Series production of high-strength composites
Perspectives for the German engineering industry
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Executive Summary

> This study draws upon the knowhow of more than 30 leading industry experts in order to determine the German engineering industry’s positioning in regard to the production of composite parts

> The market for high-strength fiber-reinforced composites will experience solid growth until 2020. At a rate of 17% per annum, demand for high-strength components made from carbon-fiber-reinforced plastics (CFRPs) will grow significantly stronger than demand for high-strength glass-fiber-reinforced plastics (GFRPs)

> The key growth drivers are automotive and aerospace applications, although demand from wind power and engineering sectors is also expected to increase

> The market growth is contingent on further cost reductions. Over the next ten years, a cost reduction of 30% for CFRP components seems realistic. These cost savings will primarily be derived from process improvements (cost reduction of 40%) rather than lower raw material costs (fibers: -20%)

> The industrialization of the production processes for medium-sized series has started with a focus on semi-automated resin-transfer molding (RTM) and compression molding, which are suitable for production of surface and structural components for a wide range of applications

> For the development of corresponding process chains, different technologies and components from various engineering segments – primarily from plastics machinery, machine tools and textile machinery, as well automation and handling systems – must be integrated. This will require intercompany cooperation

> Given the current modest size of the market for composite production systems, most engineering companies are adopting a strategy of adjusting and improving existing technologies and products

> In the period following 2020, additional cost reductions and, in particular, the hybridization of composite parts (combining continuous fibers with further materials such as metal or short fibers) will trigger dramatic market expansion. Hybrid materials can be produced using processes similar to the ones adapted for pure composites

> Those engineering companies that consciously enter the “composite production” segment and adopt a clear strategic positioning will dominate the market in the medium to long term and will make the most of the expected market growth
1. Study design – Objectives and methodology

In every industry one might care to mention, the tremendous importance of energy and resource efficiency brings lightweight products in the spotlight. As a result, traditional construction materials such as aluminum and high-strength steels increasingly make room for fiber-reinforced composites that can exhibit a significantly greater lightweight potential in certain applications. This is especially true for components for which both the strength and stiffness are crucial to their design.

Ten to fifteen years ago, fiber-reinforced materials were the exclusive preserve of high-end applications such as in the aviation and aerospace or Formula 1 racing segment but have by now become an established feature in other segments too. Despite the fact that they are mainly deployed in niche applications within a modestly sized overall market, all interviewed experts anticipate a forceful growth in high-strength composites in the years ahead – primarily due to their potential in lightweight construction.

Considerable media attention has, for example, been drawn to the topic by the BMW i project, which for the first time will see a medium series of some tens of thousands of automobiles built around a body made of CFRP in 2013. Other publically noted projects include the construction of new aircraft such as the A350 and the B787 that both feature a structure with more than 50% made out of CFRP. While resultant coverage has highlighted many important aspects, the focus was mostly derived from the perspective of either the end customer or the manufacturer of high-strength composites.

However, the more widespread use of high-strength fiber-reinforced plastics in various areas of application also raises interesting questions from the production technology perspective: Which series volumes are expected in future? Are today’s manual production processes suitable for the future? Which manufacturing concepts are best suited to series production? What can the German engineering industry contribute to further development? Which business potential does the future hold?

In light of these questions, VDMA German Engineering Federation’s Composite Technology Forum and Roland Berger Strategy Consultants decided to conduct a joint study to investigate the future challenges and opportunities for the German engineering industry in this segment.

The key questions and objectives addressed by the study are summarized in Figure 1.
The focus are high-strength composites based on thermoset or thermoplastic matrix materials and reinforced by continuous glass and carbon fibers. Methods and concepts of production processes from fiber to finished part constitute the object of the study. The study did not include a detailed analysis of the component processing, joining technology, surface treatment and inspection systems segments.

Extensive research into the technology and relevant areas of application was followed by more than 30 expert interviews conducted in a broad empirical approach. Interviewed experts cover the entire value chain of high-strength composite, ranging from fiber production and the manufacture of semi-finished products to OEM application in various industries (automotive, aerospace, wind power and engineered products). Experts representing the research and scientific communities were also included to identify the direction of current technological development. The engineering industry was represented primarily by experts from plastic and rubber machinery, machine tools, textile machinery, robotics and automation segments.

On completion of the study, the gained insights relevant to the engineering industry were condensed to a series of hypotheses that were validated with members of the VDMA Forum. The interviewees represent every segment of engineering that is relevant in developing production facilities for high-strength fiber-reinforced composites.
2. Continuous-fiber-reinforced composites at a glance – Materials, performance, manufacturing processes and costs

This section seeks to establish a basic understanding of the cost and performance of various high-strength fiber-reinforced composites and their existing manufacturing processes. This is essential to fully grasp and assess the conclusions derived in the following sections.

