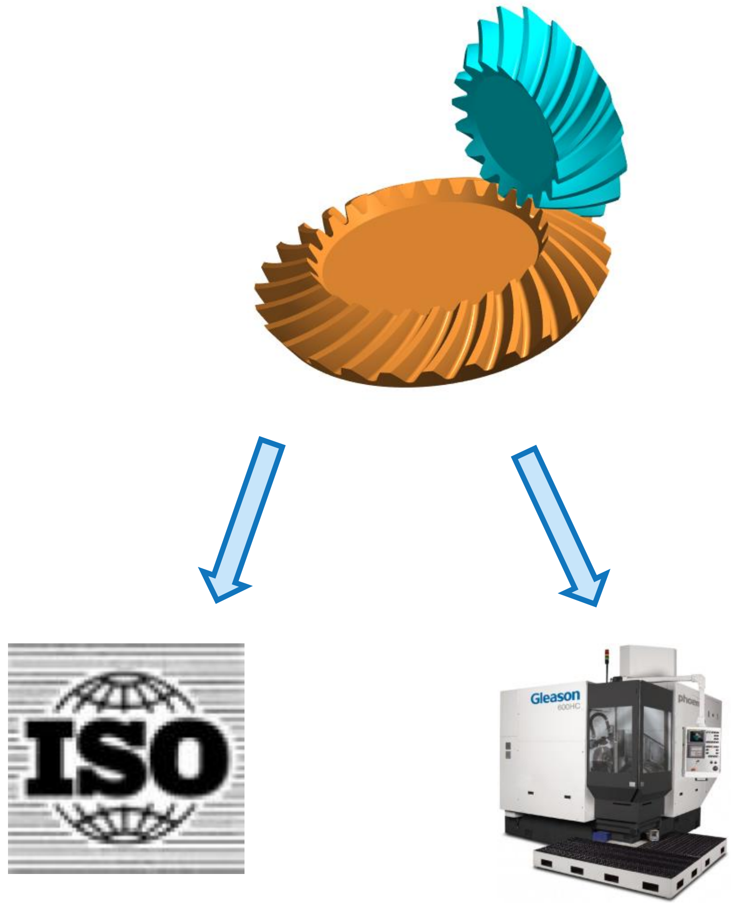
Design of bevel gears is closely linked with the manufacturing simulation:

- parameters from the manufacturing simulation needed for the design calculation

Vice versa, the the manufacturing calculation requires data from the design:

- displacement parameters from the design drivetrain are needed for contact analysis

It is a common process between design and manufacturing calculations.



Design calculation by ISO standard – failure modes

The ISO rating standard 10300 provides reliable and widely accepted calculation approaches.

- root breakage
- flank pitting
- scuffing (draft)
- tooth flank fracture (planned)
- micro pitting (planned)

ISO standards are under continuous discussions and include the latest results from research and all the members of the ISO committee.

KISSsoft is also member in WG13 and actively working in the committee.

Some parameters for bevel gear strength rating are shown next.

Source: Dissertation Wirth

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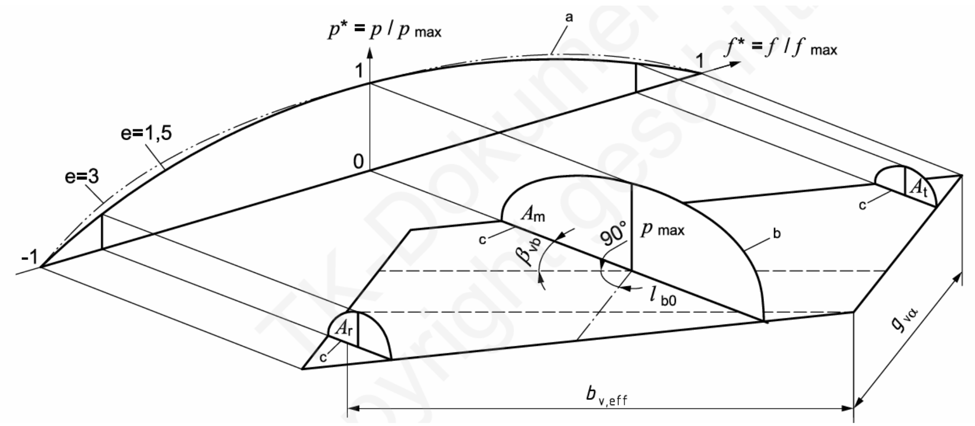
Design process by ISO standard – Load sharing

The load sharing along the path of contact is influenced by the profile crowning:

The load sharing factor ZLS results in different parabolic courses.

- high: for industrial bevel gears, manufactured with standardized cutter heads
- low: for automotive bevel gears, manufactured with individual blade designs



Source: ISO 10300-2:2014

Bevel gears may have shortened contact patterns.

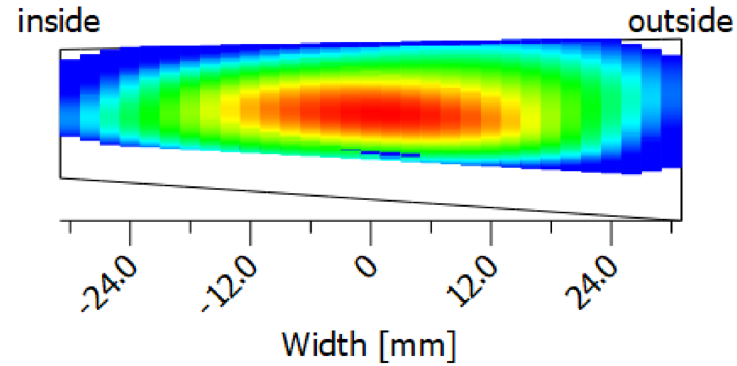
Parameter effective face width b_{eff} :

- The active face width in percentage to the nominal face width
- measured by the total length of the contact

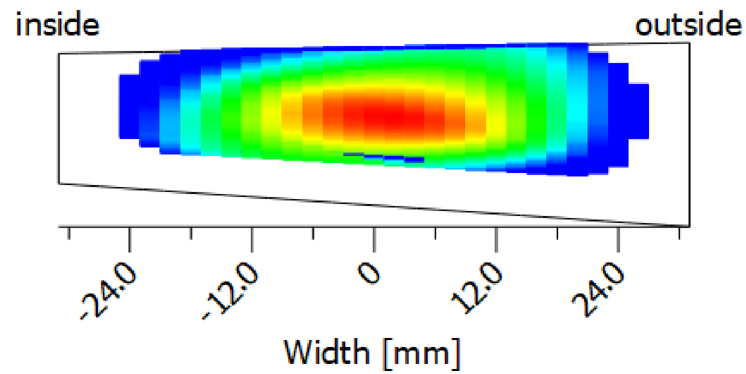
The ISO standard gives a default value of 85%, which may be realistic but conservative.

