

Chapter 2

The CRC666 Approach: Realizing Optimized Solutions Based on Production Technological Innovation

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2.1 Motivation for and Goals of a New Development Approach

Finding technical solutions for given problems is one of a designer's key challenges. The task is especially demanding since the designer tries to find not only one possible solution but also the best possible solution, taking all existing conditions, limitations, and requirements into account (Pahl et al. 2007). There are many product development approaches that support the designer in this. The focus and drivers of the approaches differ:

- Reduction of complexity (Suh 1998)
- Integration of product development in company processes (Ehrlenspiel and Meerkamm 2013)
- Methodical approach based on analysis and synthesis steps (VDI 2221 1993)
- Cross-domain development of systems with a focus on mechatronic systems (VDI 2206 2004)
- Sustainable product design (Birkhofer et al. 2012)
- Effectiveness and efficiency (Lindemann 2009)
- Flexibility (Lindemann 2009)

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- Cost and time reduction; quality improvement (Eder and Hosnedl 2010)
- Computer-aided automatization (Weber 2005)

In addition, there is one especially important driver of product development approaches: *manufacturing technologies* (Sect. 1.2). Manufacturing technological knowledge, along with further knowledge about engineering and natural sciences, is important for the designer to be able to find feasible technical solutions (Pahl et al. 2007). Especially in technology-pushed development projects, knowledge about manufacturing technologies is essential for finding innovative solutions with comprehensively realized manufacturing potentials (Sect. 1.3). This knowledge is not always available for the product designer.

Although a huge number of manufacturing technologies are available, many manufacturing possibilities have not yet been taken into account, resulting in a high potential for realizing additional benefits in product and process solutions (Sect. 1.1). Innovative manufacturing technologies or novel combinations of manufacturing technologies especially offer new design possibilities (Sect. 1.3). A comprehensive analysis of these manufacturing technologies is required to provide the designer with knowledge about how to systematically realize manufacturing technological potential.

Unfortunately, there is no development approach that combines the mentioned aspects to find the best possible technical product and process solution and to realize manufacturing technological potentials on the basis of manufacturing technological knowledge. Many approaches focus on manufacturability of product solutions. Often, manufacturing information is only considered in later stages of the development process, during embodiment and detail design, resulting in iterations. Actual solution finding in the early phases of product development is typically not affected by manufacturing information. There are also approaches that focus on integrating manufacturing information into the development process. These approaches address the product in the context of its life cycle processes (including manufacturing) and support concurrent development of products and processes. Many of these approaches lack comprehensive operationalization due to the lack of a consistent system of concepts, models, methods, and tools (Sect. 1.2).

The goal is to provide a consistently formalized approach for realizing *manufacturing technological potential*, leading to an *innovative* as well as an *optimal product and process solution*. Manufacturing is no longer just a “service provider” for product development. Instead, an *integrated view* of the product and its *life cycle processes* during the *early development phases* is the focus, which can result in the following benefits:

- Ensuring optimality of the product and process solution
- Realizing technological possibilities, leading to product and process benefits in time, cost, and quality
- Realizing product and process innovations
- Increased product and process maturity in early phases of the development process, especially when considering new manufacturing technologies

2.2 Options in Manufacturing Technologies

Today’s industry offers many options in manufacturing technologies to produce a specific workpiece. According to Grote and Antonsson (2009) the term manufacturing is the production of workpieces of geometrically defined shapes, whereas manufacturing technologies allow for the production of products which are distinguished by material and geometric characteristics. According to DIN 8580 (2003) the numerous different manufacturing processes can be classified into six main groups: primary shaping, forming, cutting, joining, coating, and changing of material properties (Fig. 2.1).

For today’s industry one of the main tasks according to Westkämper and Warnecke (2010) is to select the manufacturing process with the greatest possible economic efficiency, taking into account the numerous criteria and given boundary conditions. In selecting the process, it is particularly important to consider the entire manufacturing chain up to the finished workpiece. A manufacturing process, which is assessed unfavorable due to an isolated view of the process chain, can prove more economical in the case of high unit numbers. In Westkämper (1997) this fact is shown in an assessment of different manufacturing chains for a gear. For a holistic view of the economic efficiency of a manufacturing process, the assessment criteria in Westkämper (1997) have to be considered (Fig. 2.2). Partially some assessment criteria are difficult to quantify, so many decisions in today’s industry are based on the employee’s experience.

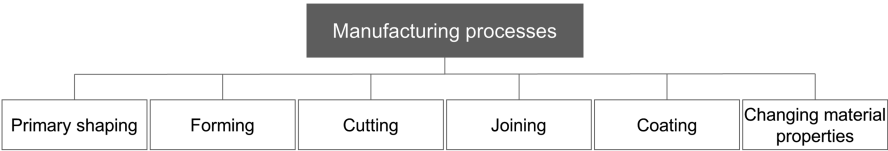


Fig. 2.1 Manufacturing processes after DIN 8580 (2003)

