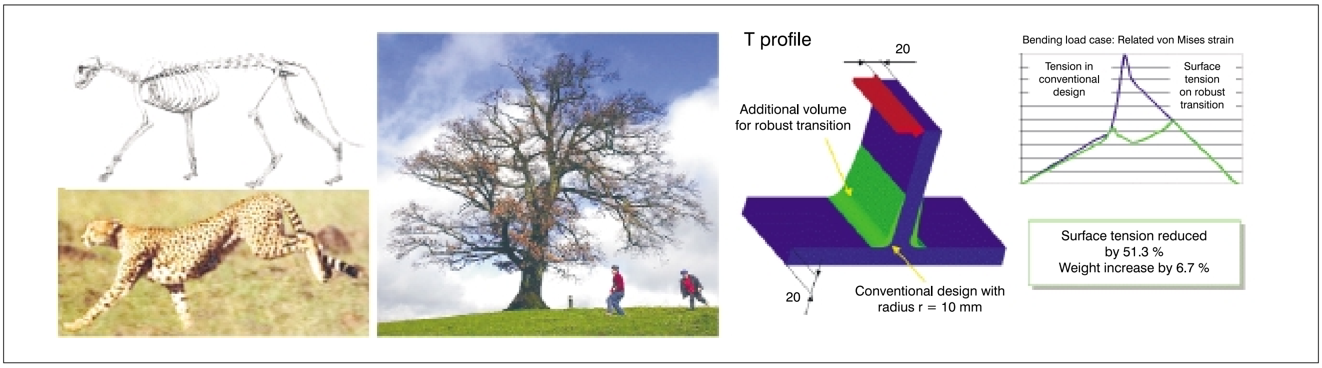

Figur 1. left: Growth processes in Nature provide templates for pre-optimization, right: Shape-optimized BIOCAST® profiles are used in constructions in the manner of confectioned articles

Learning from Nature – novel, power flux compliant design of castings

Ernst du Maire and Thorsten Schmidt

With a headcount of 190, Heidenreich & Harbeck AG in Mölln near Hamburg is a maker of castings for general machine construction. In addition to the foundry shop with patternmaking, moulding shop and melting shop, the company also has an extensive pool of machines for flexible automated machining of large parts, which enables the company to make and supply ready-to-install components complying with highest quality standards.

An in-house development department was set up over 15 years ago and has been constantly improved. By bringing together expert know-how and production expertise under the roof of Heidenreich & Harbeck, the company has become an innovation partner for machine construction with an extensive portfolio of services. The growing number of orders received in this field shows that there is a brisk demand for development services which involve both functional and economic aspects. The explanation for this is that many customer firms do not have or do not have enough know-how for the development of components under cost-saving aspects, whereas the cost pressure from international competition is mounting. Besides, as the requirements on dynamic characteristics and the precision of many products increase, temporary access to calculation resources must be available, which are out of reach for most of our customers' development departments and whose installation would not be cost-efficient for an individual project or two.

Simultaneous engineering practiced on the basis of the closeness of the organization and location of component development and production makes the company one of the first addresses for quick prototyping and overlapped preproduction series to the production of medium series of large, ready-to-install structural components. Modifications and changes identified mainly at the time of serial production start from knowledge gained in assembly and commissioning can be incorporated without delay based on the availability of data models at all stages and therefore without interruption of the delivery of parts to the customer. The supplier's capability to act as a development partner is a critical aspect of securing the continued existence of both partners in the era of globalization and harsh competition.

However, there is at least one weak point in the function as development partner: A design principle once worked out and made public cannot be protected from imitation.

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[1] BioCast is a protected brand name

