ISSUE
FOCUS

GEAR DESIGN / GEAR INSPECTION

INTEGRATED OPTIMIZATION OF GEAR DESIGN AND MANUFACTURING

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The integration, optimization, design, and manufacturing of gears using state-of-the-art software allows cutting tools to be harmonized.

By MASSIMILIANO TURCI

The word "optimization" is becoming fashionable, also with regard to gear design. It is applied to both macro-geometry and micro-geometry. The approach can be of various types: analytical pre-optimization with different objectives, bulk generation of variants, multi-objective and multi-disciplinary commercial optimizers, generative optimization, and even artificial intelligence. Sometimes, the best solution is presented directly; other times, the choice is left to the user according to multiple criteria. However, these are all scenarios that assume the manufacturer will accept any geometry indicated by the designer. This is certainly not the case with the industrial gearboxes on catalog for which standard cutting tools are used to reduce cost and keep available the interchange of suppliers, nor with special gearboxes, "goods to order," in which the producers try to use cutting tools already in the tool room. Even in the automotive industry, manufacturers try to use existing cutting tools as much as possible, at least during prototyping and for small batches.

After presenting some design optimization techniques adopted in different companies, the focus of the article shifts to some business scenarios where manufacturing has been equipped with a software for a semi-automatic selection of hobbing- and pinion-type tools starting from the macro-geometry of the gear. In particular, it will look at the case where a paper database of more than 10,000 hobs, with different dimensioning modes, has requested to be harmonized into a single computer database. The software allows the search for a hob even with "modified rolling," a method very widespread in the automotive industry, practically "unknown" for industrial gearboxes.

Finally, for companies that have both design and manufacturing departments, a design optimization with a list of cutting tools as a main boundary will be presented.

1 INTRODUCTION

The key issues of this article are design and manufacturing. So, our starting point will be the opening words of two classic university books focusing on these issues:

Number	Title
ISO 6336-1:2019	Calculation of load capacity of spur and helical gears – Part 1: Basic principles, introduction and general influence factors
ISO 6336-2:2019	Calculation of load capacity of spur and helical gears – Part 2: Calculation of surface durability (pitting)
ISO 6336-3:2019	Calculation of load capacity of spur and helical gears – Part 3: Calculation of tooth bending strength
ISO/TS 6336-4:2019	Calculation of load capacity of spur and helical gears – Part 4: Calculation of tooth flank fracture load capacity
ISO 6336-5:2016	Calculation of load capacity of spur and helical gears – Part 5: Strength and quality of materials
ISO 6336-6:2019	Calculation of load capacity of spur and helical gears – Part 6: Calculation of service life under variable load
ISO/TS 6336-20:2017	Calculation of load capacity of spur and helical gears – Part 20: Calculation of scuffing load capacity (also applicable to bevel and hypoid gears) – Flash temperature method
ISO/TS 6336-21:2017	Calculation of load capacity of spur and helical gears – Part 21: Calculation of scuffing load capacity (also applicable to bevel and hypoid gears) – Integral temperature method
ISO/TS 6336-22:2018	Calculation of load capacity of spur and helical gears – Part 22: Calculation of micropitting load capacity
ISO/TR 6336-31:2018	Calculation of load capacity of spur and helical gears – Part 31: Calculation examples of micropitting load capacity
ISO/TR 6336-30:2017	Calculation of load capacity of spur and helical gears – Part 30: Calculation examples for the application of ISO 6336 parts 1,2,3,5

Table 1: ISO standards, technical specifications, and technical reports for cylindrical gear design.

Number	Title
ANSI/AGMA 2001-D04	Fundamental Rating Factors and Calculation Methods for Involute Spur and Helical Gear Teeth
ANSI/AGMA 2101-D04	Fundamental Rating Factors and Calculation Methods for Involute Spur and Helical Gear Teeth (Metric Edition)
ANSI/AGMA 6014-B15	Gear Power Rating for Cylindrical Shell and Trunnion Supported Equipment
ANSI/AGMA 6015-A13	Power Rating of Single and Double Helical Gearing for Rolling Mill Service
ANSI/AGMA 6032-B13	Standard for Marine Gear Units: Rating and Application for Spur and Helical Gear Teeth
ANSI/AGMA 6035-A02	Design, Rating and Application of Industrial Globoidal Wormgearing
ANSI/AGMA 6114-B15	Gear Power Rating for Cylindrical Shell and Trunnion Supported Equipment (Metric Edition)
ANSI/AGMA 6115-A13	Power Rating of Single and Double Helical Gearing for Rolling Mill Service – Metric Edition
ANSI/AGMA 6132-B13	Standard for Marine Gear Units: Rating and Application for Spur and Helical Gear Teeth (Metric Edition)
ANSI/AGMA 6135-A02	Design, Rating and Application of Industrial Globoidal Wormgearing (Metric Edition)
AGMA 932-A05	Rating the Pitting Resistance and Bending Strength of Hypoid Gears

Table 2: AGMA standards for cylindrical gear design.

◗ "The main task of engineers is to apply their scientific and engineering knowledge to the solution of technical problems, and then to optimize those solutions within the requirements and constraints set by material, technological, economic, legal, environmental and human-related considerations." [1]

◗ "Machine tools are used for the purpose of manufacturing parts, which meet design requirements concerning shape, size tolerance, and surface characteristics from both a technical and economic viewpoint." [2]

It is clear how the three requisites — material, technological, and economic — listed in the work focusing on design are linked to manufacturing, and, reciprocally, manufacturing refers to design requirements.

The need for increasing integration of these two phases is also pursued by CAD/CAM system developers to the extent that books such as "Integrated Design-to-Manufacturing Solutions: Lower Costs and Improve Quality" [3] are distributed online by these types of companies.

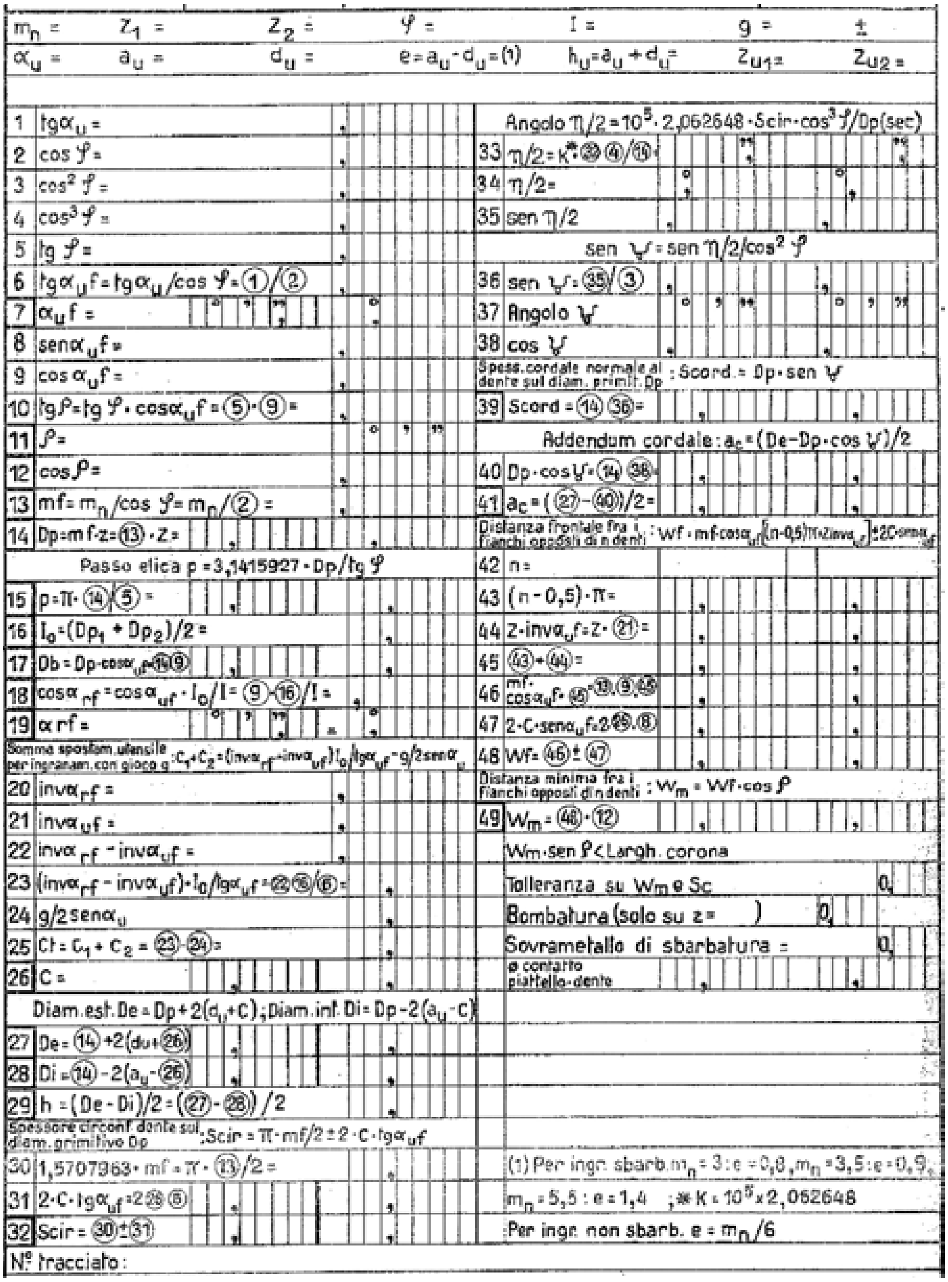
Moreover, the term "optimization" is becoming increasingly popular, especially in papers presented at various conferences, such as AGMA's Fall Technical Meeting.

So, firstly, we have to focus individually on the four terms found in the title of this article (integration, optimization, design, and manufacturing), clearly restricting ourselves to the field of gears. We will look at them in "chronological" order:

◗ Firstly design, because man is above all homo sapiens, a thinker, able to plan and project.

◗ Followed by manufacturing, in other words, the ability to construct, which is a hallmark of homo faber, a Latin expression that became popular once more during the Renaissance.