The design engineer is **requested to modify** the parameter according to test rig or simulation results.

effective face width = 100%



effective face width = 84%



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The contact ratio is a typical parameter for noise rating:

high contact ratio leads to low transmission error

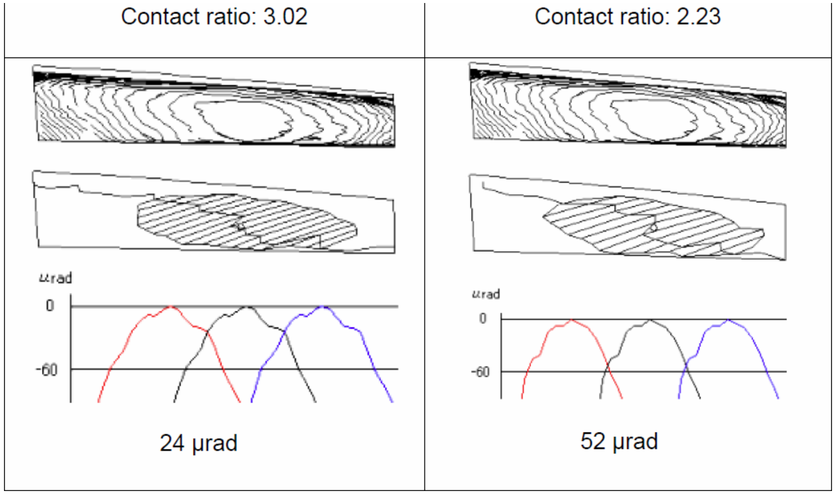
In ISO 10300:2014, the contact ratio uses the effective face width instead of the nominal face width.

This gives realistic results.

The design engineer has to be aware when calculating the contact ratio in ISO 10300:2014:

- to achieve the same contact ratio as in ISO 10300:2001, apply $b_{eff} = 1$

high contact ratio | low contact ratio



Source: ISO/TR 22849

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Root radius is to be checked with the manufacturing simulation.

The slot width of bevel gears depends on:
- the cutting method Face Hobbing or Face Milling
- the cutter head size

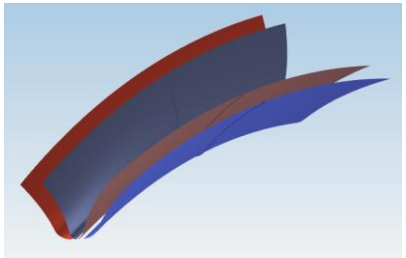
Face Hobbing: slot width varies, depending on cutter head size
- check at smallest slot width for cutting interference
- check at largest slot width for remaining areas

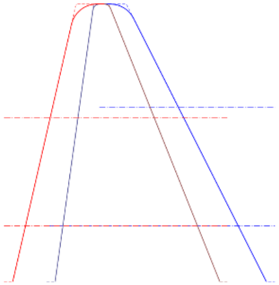
Face Milling: constant slot width (*)

Blade design and cutter head:
- separated in an inner and outer blade
- appropriate chip flow on the non-cutting side is needed.

Based on the blade point width and the slot width, the root radius is determined.

bevel gear cutter head


slot analysis


blade design

Design process by ISO standard – face load factor $K_{F\beta}$

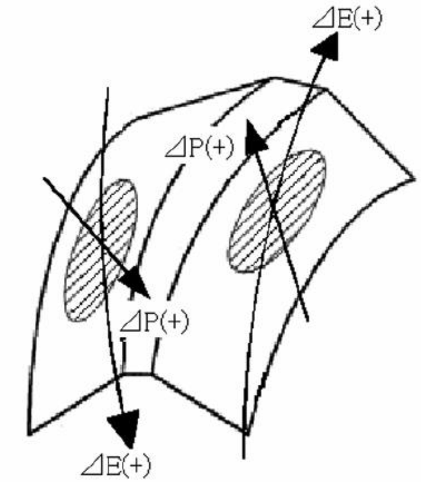
The face load factor for bending stress $K_{F\beta}$ depends on the cutter head size.

Bevel gears with **small cutter head** have a ‘self-centering’ effect for the contact pattern under load:

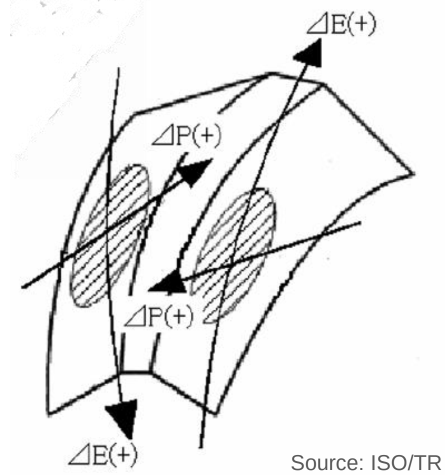
- for small cutter designs, the characteristic line of the P-displacement turns into the direction of the characteristic line for the E-displacement.