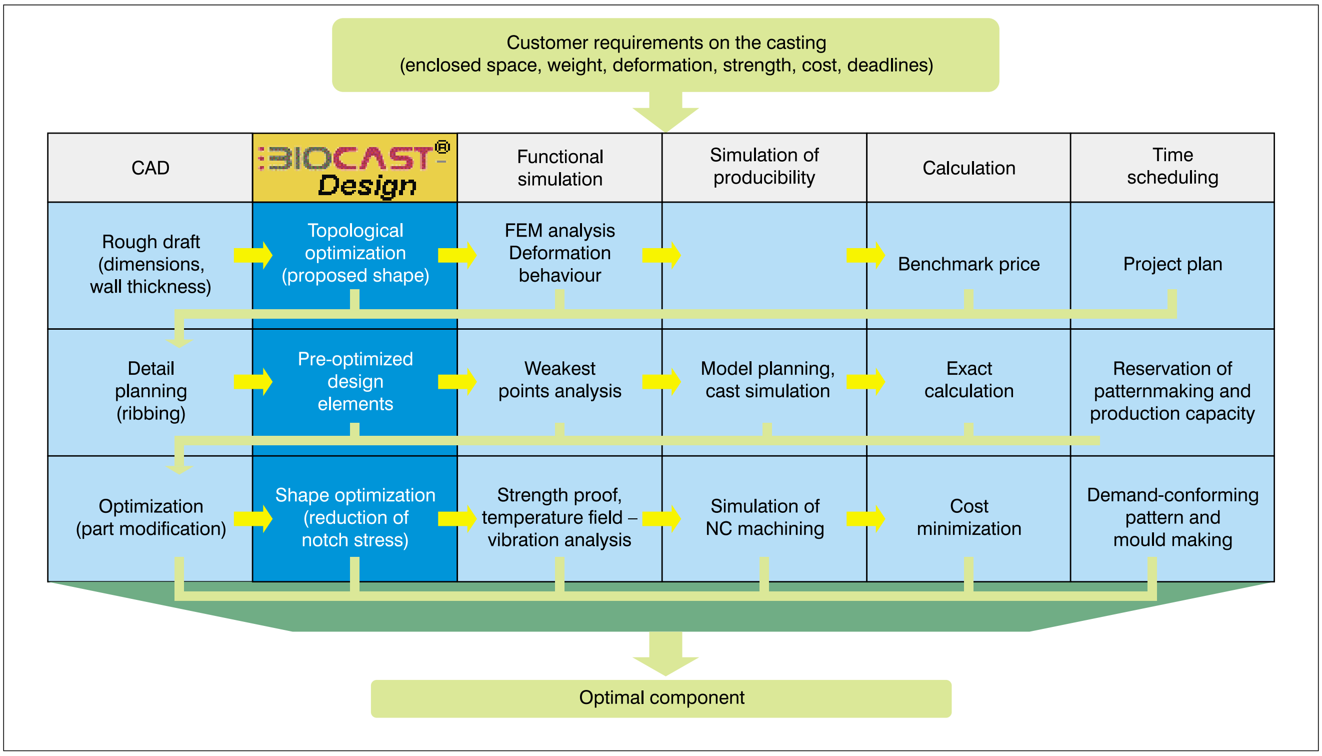

Figure 2. Service portfolio with the new BIOCAST® component

Theft of ideas is a driving force of permanent innovation if you want to be the Number One address as a development partner. This challenge is an extreme one because the task is to find ever better solutions and develop entirely new rationalization ideas at manageable costs and at an every shorter time scale and in this way develop the tailored solution fulfilling the task in ideal manner.

“BioCast”[1)] Design

Taking a wider approach is extremely helpful in this respect. Nature supplies proof every day that there is nothing utopian in meeting extremely challenging tasks with a minimum input of material, energy and operating costs. For example, a developer of structural components would be well-advised to be inspired by the growth of trees and bones (**Figure 1**). The fact that plane surfaces and right angles are not typical of natural forms and shapes should not deter him. On the contrary, because casting is a production technology with which power flux conforming contours can be made without high expense. And you will probably know that these contours are at the same time moulds for efficient pouring and cooling.

For example, under a research project for speeding up and improving the development of cast components, new software for shape and topology optimization was advanced to application maturity and integrated in the service portfolio. The application of bionic methods in the development of castings and the use of pre-optimized design elements in complex designs, for which codes of practice are installed, have been subsumed under the protected brand name “BIOCAST” (**Figure 2**).

Topology and shape optimization either lead to components with reduced weight which can run at higher speed while observing the required stiffness parameters or the weight of the component remains virtually the same but it is stiffer and its structure able to support more weight. In this way, what so far seemed to be limits of performance can be overcome by approaching the functional optimum by means of advanced optimization software.

Heidenreich & Harbeck is one of the first in the industry to use these methods routinely in the development of components for general machine construction and thus combines in ideal manner the requirements of production complying with stress and fabrication.

Imitating natural growth processes

Optimization of shape aims at improving the load-bearing capacity of structures exposed to high load by moderate modification of geometry. It is applied to components with seemingly no design reserve and reduces the peak strain at the surface of a component. The underlying computer algorithms were developed by Prof. Mattheck from Karlsruhe. His studies in the growth of trees and the structure of bones (**Figure 2**) led to the finding that nature is extremely thrifty with the input of building material; material is input only where stress or strain is especially high. Because the resulting geometries follow the axiom of constant surface tension, weak points with higher notch effect, such as occur frequently in man-made systems, are avoided.

In the course of the aforementioned research project, the load-bearing capacity of recurrent construction elements in a critical load case was pre-optimized for each shape optimization. Before the results were translated into codes of practice, production-improving modifications of geometry found by casting simulation were included (Figure 2). Today, these pre-optimized elements are used in many designs to reduce the notch effect and improve stiffness and thus are an aspect of making optimal use of material.

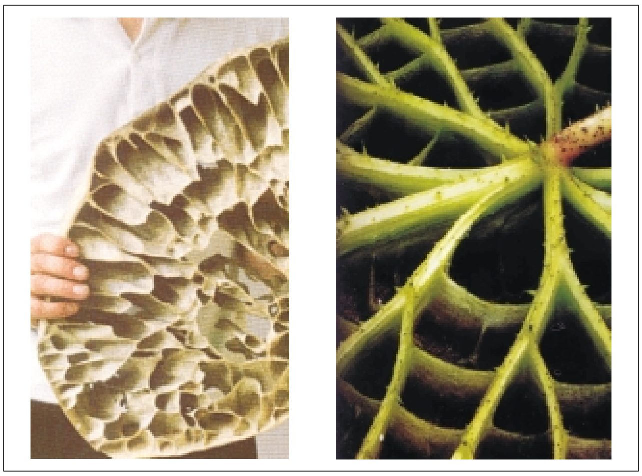

Figure 3. The lamellar-type bone tissue in an elephant's skull (left) adds a lot of stiffness to the external structure. A nice example of successful ribbing is this leaf of a giant water lily (right).
(Source: Nachtigall, Blüchel: Das große Buch der Bionik)

Of light weight yet stiff?