◗ Lastly, optimization and integration,



$m_n =$ $Z_1 =$ $Z_2 =$ $\varphi =$ $I =$ $g =$ $\pm$

$\alpha_u =$ $a_u =$ $d_u =$ $e = a_u - d_u =$ (1) $h_u = a_u + d_u =$ $Z_{u1} =$ $Z_{u2} =$

1 $tg\alpha_u =$

2 $\cos\varphi =$

3 $\cos^2\varphi =$

4 $\cos^3\varphi =$

5 $tg\,\varphi =$

6 $tg\alpha_u f = tg\alpha_u/\cos\varphi =$ ①/②

7 $\alpha_u f =$

8 $sen\alpha_u f =$

9 $\cos\alpha_u f =$

10 $tg\rho = tg\varphi \cdot \cos\alpha_u f =$ ⑤·⑨ =

11 $\rho =$

12 $\cos\rho =$

13 $mf = m_n/\cos\varphi = m_n/$② =

14 $Dp = mf \cdot z =$ ⑬ $\cdot Z =$

Passo elica $p = 3{,}1415927 \cdot Dp/tg\,\varphi$

15 $p = \pi \cdot$ ⑭/⑤ =

16 $I_0 = (Dp_1 + Dp_2)/2 =$

17 $Db = Dp \cdot \cos\alpha_u f =$ ⑭·⑨

18 $\cos\alpha_{rf} = \cos\alpha_{uf} \cdot I_0/I =$ ⑨·⑯/I =

19 $\alpha rf =$

Somma spostam. utensile per ingranam. con gioco g: $C_1 + C_2 = (inv\alpha_{rf} - inv\alpha_{uf}) I_0/tg\alpha_{uf} - g/2 sen\alpha_u$

20 $inv\alpha_{rf} =$

21 $inv\alpha_{uf} =$

22 $inv\alpha_{rf} - inv\alpha_{uf} =$

23 $(inv\alpha_{rf} - inv\alpha_{uf}) \cdot I_0/tg\alpha_{uf} =$ ㉒·⑯/⑥ =

24 $g/2\,sen\alpha_u$

25 $Ct = C_1 + C_2 =$ ㉓·㉔ =

26 $C =$

Diam. est. $De = Dp + 2(d_u + C)$; Diam. inf. $Di = Dp - 2(a_u - C)$

27 $De =$ ⑭ $+ 2(du +$ ㉖$)$

28 $Di =$ ⑭ $- 2(a_u -$ ㉖$)$

29 $h = (De - Di)/2 =$ (㉗ − ㉘) /2

Spessore circonf. dente sul diam. primitivo Dp: $Scir = \pi \cdot mf/2 \pm 2 \cdot C \cdot tg\alpha_{uf}$

30 $1{,}5707963 \cdot mf = \pi \cdot$ ⑬/2 =

31 $2 \cdot C \cdot tg\alpha_{uf} = 2$ ㉖ ⑤

32 $Scir =$ ㉚ ± ㉛

Angolo $\eta/2 = 10^5 \cdot 2{,}062648 \cdot Scir \cdot \cos^3\varphi/Dp$ (sec)

33 $\eta/2 = K^* \cdot$ ㉜ ④/⑭

34 $\eta/2 =$

35 $sen\,\eta/2$

$sen\,\psi = sen\,\eta/2/\cos^2\varphi$

36 $sen\,\psi =$ ㉟/③

37 Angolo ψ

38 $\cos\psi$

Spess. cordale normale al dente sul diam. primit. Dp: $Scord. = Dp \cdot sen\,\psi$

39 $Scord =$ ⑭ ㊱ =

Addendum cordale: $a_c = (De - Dp \cdot \cos\psi)/2$

40 $Dp \cdot \cos\psi =$ ⑭ ㊳

41 $a_c =$ (㉗ − ㊵)/2 =

Distanza frontale fra i franchi opposti di n denti: $Wf = mf \cdot \cos\alpha_{uf}[(n - 0{,}5)\pi + z\,inv\alpha_{uf}] \pm 2C \cdot sen\alpha_{uf}$

42 $n =$

43 $(n - 0{,}5) \cdot \pi =$

44 $z \cdot inv\alpha_u f = z \cdot$ ㉑ =

45 ㊸ + ㊹ =

46 $mf \cdot \cos\alpha_u f \cdot$ ㊺ = ⑬·⑨·㊺

47 $2 \cdot C \cdot sen\alpha_u f = 2$ ㉖·⑧

48 $Wf =$ ㊻ ± ㊼

Distanza minima fra i fianchi opposti di n denti: $W_m = Wf \cdot \cos\rho$

49 $W_m =$ ㊽·⑫

$W_m \cdot sen\,\rho <$ Largh. corona

Tolleranza su W_m e Sc 0,

Bombatura (solo su z =) 0,

Sovrametallo di sbarbatura = 0,

ø contatto piattello-dente

(1) Per ingr. sbarb. $m_n = 3 : e = 0{,}8$, $m_n = 3{,}5 : e = 0{,}9$;

$m_n = 5{,}5 : e = 1{,}4$; * $K = 10^5 \times 2{,}062648$

Per ingr. non sbarb. $e = m_n/6$

N° tracciato:

Figure 1: "Historical" manual calculation sheet.

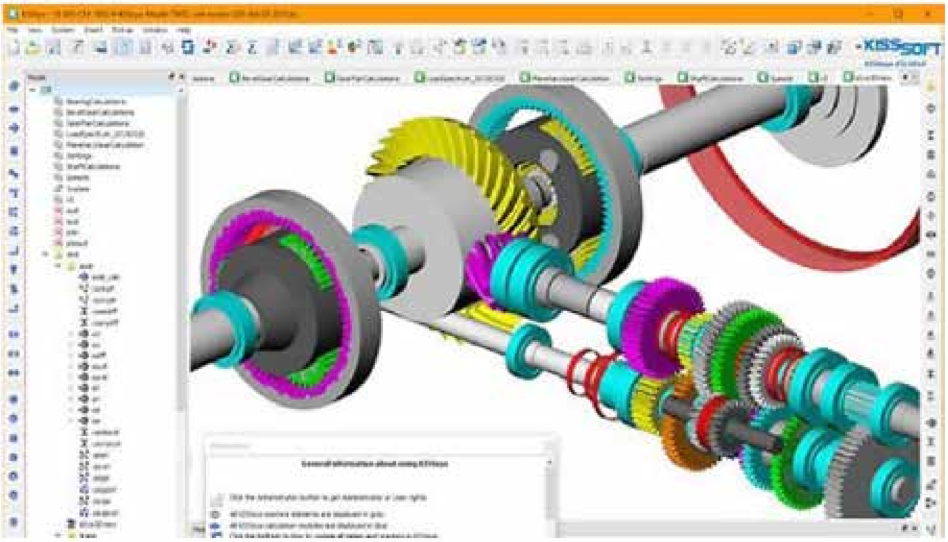
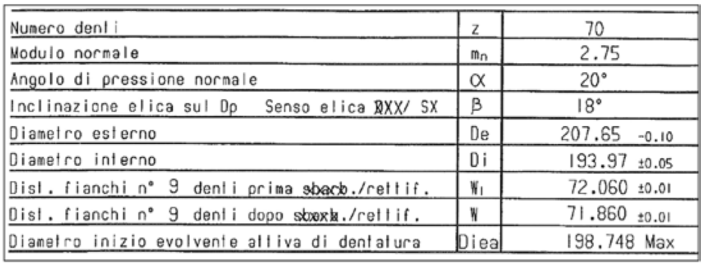


Figure 2: Example of modern software for gear calculation.



Numero denti	z	70
Modulo normale	m_n	2.75
Angolo di pressione normale	α	20°
Inclinazione elica sul Dp Senso elica ~~DX~~X/ SX	β	18°
Diametro esterno	De	207.65 -0.10
Diametro interno	Di	193.97 ±0.05
Dist. fianchi n° 9 denti prima ~~sbarb~~./rettif.	W_1	72.060 ±0.01
Dist. fianchi n° 9 denti dopo ~~sbarb~~./rettif.	W	71.860 ±0.01
Diametro inizio evolvente attiva di dentatura	Diea	198.748 Max

Figure 3: Gear data in the drawing.

which are new words.

We will limit ourselves to cylindrical gears, which are the most common. We will put to one side wormgears, which I have already covered in other publications [4] [5], and bevel gears, which are highly branded [6].

2 DESIGN

Generally speaking, gear design is lifetime-based: The aim is to transmit a specific load for a set period of time. The ways in which tooth failure occurs are taken into account in order to satisfy this requisite.

Recent updating of document numbers ISO 6336 allows for an easy overview of the main ones (bending, pitting, micropitting, scuffing, TFF) and stresses the importance of focus on the type of failure in order to achieve correct sizing.

The terms used in the title of the standards (Table 1 and Table 2) play on the nuances that can be given to design goals: calculation or rating, strength, load capacity, durability, resistance.

From a historical viewpoint, the geometrical principles of toothing were established first of all, especially involute toothing, and then rating criteria, above all for bending and surface fatigue [7, 8]. The formulas contained in the various standards and bibliographical references were then implemented in manual calculation sheets (Figure 1) and subsequently in electronic spreadsheets and software (Figure 2) to simplify the work of designers.