- for large cutter designs, the characteristic line of the P-displacement is in vertical direction.

small cutter design



large cutter design



Source: ISO/TR 22849

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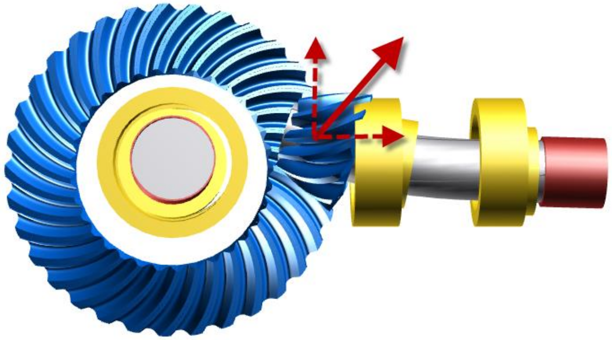
Example: RH ring gear, small cutter design



The displacements of the pinion under load are in:

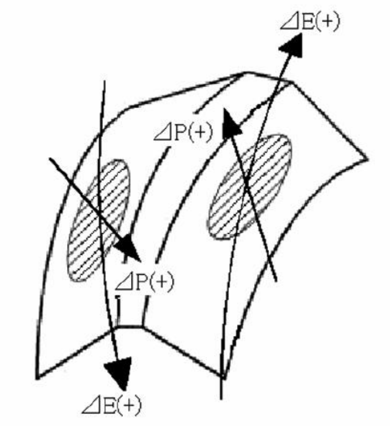
- E-minus
- P-plus

E-minus: the contact pattern moves to the heel (and slightly to the root).

P-plus: the contact pattern moves 'back' to the centre.

Having a small cutter design, the tooth root stresses are reduced through the face load factor by maximum 15%.

small cutter head



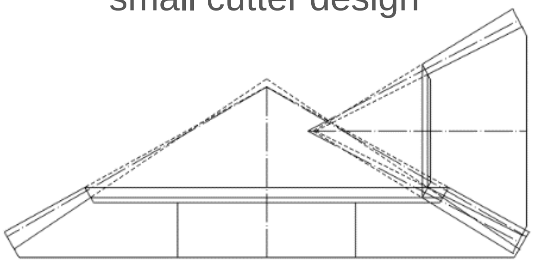
For **hypoid gears**, the cutter radius has a major influence on the pitch cone angles.

Comparing two hypoid gear sets, having the same ratio and ring gear diameter:

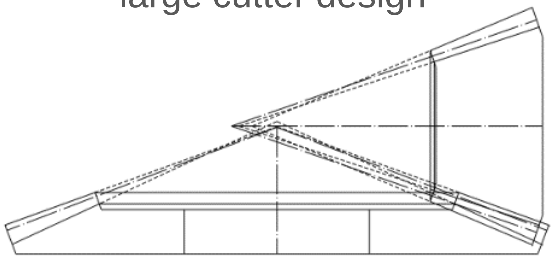
- the small cutter design has much higher pitch cone angles on the pinion
- the large cutter design much smaller pitch cone angle on the pinion

This results in significantly different blank dimensions.

small cutter design



large cutter design



Design process by ISO standard – generated and non-generated wheel

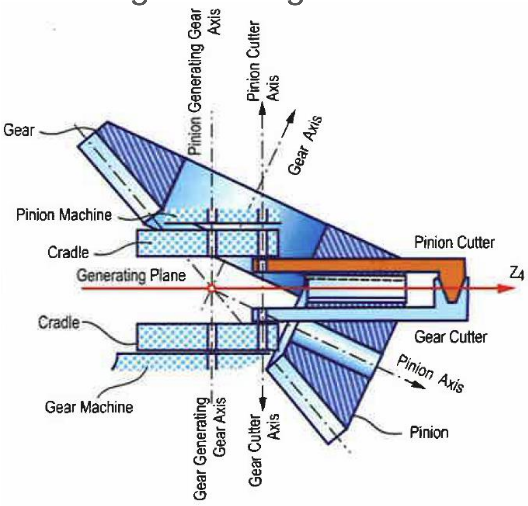
Bevel gears can be manufactured in ‘generated’ or ‘non-generated’ process (Face Hobbing and Face Milling):

- the ‘generating’ method has a generating motion for pinion and wheel
- the ‘non-generating’ method has only plunge motion for wheel (for ratio > 2.5)

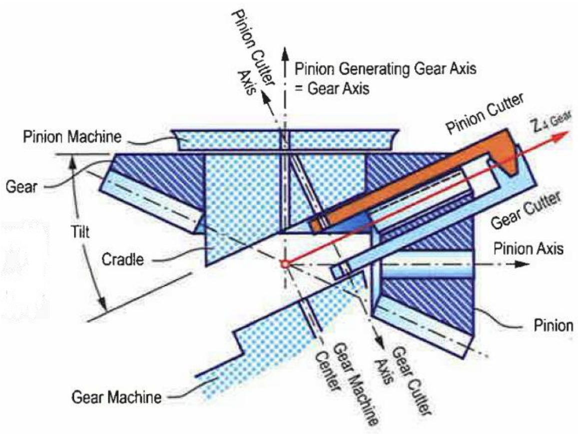
The generating motion leads to a smaller tooth root thickness, but larger root rounding radius.

This is beneficial for reduced root stress in the tooth root.

generating method



non-generating method



Source: Bevel Gear Technology, Gleason

The cutting method and hard-finishing process influences the geometry, the achievable quality and the costs.

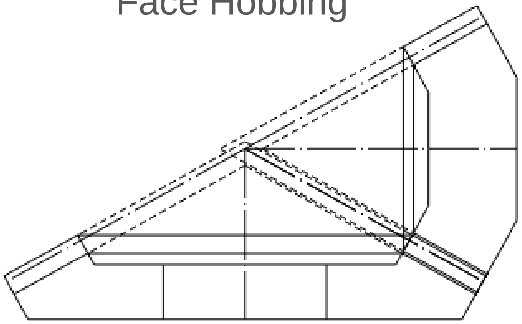
Geometry of the blanks:

- Face Hobbing has a constant tooth depth
- Face Milling has a tapered tooth depth.