Topology optimization is applied at a very early stage in development. Examples of topology optimization can also be found in the plant and animal kingdoms, where tissue and bone structures add significant stiffness to the actual functional elements with little use of material (**Figure 3**).

The requirements made on the components to be developed by Heidenreich & Harbeck often coincide with the features known from load-carrying structures in Nature: Often, the outer enclosure which is required for the function of a components must be very stiff, especially for components in the machine tool sector, where a micrometer of deformation can make all the difference. At the same time, the structure must be cost effective, i.e., require little material input, to secure a competitive advantage.

The topology optimization for the automatic detection of the structures meeting these requirements was applied by Heidenreich & Harbeck as part of the research project. Important success was already achieved in one of the first industrial applications in which the optimization was applied to a simplified two-dimensional model (**Figure 4**). Based on a finite-element model of the solid body filling the available construction space and the loads acting on it, the ideal shape of the component which complies with the force flux is calculated by a fully automatic process. The force flux compliant design proposal found by topology optimization, which using the availably production know-how, was translated into production-compliant ribbing, reduced the weight of the machine frame by 30% in comparison with the forerunner design. As, in addition, the number of cores was reduced from about 80 to 16 (80% less!), the cost of making the raw part dropped dramatically without reducing the stiffness of the part.

Meanwhile, investment in extremely powerful workstation computers allows to carry out topology optimization based on 3-dimensional models with several load cases. Only the volume model of the available construction space must be known, which is transformed into an FEM model and to which the relevant forces of each load case are applied. (**Figure 5**). A series of iterations develops shape proposals with maximum stiffness and load, respectively, for the weight remaining in each case (Figure 5). The developer, by applying his production engineering know-how, develops a design complying with of production and the force flux (Figure 5).

When compared to the conventional approach, the difference of the development process with integrated topology optimization is that the starting point is not a production-compliant design of a complex casting which in most cases is discarded after the first FEM calculation or must at least be modified extensively by numerous subsequent iterations. Instead, a simple-to-make model of the construction space marks the beginning. Depending on the size of the component and the number of load cases, the topology optimization yields the picture of a component of optimal shape after a few hours or days without manual intervention.

Higher production output in blow moulding

The fact that the combination of present production know-how with the smart use of calculation programs specifically tailored to a development objective can often lead to customized solutions within a stunningly short time was also the experience of a maker of blow moulding machines (**Figure 6**).

In this example, Heidenreich & Harbeck was commissioned with the new development of all cast components for a larger machine. Serious challenges were the limited construction space and the weight and quality requirements,

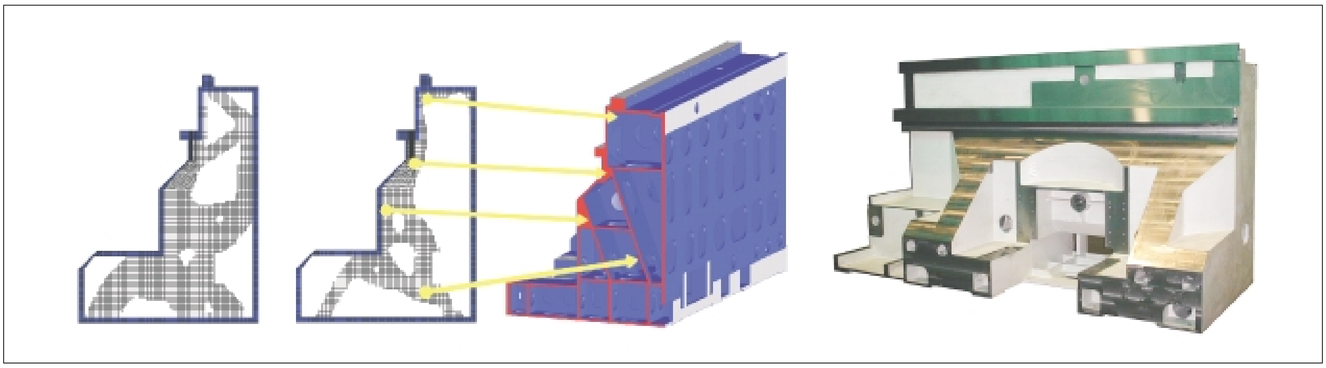

Figure 4. Machine base of a vertical lathe (left to right: Proposed designs, implemented 3D-CAD construction, ready-to-install machined component; Material: EN-GJL-250, Dimensions: 3,600 × 1,950 × 1,430 mm, weight: 7,400 kg)

because the new product was to be of compact design and have high output. So the use of a topology optimization program was indicated.