2.1 Common fiber matrix combinations and their properties

Fiber-reinforced composites are a relatively recent group of materials that essentially combine a textile reinforcement structure (fibers) with matrix material. Performance, production, and costs are determined by both the choice of fiber or matrix materials and the nature or structure of the reinforcement – in particular the length of the fibers used. Figure 2 illustrates the point.

Parts that are subject to significant mechanical stresses can be almost entirely created from continuous fibers whose length is restricted only by the dimensions of the part itself. These composites thus contrast with those that use short (no more than a few millimeters) or long fibers (up to approximately 50 mm).

Continuous-fiber-reinforced composites used in volume applications only consist of glass or carbon fibers. These composites are referred to as glass-fiber-reinforced plastics (GFRPs) or carbon-fiber-reinforced plastics (CFRPs).

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**Figure 2: Composites at a glance**

- **FIBER MATERIAL**
  - Aramide
  - Carbon
  - Glass
  - Mineral fiber (e.g., basalt)
  - Natural fiber (e.g., hemp)

- **MATRIX MATERIAL**
  - Ceramics
  - Plastics:
    - Thermoset
    - Thermoplastics
  - Metal
  - Concrete

Continuous-fiber-reinforced plastics for high-performance applications

Source: VDMA; Roland Berger
Aramid fibers are used in applications that require exceptionally high energy absorption in the event of an impact. Examples include bullet-proof vests and armor-plating for vehicles. Just like mineral fibers, they have so far played no more than a minor role in volume applications. Natural fibers, which are becoming more popular in an array of applications, likewise are of minor importance in the context of continuous fiber reinforcement. This is because they exist in nature only in the form of short fibers (such as the 20-40-mm elementary fibers that make up flax). Additional ceramic and metallic fibers are used in niche markets such as high-temperature applications in astronautics. These types of fiber are ignored for the purpose of this study due to fact that they do not have a significant market volume in volume applications.

For industrial volume applications, only polymers are used as matrix materials. Polymers break down into two major categories: thermosets and thermoplastics. Ceramic matrix materials only occur in highly specialized niche segments such as extremely high-temperature applications. Usually, only one matrix material is used per component, whereas combinations of different fibers occur more frequently.

From the two fibers and two matrix materials used in volume applications for continuous-fiber-reinforced parts, four possible combinations can be derived that all exhibit different properties (see Figure 3). The combination of thermosets and carbon fibers holds the best mechanical properties but is also the most expensive of the four options. Combinations involving glass fibers cost significantly less but exhibit inferior mechanical properties.
In many applications, the "essential" elements – fibers and matrix materials – are complemented by additional materials. Examples include fillers to improve edge strength, dyes to adjust visual properties and cores (e.g. foam, balsawood and honeycomb structures) that increase bending stiffness when inserted between two thin layers of fiber composites.

As a general rule, the stresses to which a part is exposed determine the choice of the material combination. However, due consideration must also be given to the consequences of a material choice on the design of the production process – especially in regard to the demands of series production (see the following section).

The fibers and the matrix that make up the composite serve fundamentally different purposes. While the fibers essentially absorb the traction that is exerted on the part, the matrix primarily maintains cohesion of the component and absorbs both compression and shear forces. Figure 4 illustrates the relative importance of the fibers and matrix for the mechanical as well as the physical/chemical properties of the resultant product. Whereas the mechanical properties are shaped mainly by the fibers, the physical/chemical properties depend to a large extent on the matrix.

**Figure 4: Relative importance of fibers and matrix materials in composites**

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<tr>
<th>Mechanical properties</th>
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<th>Matrix</th>
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<td>Strength</td>
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<th>Physical and chemical properties</th>
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<td>Corrosion behavior</td>
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High-strength fiber-reinforced composites have two major advantages over traditional materials: a very high specific stiffness and a very high specific strength ("specific" meaning "in relation to the mass").
As shown in Figure 5, this especially applies to unidirectional laminates in which the fibers run in one direction only. Channeling stress in the direction of the fiber makes optimal use of the fiber’s outstanding mechanical properties and can achieve more than five times the stiffness and strength of steel. In the case of quasi-isotropic laminates (i.e. laminates whose properties are identical in all directions), the advantage over traditional materials is less pronounced but usually still present (see Figure 5).

Unlike isotropic construction materials, fiber composites allow part-specific material properties to be optimized, for example by aligning fibers in the direction of stress. Full exploitation of the benefits associated with these materials can only be achieved through such specific adaption.

**Figure 5: Mechanical parameters of selected composites and metals**

![Diagram showing mechanical parameters of selected composites and metals](image)

1) Unidirectional 2) In relation to steel = 1

Source: Swiss Federal Institute of Technology (ETH), Zurich

### 2.2 Production methods

The properties of parts manufactured from isotropic materials are primarily determined by the properties of the input material. For composites, however, the production method has a comparatively significant influence on the properties of the final part.