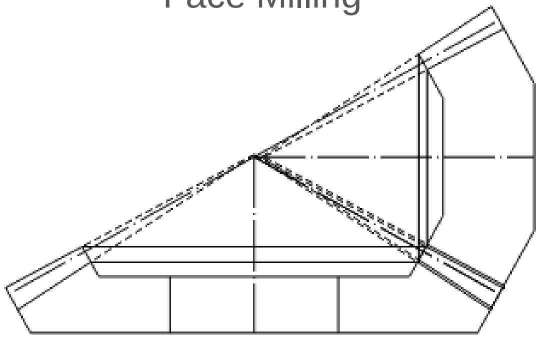
When **changing cutting method** between Face Hobbing and Face Milling:

- different outer tip diameters (casing, blanks)
- different cutter head sizes:
  Face Milling only large cutter designs,
  Face Hobbing also small cutter designs
  → different displacement behavior

Face Hobbing



Face Milling



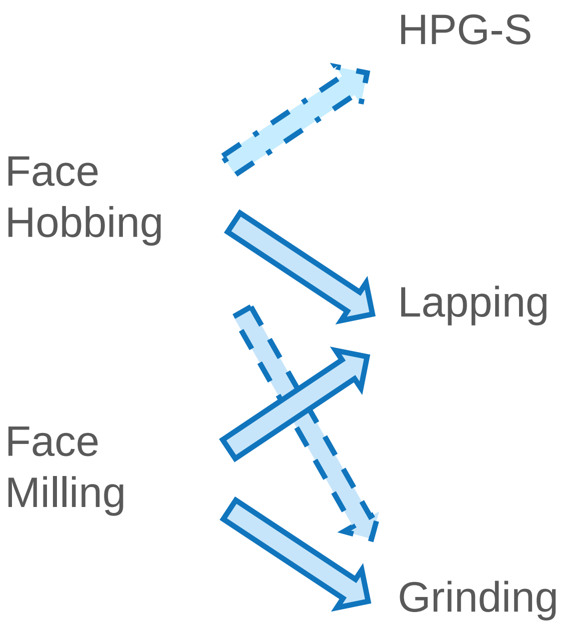
Face Hobbing allows lapping or hard-skiving, no grinding (respectively the semi-completing method).

Face Milling allows grinding and lapping.

Lapped bevel gear (hypoid gears) have higher scatter within the production series.

Economical aspects:

- for small batches, but high number of ratios, an universal cutter system typically is applied (cutter head, grinding only, ..)
- for large batches, individual cutter systems are applied.



Considering the strength, noise and economical aspects, the best suitable manufacturing process is determined.

Micro geometry optimization – definition of displacements

The contact analysis requires:

- the really applied machine settings and blade design
- the bevel gear displacements under load

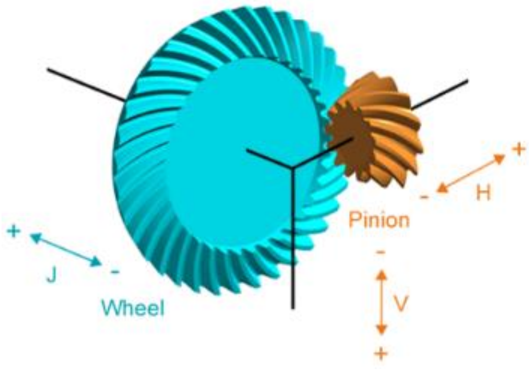
The bevel gear displacements

- are calculated from the drivetrain
- based on four parameters E, P, G and sigma
- defined in the crossing point

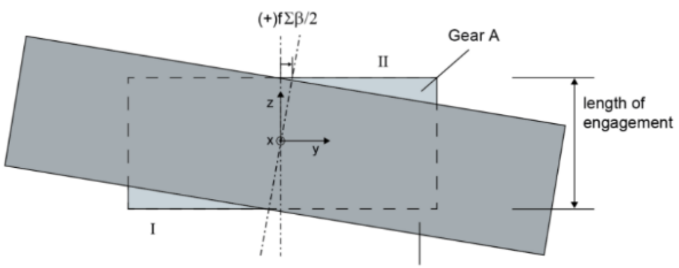
The four parameters provide a full definition of the displacements (misalignment) of the gears.

For cylindrical gears, the displacements are defined in the gear meshing contact.

Definition of displacements for bevel gears



Definition of displacements for cylindrical gears



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Micro geometry optimization – calculation of displacements

Without load:

- the axes of pinion and ring gear intersect at the crossing point.
- The axes of hypoid gears are skewed with the distance of the nominal pinion offset

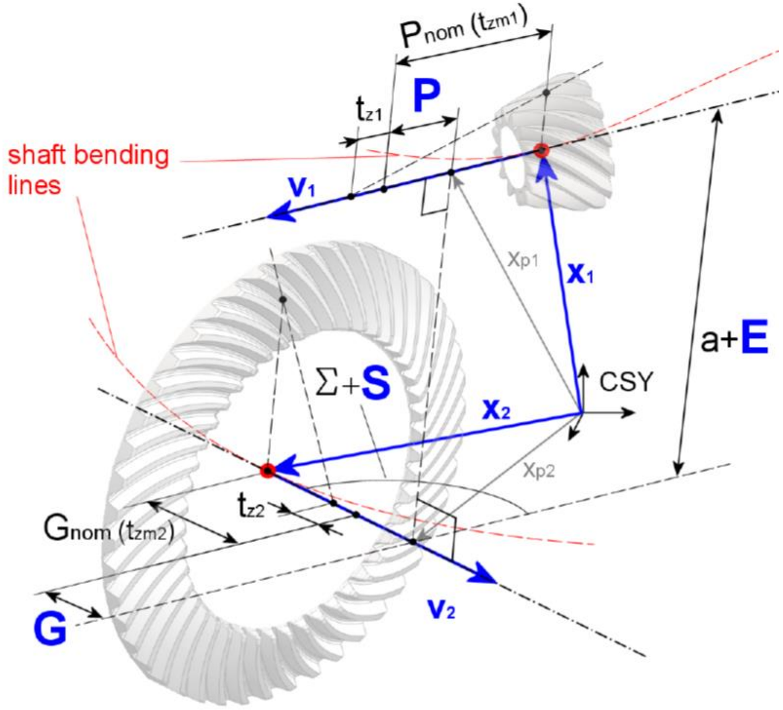
Under load:

- the shafts are bended
- axes of pinion and ring gear are skewed arbitrarily

Displacements of pinion and ring gear:

- axial shift of the gears
- change in the distance between the axes of pinion and ring gear (perpendicular drop)

The implementation into ISO standard is currently under discussion.