To keep the later costs of pattern adaptation and production, which were also in focus, at a minimum by coreless construction of the mould, restrictions for manufacture were considered in the optimization process. As a consequence of this, the proposed shape of the clamping plate had no undercuts. The component developed on this basis with comparatively little expenditure was subjected to production simulations and the proof of the required strength provided mathematically. In addition, to make sure that the part functioned, the deformation behaviour of the completer assembly was analysed to avoid burrs at the blow-formed end products. The calculated outstanding stiffness parameters were confirmed by measurements during start-up.

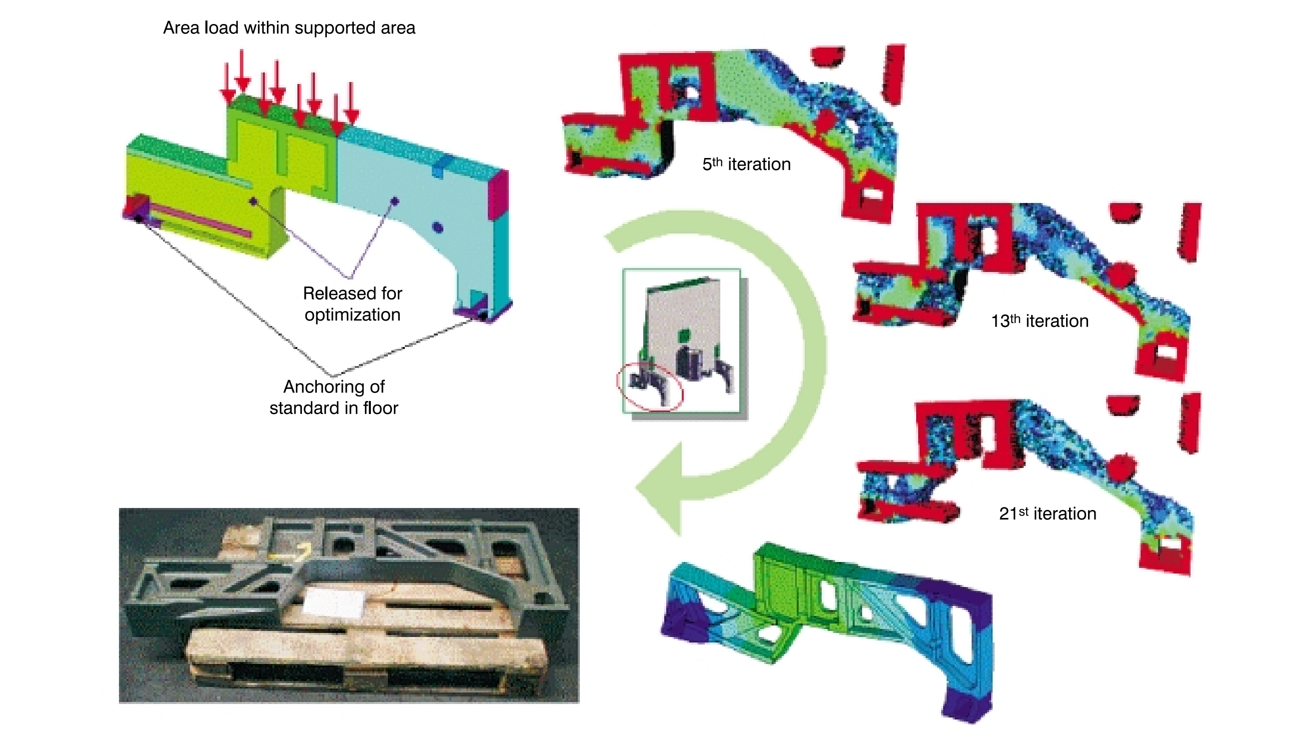

Figure 5. Development process for a standard with integrated topology optimization; Material: EN-GJL-250, dimensions: 1,460 × 550 × 150 mm, weight: 170 kg.