Different process chains can be used to transform the fibers and the matrix material into the final composite component, as shown in Figure 6. In addition to the direct use of fibers and resin (e.g. in fiber-winding processes), semi-finished goods are employed in the majority of applications.
These can, for example, take the form of semi-finished textile products that are made from the fibers using textile production techniques such as weaving and looming, etc., before being impregnated with resin and cured at the end of the process.

Alternatively, fibers and resin can be combined in the semi-finished product itself. In the case of thermostet resin, these semi-finished products are known as prepregs (preimpregnated multiaxial fabrics or textiles). If thermoplastics are used, the resultant semi-finished products are referred to as organo sheets, in which the fibers are embedded in the thermoplastic matrix.

For component production, raw parts are derived from semi-finished materials that, in turn, are further processed, e.g. by trimming the edges and/or preparing the surfaces for subsequent joining operations.

In detail, a wide array of methods can be used to produce components. An overview of relevant methods – depending on component geometry – is provided in Figure 7. The figure only shows methods that can be used to manufacture continuous-fiber-reinforced parts (flow molding is suitable only if fiber-textiles are added). Methods such as injection molding, which are only suitable for short- or long-fiber-reinforced composites, are excluded from the figure. The same applies to variations or derivations of particular methods.
Pultrusion (1) and fiber-winding (2) are essentially suitable only for (largely) symmetric parts. The pultrusion method involves pulling fiber rovings first through a resin bath and then through a heated mold. In the mold, the resin and the fibers are compressed to create a continuous section. The cured section can then be cut to size as required. With the “pull-forming” variant, the partially cured section is subsequently pressed into its final geometry before fully curing it. Typical applications include beams, stiffening ribs and structural sections.

Fiber-winding involves passing fibers through a resin bath and then winding them around a mandrel. Almost without exception, this is done on automated systems on which the direction of the fibers can be influenced by the speed of rotation and the position of the winding head. However, it is not possible to completely align the fibers in parallel to the mandrel’s axis of rotation. Since automation is already highly advanced, this method is well suited to volume processes and is typically used for pipes, tanks, pressure vessels, axle shafts and similar components.

The placement and curing of pre-impregnated semi-finished products in autoclaves (3), vacuum-assisted infusion (4) and hand lamination (5) are all methods that are especially well suited to large and geometrically complex parts.
The hand lamination method is based on dry semi-finished fiber products (woven and multiaxial fabrics, etc.) that are manually placed in a mold, impregnated with resin, and manually consolidated (e.g. using rollers). Curing can take place under a variety of conditions. In addition to standard pressure and room temperature, heated molds are often used to expose components to higher temperatures. Typical applications cover a broad spectrum of large parts, e.g. for boat and tank building.

Vacuum-assisted infusion involves placing dry semi-finished textile products in a mold, covering them with a breather and then sealing them with a vacuum bag. Withdrawing the air leads to the creation of a vacuum that draws the resin into the laminate as soon as the resin inlets are opened. The vacuum-assisted resin infusion process leads to a more compact part than the hand lamination method. Typical applications include the rotor blades for wind turbines, as well as structural and non-structural parts for trucks and railroad wagons.

The placement of "prepregs" involves placing pre-impregnated, semi-finished goods into a mold. Heating in autoclaves then liquefies the resin before the part is cured. Thanks to the higher pressure added in autoclaves, this method can deliver more compact parts than the vacuum-based process. Relevant applications include structural components to be used in aircrafts, Formula 1 racing cars, and high-quality pairs of ski.

The remaining methods – compression molding (6), the placement of impregnated fibers (7), resin-transfer molding (RTM) (8) as well as flow molding (9) – only allow for more modest forms of geometry in terms of size and maximum complexity.

Compression molding often involves placing either an organo sheet or a semi-finished textile pre-impregnated with resin (a sheet-molding compound or SMC) in a mold. Similarly, flow molding involves the same process with a preheated bulk molding compound (BMC). In both cases, the mold is then closed and the part is cured by exposing it to heat and pressure. The two methods often use long fibers of up to around 50 mm, although compression molding also makes frequent use of continuous fibers (organo sheets). Typical applications include small to medium-sized parts from various industries that are rarely exposed to a high level of stress.

RTM methods are based on the use of double-sided molds. Normally, a dry textile pre-form is produced first and then placed in a mold. Upon closure of the mold in a press, resin is injected into the cavity. The curing process, which is often supported by heating the mold, begins as soon as the resin inlets are closed. Typical applications include automotive, rail vehicle and aircraft components with relatively complex geometry requirements.
The placement process of impregnated fibers is very similar to the placement of prepreg. Instead of prepregs, however, individual fiber rovings are spread and placed. While this means that greater geometric complexity can be achieved, the resultant trade-off – a far slower placement rate – places restrictions on the size of parts that are economically feasible with this method. Complex structural components for aircraft are the main application.