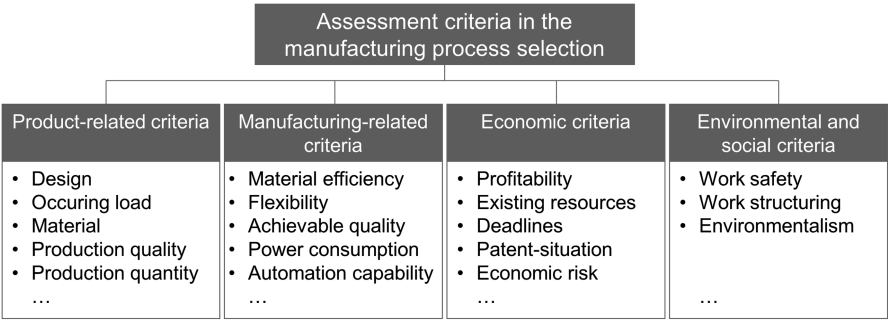


Fig. 2.2 Some assessment criteria in the selection of the suitable manufacturing process (Westkämper and Warnecke 2010)

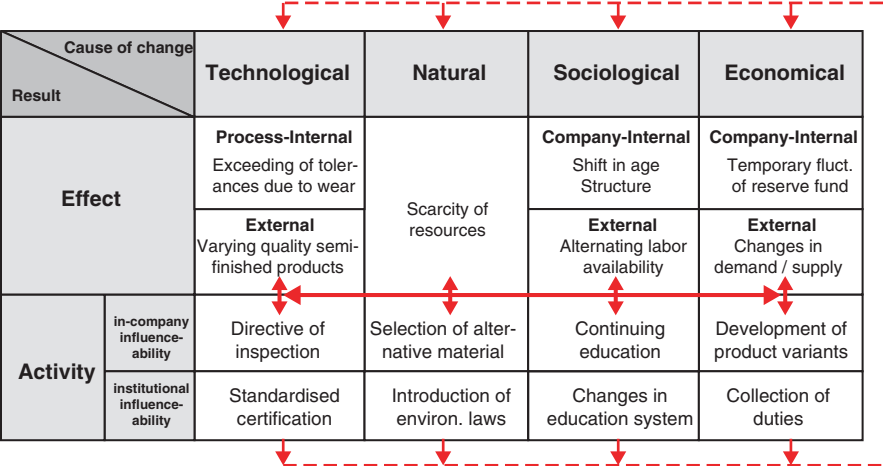


Fig. 2.3 Classification of uncertainties (Schmitt et al. 2012)

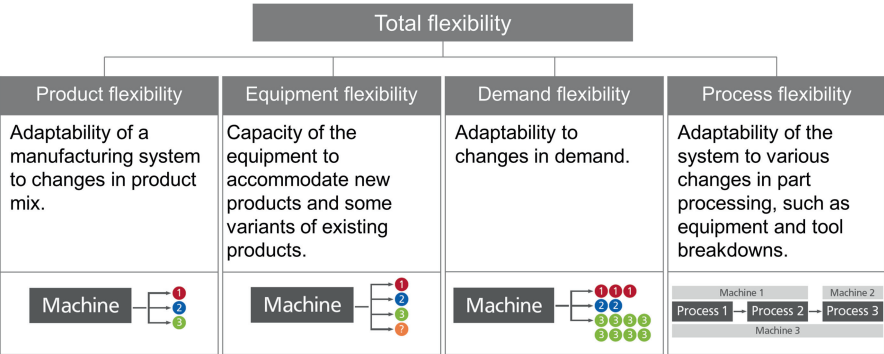


Fig. 2.4 Flexibility according to Son and Park (1987)

Uncertainties in Manufacturing Processes: Besides the decision of the economic manufacturing process, today’s forming companies are influenced by numerous uncertainties which are characterized in Schmitt et al. (2012) into four main categories of influencing parameters: technology, nature, society, and economy. Considering all four categories with regard to the cause of change and the result, 15 different kinds of uncertainties are classified (Fig. 2.3). There are also interrelationships between effects and activities as well as between different causes of change. For example, ecological developments can lead to nature conservation measures, which in turn require technological effects, such as the demand for a manufacturing process with reduced pollutant emission.

One approach to encounter the numerous uncertainties in the field of manufacturing is the concept of an increased flexibility of the applied systems and processes (Groche et al. 2010). According to Son and Park (1987) total flexibility consists of four different kinds of flexibility, which is shown in Fig. 2.4.

Product flexibility is determined as the adaptability of a manufacturing system to variances in the product mix. Equipment flexibility is the capability of a system to integrate new products and variants of existing products. Demand flexibility describes the adaptability of a manufacturing system to changes in the market demand. Last, process flexibility is defined as the adaptability of the system to changes in part processing, for example caused by changes of technology.

The trend of today's manufacturing lies in the flexible design of the total process chain. This often requires a higher initial investment by the manufacturer, but the manufacturing system can encounter the numerous uncertainties in a better way and could lead finally to a cost reduction. Flexibility is also regarded as an important objective for the development of new manufacturing processes. Since the area of application is unknown in the beginning, possibilities to produce a variety of product geometries made out of different materials are essential. The book at hand will demonstrate the expansion of basic technologies into a highly flexible class of manufacturing opportunities.

Manufacturing Processes for Branched Profile Geometries: For the production of profiles with branched cross sections, various manufacturing processes of DIN 8580 (2003) can be considered. On the basis of a targeted double-T-profile geometry, some of the possible processes are shown in Fig. 2.5. Against the background of thin-walled profiles in mass production, the manufacturing technologies of primary shaping, cutting, or joining are not effective enough and can be neglected. On the other hand, forming technologies offer many advantages, due to the material utilization or the improvement of the material properties and represent the main technologies to manufacture thin-walled profile geometries.