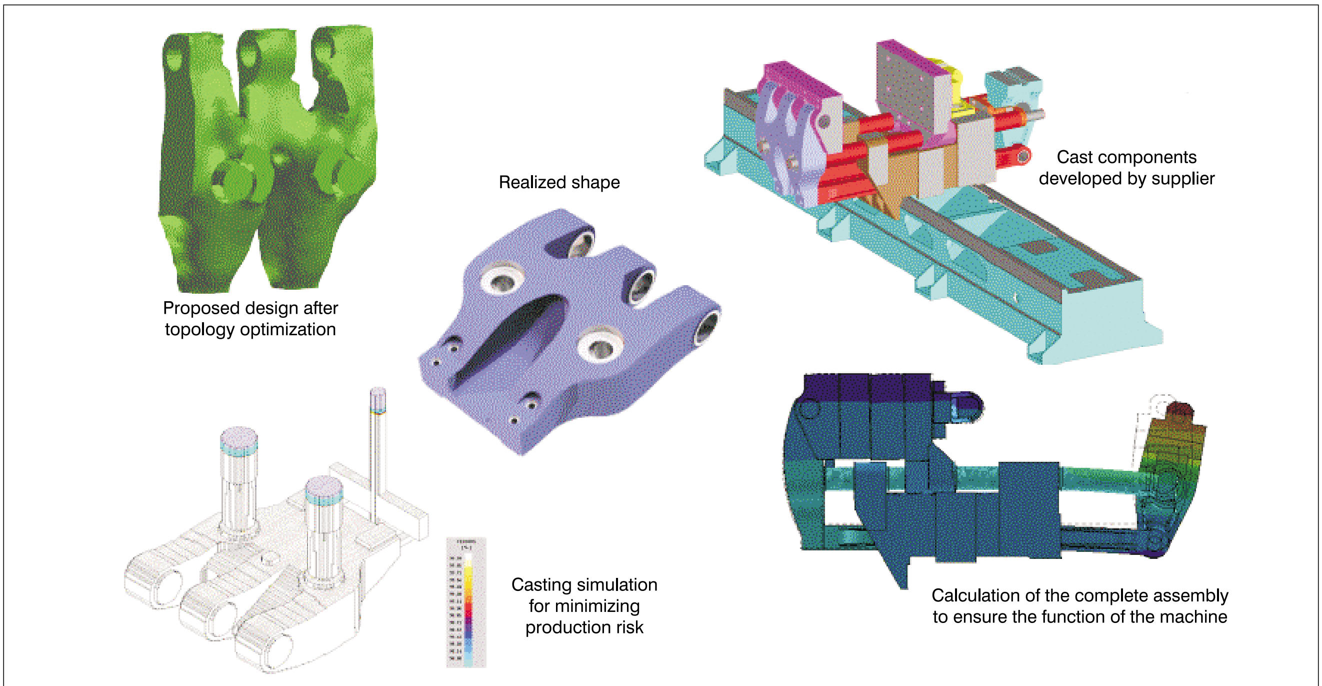

Figure 6. Topology-optimized clamping lever of a blow-forming machine, Material: EN-GJS-400-18, dimensions 770 × 640 × 200 mm, weight: 350 kg)

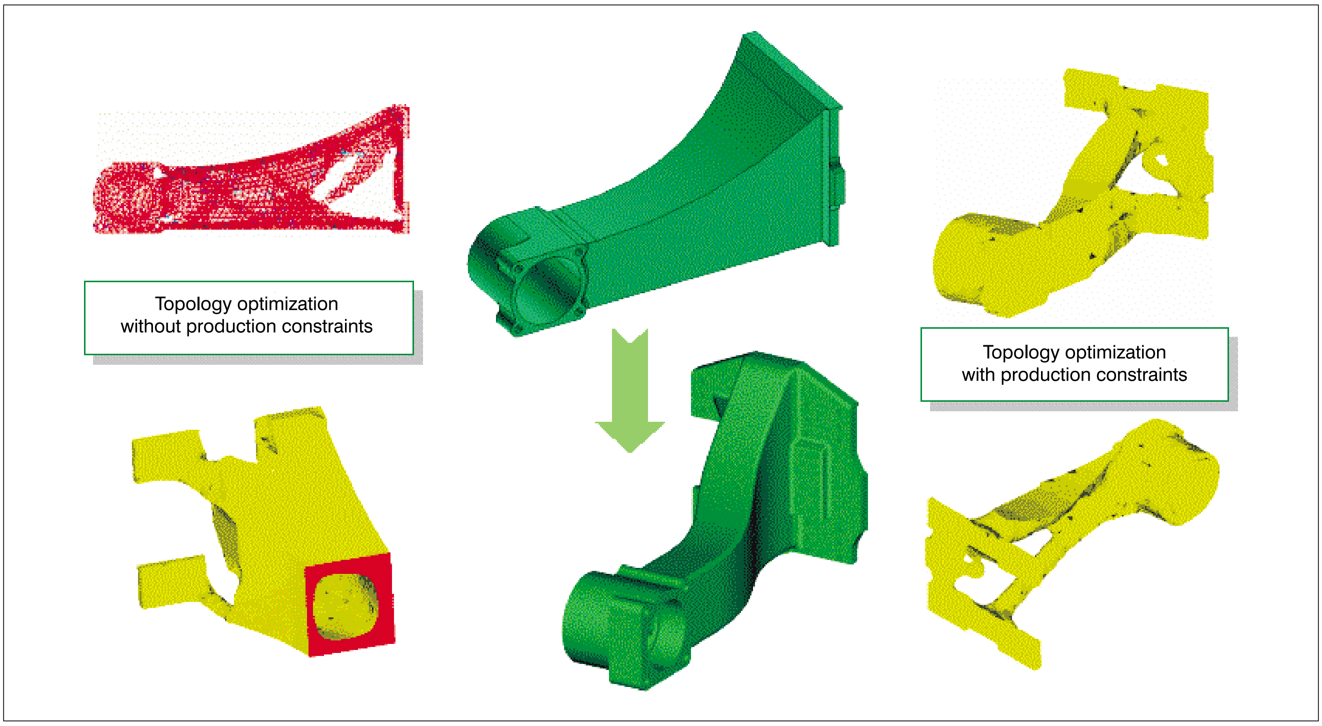

Figure 7. Supporting arm of a winder station: From the construction space (top) to the integrated part (bottom) with topology optimization. Material: EN-GJS-400, dimensions: 1,015 × 495 × 490 mm, weight: 155 kg.

Load-conforming shape of a supporting arm

Under a value analysis project, a customer commissioned the component supplier, Heidenreich & Harbeck, with the new development of a supporting arm.