In principle, four key criteria must be taken into account when defining a suitable production method for continuous-fiber-reinforced parts: the size of the part, the achievable level of geometric complexity, the production volume, and the requirements for specific properties and levels of quality. The size and geometric complexity restrictions discussed above are mandatory criteria that must always be addressed when selecting a suitable method.

The production volume is important primarily in light of economic feasibility considerations. In this context, the cost of semi-finished products, process costs and the capital investment required for production equipment must each be examined as a function of the method adopted.

Requirements relating to a part’s mechanical properties or its surface quality can also preclude an otherwise suitable method. If the surface has to be perfect on both sides, for example, this can only be achieved through a double-sided mold (which would therefore rule out vacuum infusion methods).

### 2.3 Comparing costs and performance with traditional materials

In comparison to other construction materials, fiber-reinforced composites occupy no more than a niche position in terms of volume. While approximately 1.3 billion tons of steel are produced annually around the world, GFRPs with 4 to 5 million tons (including short and long GFRPs) and CFRPs with a mere 40,000 tons together account for less than 1% of the global steel volume.

Among the several reasons that currently prevent usage of continuous-fiber-reinforced composites on a large scale, associated costs are clearly the dominant factor. The overall cost for components is significantly above the one of parts manufactured from traditional materials. For illustration, Figure 8 shows the divergence of two key parameters – weight and (current) cost – for structural automotive parts that fulfill identical functions but are made of different materials. Whereas CFRPs exhibit considerable potential in lightweight construction – especially for parts that are predominantly exposed to unidirectional stresses – their costs outgrow the ones of traditional steel parts by more than 500%. The same correlation between costs and benefits applies to comparisons with high-strength steels and aluminum: Significant weight reductions can be achieved in return for costs that are several times higher than the weight benefits.
Despite the fact that the level of costs and the cost structure will always depend on the specific part to a certain extent, reference parts can be a useful way to identify the key drivers of cost.

A cost structure comparison between a CFRP reference part made using the RTM process and a steel part with similar functionality reveals major differences with regard to the key cost drivers (see Figure 9).

Material costs alone currently account for roughly 50% of the total cost of CFRP parts manufactured using the RTM method. The other half consists of process costs (primarily machines and tools), labor costs and miscellaneous costs such as energy. The carbon fiber itself is the most expensive single item, accounting for as much as 45% of the total part cost.

More than half of the cost of the carbon fiber, on the other hand, is attributable to its precursor polyacrylnitrile (PAN), which must be of high quality if the carbon fiber is to possess suitably good mechanical properties. In a multi-step and very energy-intensive process, this precursor is oxidized, carbonized and – in the case of high-modulus fibers – graphitized. All this must be done at temperatures of over 2,000 °C (3,000 °C in the case of high-modulus fibers), which explains why energy is responsible for nearly 20% of the cost of fiber. Since the process runs in extensively automated plants, labor accounts for only around 10% of the total fiber cost – whereas write-offs and other fixed costs weigh in with approximately 20%.
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The total cost of the part made from sheet steel amounts to only about 15% to 20% of the cost of the CFRP part and is therefore roughly equivalent to the share in costs that are attributed to the precursor of the fibers in the CFRP part.

The cost structure is also very different for the steel sheet component. Material costs dominate, accounting for around 75% of the total cost, and are largely attributable to ore. Consequently, process costs account for no more than about 25% to the total cost.

2.4 Material and process innovation and how it can improve the cost position

Development currently takes place at virtually every step in the value chain, from raw materials to the individual steps in the part production methods. Multiple directions are explored to achieve various degrees of cost-cutting potential between now and 2020 (see Figure 10).

With regard to fiber, two different approaches are being pursued for that purpose. For carbon fiber, the primary focus is on reducing the fiber cost. For glass fiber, the principal aim is optimization of the fibers’ mechanical properties.

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With regard to fiber, two different approaches are being pursued for that purpose. For carbon fiber, the primary focus is on reducing the fiber cost. For glass fiber, the principal aim is optimization of the fibers' mechanical properties.
In the case of carbon fiber, new conversion technologies that can heat fiber directly through the use of microwaves or a combination of microwaves and plasma are developed. At the same time, research is conducted to find a way to modify the oxidation technology and the final surface treatment (finish). The second major field of research is looking into a new precursor technology that is no longer based on PAN.

For example, lignin-based materials are investigated for fibers with slightly inferior mechanical qualities. Given that the precursor currently accounts for roughly 50% of the total cost of carbon fibers (see Figure 9), this strategy theoretically promises substantial potential. As things stand today, however, no major innovation is expected in this field within the next five to ten years, given the straight-forward fact that mechanical properties of lignin-based fibers currently are not even close to the level of PAN-based fibers.