In the roll-forming process, a flat sheet metal can be continuously formed through several roll-forming tools to an open or closed profile geometry with any length. At the same time, the thickness of the sheet metal shall not be reduced. The common speed for production is between 40 and 100 m/min. Sheet metals with a thickness of 0.3–12 mm can be manufactured (Lange 1990). However, branched profile geometries can only be manufactured by roll forming by doubling the material, which could be in conflict with a lightweight profile design. In the process

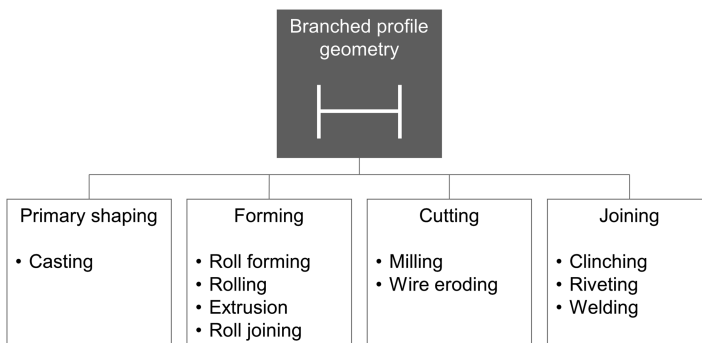


Fig. 2.5 Options in manufacturing of branched profile geometries

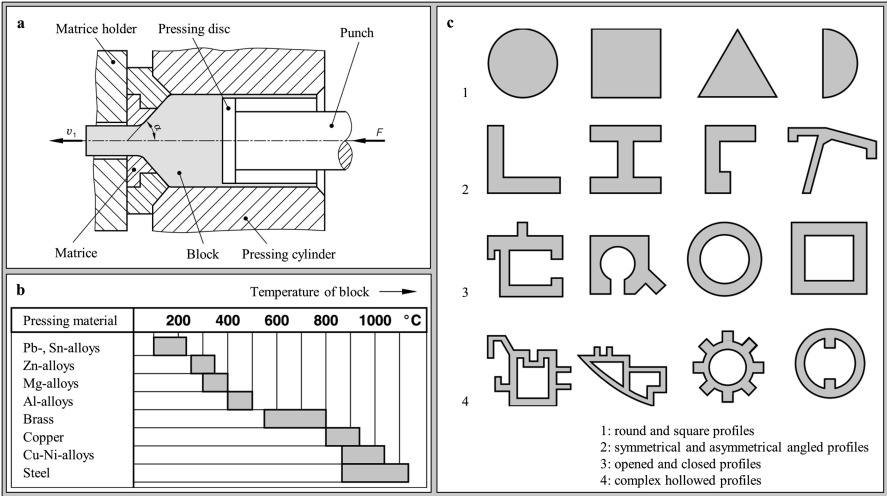


Fig. 2.6 Extrusion by Fritz and Schulze (2008): (a) process principles, (b) block temperature of pressing material, (c) possible profile geometries through extrusion

of rolling, slabs are formed by shaped rolls to the targeted profile geometry. The slab is usually heated and formed by several roll stands, whereas it is not possible to form a rectangular cross section directly to the final geometry. Rather a calibration sequence is necessary, which is often experience based (Lange 1988). However, rolling is usually used for thick-walled profile geometries. Other conventional forming technologies are represented by extrusion or roll joining, which are described in detail in the following section.

Extrusion: In the process of extrusion, a heated block is compressed by a punch in a pressing cylinder. The material starts to flow and exits the matrices as a continuous thread. The length of the manufactured threads is limited according to Fritz and Schulze (2008) to 20 m, whereas various profile geometries with undercuts or hollow spaces are possible. For extrusion well-formable materials are suitable, such as aluminum, copper, zinc, tin, lead, and their alloys. The temperature for the preheating of the block has to be adjusted to the material and is shown in Fig. 2.6.

Under certain conditions the extrusion of steel is also possible and can be realized by the *Ugine-Séjournet* process. Due to the high temperatures glass is used as lubricant. Very complex profile geometries are possible with the process of extrusion. The minimal wall thickness is limited to 3.5 mm for steel (Fritz and Schulze 2008).

Roll joining: The roll-joining process allows the continuous manufacturing of T-joint beams out of flat sheet metal strips and other materials and its combinations for lightweight constructions. New opportunities in the design of profiles are possible and are no longer limited to restrictions regarding sharpness or constant wall thickness such as in conventional roll-formed profiles (Lappe and

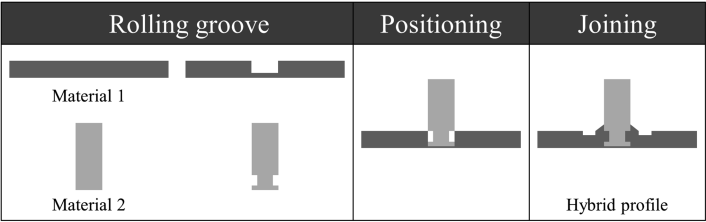


Fig. 2.7 Process principles of roll joining

Niemeier 2002). The process of roll joining consists of several stages, which are shown in Fig. 2.7.