One of the first areas of focus in all publications dating from the

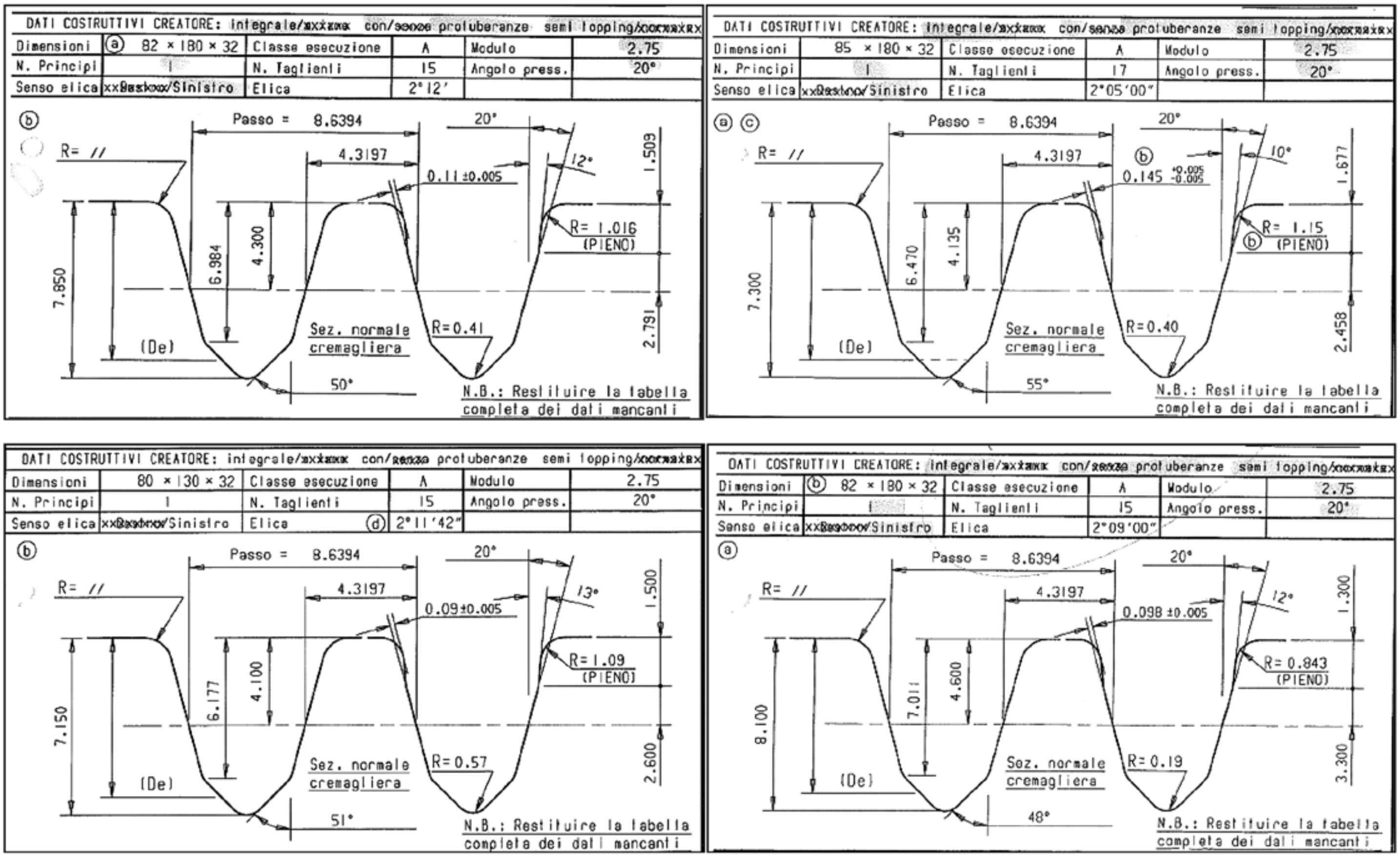


Figure 4: Different hobs with the same module and pressure angle of gear in the previous figure.

last century was the definition of the proportions to be given to gears following the rules cited at the beginning of this article, in other words “within the requirements and constraints set by material, technological, economic considerations.” Here are just a few examples:

- Dudley, in his book unmistakably titled “Practical Gear Design,” later re-titled “Handbook of Practical Gear Design” [9].
- Niemann [10] with his formulas to split the transmission ratios of a parallel-axis reducer so as to minimize the costs of gear materials and housing (a concept further developed by Schlecht [11] at a later date).
- Severin [12] with his translation of the Russian work titled “Increasing the load on gearing and decreasing its weight.”

From a standardization viewpoint, the ISO documents listed in Table 1 provide methods to verify gears whose geometry is known. In some of the AGMA documents listed in Table 2, design suggestions depending on the application are also provided. There are no universal criteria. While in the automotive field small b/d ratios are common, in rolling plants, b/d ratios are often greater than 1.

3 MANUFACTURING

We will limit ourselves to looking at metal cylindrical gears, cut mostly using hobs, pinion-type cutters or power skiving, with possible grinding for finishing, to correct distortion error caused by any thermal or surface treatments or to define micro-geometric modifications [13].

For obvious reasons of space, we will put to one side gears boasting a “free” geometry: plastic, sintered, obtained by additive manufacturing, 5-axis milling, or form cutting.

Therefore, the main job of the person who receives the gear drawing, such as the one in Figure 3, is to define the dimensions of the most suitable tool, in this case a hob, trying not to buy a new one, but to choose from those already available (Figure 4).

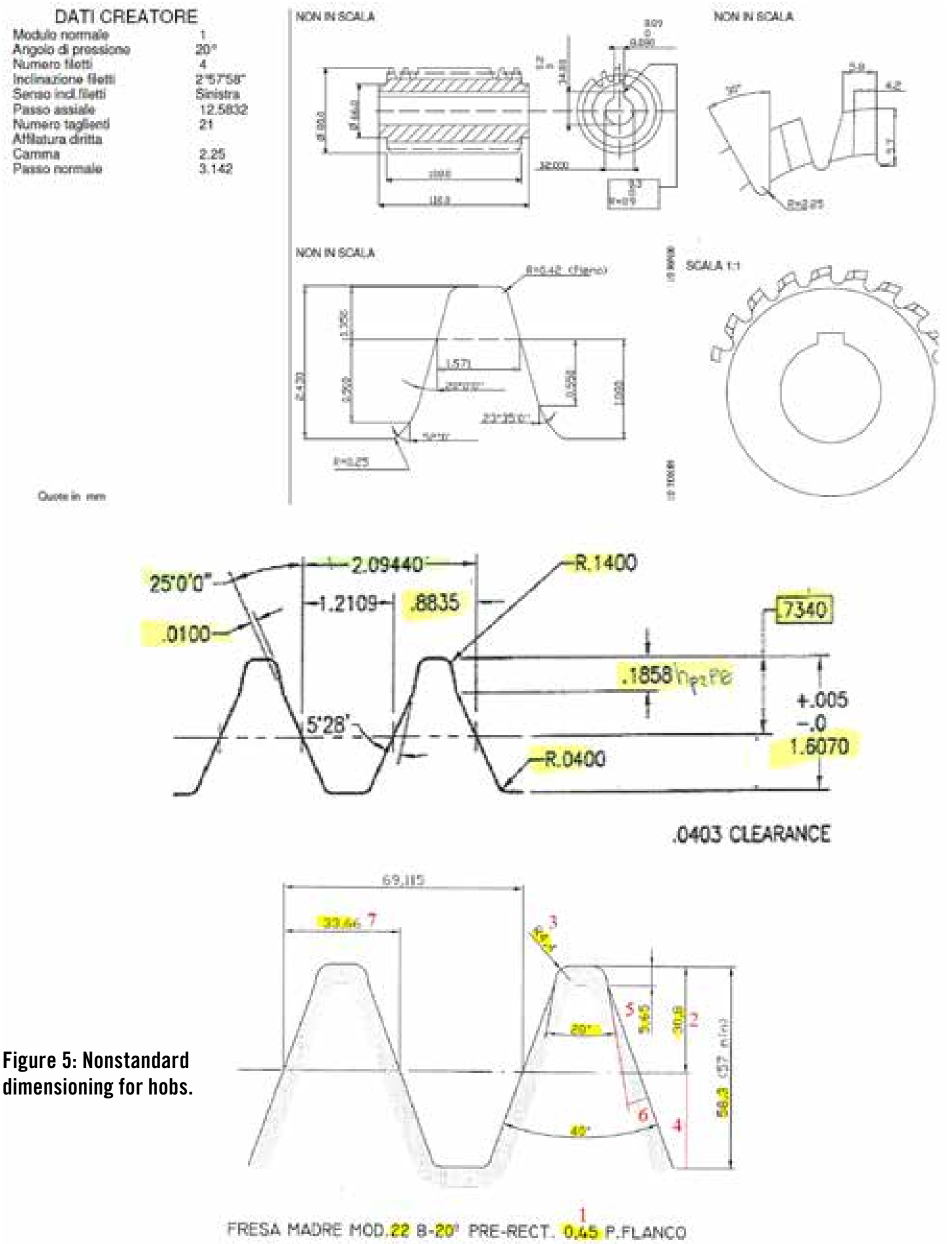


Figure 5: Nonstandard dimensioning for hobs.

Let us now try to describe some atypical situations that can occur in the hob’s dimensioning that may result in a difficult interpretation of the geometry for the reader of the drawing in Figure 5, which is often not even to scale. There is no standard that regulates a single method of dimensioning for these tools.

When there is protuberance:

- Only two out of its three dimensions are independent.
- If the wording “full-radius” is included for the hob’s tip radius, an iterative calculation is needed to calculate the value of the root radius.
- The reference line, in relation to which the other dimensions such as addendum and dedendum are provided, may not be the line that divides the space thickness the same as the tooth thickness as, instead, assumed by some calculation software.
- Semi-topping can have a double inclination or radius not dimensioned in the change of the pressure angle.

As for design, the focus in this case is also on aim and criteria. The aim is the one cited in the introduction “to manufacture parts that meet design requirements concerning shape, size tolerance, and surface characteristics from both a technical and economic viewpoint.”

The choice of hob, which allows for the required shape to be obtained, can be made by entering the data of the required geometry and the data of the hob (uniquely established, as we said) into specific calculation software (Figure 6) and superposing the calculated geometry with the one produced via enveloping (Figure 7). For example, in the case of the use of a pre-grinding tool with no protuberance, it is easy to note the grinding notch. The grinding notch is accepted for small-size industrial gearboxes, clearly not in the case of automotive or aerospace gears.

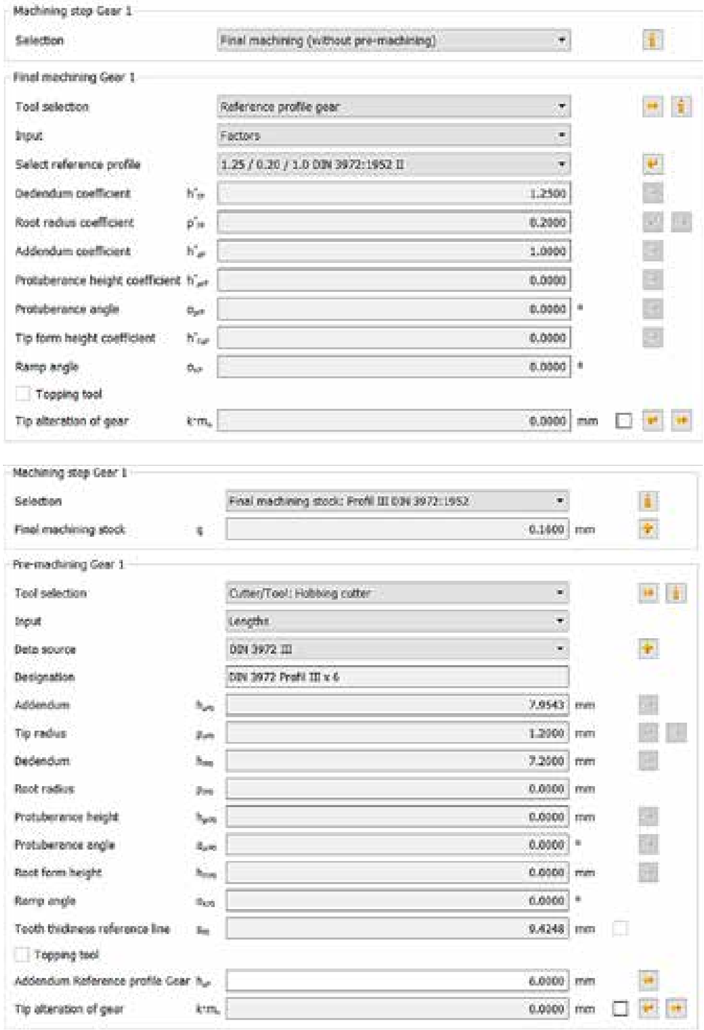
Once the technical aim has been achieved, there is not a single criterion for the most economic choice. For example, it could be attempted to obtain the maximum efficiency from the hob *K* [14]

$$K = \frac{p \cdot z \cdot l \cdot t_{m}}{1000 \cdot i_{m} \cdot \cos\beta \cdot b_{1}}$$

Equation 1

where

K is the efficiency of the hob; in m/tooth.