Based on the customer-modelled available largest construction space, the task was to develop a stiff safety component at reasonable cost. As part of the job, the link-up of the guide carriages also had to be considered.

In view of the freedom allowed for design finding, topology optimization was the method of choice. Due to a vertical load attacking at a point with a lateral offset and the resulting torsional strain, a hollow section was proposed (**Figure 7**), even if it barred access to the mounting bolts. A second calculation run also considering marginal constraints for production, which was completed at a negligible input of human resource and yielded a design proposal that was optimal under assembly aspects (Figure 7).

The realized solution combined the advantages of both versions (access to the mounting bolts, extra function of the torsionally stiff hollow section: cable duct). Even if neither of these design proposals was finally implemented 100%, the topology optimization proved to be the decisive provider of a design idea for new solution approaches.

Compared with the forerunner design, which consisted of several parts, a weight reduction of 30% with significant improvement of the stiffness was obtained. The development costs were recovered within a few months.

Dramatic acceleration potential

Topolgy optimization proved to have a substantial potential for accelerating development processes, both in benchmarking examples and real-life development projects. In most cases, after translating the proposed design in a production-compliant design, should such translation happen at all, all that is needed is another iteration with modified wall thickness data to meet the customer's specifications of component stiffness and weight.

For example, the development of a split casing for the double-spindle vertical turning machine (**Figure 8**) was reduced from four (estimated time input for conventional approach) to one week, which cut the total development period from the first activity to submission of the production documents from 6 to 3 weeks.

Despite this extreme acceleration of component development, no compromises must be made in terms of component functionality. On the contrary: the diagram (Figure 8) shows that the development result s in an outstanding ratio of stiffness to material input in the area for optimization defined by the theoretical extremes (solid component and hollow, no-rib component with wall thickness suitable for production). With only 20% higher weight than the hollow design, stiffness increases by 350%, so that the deformation limit defined in the target specification is complied with.

Over 80 new developments with topology optimization in combination with the computation of all important functional parameters and the simultaneous virtual optimization of makability have shown the superiority of the bionic approach.

In all cases, solutions close to the theoretical optimum were obtained within short time, the reason being that not only, as is common in bionics, individual solutions from nature were applied to technical environments but also – by all we know – this is the first ever use of optimization programs in general engineering which follow the internal laws of natural growth.

Thus, it is no longer state-of-the-art to replicate optimized structures or constructional shapes provided by Nature. More intelligent, tailor-made solutions can be made today at very reasonable cost by applying the growth laws of Nature to the development of technical

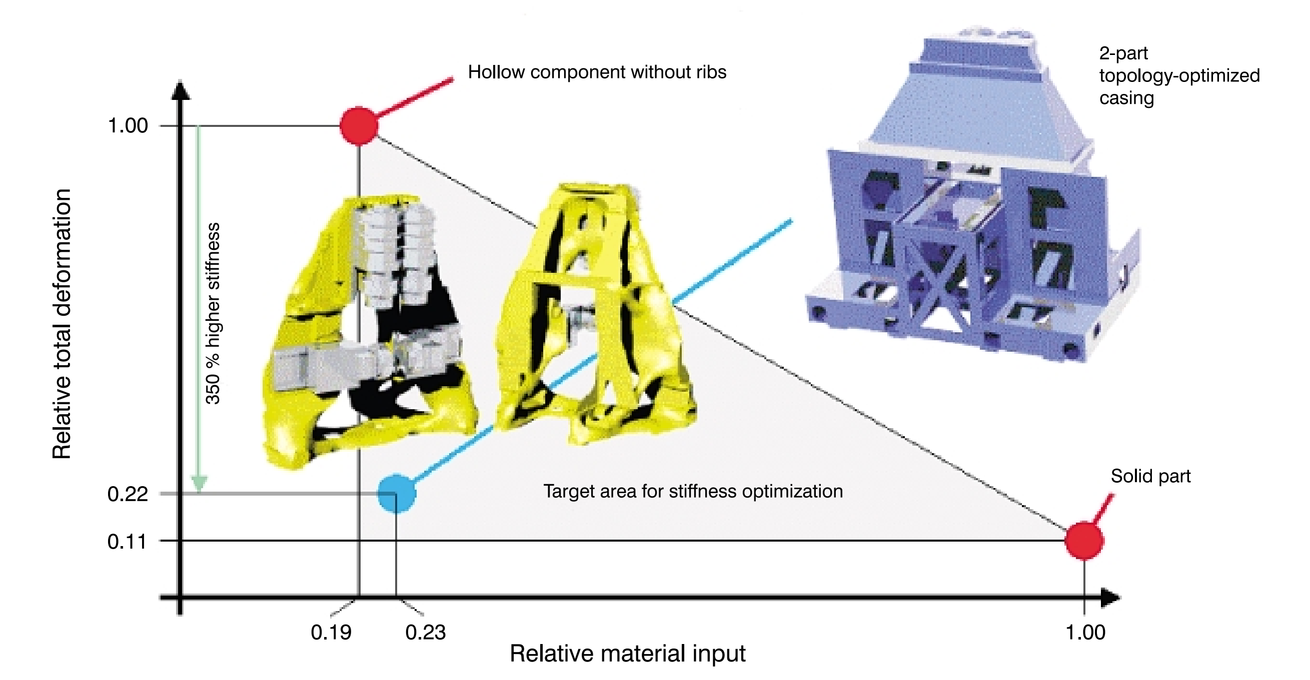

Figure 8. Deformation/weight diagram of a split machine; material: EN-GJL-300, dimensions: 3,600 × 2,260 × 1,450 mm, weight: 4,700 kg.