Source: ATA Gears OY, FI-Tampere

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Micro geometry optimization – contact pattern under load

Effects on displacement values:

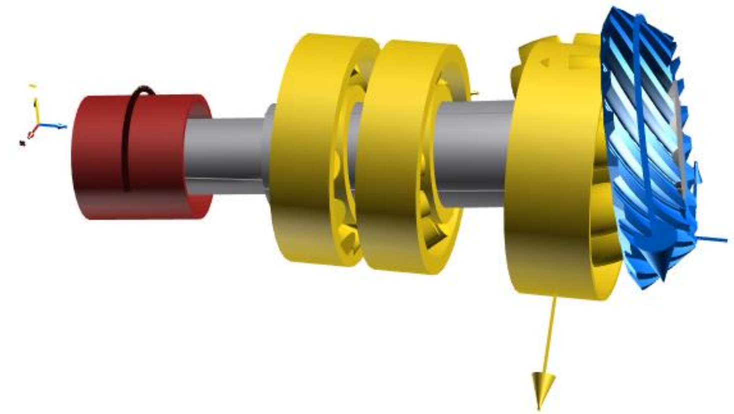
- shafts deformations
- rolling bearing stiffness (axial, radial, tilting)
- thermal elongations of shafts, casing and gear bodies
- casing compliance (for sensitive designs)

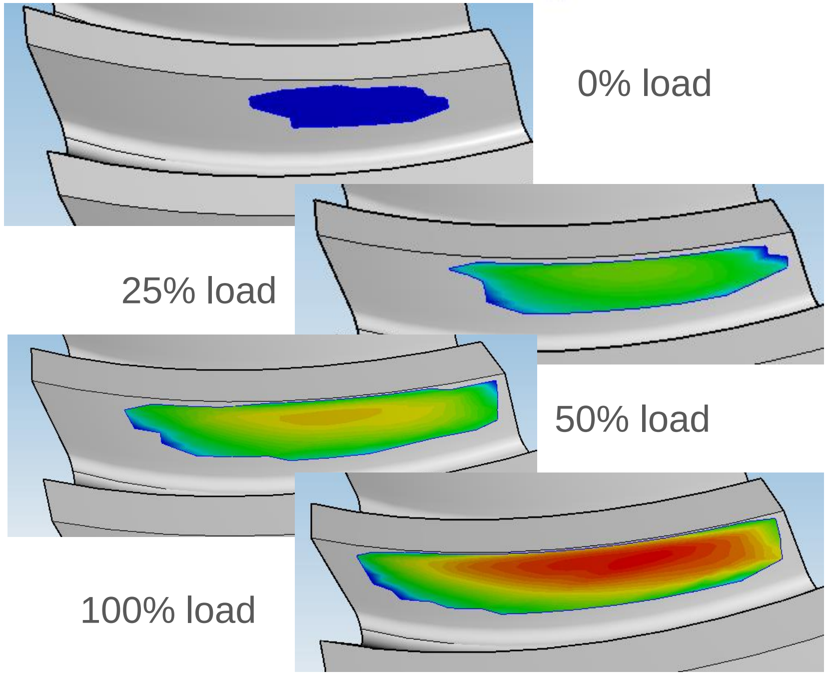
Micro geometry optimization:

- several load stages & temperature conditions
- by machine settings & blade design
- drive and coast mode

The results are:

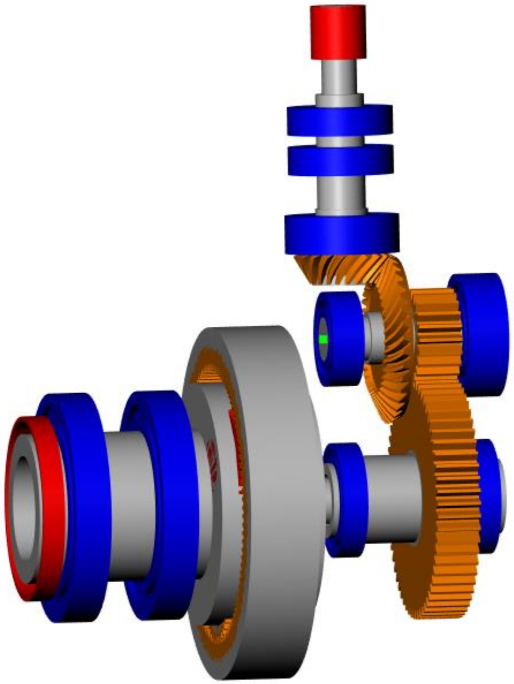
- contact patterns (also for no load!)
- transmission error, sliding velocities and local friction coefficients, etc.





A practical sample – specifications and conditions

Industrial 3-stage bevel – cylindrical – planetary gearbox, with total ratio of 1:28 and an output torque of around 100 000 Nm.



Data for the bevel stage:

- input torque of the pinion is 3500 Nm, speed is 1450 rpm
- ratio of the bevel gear set is 1.85
- Face Milling, grinding, generated wheel

Data for rating standard ISO 10300:

- case-hardened steel
- required safeties 1.4 for root and 1.2 for flank pitting
- the effective face width is applied with b/b_{eff} = 0.92
- the load sharing is selected with 'high profile crowning'
- the application factor K_A is 1.25
- the mounting factor $K_{H\beta\text{-}be}$ is 1.1
- provisory root radius factor ρ^*= 0.25.