Machining step Gear 1			
Selection		Final machining (without pre-machining)	
Final machining Gear 1			
Tool selection		Reference profile gear	
Input		Factors	
Select reference profile		1.25 / 0.20 / 1.0 DIN 3972:1952 II	
Dedendum coefficient	h^*_{fP}	1.2500	
Root radius coefficient	ρ^*_{fP}	0.2000	
Addendum coefficient	h^*_{aP}	1.0000	
Protuberance height coefficient	h^*_{prP}	0.0000	
Protuberance angle	α_{prP}	0.0000	°
Tip form height coefficient	h^*_{FaP}	0.0000	
Ramp angle	α_{KP}	0.0000	°
☐ Topping tool			
Tip alteration of gear	$k \cdot m_n$	0.0000	mm ☐
Machining step Gear 1			
Selection		Final machining stock: Profil III DIN 3972:1952	
Final machining stock	q	0.1600	mm
Pre-machining Gear 1			
Tool selection		Cutter/Tool: Hobbing cutter	
Input		Lengths	
Data source		DIN 3972 III	
Designation		DIN 3972 Profil III x 6	
Addendum	h_{aP0}	7.9543	mm
Tip radius	ρ_{aP0}	1.2000	mm
Dedendum	h_{fP0}	7.2000	mm
Root radius	ρ_{fP0}	0.0000	mm
Protuberance height	h_{prP0}	0.0000	mm
Protuberance angle	α_{prP0}	0.0000	°
Root form height	h_{FfP0}	0.0000	mm
Ramp angle	α_{KP0}	0.0000	°
Tooth thickness reference line	s_{P0}	9.4248	mm ☐
☐ Topping tool			
Addendum Reference profile Gear	h_{aP}	6.0000	mm
Tip alteration of gear	$k \cdot m_n$	0.0000	mm ☐

Figure 6: Design and manufacturing data.

p is the number of gears (pieces).
z is the number of gear teeth.
l is the face width, mm.
t_{os} is the axial pitch of the hob, mm.
i_{os} is the number of hob gashes or flutes.
β is the helix angle of the gear.
b_1 is the working length of the hob (Figure 8).

The efficiency *K* should be between 4 and 5 m/tooth in order to be assessed as good. Before calculating *K*, the level of wear of the hob to be reached prior to replacement needs to be set and the cost of the tool and grinding taken into account.

Even if more advanced methods have been proposed [15], Hoffmeister's formula can still be used to calculate the chip's maximum thickness given a set progress for each part revolution.

$$h_{1,max} = 4.9 \cdot m_n \cdot z_0^{(9.25 \cdot 10^{-3} \cdot \beta_0 - 0.542)} \cdot e^{-0.015(\beta_0 + x_p)} \cdot \left(\frac{f_a}{m_n}\right)^{0.511} \cdot \left(\frac{d_{a0}}{2 \cdot m_n}\right)^{(-8.25 \cdot 10^{-3} \cdot \beta_0 - 0.225)} \cdot \left(\frac{i_0}{z_0}\right)^{-0.877} \cdot \left(\frac{h}{m_n}\right)^{0.319}$$

Equation 2

where

$h_{1,max}$ is the maximum chip thickness.
m_n is the standard module.
β_0 is the angle of the hob's helix.
x_p is the addendum modification factor.
f_a is the axial feed.
d_{a0} is the hob head's diameter.
i_0 is the number of gaps.

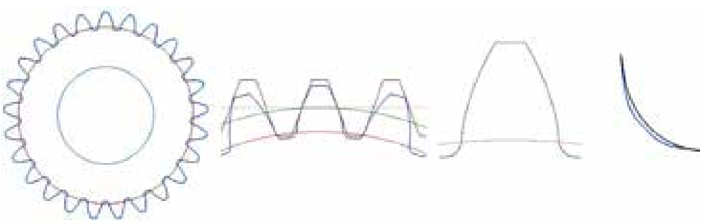


Figure 7: From left to right: Required tooth form, hobbing simulation, comparison between required (black) and ground (blue) tooth form, focus on the grinding notch.

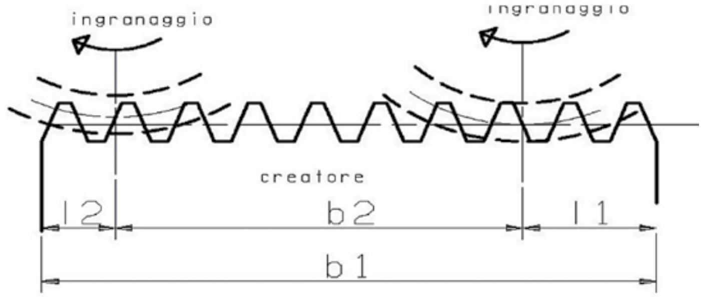


Figure 8: Hob and gear.

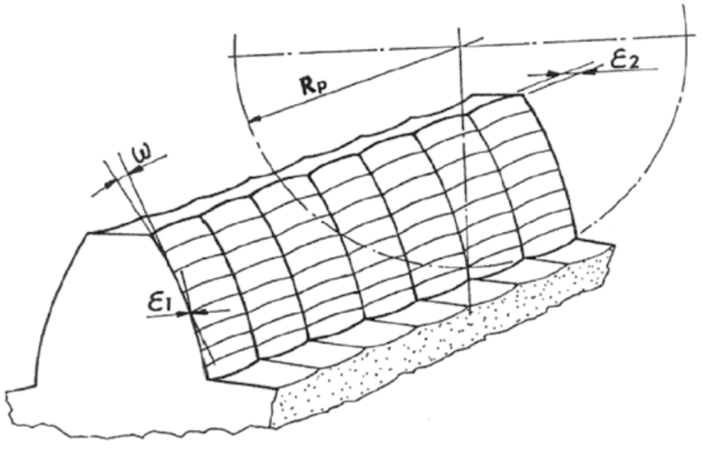


Figure 9: Profile and helix deviations generated by the hob.

z_0 is the number of threads.
h is the cutting depth.

As regards to cutting parameters, it must be remembered that it is possible to estimate profile ε_1 and helix ε_2 deviations caused by the progress value (Figure 9).

$$\varepsilon_1 = R_p \cdot \tan\alpha \cdot (1 - \cos\frac{\eta}{2}) \text{ where } \eta = \frac{360 \cdot z_0}{z \cdot i_0}$$

Equation 3

$$\varepsilon_2 = \frac{f_a^2 \cdot \cos^2\beta_0 \cdot tg\alpha}{8 \cdot R_p}$$

Equation 4

where

ε_1 is the profile deviation.
ε_2 is the helix deviation.
z_0 is the number of hob teeth.
i_0 is the number of hob starts.
z is the number of gear teeth.
R_p is the pitch radius of the hob; mm.
f_a is the progress per part revolution; mm/rev.
β_0 is the angle of the hob's helix.
α is the pressure angle.

Therefore, with the same reference profile of the hob, the choice of hob is determined by:

- Other geometric characteristics of the hob, such as the number of cutters, external diameter, number of principles, helix angle length.

- Cutting parameters, such as cutting speed and progress/tooth, the recommended values for which can be found in the bibliography [14].
- Number of parts to be cut.

All these values can be used in the Equation 2 and 1, in order to check that:

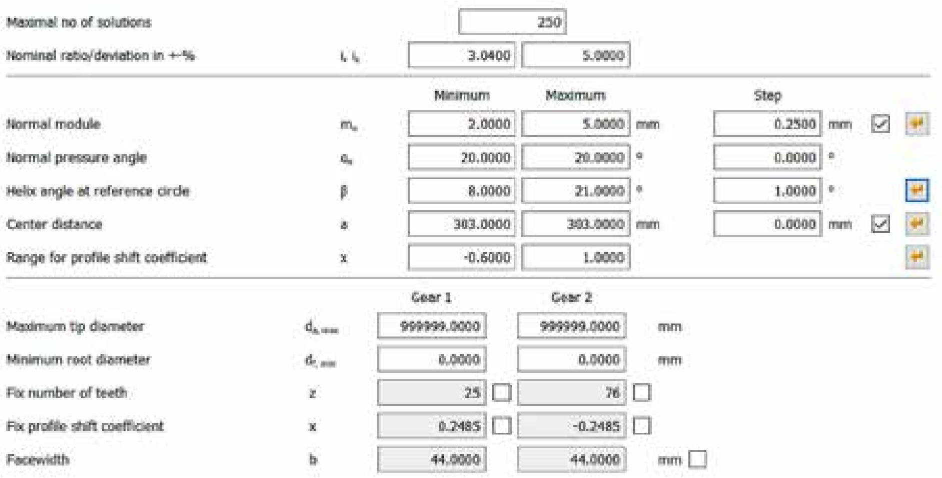
- The chip thickness is not excessive.
- Efficiency falls into the 4-5 m/tooth interval.

But this is not the only criterion for assessing the advantageousness of specific working conditions. For example, the choice of favoring an increase in cutting speed and hence a reduction in cutting time is commonplace, resulting in the waiver of a good level of hob efficiency.

We have tried to present simple formulas with a deep educational value [14]. Some other examples are in [16] and [17]. A more precise approach can be found in [18]. For pinion-type cutter, see [19].

4 OPTIMIZATION

We will focus on the optimization of design and the optimization of manufacturing as separate, independent activities: The former to be adopted in the technical department and the latter in the workshop, even in the case of two different companies, i.e., an engineering company and a subcontractor.



Maximal no of solutions 250

Nominal ratio/deviation in +-% i, i_t 3.0400 5.0000

		Minimum	Maximum		Step			
Normal module	m_n	2.0000	5.0000	mm	0.2500	mm	☑	
Normal pressure angle	α_n	20.0000	20.0000	°	0.0000	°		
Helix angle at reference circle	β	8.0000	21.0000	°	1.0000	°		
Center distance	a	303.0000	303.0000	mm	0.0000	mm	☑	
Range for profile shift coefficient	x	-0.6000	1.0000					

		Gear 1		Gear 2		
Maximum tip diameter	$d_{a,max}$	999999.0000		999999.0000		mm
Minimum root diameter	$d_{f,min}$	0.0000		0.0000		mm
Fix number of teeth	z	25	☐	76	☐	
Fix profile shift coefficient	x	0.2485	☐	-0.2485	☐	
Facewidth	b	44.0000		44.0000		mm ☐

Figure 10: Optimizer interface: goal, variables, and boundary condition for the DOE.