In the first step, a continuous groove is rolled into the web of the profile and a discontinuous groove in longitudinal direction is rolled into the other joining part. In the second step, the two materials are positioned to each other. In the last step, the web of material 1 is locally rolled, whereby the material is plastified and flows into transversal direction. The gap between the two materials is closed and the result is a form- and force-locked hybrid connection.

Today’s manufacturing processes are severely limited with regard to the production of branched profile structures made of sheet metal. Up to now, there is no manufacturing process of DIN 8580 (2003), which allows the production of thin-walled, branched profile geometries with any length out of high-strength steels in integral style. This gap is closed with the new manufacturing processes linear flow splitting and bend splitting described in the following Chap. 3.

2.3 Manufacturing-Induced Properties

The realization of a novel development approach that strongly integrates production and product design (Sect. 2.1) is accompanied by the following key question: What information is fundamental for the designer’s perspective as well as for the manufacturer’s perspective in order to realize an integrated view of the product and its manufacturing processes?

Answering this question is only possible by characterizing the conceptual differences between manufacturing technologies in a formalized way. Each manufacturing technology, along with its manufacturing processes, describes a distinct way of realizing products with defined properties, starting from the workpiece’s initial state (Heidemann 2001). The product’s final state is mainly dependent on the chosen manufacturing technology and its underlying procedural principle, as well as the material used. The procedural principle characterizes and describes the generally valid transformation procedure from workpiece to product for a specific manufacturing technology (Gramlich 2013).

Considering manufacturing technologies for realizing external threads, there are primarily two options, thread cutting and thread rolling. The procedural principle of

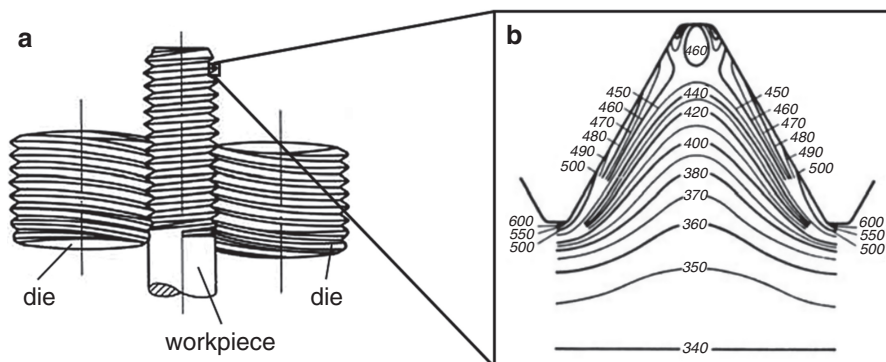


Fig. 2.8 (a) Die arrangement for thread rolling (through feed method), (b) grain direction and hardness pattern in rolled threads (alloy steel) according to Tschaetsch (2006)

thread rolling, which is used in the vast majority of applications, is based on plastic deformation of the blank using a set of rolling dies (Tschaetsch 2006) (Fig. 2.8a). The penetration of the rolling dies into the blank surface not only creates the thread geometry but also changes the local material properties (Fig. 2.8b). Due to work hardening, the yield strength of the material increases substantially, especially in the root and at the flanks. Furthermore, strain gradients during the manufacturing process result in the formation of subsurface compressive residual stresses in axial direction. In contrast to thread cutting, the grain flow remains intact, thus avoiding preferred crack initiation sites near the root (Tschaetsch 2006).

Based on the specific procedural principle, the manufacturing technology realizes characteristic and reproducible product properties. These characteristic properties are called manufacturing-induced properties (Groche et al. 2012). Manufacturing-induced properties are always assigned to manufacturing-induced design elements, such as the external thread. Consequently, manufacturing technologies are unambiguously characterized by a specific set of manufacturing-induced properties realized in specific products (Groche et al. 2012). The formal description of products by their properties gives the product designer the opportunity to formally model and document all technical products (Birkhofer and Wäldele 2008). Thus, manufacturing-induced properties are crucial for both the product designer and the manufacturer who focuses on manufacturing processes, especially their output. Within an integrated development approach, manufacturing-induced properties are a key element for establishing the link between designer and manufacturer perspectives.

The example of thread rolling clarifies that manufacturing technologies not only realize the geometric properties of products but also have a significant influence on material properties. Material properties involve mechanical properties (mechanical resistance, impact resistance, fatigue resistance, formability, residual stresses, etc.), surface properties (surface topography, wear resistance, corrosion resistance, etc.), and physical properties (electrical properties, magnetic properties, optical properties, etc.) (Tekkaya et al. 2015). Consequently, manufacturing-induced properties

are comprised of geometric and material properties, which necessitates the investigation of both (Chaps. 3 and 4) when considering them within a manufacturing-integrated development approach. Utilizing the potential of manufacturing-induced properties can lead to products with higher performance and functionality (Sect. 4.3).

2.4 Mathematical Optimization of Product Geometries and Manufacturing Processes

Optimization is an important tool to improve the efficiency and effectiveness of mechanical devices. Depending on the scientific discipline, optimization processes are understood differently. From an engineering point of view, an optimized process often only means the improvement of one parameter like the production volume per hour (Pahl et al. 2006). Optimization in a mathematical sense implies finding the proven best solution under defined constraints using an optimization model (Jarre and Stoer 2013). This chapter provides an introduction to the mathematical optimization of product structures and manufacturing processes. Later on, we will introduce optimization procedures applied to the design of branched structures (Sect. 5.2) and the manufacturing processes to produce them (Sect. 5.3).