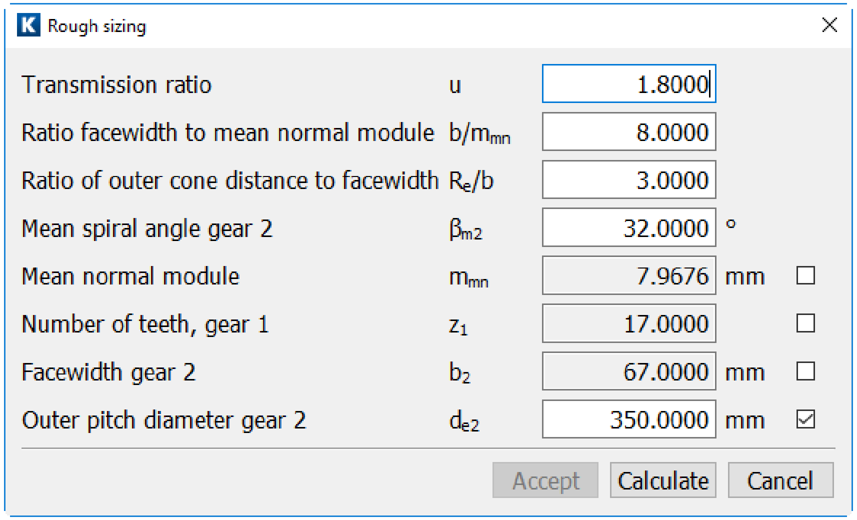
A practical sample – rough sizing

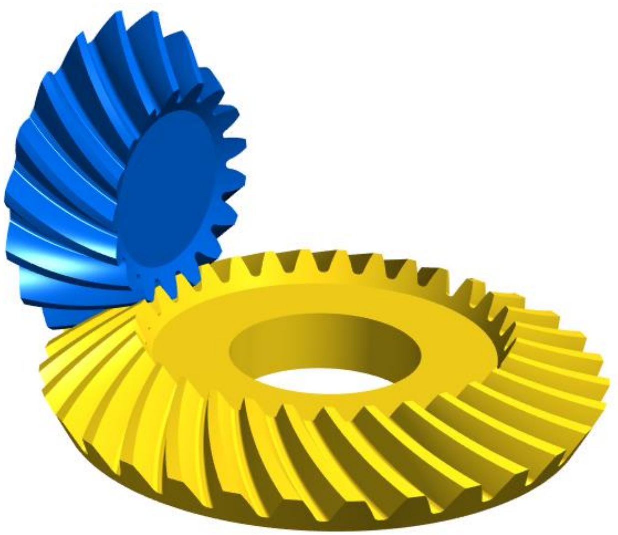
Data for first sizing:

- normal module to face width mn/b = 8
- ratio of outer cone distance to face width r_e/b = 3
- spiral angle = 32°

This results in a bevel gear pair with 17:31 and an outer diameter of 350 mm, which is a good first design.

Cutter head size: 16” (according to literature)





A practical sample – fine sizing

For macro geometry, the gear pair is optimized using the parameter variation:

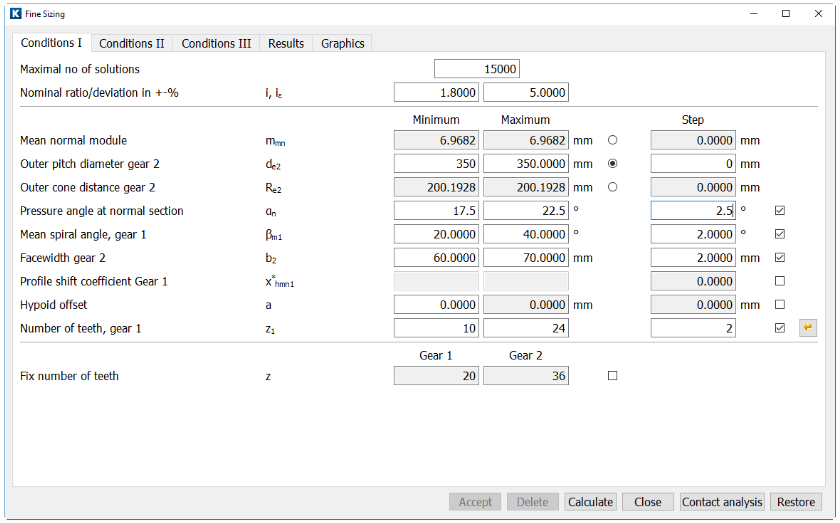
- number of teeth from 10 to 24
- spiral angle from 20º to 40º
- pressure angle from 17.5º to 22.5º

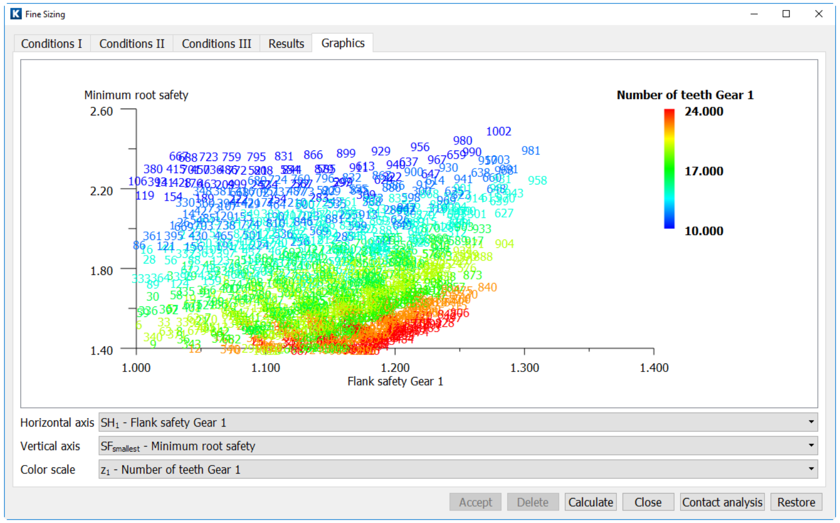
Within shortest time, more than 15’000 solutions are calculated. By manual or automatic mode, solutions are filtered.

500 suitable solutions for further evaluation:

- strength safeties
- forces
- efficiency
- contact ratio, etc.

As a best design, we find a gear pair with 20:36 teeth and a spiral angle of 32º





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Enter the design in GEMS® and check the blanks, slot width and the basic blade design.