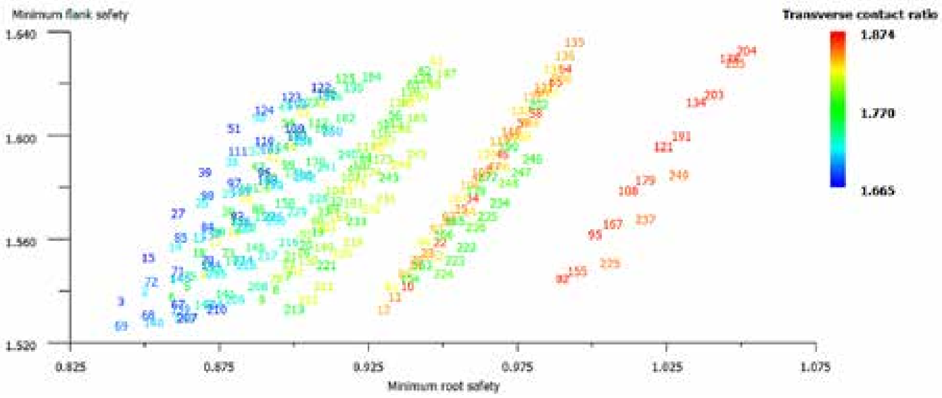
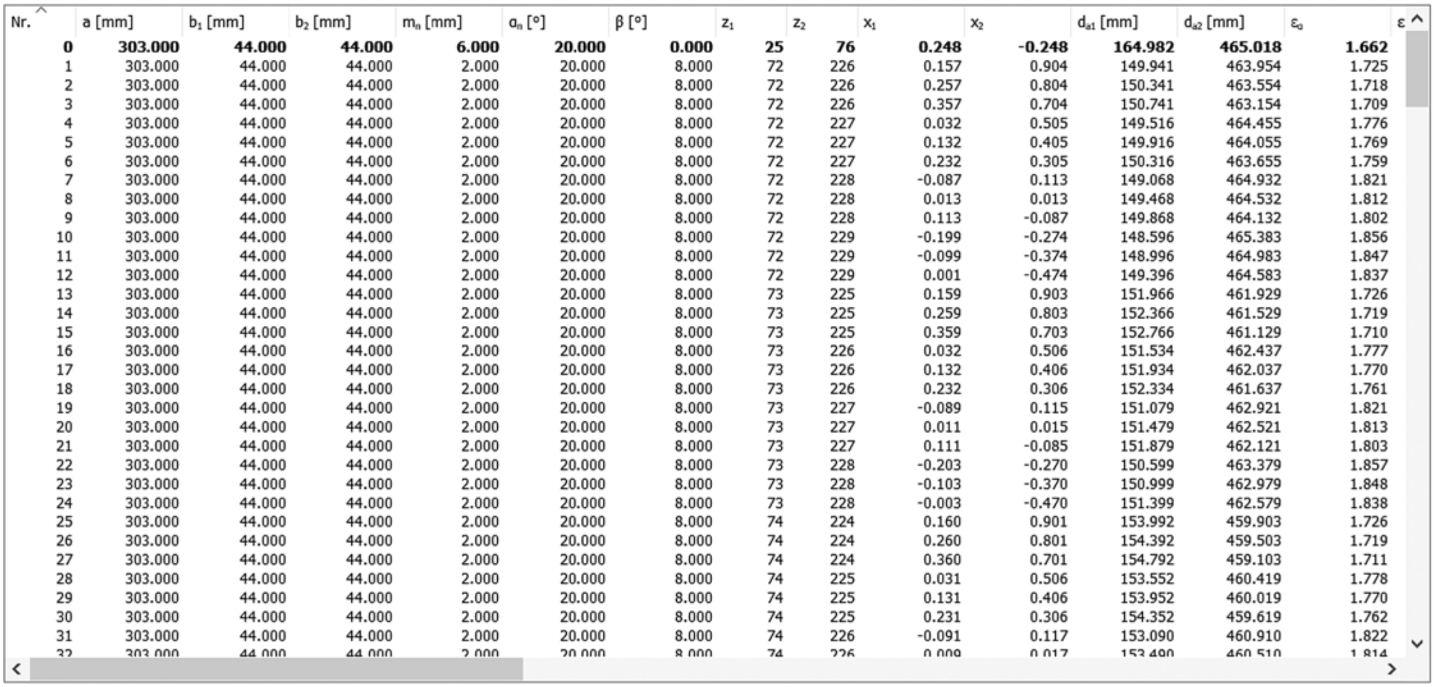


Figure 12: Optimizer interface: graphic with Pareto front.

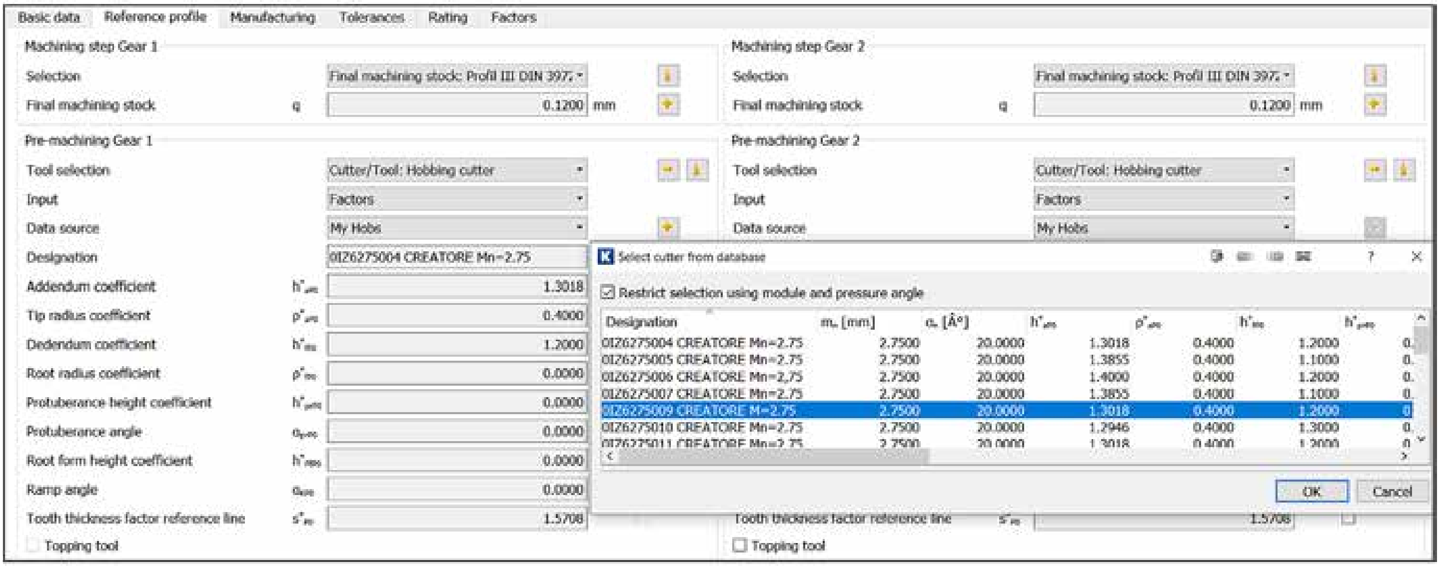
4.1 OPTIMIZATION OF DESIGN

As stated in the introduction, design consists of a choice of variants, while generating and selecting them forms part of the optimization process. Without going into detail, the notion of optimization is based on three concepts: objective/s, constraints, variables. Once these three concepts have been established, a multitude of vari-



Nr.	a [mm]	b_1 [mm]	b_2 [mm]	m_n [mm]	α_n [°]	β [°]	z_1	z_2	x_1	x_2	d_{a1} [mm]	d_{a2} [mm]	ε_α	ε
0	**303.000**	**44.000**	**44.000**	**6.000**	**20.000**	**0.000**	**25**	**76**	**0.248**	**-0.248**	**164.982**	**465.018**	**1.662**	
1	303.000	44.000	44.000	2.000	20.000	8.000	72	226	0.157	0.904	149.941	463.954	1.725	
2	303.000	44.000	44.000	2.000	20.000	8.000	72	226	0.257	0.804	150.341	463.554	1.718	
3	303.000	44.000	44.000	2.000	20.000	8.000	72	226	0.357	0.704	150.741	463.154	1.709	
4	303.000	44.000	44.000	2.000	20.000	8.000	72	227	0.032	0.505	149.516	464.455	1.776	
5	303.000	44.000	44.000	2.000	20.000	8.000	72	227	0.132	0.405	149.916	464.055	1.769	
6	303.000	44.000	44.000	2.000	20.000	8.000	72	227	0.232	0.305	150.316	463.655	1.759	
7	303.000	44.000	44.000	2.000	20.000	8.000	72	228	-0.087	0.113	149.068	464.932	1.821	
8	303.000	44.000	44.000	2.000	20.000	8.000	72	228	0.013	0.013	149.468	464.532	1.812	
9	303.000	44.000	44.000	2.000	20.000	8.000	72	228	0.113	-0.087	149.868	464.132	1.802	
10	303.000	44.000	44.000	2.000	20.000	8.000	72	229	-0.199	-0.274	148.596	465.383	1.856	
11	303.000	44.000	44.000	2.000	20.000	8.000	72	229	-0.099	-0.374	148.996	464.983	1.847	
12	303.000	44.000	44.000	2.000	20.000	8.000	72	229	0.001	-0.474	149.396	464.583	1.837	
13	303.000	44.000	44.000	2.000	20.000	8.000	73	225	0.159	0.903	151.966	461.929	1.726	
14	303.000	44.000	44.000	2.000	20.000	8.000	73	225	0.259	0.803	152.366	461.529	1.719	
15	303.000	44.000	44.000	2.000	20.000	8.000	73	225	0.359	0.703	152.766	461.129	1.710	
16	303.000	44.000	44.000	2.000	20.000	8.000	73	226	0.032	0.506	151.534	462.437	1.777	
17	303.000	44.000	44.000	2.000	20.000	8.000	73	226	0.132	0.406	151.934	462.037	1.770	
18	303.000	44.000	44.000	2.000	20.000	8.000	73	226	0.232	0.306	152.334	461.637	1.761	
19	303.000	44.000	44.000	2.000	20.000	8.000	73	227	-0.089	0.115	151.079	462.921	1.821	
20	303.000	44.000	44.000	2.000	20.000	8.000	73	227	0.011	0.015	151.479	462.521	1.813	
21	303.000	44.000	44.000	2.000	20.000	8.000	73	227	0.111	-0.085	151.879	462.121	1.803	
22	303.000	44.000	44.000	2.000	20.000	8.000	73	228	-0.203	-0.270	150.599	463.379	1.857	
23	303.000	44.000	44.000	2.000	20.000	8.000	73	228	-0.103	-0.370	150.999	462.979	1.848	
24	303.000	44.000	44.000	2.000	20.000	8.000	73	228	-0.003	-0.470	151.399	462.579	1.838	
25	303.000	44.000	44.000	2.000	20.000	8.000	74	224	0.160	0.901	153.992	459.903	1.726	
26	303.000	44.000	44.000	2.000	20.000	8.000	74	224	0.260	0.801	154.392	459.503	1.719	
27	303.000	44.000	44.000	2.000	20.000	8.000	74	224	0.360	0.701	154.792	459.103	1.711	
28	303.000	44.000	44.000	2.000	20.000	8.000	74	225	0.031	0.506	153.552	460.419	1.778	
29	303.000	44.000	44.000	2.000	20.000	8.000	74	225	0.131	0.406	153.952	460.019	1.770	
30	303.000	44.000	44.000	2.000	20.000	8.000	74	225	0.231	0.306	154.352	459.619	1.762	
31	303.000	44.000	44.000	2.000	20.000	8.000	74	226	-0.091	0.117	153.090	460.910	1.822	
32	303.000	44.000	44.000	2.000	20.000	8.000	74	226	0.009	0.017	153.490	460.510	1.814	

