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SUPPORT FOR DESIGNERS USING FEA

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1. The Objectives

In the past, modern computationally based design- and analysis-tools like CAD- and FE-Systems were introduced into the product development process. The complexity of this software creates different types of engineers: the design engineer and the analysis engineer. In larger companies, even different divisions have been founded for design and analysis tasks. Therefore, there is no direct exchange of informations between design and analysis, which is often time consuming, because data arrive too late which prolongs iteration cycles in the product development process. Nowadays, design and analysis are supposed to be more integrated again in order to optimise the product development process and therefore to shorten the time to market [1]. To achieve this goal, the design engineer is supposed to be able to solve the simpler and repeating analyses himself. Only the more difficult and complex tasks will be reserved for the analysis engineer [2] [3].
This paper provides a new method to help designers perform the above mentioned types of analysis. The new method accelerates the interaction between design and analysis and reduces the time of iteration cycles. By the acceleration of the design and analysis part, the product development process will be shortened as a whole.

2. The Focus

The designer is mostly focused on elastic-static analyses based on 3D-CAD models: As a result of a questionnaire asking Northern Bavarian FEA-Applicants 90 % of the companies are performing static analyses (Table 1) [4]. Therefore there is a high possibility to shorten iteration cycles, if the designer performs static analysis for simple structures by himself.

Table 1. Results of the questionnaire: Frequency of analysis types (Doubles were possible) [4]

Type of Analysis	*Per Cent*
Static	90
Thermal	20
Contact	25
Dynamic	10
Molding	10
Fluid	15
Optimisation	25
Modal	25
Forming	10
Material	10

Another result of the questionnaire was a representation of the CAD-Environment within which FE-Analyses are performed. Table 2 shows that 86 % of static analyses are performed in a 3D-CAD environment.

Already today and even more in the future this 3D-CAD environment will provide 3D FE-Models, even if simplifying is possible, because the time for simplifying structures will be more expensive than analysis time. In addition, the direct exchange of models between CAD and FEA will reduce time consuming adjustments and therefore also shorten the product development process. This will force a more frequent use of three dimensional finite elements like tetrahedrons and hexahedrons, which are the main focus of this paper.

Table 2. Results of the questionnaire: CAD-Environment performing static analyses [4]

CAD-Environment	***Per Cent***
2D	14
3D	86

There are many parameters to consider during an FE-Analysis (Figure 1). The parameters influence each other, which is difficult to estimate for the design engineer as well as for the analysis engineer. This paper is focused on one of these aspects: the selection of element type, because the element type influences significantly the result quality.