Optimal structures can be characterized by the following properties:

- Multifunctional
- Functional and stressable
- Maximized strength and operationally stable
- Weight minimized
- Optimized in terms of heat conduction and transfer
- Minimum number of individual parts

If technical branched structures with regard to these requirements are investigated, some deficits can be observed. This is due to the fact that in most structures only certain requirements were optimized. Furthermore, some requirements cannot be optimized at the same time since they are contradicting. Therefore, this leads to conflicts of objectives. For example, focusing on the minimum number of parts leads to geometrical limits caused by the used manufacturing process. These geometrical limitations can be in conflict with functional requirements. Here, multiobjective algorithms offer the possibility of finding an optimal solution for these complex problems not only for the product itself. Conflicting manufacturing process parameters can be optimized, too.

Optimality of a product often is not reached due to the fact that the development process of a new component typically strongly depends on the intuition and experience of the designer. For instance, it depends on intelligence and creativity of the developers. In a conventional development process, the subjectivity manifests especially in the evaluation of proposed solutions. The choice of evaluation

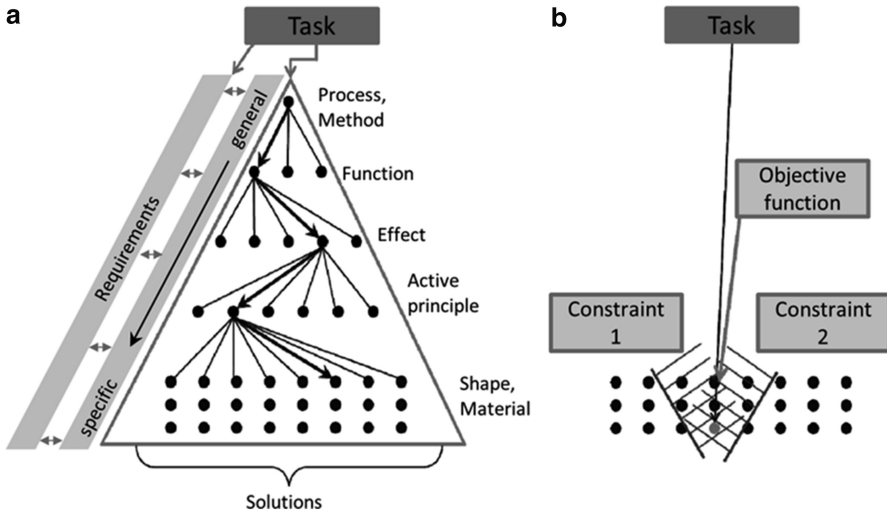


Fig. 2.9 (a) Conventional development, (b) algorithm-based development

criteria and subsequent evaluation of solutions can lead to people-related errors and is often the weak spot of a methodical development process (Pahl et al. 2006).

An algorithm-based product development combined with a mathematical optimization increases the degree of automation of this process and improves product properties. It also provides a decision assistance for the designer. Figure 2.9 shows the differences between a conventional (a) and an algorithm-based development process (b). Proceeding along the conventional development process, the number of possible solutions increases for the initial problem. With the variety of existing solutions, it is difficult to find the ideal solution. The rating of the solutions is, as mentioned before, strongly depending on the planner. In contrast, the algorithm-based approach to solve the design task leads directly to an optimal solution. The objective function rates the different solutions objectively and constrains the solution space. Therefore, the optimal solution for a design task can often be found quicker and more accurately. However, a mandatory requirement for a mathematical optimization-based development task is that we can model the problem.

Computational costs often limit the application of optimization methods. Simulation techniques, like finite element analysis (FEA) or computational fluid dynamics (CFD), are very expensive in terms of time consumption and system requirements (Roy et al. 2008). The calculation time for an optimization task depends on the problem size. The range of time to find the optimum varies from a few seconds up to years for complex algorithms. However, Bixby (2002) found that the combination of algorithm improvement and further development of computer chips continuously provides new opportunities to solve increasingly complex optimization tasks. In the time range of 10 years, both algorithmic speed and solving power increased by a magnitude of three orders and thus accelerate

the solution of a complex linear problem by a factor of more than one million (Bixby 2002).

Finally, developments using mathematical optimization methods provide several additional benefits. Many experimental iteration steps in product developments are replaced by automatically conducted computational iterations. These procedures require fewer resources and man power. The formulation of the optimization model itself leads to a new perspective and a deeper understanding of the development task or the process. Even if the optimum cannot be found, the developer gets an overview on the influences and effects of design/process parameters. Although the algorithm-based development possesses a high degree of automation, the formulation of the optimization model and the choice of the algorithm still depend on personal know-how. An automatic setup of the optimization task is not possible in most cases. Algorithms are often derived from related problems.

Another advantage of mathematical optimization is the fact that optimality can be proven. A popular example for a requirement of an optimum are the Karush-Kuhn-Tucker conditions (Nocedal and Wright 2006). They generalize the necessary condition $F(x) = 0$ for a convex nonlinear first-order problem.