The root radii for pinion and ring gear are developed as:

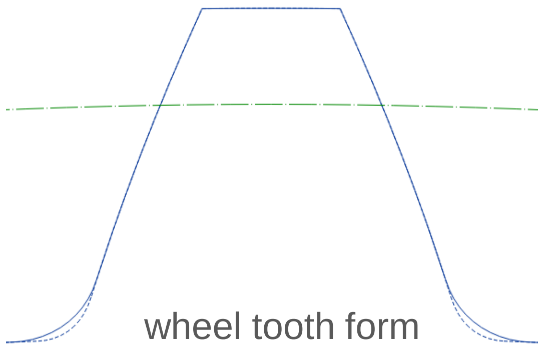
- root radius pinion: 2.3 mm
- root radius ring gear: 3.2 mm

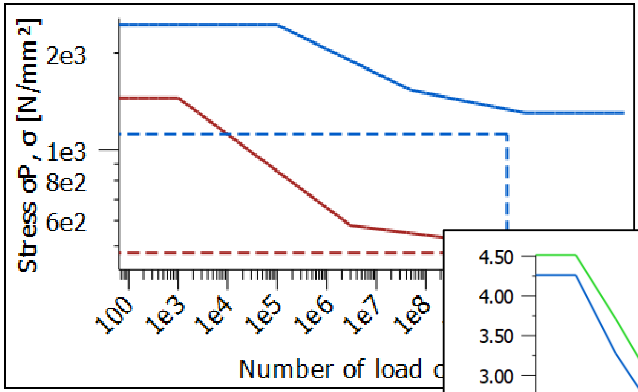
The cutter head size of 16" is confirmed.

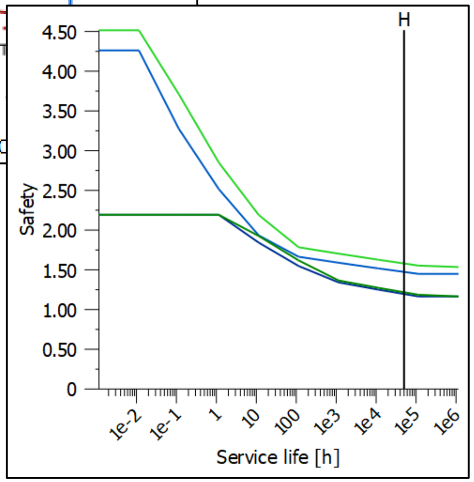
Final rating with ISO standard in KISSsoft:

- root safety: 1.55 resp 1.58
- flank safety: 1.19 resp. 1.22

Additional evaluation and documentation for safety factor curve, S-N curve, load spectra, damages, etc. are available in KISSsoft.







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A practical sample – displacements calculation and Contact analysis

In KISSsys, the displacement values are determined.

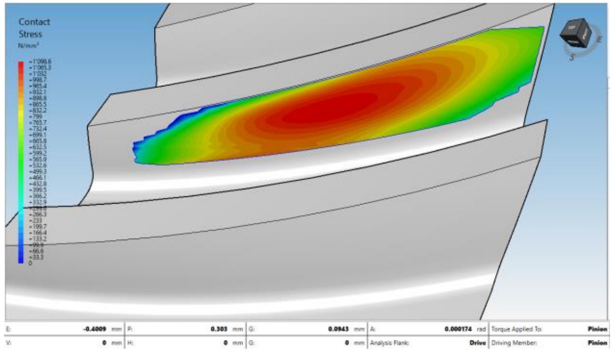
Settings:
- temperature shafts: 60º C
- cast iron casing temperature: 90º C
- roller bearings with stiffness
- no casing (not available)

Micro geometry development in GEMS® :
- no edge contact for several load stages
- sensitivity values EP for no load
- the effective face width matches good with 92%

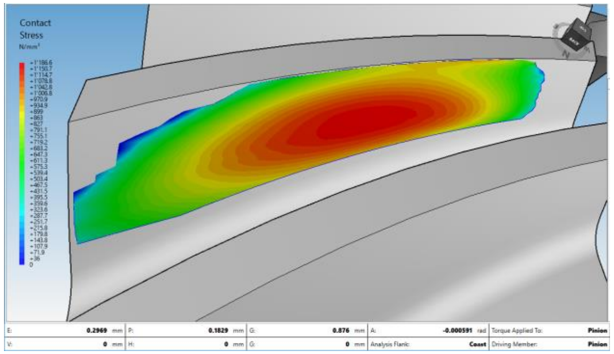
The results are transferred from GEMS® to KISSsys to rate e.g. the transmission error of the bevel gear stage.

Name	E_mm	P_mm	G_mm	S_deg
Drive	-0.40086	0.30304	0.094317	0.0099775
Coast	0.2969	0.18286	0.87601	-0.033887

Displacements in KISSsys



LTCA drive side in GEMS®



LTCA coast side in GEMS®

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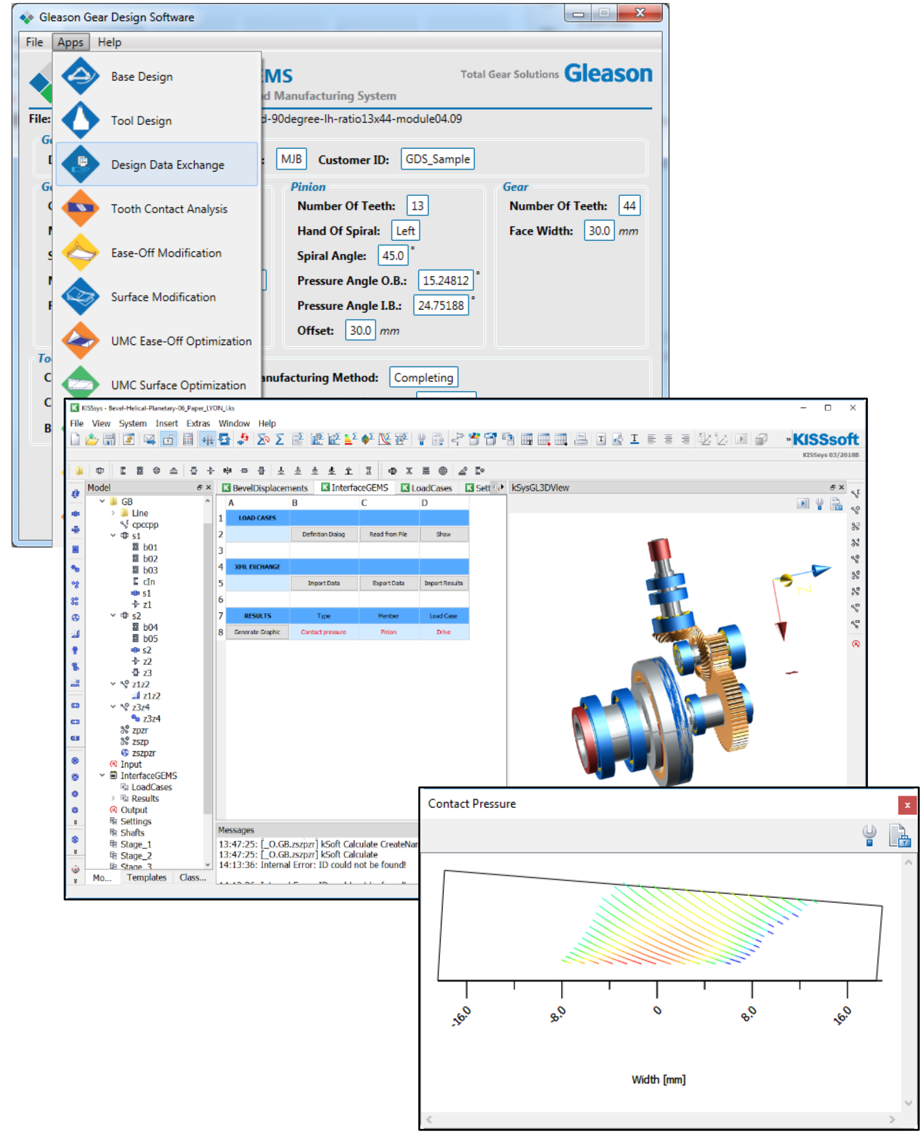
Connection of design and manufacturing process