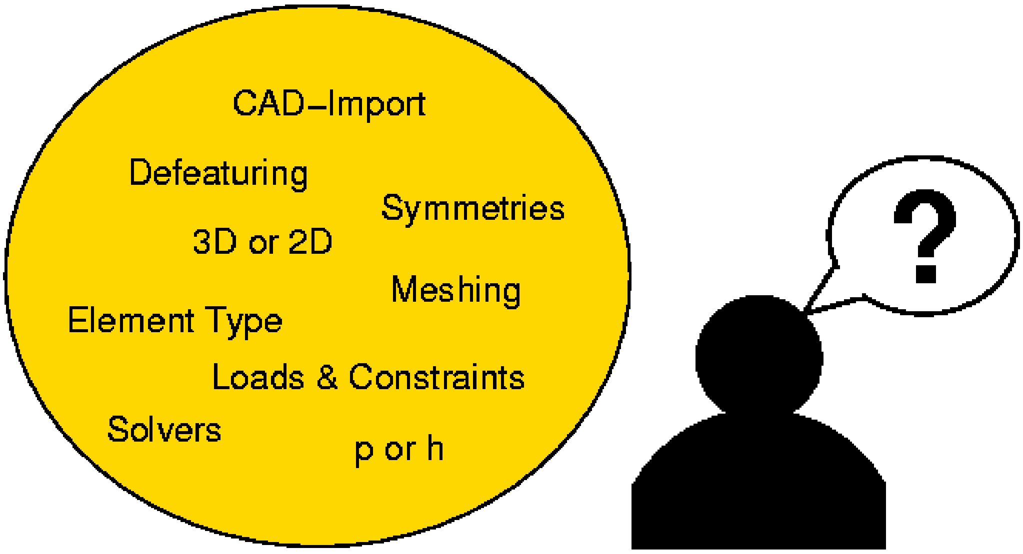


Figure 1. FE-Preprocessing Parameters

To support the design engineer, software companies have introduced simplified, defeatured and more design oriented FEA-Programs in addition to their traditional multi-purpose FEA-Software [5] [6]. Similar to the development of CAD-Programs, FEA-Software seems to be also separated into high-end and mid-range software. The use of mid-range products for simple and repeating tasks during the design process and high-end products for complex or highly sophisticated analysis will increase in the future [7]. But these programs are rather geometry oriented than reflecting the mechanical and mathematical background. Thus, they offer automatic meshing procedures for instance, but no support for the selection of the appropriate element type in respect of the main loadcase. For this parameter, an additional support for the design engineer will be exemplarily offered by this paper. The provided method could be used for other parameters of Figure 1 as well.

3. The Problem

The problem of element selection considering result quality will be demonstrated using two simple examples. The first one is the beam in Figure 2. This beam is fixed on the left hand side and is loaded with a shear force of 1000 N on the right hand side. In addition, the beam has got a squared cross-section of 100 mm x 100 mm, a length of 2000 mm and a resulting moment of inertia of about $8{,}333 \cdot 10^6$ mm^4. The material is steel with a module of elasticity of 206,000 N/mm^2 and a Poisson's Ratio of 0.3. According to these data the displacement on the right hand side will be 1.524 mm using equation

(1). The result is in the range of a kinematic linear problem without a significant shear influence because of a high length-to-diameter ratio.

Figure 2. Overhanging Beam loaded with Bending

$$w(x) = \frac{F \cdot x^3}{3 \cdot E \cdot I_b} \quad (1)$$

This analytic solution is compared with a three dimensional elastic continuum. The finite elements used here are tetrahedrons and hexahedrons with linear shape functions (*Tet4*, *Hex8*) as well as quadratic shape functions (*Tet10*, *Hex20*). Table 3 shows the relative error compared with the above mentioned analytic result for each element. The notation of the elements is used according to the FEA-System MSC.Marc, which provides a short form of the element basic geometry, *Tet* or *Hex*, in the beginning of the element names, followed by the number of nodes [8]. According to this notation, *Tet4* is a tetrahedron with four nodes, for instance.

Table 3. Bending results: maximum displacement at the right end of the beam

Type of Element	*Number of Elements*	*Relative Error in %*
Tet4	18029	9.0
Tet10	17	8.0
	120	1.0
Hex8	4000	1.4
Hex20	10	1.6

The result quality and even more the efficiency of the used elements differ a lot. Elements with quadratic shape functions (*Tet10*, *Hex20*) have got a higher result quality and a higher efficiency than elements with linear shape functions (*Tet4*, *Hex8*). For nearly the same result quality 18029 *Tet4* elements are needed but only 17 *Tet10* elements, thus the analysis time will be much higher for *Tet4* elements. For hexahedrons it is the same: 4000 *Hex8* elements provide a similar result quality as 10 *Hex20* ones. Comparing the element type hexahedrons are more efficient than tetrahedrons: 120 *Tet10* to only 10 *Hex20*. *Tet4* elements provide a poor result quality, even using large numbers of them.

Figure 3. Overhanging Beam loaded with Traction

If the same structure is loaded with traction instead of bending (Figure 3), the results are completely different (Table 4). The results have got a high quality, independent of the element type and the used shape function. *Tet4* and *Hex8* elements are more efficient in this case, because of a shorter analysis time.