2.4.1 *Classification of Optimization Tasks*

This section classifies the optimization types in several categories. After a short introduction of the general optimization process, a classification of product optimization algorithms is presented, followed by a characterization of process optimization. Then, a brief mathematical view on the topic is given. Eventually, after the aspect of optimization under uncertainty is introduced, some examples for classical optimization tasks are given in the next section.

Adamy (2011) describes the general flow of an optimization process in three steps:

1. Mathematical formulation of the optimization problem
2. Selection of a suitable algorithm
3. Determination of a solution

Roy et al. give an extensive overview on the topic of engineering design optimization (EDO) (Roy et al. 2008). Table 2.1 shows several criteria for the classification of EDO algorithms.

The design variables are a possible classification scheme. The number, nature, or dependence of the variables are subcategories. The constraints lead to another way of categorization of an EDO. The number and type of constraints have a significant influence on the optimization process. Furthermore, the problem domain, characterized by the physics of the problem, or its environment with further subcategories provides another possible ranking. From a mathematical perspective, the objective functions are another possible classification category. Their number, nature, and separability lead to many categories of optimization problems (Roy et al. 2008).

Table 2.1 Classification of EDO algorithms (Roy et al. 2008)

Category	Subcategory
Design variables	Number of variables
	Nature of design variables
	Permissible values of design variables
	Dependence among design variables
Constraints	Existence of constraints
Objective functions	Number of objective functions
	Nature of objective functions
	Separability of objective functions
Problem domain	Physics of problem
Environment	Uncertainty
	Existing knowledge about the problem
	Designer confidence required
	Nature of the environment

Besides product optimization, process optimization is a category of its own. However, the former mentioned EDO classifications can be adopted by using the number of processes as a possible classification scheme. Besides single processes, an optimal order of a process chain can also be calculated with the aim of the smallest throughput time. This approach can also be added to be called process optimization. This optimization is also useful to shorten downtimes in production processes.

The mathematical representation of the task can be summarized in the minimization (or maximization) of an objective function $F(x)$ for the variables x , respecting the given constraints. From a mathematical perspective, optimization problems can be separated into three classes (Biegler 2010):

- Differentiable (derivative based)
- Nondifferentiable (derivative free)
- Discrete

Derivative-based strategies search for an optimal solution by using the derivative of the objective function $F(x)$ and try to find feasible solutions x that lead to $F(x) = 0$. If $F(x)$ is differentiable, this is the most common way to solve optimization problems, because of its speed and the fact that local optimality of the solution can be proven. Classical examples are the Newton method or the sequential quadratic programming (SQP) method (Nocedal and Wright 2006). However, practical problems are often of a complexity that the differentiation and evaluation of the objective function are too expensive. Derivative-free algorithms like the Nelder-Mead method are a possible alternative (Conn et al. 2009). Finding a local optimum with a derivative-free algorithm is often more time consuming because the solutions are found iteratively and built on top of each other, allowing to use less

information about the problem. Discrete algorithms, dealing with integer problems, are the third class. The branch-and-bound algorithm, with its tree structure, is a typical algorithm for this class (Lawler and Wood 1966). They are often used to solve logical or combinatorial problems.

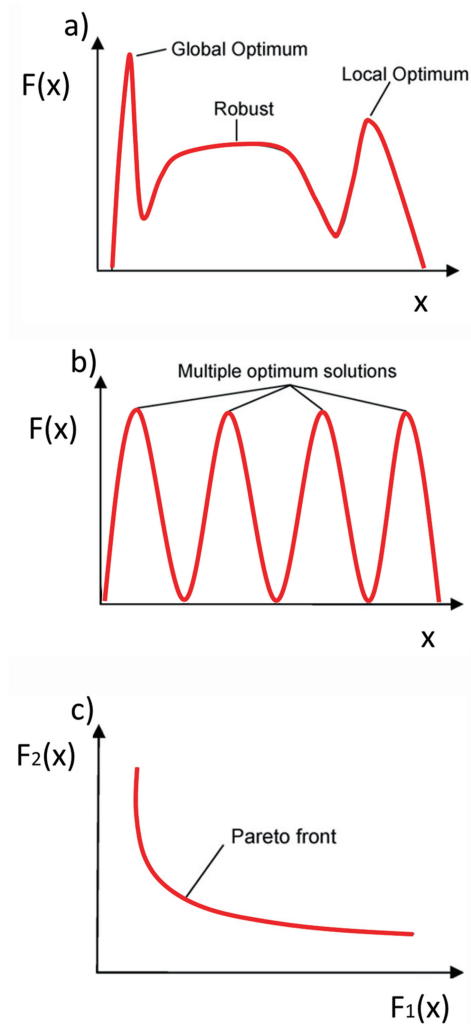
Furthermore, evolutionary and genetic optimization strategies have to be mentioned as an important algorithm group that is often referred to as *heuristic*. They are derivative free but do not fit exactly in one of the three formerly mentioned classes. Evolutionary and genetic algorithms are often used to find an approximation of a global optimum of a problem. There are no quality criteria for this class of algorithms. This type of optimization method is limited in its usefulness because it is impossible to determine the quality of the solution and whether or not it would be worth to continue with the optimization. However, their application in technical backgrounds has become more important as several examples show (Adamy 2011).