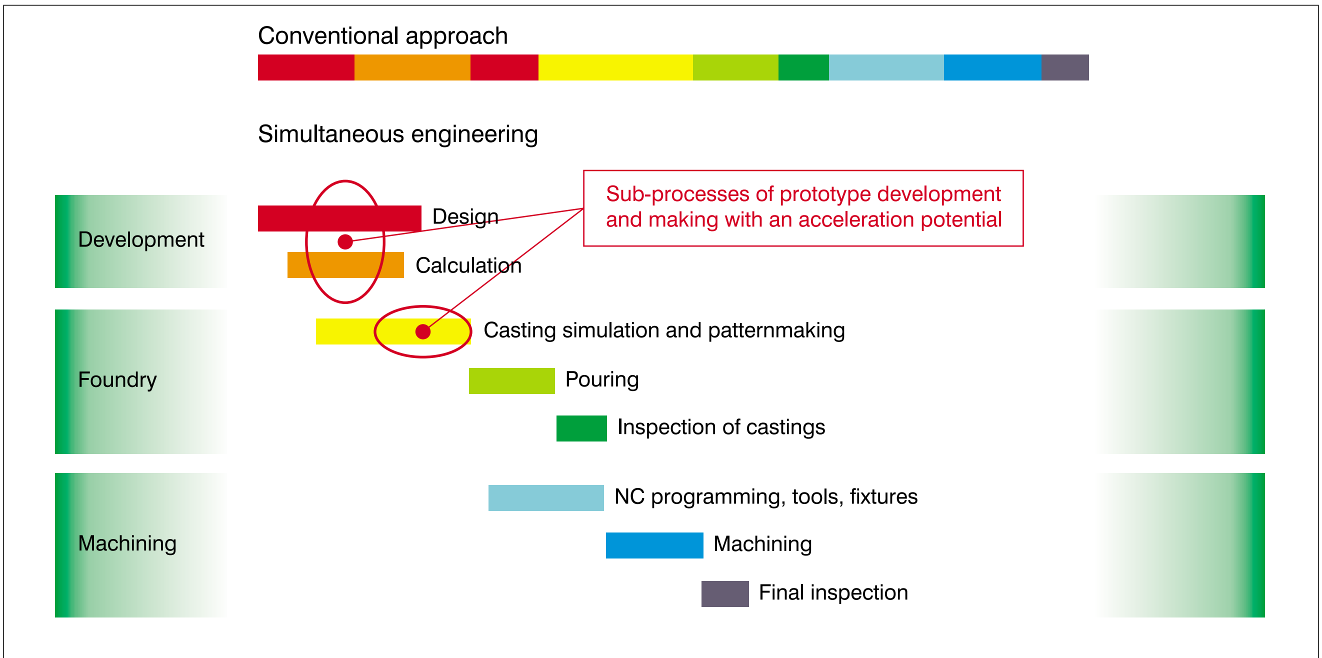

Figure 9. Simultaneous engineering: Sub-processes with an acceleration potential

components. The use of bionic optimization methods will increasingly yield entirely new design solutions adapted to stress and strain and thus contribute to making problem solutions in machine construction – as in nature – approach the absolute minimum in terms of the input of material and energy.

Direct milling of patterns accelerates the production of prototypes

Simultaneous engineering as practiced with the development partner makes the development and production of prototypes substantially faster than in conventional conditions. Despite the constant shortening of product lifecycles, the demands for reducing the time input for these processes in the design of complex iron castings are becoming louder. The fact that the design phase with concurrent part calculation by topology optimization helps save several weeks of development effort, has shifted the focus on actual production.

Therefore, investment in a modern ERP system, the wider use and flexibilization of machine tools as well as the expansion of the production network will help avoid bottlenecks in production and further optimize and shorten

Figure 10. Milled sand mould (left) for cast prototypes (right)

processes in the foundry shop and in mechanical production departments.

A significant potential for making the overall process faster is also seen in pattern and sand mould making. Because if traditional manual processes are followed, much of the time needed is for patternmaking (**Figure 9**).

The maximum time gain can be realized if the digital pattern of the target casting is used directly for making the sand mould. Rapid prototyping, for some time standard in the production of small parts, has not been applicable to larger components due to the lack of production equipment for generative mould construction methods.

Now it has become possible to make moulding material blocks directly in special machining centres and produce sand moulds of correct dimensions within very short time (**Figure 10**). The process termed DirektForm® will in future find application both in the production of individual parts, very small batches and also serially made components, even if targets are different.

In the production of individual parts and very small batches, direct mould milling is used for making complex sand moulds of high precision for pouring prototypes very much of exact size. As undercuts are no problem with this method and complex moulds have a substantial core savings potential, this method can be a viable alternative to conventional approaches of making extremely complex parts with suitable patterning equipment, including for very small batches.