Table 4. Traction results: maximum displacement at the right end of the beam

Type of Element	*Number of Elements*	*Relative Error in %*
Tet4	240	-0.4
Tet10	240	-0.2
Hex8	10	-0.4
Hex20	10	-0.3

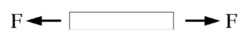
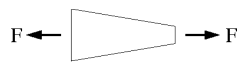
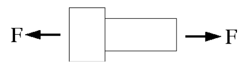
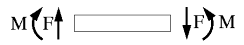
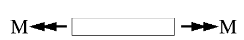
To get accurate results and reasonable analysis times, the element type and even more the shape function are important parameters. The appropriate shape function depends on the current load case: quadratic ones for bending and linear ones for traction. The influence of the element type is less important. Thus it should rather be selected according to geometric aspects.

In addition, especially for bending load cases several authors recommend the usage of finite elements with quadratic shape functions instead of linear shape functions [9] [10]. Other authors also recommend the usage of hexahedrons instead of tetrahedrons [11].

4. To Make It Suitable

To make these conclusions suitable for a design engineer during his daily work, these results are presented in an extended form of a design catalogue [12]: The classifying part of the catalogue enables the assignment of the analysing task to one of the investigated states of stress (Table 5). An additional classification is offered by the idealised geometries. Looking at bending as the main loadcase and a non-variational cross-section over the length, the classifying part of the catalogue leads the user to the 4th item in the main part of the catalogue, which provides a cubic relationship between force and length (1).

Table 5. Extract of extended design catalogue: classifiying part [13]

Classifying Part			Main Part		
Dimen-sion	Main Load Case	Variational Cross-Section	Function F(l)	Example	No.
1	2	3	1	2	3
1D	traction	no	linear		1
		linear	logarithmic		2
		constant	linear		3
	bending	no	cubic		4
	torsion	no	linear		5

The access part of the catalogue makes a proposal for the element selection (Table 6). Usually the catalogue provides several proposals. The designer can select one of these proposals according to his priorities with respect to less modelling effort or higher result quality. Considering the chosen number 4, one- and three-dimensional finite elements are offered. If the designer wants to perform a dig-and-dirty analysis, he will be interested in less modelling effort and low analysis time. So he could choose *Tet10* elements and thus automatic meshing as well as "good" result quality, which will be sufficient for that kind of analysis.

Table 6. Extract of extended design catalogue: access part [13]

No.	Access Part					
	Recommended Type		Meshing Technique	Modelling Effort	Analysis Time	Result Quality
	Dimension	Type				
	1	2	3	4	5	6
1	1D	*Truss2*	manually	high	low	exact
	3D	*Tet4*	automatically	low	low	good
		Hex8	manually	high	middle	very good
2	3D	*Tet10*	automatically	low	middle	good
		Hex20	manually	high	high	very good
4	1D	*Beam2*	manually	high	low	exact
	3D	*Tet10*	automatically	low	middle	good
		Hex20	manually	high	high	very good

5. Application

All the results presented above are based on displacement, not on tension. Of course, tensions are very important for the dimensioning of design parts. But in many cases, the main criteria for dimensioning are rather displacements than tensions. The problem is often not the displacement of the design part, but the displacement of the product, which is manufactured by the design part. These displacements directly influence the product quality, which is usually a very important aspect.

One example for this kind of design part is the press frame in Figure 4. In the figure, the tool, which moves up and down in the middle of the frame is missing. Moving downward, it forms a sheet metal, which is situated on the bed of the press.

The press frame consists of two dimensioning problems related to displacements. The frame should be very stiff to minimise displacements in all Cartesian coordinates. At first, the displacements in the direction of the moving tool are important. If there are too large displacements in this direction, the measures of the formed sheet metal are not within the correct range. The product quality requirements cannot be satisfied. Secondly, the displacements in the other two Cartesian coordinates are important: If the porters of the press frame buckle too much, the tool gets stuck. This can cause a breakdown of the whole press and probably of the whole assembly line.

The main load is the pressure of the tool during the forming of the sheet metal. This load causes a bending load case resulting in a displacement of the porters, the cross head and the bed. According to the bending load case and the non-variational cross-sections (item 4), the catalogue provides elements with quadratic shape functions like *Tet10* and *Hex20*. Because the designer wants to reduce modelling time as well, he meshes the part automatically with *Tet10* elements considering the access part of the catalogue.