Figure 11: Optimizer interface: generated variants (list).



Machining step Gear 1

Selection: Final machining stock: Profil III DIN 3972

Final machining stock q 0.1200 mm

Pre-machining Gear 1

Tool selection: Cutter/Tool: Hobbing cutter

Input: Factors

Data source: My Hobs

Designation: 0IZ6275004 CREATORE Mn=2.75

Addendum coefficient h^*_{aP0} 1.3018

Tip radius coefficient ρ^*_{aP0} 0.4000

Dedendum coefficient h^*_{fP0} 1.2000

Root radius coefficient ρ^*_{fP0} 0.0000

Protuberance height coefficient h^*_{prP0} 0.0000

Protuberance angle α_{prP0} 0.0000

Root form height coefficient h^*_{FaP0} 0.0000

Ramp angle α_{KP0} 0.0000

Tooth thickness factor reference line s^*_{P0} 1.5708

☐ Topping tool

Machining step Gear 2

Selection: Final machining stock: Profil III DIN 3972

Final machining stock q 0.1200 mm

Pre-machining Gear 2

Tool selection: Cutter/Tool: Hobbing cutter

Input: Factors

Data source: My Hobs

Tooth thickness factor reference line s^*_{P0} 1.5708

☐ Topping tool

Select cutter from database

☑ Restrict selection using module and pressure angle

Designation	m_n [mm]	α_n [Å°]	h^*_{aP0}	ρ^*_{aP0}	h^*_{fP0}	h^*_{prP0}
0IZ6275004 CREATORE Mn=2.75	2.7500	20.0000	1.3018	0.4000	1.2000	0.
0IZ6275005 CREATORE Mn=2.75	2.7500	20.0000	1.3855	0.4000	1.1000	0.
0IZ6275006 CREATORE Mn=2,75	2.7500	20.0000	1.4000	0.4000	1.2000	0.
0IZ6275007 CREATORE Mn=2.75	2.7500	20.0000	1.3855	0.4000	1.1000	0.
0IZ6275009 CREATORE M=2.75	2.7500	20.0000	1.3018	0.4000	1.2000	0
0IZ6275010 CREATORE Mn=2.75	2.7500	20.0000	1.2946	0.4000	1.3000	0.
0IZ6275011 CREATORE Mn=2.75	2.7500	20.0000	1.3018	0.4000	1.2000	0

Figure 13: Tool selection from Database in KISSsoft.

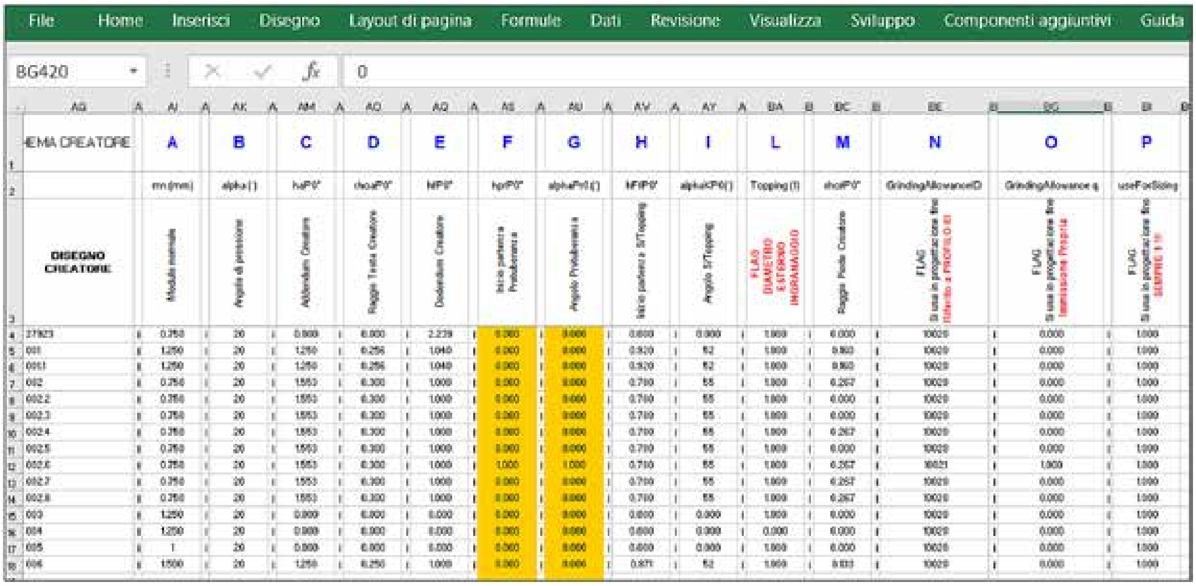
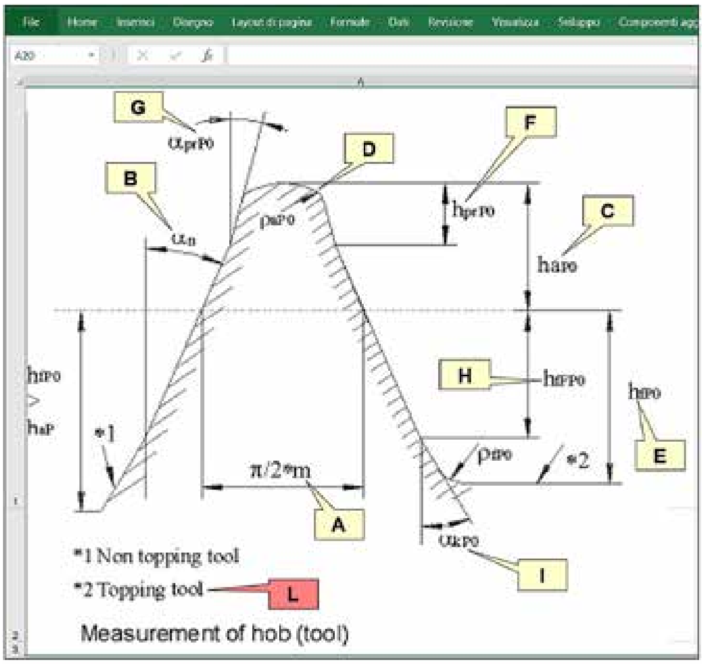


Figure 14: Hobs database in Excel.



ants are generally obtained and the optimal solution chosen among these, based on well- defined criteria.

Let us have a look at some cases of optimization applied solely to gear design:

4.1.1 ANALYTICAL OPTIMIZATION

Some years ago, Schöler [20] presented an evolution, hence an optimization, of the traditional proportioning and pre-dimensioning formulas. The paper refers to beveloid gears, but it offers a clear idea of what has also been done with regard to cylindrical gears.

4.1.2 FAST GENERATION OF VARIANTS

Kissling [21] has shown how quick the generation of macro-geometry variants can be, using software already widely adopted in technical departments (Figure 10). The numerous variants generated (Figure 11) are then selected by the designer with the help of filters and graphs (Figure 12). The choice is up to the designer. The same approach is used to generate micro-geometry variants, as presented in a recent FTM [22].