If the components are developed for serial production, high-quality moulds are still needed. The milling of the hollow mould for the prototype based on digital product data can be a reasonable alternative also in this segment.

For one, to meet increasingly shorter deadlines and realize extremely short delivery periods. If the digital volume model is used throughout for milling the moulds, dimensional control and the generation of NC programs for chipping, development and production times for finish-machined prototypes of less than 10 weeks even for larger structural components are not a utopian target (**Figure 11**).

If time is of the essence and modifications of the mould are likely, the milling of the hollow mould for the prototype of a serially made part is the preferred approach even if frequent mould modifications can be expected or the serially made part must meet extremely close dimensional tolerances. In the latter case, the prototype should be gauged so that deviations from the target geometry due to shrinkage can be detected. Despite considerable progress in production simulation, such deviations can not always be foreseen exactly. Only the compensation of the gauged deviations in the blank's data record allows the CNC-backed production of pattern equipment for making a mould of extremely accurate castings.

Summary

The use of bionic optimization methods yields entirely new design solutions adapted to stress and strain and thus contributes to making problem solutions in machine con-

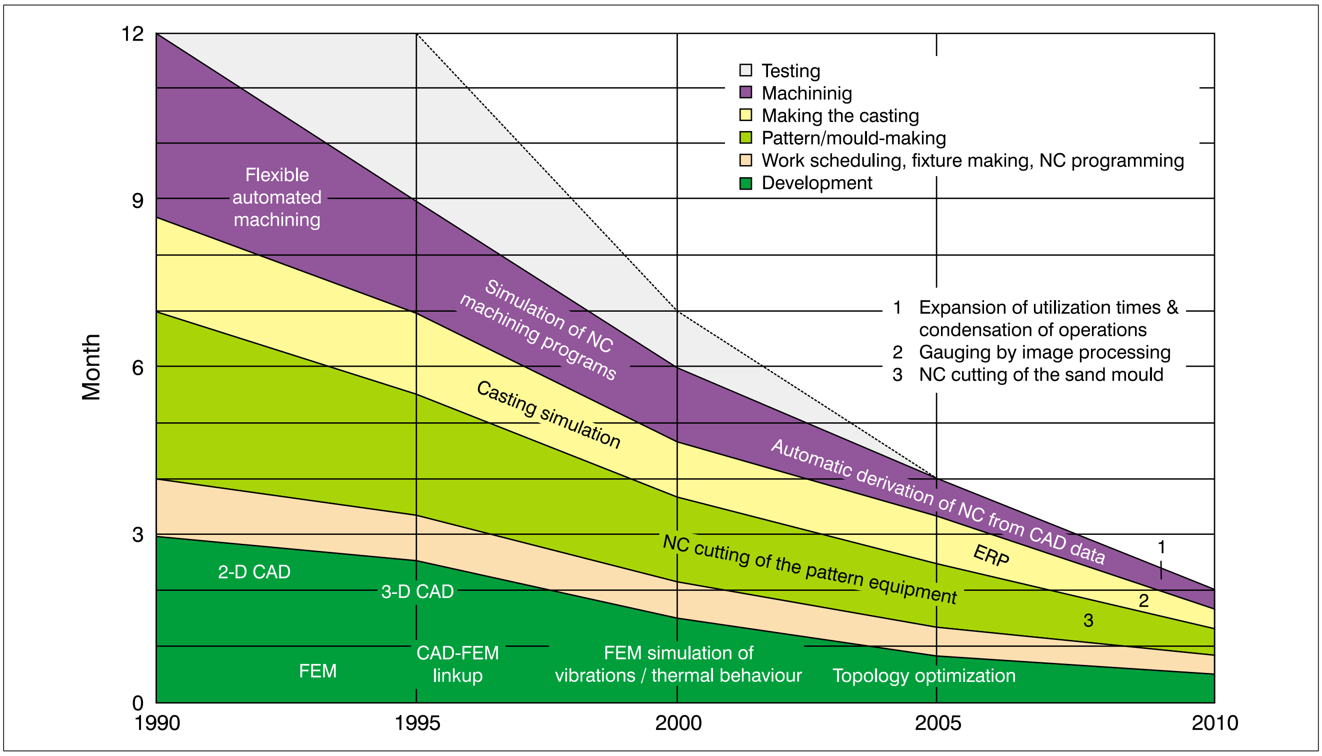

Figure 11. Cutting the time for prototyping by CAx methods

struction – as in nature – approach the absolute minimum in terms of the input of material and energy.

Already today, up to 25% lower costs and up to 50% better function (e.g., higher stiffness) are frequently obtained. The calculation and optimization expenditure can very well be adapted to the expected production volume.

In many of over 350 development projects for complex part designs we have seen that the entire input of computation and optimization was already recovered after 2 or 3 parts. Besides, the development process is accelerated by the simultaneous computation processes because fact-based decision-making processes hardly take any time.

On this background, is seems irresponsible not to run the calculation processes of a part in parallel with the design. The present state of the art is an exact FEM calculation, possibly with proof of strength on the basis of the applicable engineering rules. This will also become more important in the context of liability in future. ■

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