The current process chain in carbon fiber production cannot exploit economies of scale in the way many other chemical processes can. The mainstream plants currently used to produce carbon fiber (with an annual capacity of around 2,000 tons per plant) are about as good as they can get in terms of process technology. Larger plants appear to be reaching the limits of process stability and reliability.
In the short to medium term, there is thus no sign of a ground-breaking innovation in the production of carbon fiber so that cost reductions through incremental evolution of technology of only 15-20% can be expected.

Developments in glass fiber rather focus on efforts to optimize the mechanical properties of the fiber than on mere cost cutting. This must be evaluated in light of the fact that the major part of glass fibers is already manufactured in China. Glass fibers are widely regarded as a commodity that bears only little potential for further cost reductions. Room for development is rather expected for special chemical formulations that make the fiber stronger or stiffer.

For matrix materials, development work in the thermoset segment currently focuses on a reduction in curing times, e.g. through the use of so-called snap-cure methods. Achieved savings do not result directly from material costs, but rather from the utilization of machine capacity thanks to shorter curing cycles. Work is also in progress to improve resin properties by optimizing the combination of mechanical properties and viscosity. All methods that impregnate dry semi-finished textile products with resin aim to minimize viscosity in order to optimize impregnation and dispersal of the resin. The downside is that it is often not possible to achieve optimal mechanical strength – hence the remaining development potential in this area. It is also the primary objective for thermoplastics to optimize viscosity without impairing the sound mechanical properties that evolved in the cured state.

Also for the development of matrix materials, there is no sign of any ground-breaking innovation that might suddenly yield significant cost reductions in the short to medium term. On the contrary, only minor direct cost cuts of less than 10% are expected in this area. Development work to reduce cycle times could, however, make a substantial contribution to lower process costs.

Likewise, methods and processes for part production are the object of intensive R&D efforts at the present time.

Over the past 10 to 15 years, a broad spectrum of production method variations has been developed, many of them designed for only one specific part in a specific application. Examples include the high-pressure RTM method and a variety of specialized vacuum-assisted infusion methods and compression methods. Many of these developments did not primarily seek to reduce costs, but rather to determine the basic feasibility of certain components or to comply with specific requirements (in aviation, for example).
In recent years, however, cost consciousness has increasingly come to the fore and now plays a prominent role in process development. In addition to improvements of specific process steps, an optimized flow along the single process steps has become a focus. BMW, for instance, has made a concerted effort on this front in the shape of its i-project. In doing so, it has taken a major step in the direction of industrialization.

Mapping these developments onto the cost structure described above and the expected cost reductions, the cost of an RTM part could be reduced by around 30% between now and 2020 (see Figure 11).

Alongside the ongoing development of input materials and production methods, a considerable amount of work also goes into the improvement of existing simulation tools.

Key aspects are a more accurate computation of parts (using the finite element method, FEM, for example) and a more realistic process simulation. Optimized calculation tools can result in part designs that require lower safety factors because part behavior can be predicted with greater accuracy.
That ultimately saves material and opens up additional cost-cutting potential that has not yet been included into the model calculation (see Figure 11).

Further improvements in process simulation will lead to lower parts costs, as the complete process chain can then be optimized before start of production. Furthermore, one should not underestimate the influence that trends like multi-material design and hybridization can have on high-strength fiber-reinforced composites and their costs in the long run. Indeed, fiber-reinforced composites can only realize their full performance potential in context of hybridization.

As we saw in Figure 5, continuous fiber reinforcements are especially useful for heavy stressed areas – ideally with a unidirectional alignment. However, almost all applications also involve areas on which only a low level of stress is applied. Accordingly, parts that are fully reinforced by continuous fibers normally use less fiber layers at those areas that are exposed to more moderate stresses in order to reduce the cost of the parts.

In this context, hybridization opens up considerably greater potential by allowing the complete exclusion of continuous fibers from areas exposed to low stresses only, see figure 19. Instead, these areas can be fitted solely with short- or long-fiber-reinforced plastics that are reinforced by continuous fiber materials along the load paths. Similarly, some carbon fibers can be replaced by far less expensive glass fibers in areas exposed to low stress levels, provided that this does not compromise the part’s required stiffness properties.

Combining fibers with metallic elements can likewise deliver significant advantages, for example at points that are exposed to considerable surface pressure or that must absorb loads in all directions.
In addition to the potential that is directly attributable to hybridization, Figure 13 outlines further innovations that are expected to evolve in connection with multi-material in the medium to long term.

Especially in the field of joining technology, intensive research is conducted to find ways to join and combine different materials. Adhesives, rivets and clinches are among several technologies whose potential appears to be far from being exhausted.