4.1.3 MULTI-OBJECTIVE COMMERCIAL OPTIMIZERS

Bonfiglioli [23] and Noesis [24] presented the use of a multi-objective

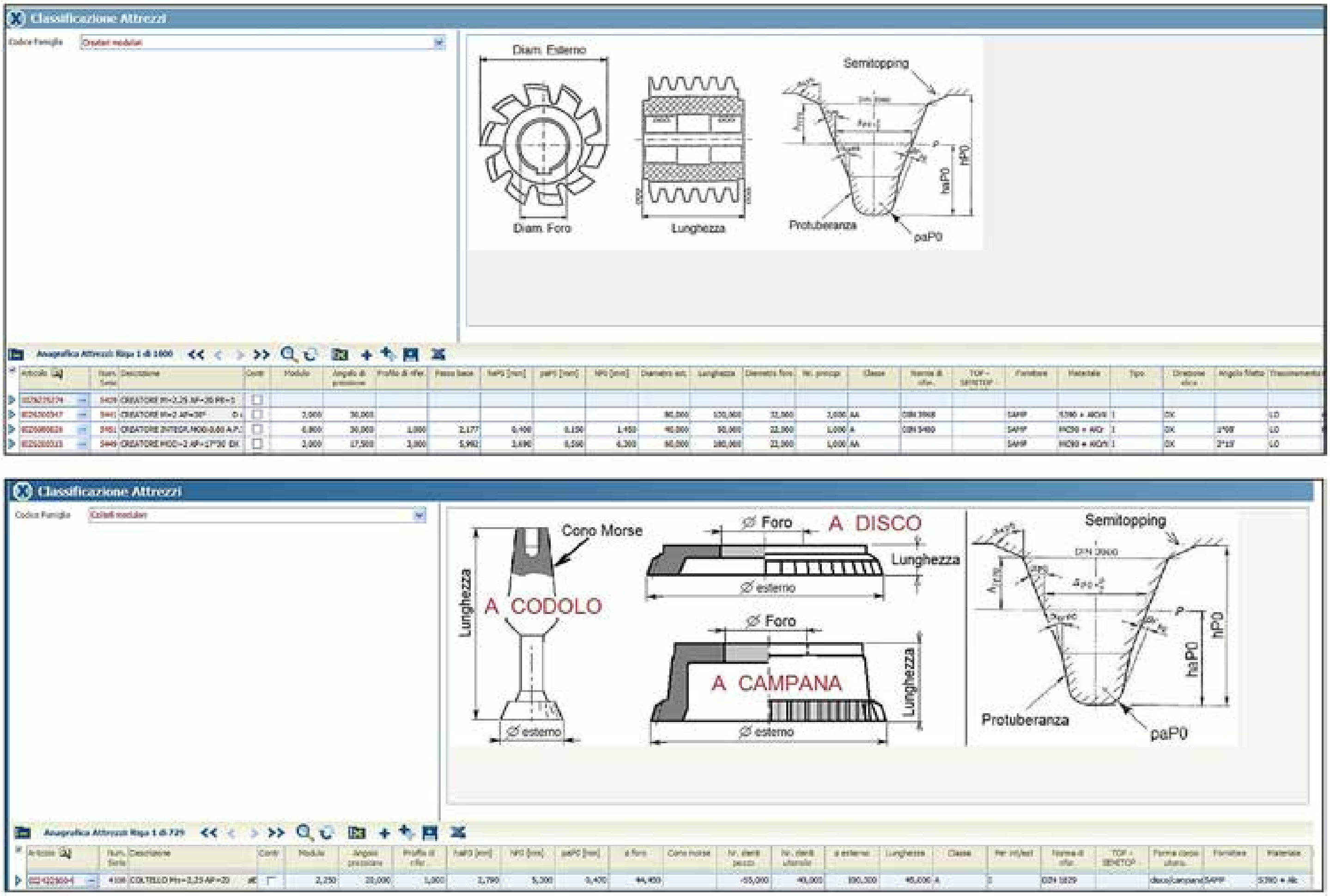


Figure 15: Hobs and pinion-type cutters database in Oracle.

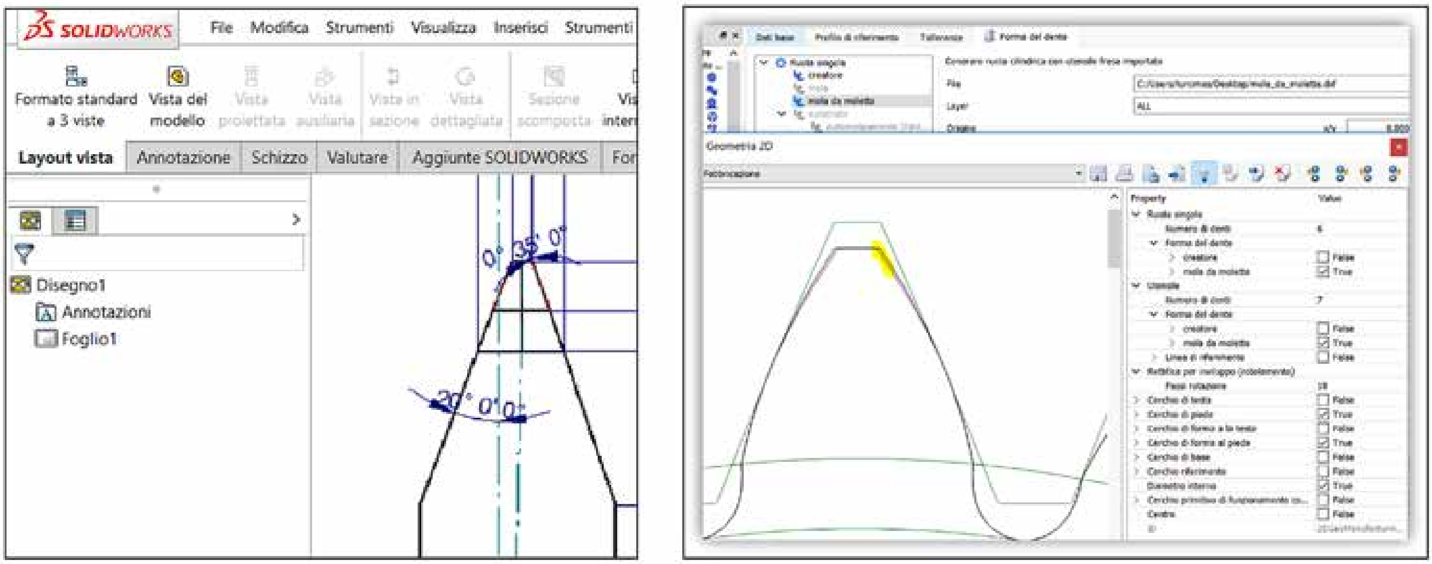


Figure 16: From left to right: CAD drawing of a dresser for gear grinding wheel, comparison between the required geometry of the gear and the ground one.

optimizer interfaced with gear calculation software. ModeFrontier and Optimus took care of the experiment design (DOE) while KISSsoft calculated each individual variant. The variant generation criterion performs better, and reporting is more functional in the face of longer processing times.

4.1.4 OPTIMIZERS FOR SUPERCOMPUTERS

UniMoRe has recently made available to some companies [25] a genetic algorithm optimizer developed by the university [26], which works exclusively on supercomputers.

4.1.5 ARTIFICIAL INTELLIGENCE

Schlecht [27] even decided to make use of artificial intelligence in order to find the optimal flank modification for a pair of cylindrical gears. Compared to all the methods described earlier, a training phase for the AI engine is needed in this case, but advanced contact

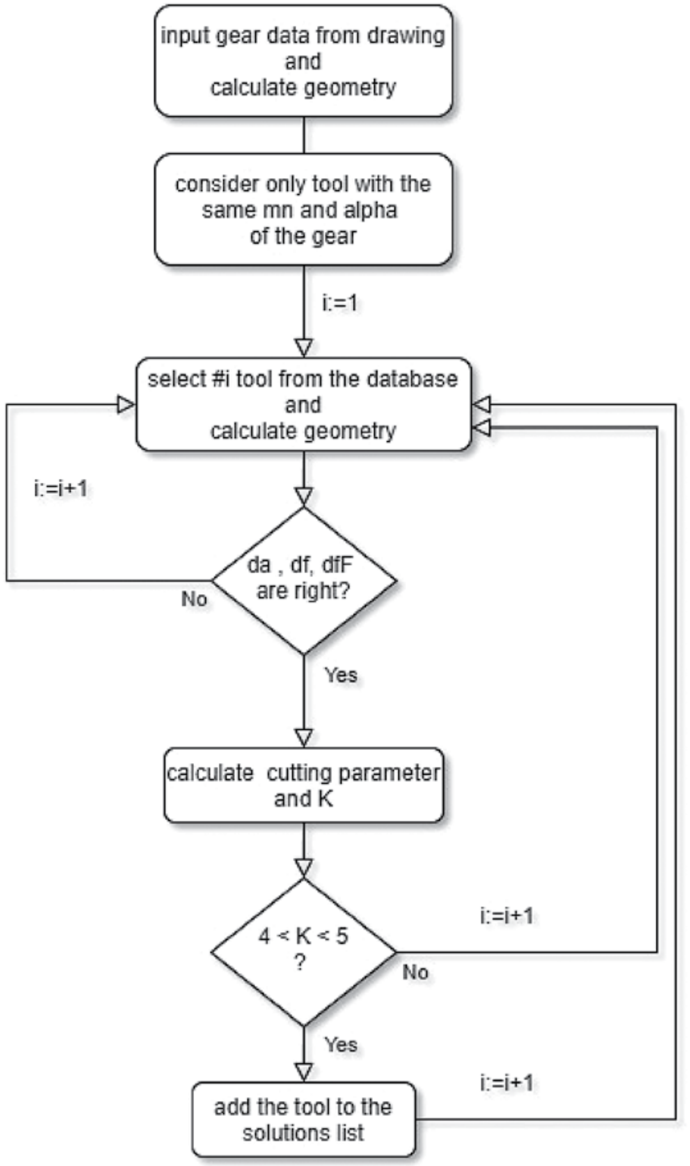


Figure 17: Workflow to generate a list of hobs (variants).

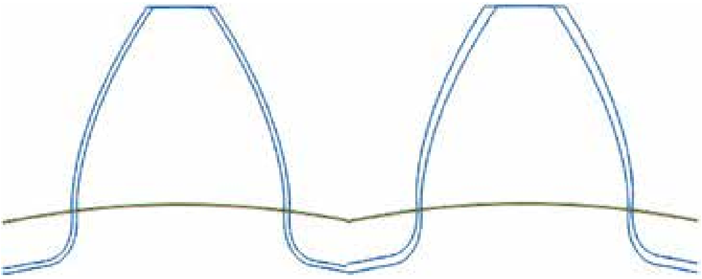


Figure 18: Gear hobbed and ground completely. Hob with same base pitch of the gear (A), hob with different base pitch of the gear (B).

analysis software can be done away with.

4.2 OPTIMIZATION OF MANUFACTURING

The same concepts seen for the optimization of design can be applied to manufacturing.

In this case, too, optimization involves the choice of the best variant, in other words, the choice of the hob that "copies" the geometry of the gear under design at the lowest cost, also taking into account the stock allowance.

As mentioned previously, the aim could be the hob's performance, which falls within the values listed earlier. The constraints concern generation of the desired profile and the maintenance of cutting parameters within the recommended ranges. The only variable is the hob. Software able to perform the calculations listed under point 3 is obviously required. An example of hob selection from database in a gear software calculation is shown in Figure 13.

4.2.1 TOOL DATABASE

Before explaining the hob's optimized selection process, let us take a deeper look at the tool database. It is necessary to have a computer database containing all the hobs' characteristics. The platform used can range from a straightforward Excel spreadsheet to PLM.

There are workshops that cut gears for medium-size reducers (with a module from 0.5 to 7 mm), that have 400 hobs entered into an Excel spreadsheet (Figure 14), and there are workshops working especially for the automotive industry that have 650 hobs in an Oracle database that also lists the resharpening (Figure 15).

There are also workshops working for the automotive and agricultural industries that handle more than 10,000 hobs for which only printed information sheets are available. Therefore, the first step is to enter data into a computer database. An Excel spreadsheet has been prepared with some formulas in order to harmonize the various ways of sizing the hobs mentioned previously. The enormous amount of work involved in compiling the database can only be justified by the savings, in economic terms, obtained by the process listed in the paragraph below.

In any case, the hobs database must contain this information:

- Reference profile (module, pressure angle, addendum, dedendum, tip and root radius, protuberance, semitopping).
- Geometric characteristics (hob diameter, cutting edge length, helix angle and hand, number of gashes, number of starts, material, coating).
- Working conditions (recommended stock).