During the design process, the engineer several times changes between the design and the manufacturing software.

Developed by KISSsoft and Gleason, the data are transferred by an XML file between KISSsys to GEMS®:

- initial geometry data from KISSsys to GEMS®
- the loads and displacement values
- results from GEMS® to KISSsys



Conclusion

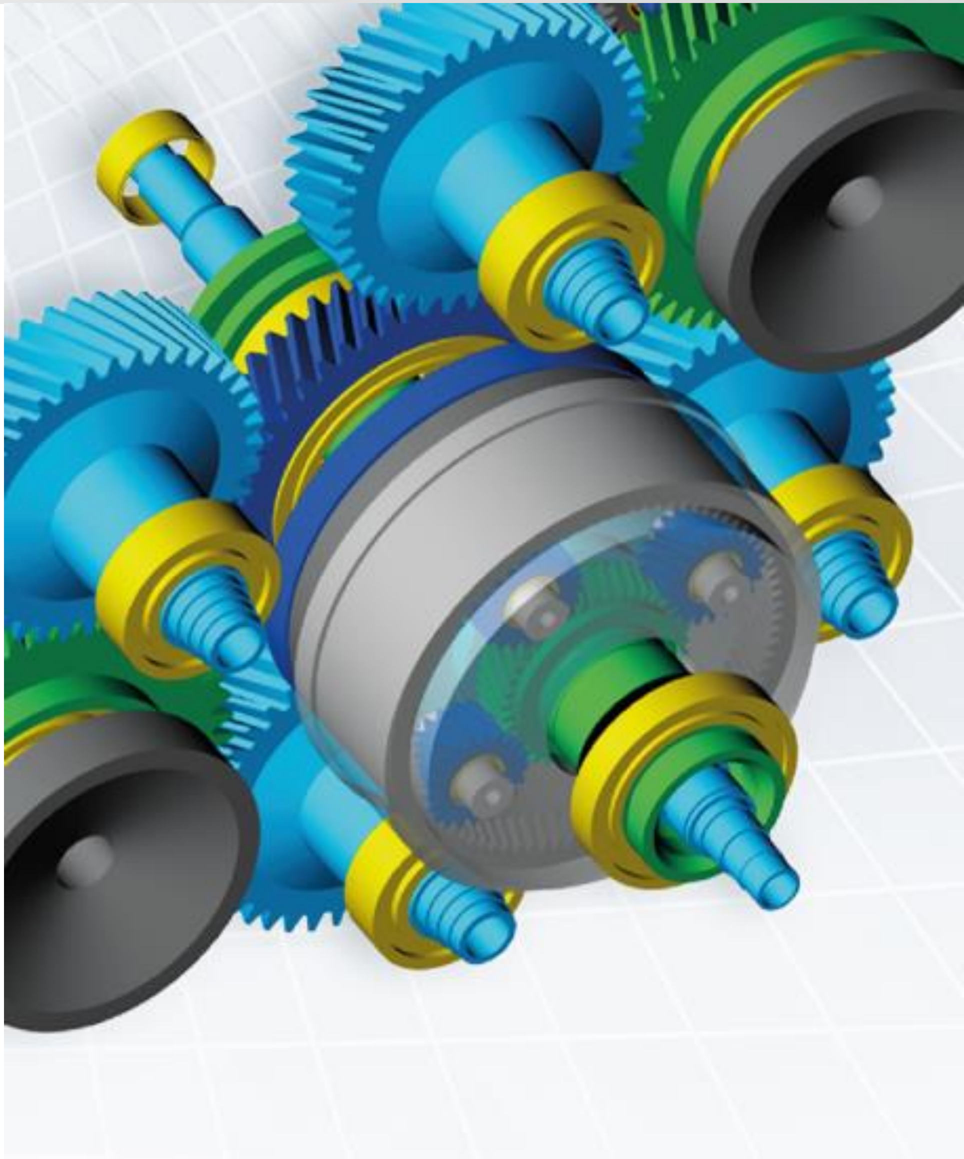
For the design and optimization of bevel gears, design and manufacturing calculations are performed at the same time.

The strength rating according to ISO 10300 in KISSsoft provides a good basis for the rating for several failure modes. The optimization of the macro geometry by the variant calculation is very fast and gives a good overview on available solutions.

The feasibility of the bevel gears is done already early in the design phase. For contact analysis, the displacements of pinion and ring gear under load are calculated in the design software and applied in the loaded contact analysis.

To achieve a most efficient and stable process in the overall design, an interface between the design and manufacturing software is developed. This allows the fast and safe data transfer between KISSsys and GEMS®.

Thank you for your attention!



Sharing knowledge

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