Table 7 shows the FEA results compared with experimental ones regarding the different element types. *Tet10* elements provide a higher result quality and a faster convergence. Therefore, quadratic shape functions are more reliable and efficient, if bending is the main load case.

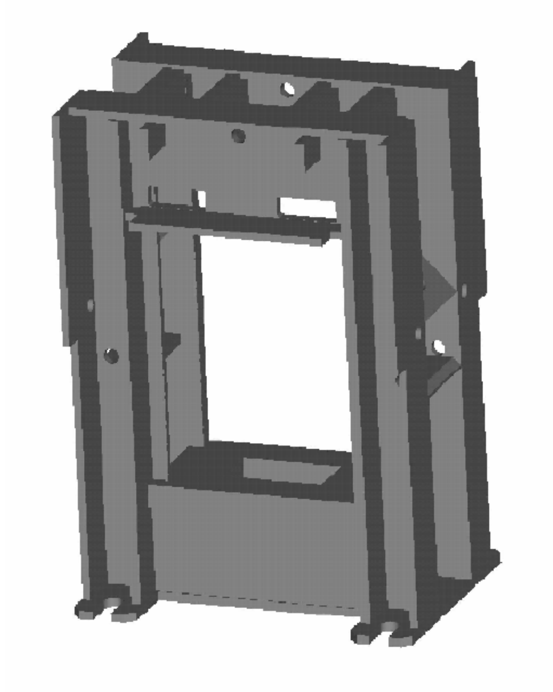


Figure 4. Press frame

Table 7. Results of experiment and FEA looking at the direction of the moving tool

Type of Element	***Number of Elements***	***Displace-ment in µm***	***Relative Error in %***
Tet4	13609	184	-19.3
Tet10	13609	211	-7.5
Tet4	27352	205	-10.1
Tet10	27352	213	-6.6
Experiment		228	---

Another example is a connecting rod loaded by pressure and traction (Figure 5). Therefore, traction is the main load case and No. 1 of the catalogue provides elements with linear shape functions like *Tet4* and *Hex8*. The designer votes for *Tet4* elements because of a 3D CAD-Model, less modelling effort and also less analysis time, which is a reasonable choice looking at the results presented by Table 8. The change of the cross-section measures over the length can be neglected. This logarithmic influence is very small, because the reduction of the cross section plane is about 5 %. The difference between experimental and analytical results is caused by an incomplete geometry representation.

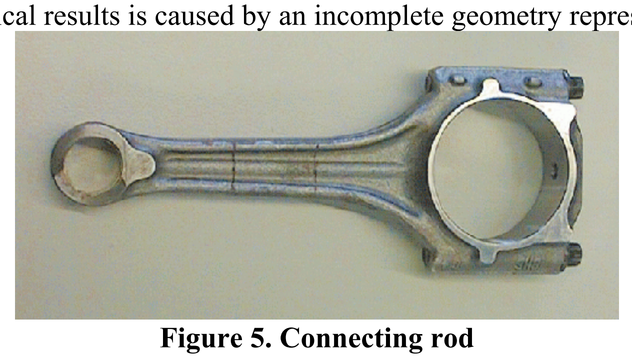


Figure 5. Connecting rod

Table 8. Results of experiment and FEA looking at the axial direction of the connecting rod

Type of Element	*Axial Displacement in μm*	*Relative Error in %*	
		experimen-tal	*analytic*
Tet4	29.600	-8.6	-1.2
Tet10	29.650	-8.5	-1.0
experimental	32.400	---	---
analytic	29.955	---	---

6. Conclusions

Based on the example of element selection, a new method supporting the designer is provided. The designer will be enabled to perform more FE-Analyses, and thus iteration cycles during the design process will be reduced. The consequence is a shortening of the design and analysis part of the product development process.

In addition to the more economic related parameters like analysis and modelling time, the catalogue provides quality assurance aspects. If a dig-and-dirty analysis is enough like in the early stages of the product development process, the designer can rather select the element type looking at analysis and modelling time. For analysis tasks requiring accurate results, however, an element selection should be done regarding that aspect. This means, the designer can decide in a flexible way according to his priorities.

Using the provided method, design parts will be developed faster and more safely.

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