Sometimes, the database also includes data [28] or drawings of dressers (Figure 16). So, this method is also used to determine the choice of roll in order to dress the grinder wheels and obtain the tip-relief listed in the drawing.

4.2.2 WORKFLOW

The process to be followed in order to generate a list of hobs used to cut the required toothing is shown in the flowchart in Figure 17, taking into account also the stock allowance.

Among the proposed variants, the optimal solution is the one that best meets the set criteria. Similarly to what we saw in Point 4.1.2, the Pareto front must also be adopted in this case.

The process can be more advanced and taken into account "modified rolling" or "short pitch tool" [29]. In this case, the hobs will not be strictly filtered on the basis of module and pressure angle initially, but also by the base pitch, optionally inside a tolerance range.

The short pitch tool usually is selected to reduce undercut when there is the protuberance, to achieve smaller root form circle after grinding and increase the lifetime of the hob. The tooth form changes only in the root, and this change should be considered in the strength calculation. In this case, both the tool and gear have the same base pitch.

In another case, the tool can have a base pitch different from the gear. Checking of the geometry obtained via enveloping will not be solely of the tip and root diameters, but also of the profile deviation, which must remain within values that can be removed by grinding. This operation can be performed only if the first selection failed to result in a solution or if the workshop normally adopts modified rolling for cutting or if a prototype or small batch is being manufactured.

In (Figure 18), there is the same gear with m = 2.5 mm and α = 20°, hobbed and ground completely (flank and root). The hob in (A) has the same base pitch of the gear (m = 2.4701 mm, α = 18°); the hob in (B) has a different base pitch (m = 2.5 mm, α = 18°); the grinding allowance is not constant, but it's acceptable for a prototype.

5 INTEGRATION

The meaning of the term "integration" in this article goes beyond the one adopted by Norton in the title of his book "Machine Design: An Integrated Approach" [30] where, instead, he refers to the educational approach. The approach tackles numerous machine parts within the same whole that are often mutually dependent.

As mentioned in the introduction, the integration we are focusing on is that of design for manufacturing; this has become a must, or at least a leitmotif for many companies.

Indeed, design decisions have a significant impact on manufacturing costs and product quality; 70 to 80 percent of the end manufacturing costs and 80 percent of the work that affects product quality are established by the end of the design phase (Figure 19). Moreover, the further along you are in the development phase, the more expensive it becomes to make modifications (Figure 20). For example, once the hob has been ordered, any geometric modifications to the design have an extremely costly impact.

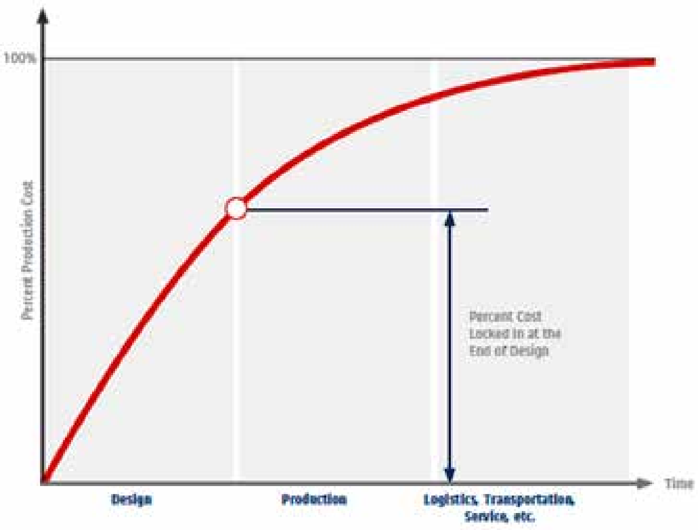


Figure 19: Up to 80 percent of product costs locked in at design (Source: Dowlatshani in [3]).

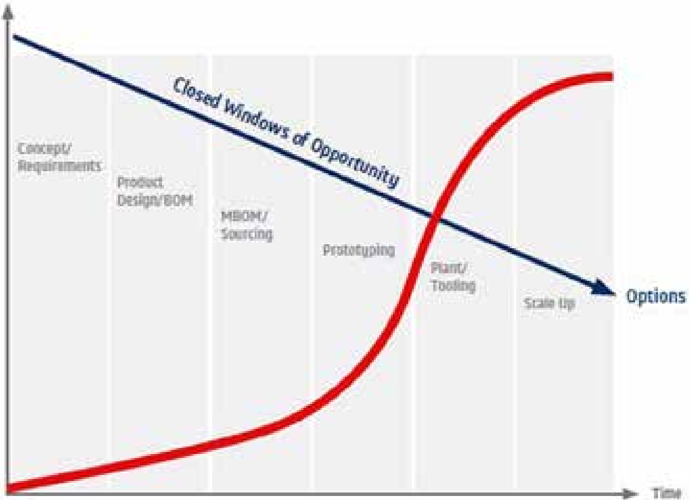


Figure 20: Closing window of opportunity for changes (Source: Tech-Clarity in [3]).

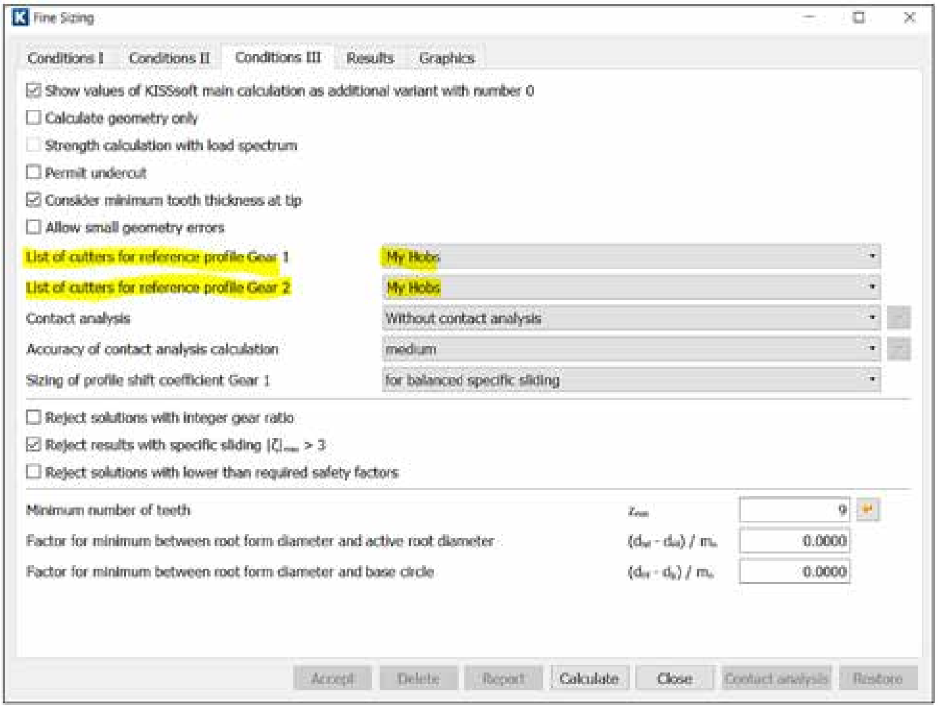
6 INTEGRATED OPTIMIZATION

We do not need to go deeper into the importance of integration. We have reached the apex of this ascent of the four terms listed in the article's title. It is just a small step to achieve integrated optimization of design and manufacturing. The following are necessary:

- Adoption of a single gear calculation software in the technical department and in the workshop. Usually, it is first chosen by the technical office and then adopted by workshop.
- Sharing of the same hobs database by the design and manufacturing divisions. If, as listed earlier, the first step is taken by the technical office, then it is the workshop that must share its information.
- In the design software, the DOE of the optimizer searches for solutions limited to those obtained by the hobs available in the database (Figure 21) [21]. For each found variants (Figure 11), the efficiency of the hob could be added as a result to help the designer in the selection of the best solution — "best" for the designer and "best" for the workshop.

The advantages are for the whole company:

- Saving money in the purchase of new hobs and time in supplying, because the designer tries to limit himself to proposing geometries generated using just the hobs available in the workshop, rather than coming up with geometric variables at a mathematical level only (e.g. pressure angle, module, addendum, dedendum).
- The designer has a greater awareness of what will be produced, even at the level of efficiency of the hob, pre-grinding quality and grinding twist, especially if the software used conveys the skills of gear designers and machine tool manufacturers [21].
- The workshop already has the files with toothing and hob data; it does not have to



☑ Show values of KISSsoft main calculation as additional variant with number 0
☐ Calculate geometry only
☐ Strength calculation with load spectrum
☐ Permit undercut
☑ Consider minimum tooth thickness at tip
☐ Allow small geometry errors
List of cutters for reference profile Gear 1: My Hobs
List of cutters for reference profile Gear 2: My Hobs
Contact analysis: Without contact analysis
Accuracy of contact analysis calculation: medium
Sizing of profile shift coefficient Gear 1: for balanced specific sliding
☐ Reject solutions with integer gear ratio
☑ Reject results with specific sliding $|\zeta|_{max} > 3$
☐ Reject solutions with lower than required safety factors
Minimum number of teeth z_{min}: 9
Factor for minimum between root form diameter and active root diameter $(d_{Nf} - d_{Ff}) / m_n$: 0.0000
Factor for minimum between root form diameter and base circle $(d_{Ff} - d_b) / m_n$: 0.0000

Figure 21: Example of DOE where the hobs database is a boundary.

interpret the drawing or enter data related to the hob, if chosen from the database. Therefore, it can focus exclusively on the technological aspects.

7 CONCLUSIONS

The sharing of information and the desire to network, which is the same as the goal of AGMA, and especially of the FTM, is the spirit that lies behind the drafting of this article. No new formulas or technologies are presented in this article. The state-of-the-art, good practices, and some real cases encountered in various situations and inside companies are presented in order for us to draw from them. "Uncomplicated" instruments that are already on hand have been described:

- To some designers in order to see whether there is already a tool to manufacture the gear wheel they have in mind.
- To the relative workshops in order to avoid having to spend time re-interpreting designs and to speed up the search for the ideal tool.

If a drawing is a way to encode design information and reading of the drawing represents decoding, an example of CODEC (an IT term used in relation to audio and video meaning COde-DECode) involving design and manufacturing is shown.

8 ACKNOWLEDGEMENTS

The author wishes to thank KISSsoft (a Gleason company) for the software. Thanks also to the companies Varvel — Mechnology, CIMA (Coesia group), Graziano (now parts of Dana group), and CEI, that provided some pictures for this article and, over the years, have dedicated resources for the integrated optimization of design and manufacturing. They have shared among themselves the same software and same database of hobs and pinion-type cutters in design and manufacturing, not without some initial problems.

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