The definition of a global optimum and some other important mathematical definitions in optimization problems are depicted in Fig. 2.10a–c. In Fig. 2.10a, the difference between local, global, and robust optima is shown. Whereas a global optimum is a best solution for the entire function, a local optimum obtains the best objective value within a region. In practical problems it is often impossible to determine whether the found optimum is a global or just a local optimum, because computing a global evaluation is not feasible or it is too expensive to prove global optimality. For practical applications it is also very important that the found solution is robust. Robustness implies that relevant changes in design values do not lead to significant changes in the value of the objective function. A representation of multiple optimum solutions can be seen in Fig. 2.10b. Here, several points lead to the best solution for the optimization tasks. Therefore, one aim is to find as many optimal solutions as possible.

In multi-objective problems with more than one objective function, the amount of optimal solutions can be summarized in a Pareto front (see Fig. 2.10c). A change of the value that leads to a better solution for one objective function leads to a worse solution for the other objective function on the Pareto front.

Uncertainties in real-life problems, like unpredictable parameters or inaccuracies in manufacturing processes and products, lead to the necessity of robust optimization. Beyer and Sendhoff give an extensive review on the recent achievements in this field of research (Beyer and Sendhoff 2007). In some approaches, the uncertainty is represented in the objective function by statistical information like the standard deviation and the mean (Roy et al. 2008). Wiebenga et al. summarize that balancing the number of time-consuming FE simulations spent on the robustness evaluation and the accuracy of the robustness predictions themselves are remaining challenges in robust process optimization (Wiebenga et al. 2012). The determination and handling of uncertainties in the optimization of process chains and mechanical structures is one central research aim of the CRC805 at TU Darmstadt. Recent developments in this area can be found in the proceedings of ICUME 2015 (Pelz and Groche 2015).

Fig. 2.10 (a) Mathematical definitions of robust optimization, global/local optimum, (b) multiple optimum solutions, (c) Pareto front (Roy et al. 2008)



2.4.2 Examples for Optimization

This section introduces examples for applied optimization and the generated benefit for product and process development. While product optimization focuses on the properties of a product, we also often try to find ideal conditions for the production in a process optimization.

Product optimization: Marsden et al. present an example for a derivative-free product optimization. The surrogate management framework (SMF) technique is applied to optimize the trailing of an airfoil to reduce noise in unsteady laminar flow. The objective function that is minimized represents the acoustic density at a

Fig. 2.11 Optimization of an airfoil shape in laminar flow regarding noise reduction; original shape (*upper plot*); upper surface optimization (*middle plot*); two-sided optimization (*bottom plot*) (Marsden et al. 2004)

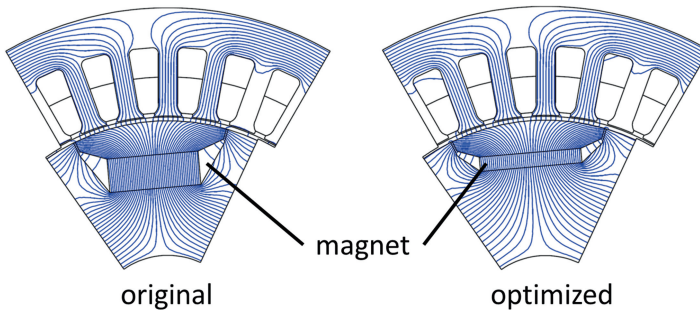
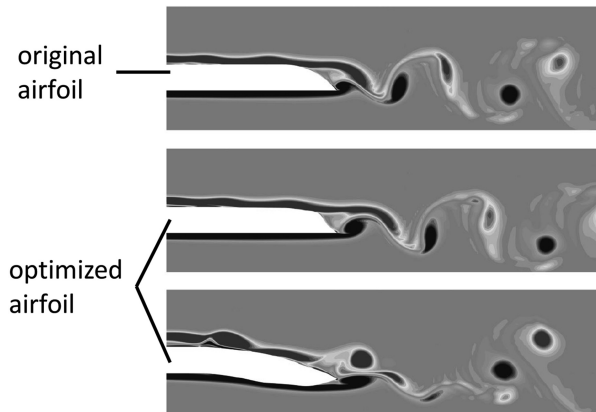


Fig. 2.12 Original and optimized magnet design of an electromagnetic machine (Alla et al. 2015)

far-field position. The dimensionless lift and drag of the airfoil are used to set the constraints for the optimization problem. A reduction of 70% in vortex shedding noise could be achieved by an optimized airfoil shape. The resulting shapes compared to the original shape are plotted in Fig. 2.11 (Marsden et al. 2004).

Another example for a mathematical product optimization is given by Alla et al. In their case, the derivative-based SQP method is applied to optimize an electromagnetic machine with permanent magnets. In order to save expensive material, the optimization goal is to minimize the volume of the magnet for a given electromotive force. The problem is transformed from 3D into a 2D problem, and as we can see in Fig. 2.12, a volume reduction of more than 50% is achieved compared to the original design without a decrease in electromotive performance (Alla et al. 2015).

Mathematical optimization can also be utilized in products of much bigger dimensions as Koch et al. (2015) show. In their book “Evaluating gas network capacities” a nationwide gas network is examined by the use of discrete-nonlinear or mixed-integer nonlinear optimization algorithms. The primary goal of the optimization problem is to find a way to transport a certain amount of gas. A challenge in this task is the consideration of active elements, like valves, in the mathematical model (Koch et al. 2015).