Comprehensive optimization of the overall design gives due consideration to both material-specific degrees of freedom and production technology aspects. In this way, the best possible use can be derived from the properties of each material. In the case of sheet steel parts, for example, it is already standard practice to factor production technology considerations into the parts as early as in the design phase (with regard to feasible bending radii or undercuts). This practice must be adopted in a standardized form for composites if the inherent trade-off between technical benefits and economic feasibility is to be optimized.
In the context of hybrid technology, it is further worth noting intrinsic hybridization, especially in combination with metals. To this end, current research investigates ways to manufacture hybrid parts on a level of efficiency that would allow to avoid complex joining processes.

Lastly, superior methods of simulating production processes open up additional areas of potential since substantial savings could be derived from testing and since limits of reliable production can be calculated with greater accuracy.
3. Market development – Application segments, drivers of demand and the market model

Section 2 provided a thorough overview of the materials, properties and production methods that are currently used for various high-strength composites. This section examines the market, i.e. the expected demand for these composites. It begins by investigating the key areas of application and their drivers, as well as conducting a detailed analysis of existing factors that impose limits on further growth in these areas. It concludes with a market forecast focused on the anticipated market volume and its structure (series volume).

3.1 Key application segments and their drivers

While growing demand for high-strength composites can be observed in a wide range of industries, the automotive, aerospace and wind power are the most important segments in terms of volume. Engineering industry, the fourth segment depicted in Figure 14, can currently boast neither high volumes nor large series. It does, however, contain a large number of high-potential niches and is therefore also analyzed in detail.

**Figure 14: Key market segments for high-strength composites**

1. **Automotive**
   - Currently dominated by niche applications in the area of motorsports and the premium/super-premium segment
   - BMW i3 is the first vehicle with a high CFRP share in a planned series larger than 10,000 units

2. **Aerospace**
   - Increasing CFRP share within structural components of new aircraft types, e.g. A350, B787 with approx. 50% structural weight
   - Interiors with high GFRP share (panels, cabinets, shelves, etc.)
   - State-of-the-art for helicopters and combat aircraft

3. **Wind power**
   - Rotor blades are almost exclusively made of GFRP – with only a minor share being CFRP-reinforced
   - CFRP to profit from trend toward longer blades because of its higher stiffness

4. **Engineering**
   - High number of relatively small niche applications with greatly varying requirements
   - Use in high-performance applications subject to extraordinary dynamic, mechanical, thermal or electromagnetic conditions

Source: Expert interviews; desk research; Roland Berger

Continuous-fiber-reinforced composites are also used in the construction, marine and sports industries. However, none of these industries is a driver of volume for high-strength composites.
In the construction industry, fiber-reinforced composites are used primarily to build structural sections and pipes, with the latter accounting for the largest volume. Pipes in particular are reinforced with continuous (usually glass) fiber to a certain extent, but mostly feature short or long fibers. Their overlap with the high-strength composites segment is therefore limited. In the marine industry, glass fiber is mostly used in the hulls and to some extent also the superstructures of yachts and boats. Very small series that use largely manual production processes are the rule to which there are virtually no exceptions; furthermore, no significant growth in demand can be observed in this industry. In the sports industry, carbon-fiber-reinforced plastics have already been used – in tennis racquets and the shafts of golf clubs, for instance – for a comparatively long time. Here again, however, there is no indication of significant growth, so the industry cannot be considered a potential volume driver.

Due to differences in the relevant market drivers, the pattern of demand varies significantly in the segments shown in Figure 14. A fundamental distinction must be drawn between specific drivers for the use of continuous-fiber-reinforced composites on the one hand and drivers of growth for the entire industry on the other. The former drivers cause composites to substitute for traditional materials and can thus fuel an increase in demand for composites even if the industry itself is stagnating. In the latter case, demand for composites is stimulated by industry growth per se. One example of the former comes from the automotive industry, in which composites are taking over from traditional materials to some extent. Conversely, wind power is a good example of the second set of drivers, as rotor blades already are almost exclusively made from continuous-fiber-reinforced composites.

Four basic requirements can be identified as specific drivers for the use of continuous-fiber-reinforced composites:

“Technical necessity” occurs where required or desired component properties cannot be realized using other materials. This criterion can apply both to mechanical properties and to other physical properties, such as the fact that CFRPs have a thermal coefficient of expansion that is close to zero. This particular property is, for example, used for special parts in textile machines where maximum precision under fluctuating temperature conditions is vital.