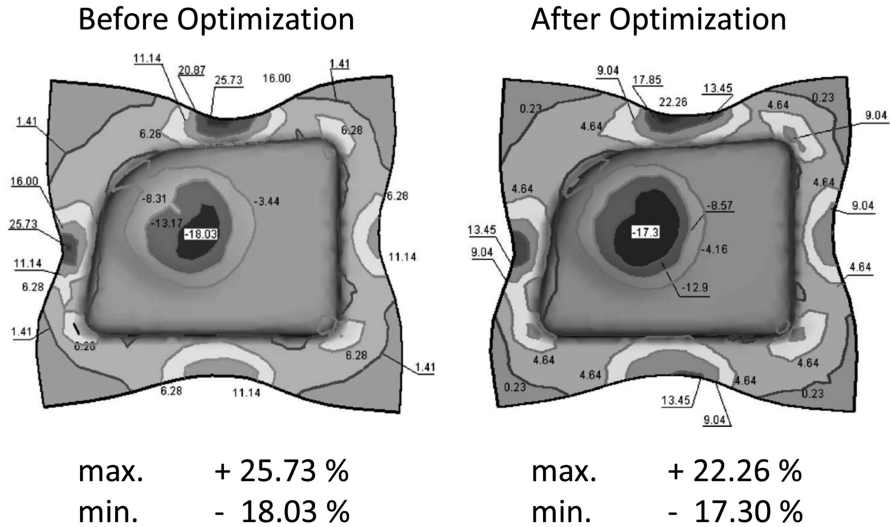


Fig. 2.13 Sheet metal thickness distribution of a deep-drawn dashpot cup before and after process optimization (Naceur et al. 2001)

Process optimization: Derivative-free optimization can also be used to find the optimal process conditions. Agapiou shows the application of the Nelder-Mead simplex method to find the best parameters for a machining process. He determines the optimum for the cutting speed and feed for a given cutting depth in a turning process. The aim is to minimize the production time and production costs which are affected by tool wear (Agapiou 1992).

Another mathematical process optimization is introduced by Naceur et al. They use the derivative-based SQP and Broyden-Fletcher-Goldfarb-Shanno (BFGS) method to improve a deep drawing process. The drawbead design and restraining forces are optimized to minimize the thinning distribution of the sheet metal part which is significant for the typical deep-drawing errors necking and wrinkling of the cup. The variations in thickness could be minimized by 97% in a square cup. The authors also present the application of the optimization on the production of a dashpot cup in a car (see Fig. 2.13). Hence, this work shows the usefulness of optimization for industrial processes (Naceur et al. 2001).

2.5 Integrated Algorithm-Based Product and Process Development

Product development and manufacturing are closely related not just because every product has to be produced. A symbiosis between both domains can be especially beneficial: An extensive exchange of information not only leads to better products

but also to manufacturing processes which better fit to product design (Sect. 1.1). Existing approaches mainly focus on developing the product and ensuring its manufacturability. Rethinking is necessary to realize the full potential of both domains. Domain-specific methods and procedures have to give way to a multi-domain consideration of the entire technical system. Developing both domains requires a consideration of the product and its life cycle processes, with a focus on manufacturing (Ehrlenspiel and Meerkamm 2013). Integrated development approaches possess the highest potential for the development of innovative products and processes (Sect. 1.2), especially when considering technology-pushed development processes. Manufacturing technologies are the starting point of the development process. A development approach aiming at successful realization of a technology-pushed product or process solution requires comprehensive and equal development of the product and the processes that are based on the initial manufacturing technology (Sect. 1.3).

Innovative manufacturing technologies and novel combinations of manufacturing technologies create new possibilities for innovative product solutions (Sect. 2.2). A development approach has to be able to identify and process essential manufacturing technological knowledge to fully realize this potential. Manufacturing-induced properties that are realized with the help of the considered manufacturing technology play a major role in formalizing this knowledge (Sect. 2.3). The challenge of an integrated product and process development approach lies mainly in the high complexity that arises from the concurrent consideration of large amounts of product and process development information and restrictions. Implementing and utilizing mathematical optimization algorithms is an adequate way to handle this complexity (Sect. 2.4).

Based on this foundation, a new approach for an *integrated algorithm-based product and process development* that allows comprehensive consideration of product and process information with the help of mathematical algorithms is introduced. The approach has the following key elements:

- *Early determination of suitable manufacturing technologies*
An early determination of suitable manufacturing technologies is mandatory for the combined consideration of product and process information. In particular, innovative technologies, like linear flow splitting, create new design possibilities that have to be determined by anticipating and analyzing manufacturing processes (Chap. 3). The characteristics of manufactured products, described with the help of manufacturing-induced properties, have to be processed specifically for product and process development purposes (Chap. 4).
- *Product and process solution finding by applying optimization algorithms*
Finding optimal product and process solutions is a key element of the development process. Especially in the context of technical problems with complex product and process requirements, solution finding can be executed more efficiently with the help of mathematical optimization algorithms (Chap. 5).

- *Consistent integration*
Computer-integrated methods, tools, and interfaces that are specifically tailored to the overall approach enable collective processing of product and process information during the whole development process (Chap. 6).
- *Product and process innovation*
To develop innovative products in the context of their life cycle processes, the approach allows the development of market-pulled and technology-pushed solutions (Chaps. 7 and 8).

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