“Efficiency/economic feasibility” occurs when there is a measurable cost advantage compared to the use of a different material for a given component. This calculation normally takes account of both direct part costs and savings realized during the operating phase. Examples of the latter include lower fuel consumption thanks to a more lightweight design and lower projected maintenance costs, as in the cases of the CFRP parts used in modern aircraft.
“Styling, lifestyle and marketing” are factors that do not relate directly to economic or technical utility. They rather have to do with a material’s perceived image (“carbon is cool”). Non-load-bearing panels, decorative elements and other visible parts fall into this category, for instance.

“Legal requirements” include all statutory prescriptions that lead to an increase in demand for high-strength fiber-reinforced composites. One example could be even stricter CO₂ emission thresholds for cars.

Figure 15 visualizes the relevance of each of these drivers to the four key market segments. Technical necessity and efficiency/economic feasibility are the most important factors across all industries. In the aerospace, wind power and engineering industries, these two factors are the engine that drives the use of high-strength fiber-reinforced composites. The importance of them, however, is slightly less pronounced in the automotive industry, in which lifestyle and marketing considerations have dominated up to now. This is reflected, for example, in the many visible parts and panels, etc. (such as the side blades on the Audi R8), that are made of fiber-reinforced composites only for design reasons. Legal requirements play a minor role overall and are completely irrelevant in the case of wind power and engineering. They only have an impact in the automotive and aerospace industries, as stricter requirements are increasingly imposed with regard to vehicle fleet consumption levels and the reduction of CO₂ emissions. Such laws drive lightweight construction and hence, indirectly, the use of fiber-reinforced components.

**Figure 15: Drivers of the use of high-strength fiber-reinforced composites**

<table>
<thead>
<tr>
<th></th>
<th>Technical necessity</th>
<th>Styling, lifestyle, marketing</th>
<th>Efficiency/economic feasibility</th>
<th>Legal requirements</th>
</tr>
</thead>
<tbody>
<tr>
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<td><img src="image2" alt="Major importance" /></td>
<td><img src="image3" alt="Major importance" /></td>
<td><img src="image4" alt="Major importance" /></td>
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<td><img src="image6" alt="Major importance" /></td>
<td><img src="image7" alt="Major importance" /></td>
<td><img src="image8" alt="Major importance" /></td>
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<tr>
<td>Wind power</td>
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<td><img src="image10" alt="Minor importance" /></td>
<td><img src="image11" alt="Major importance" /></td>
<td><img src="image12" alt="Major importance" /></td>
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<tr>
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<td><img src="image13" alt="Major importance" /></td>
<td><img src="image14" alt="Major importance" /></td>
<td><img src="image15" alt="Major importance" /></td>
<td><img src="image16" alt="Major importance" /></td>
</tr>
</tbody>
</table>

Source: Expert interviews; desk research; RBSC/VDMA survey results
The indicators for the rate of growth in demand shown to the right of Figure 15 for each segment were derived by consolidating the current use of fiber composites and the associated drivers in each industry. The paragraphs to follow take a closer look at all four segments.

3.2 Forecast demand patterns in the relevant volume segments

3.2.1 Automotive

Automotive applications for high-strength fiber-reinforced composites in general and carbon-fiber-reinforced composites in particular are currently attracting considerable media attention. In the past, these materials were restricted virtually without exception to the series production of high-end sports cars (not exceeding series volumes of 1,000 cars) and professional sports vehicles (such as Formula 1 racing cars). Now, however, a shift of emphasis has set in, and vehicles manufactured in slightly larger series (such as the Audi A8 with a volume of a few thousand) are increasingly equipped with CFRP parts. One flagship project in this context is the BMW i project, in which for the first time the entire bodywork will be made of CFRP - for a planned production series of several tens of thousand vehicles. The first of these cars are due to be shipped in 2013. For this project, the entire value chain – from carbon fiber to the finished component – was completely redesigned. New production facilities were built accordingly.

Thanks to its initiative, BMW unleashed a wave of hype that significantly boosted public awareness of composites in the media.

Aside from this attention attracting project, the automotive sector is engaging in further activities that generate less of a stir in the media. In isolated cases, functional parts (such as leaf springs made of glass-fiber-reinforced composites) are already manufactured in larger series. A wide variety of further parts is made for interior components, mostly decorative trim and further visible parts. As a rule, however, these parts consist merely of a thin layer of carbon that coats a different type of material.

Other forms of application already exist in the truck segment, where glass-fiber-reinforced composites are used for panels on driver’s cabins, for example. To date, however, such applications only use continuous-fiber-reinforced parts to a minor extent. Short and long fibers are used more frequently – in sheet molding compound (SMC) parts, for instance.

Primarily due to cost reasons, there is currently no reason to expect that any other medium-sized to large vehicle production series (upward of at least 10,000 units per annum) will also feature bodies made entirely of fiber-reinforced composites.
On the other hand, it is conceivable that such parts could be used selectively in a larger number of premium vehicles at positions where they yield exceptional benefits in terms of lightweight potential or crash safety. While the spectrum of relevant parts could be very broad, complex section and surface structures will predominate.

### 3.2.2 Aerospace

High-strength fiber-reinforced composites have already been an established material in commercial aviation for a long time. The first vertical stabilizer made of carbon-fiber-reinforced plastic was shipped for the A310 as far back as 1983, for example. Figure 16 shows how the share of carbon-fiber-reinforced composites in the total of materials used in wide-body aircraft has evolved. CFRPs were initially restricted to selected parts, accounting for around 15% of the airframe weight for aircraft types A320 and A330/340. The material most commonly used in this generation of aircraft is aluminum.

In particular thanks to the introduction of the new generation of long-haul jets (the B787 and A350), however, CFRPs have significantly increased their share in airframes of modern aircrafts. These two types noted are the first ever to have CFRP fuselages and have a CFRP share of roughly 50% of their airframe weight. Compared to short-haul aircraft, however, far fewer units of either the B787 or the A350 will be manufactured (Planned are between 110 and 130 of each per annum).

Updated short-haul jets (the B737max and A320neo) are scheduled to go off the blocks in 2015/16, with unit volumes projected to exceed 400 per annum in both case. However, there are no plans to significantly increase the composite content of these aircraft. It is nevertheless expected that several parts that are currently made of metal will also be replaced in these aircrafts. The material mix for subsequent (“post-neo”) generations has not yet been decided.

Due to the crucial significance of the airframe weight, the aerospace industry nevertheless is a pioneer in the use of high-strength fiber-reinforced composites. In this sector, the substantial cost can be amortized comparatively easy, as the following model calculation demonstrates: Given a service life of 60,000 hours, every kilogram of weight saved results in the consumption of three tons less kerosene. Spread over the aircraft’s life span, this means that extra costs of between EUR 400 and EUR 500 per eliminated kilogram of weight can be amortized. Maintenance promises additional savings potential, as CFRPs are normally not as prone to fatigue as conventional materials.
Since purchasing costs for short-haul aircrafts are relatively high in comparison to operating costs, the aviation industry is working on methods that will enable CFRP parts for aircrafts to be manufactured at lower cost. This goal could, for example, be achieved by finding alternatives to the very cost-intensive prepreg method that involves curing in autoclaves.

In addition to airframe parts, many fiber-reinforced composites – primarily GFRP parts – are also used in aircraft interiors. The spectrum is highly diverse, ranging from paneling and trim to built-in fixtures such as shelves and cupboards. Driven by specific customer preferences and/or alternative structural geometries, there is normally a high degree of variation even in parts that serve identical functions.

Broadly speaking, typical series volumes in aviation vary considerably from part to part. While large parts such as wing skins are needed in series that run into the hundreds, smaller parts such as stringers and clips have to be produced by the thousands or even the tens of thousands. In contrast, individual customer preferences mean that interior fittings are often produced in series of just a few dozen units.
3.2.3 Wind power

Around 60,000 rotor blades a year are currently built globally for the wind power segment. However, this number is shared among more than twenty major manufacturers and across a wide range of models. Typical series volumes therefore do not exceed a few hundred. Given that practically all rotor blades are fully made of high-strength fiber-reinforced composite structures, a boost of demand for composites in this industry is closely linked to the development of the industry as a whole. There is no prediction that further substitution will take place between traditional materials and fiber-reinforced composites.

Recent years have seen a stronger trend toward ever larger turbines and, hence, longer rotor blades. Especially for offshore applications, precedence is increasingly given to larger turbines that deliver output of 5 MW or more due to both heavy installation and logistical costs and prevailing wind conditions. Most relevant OEMs either already manufacture turbines of such size or currently develop them. As things stand today, medium-term global growth rates of 4% to 5% per annum are forecasted for new installed capacity. However, this growth will not significantly increase the number of rotor blades required, since it almost exclusively results from the growing size of wind turbines. Actually, the number of turbines installed each year will stagnate or even slightly decrease.

Newly installed rotor blades will considerably exceed the length of 40 to 50 meters for 1.5 to 2.5 MW turbines which has been considered a typical size, reaching 80 meters within a couple of years.

The resulting heavier loads will place substantially greater demands on blade strength and stiffness. One challenge, for example, relates to the clearance between the blades and the tower that has to be guaranteed by sufficiently stiff blades. Accordingly, the increasing use of more expensive carbon fiber – especially for stiffening girders – instead of glass fiber can be observed. Cost considerations will ultimately determine the extent to which carbon fiber replaces glass fiber in this application since superior mechanical properties of carbon fiber go hand in hand with substantially higher costs.

One potential trend could be disassembling the rotor blades into individual segments or modules that are only assembled on location. One American company in particular is very active in this field and plans to install an initial prototype next year at the latest. If implementation proves successful in both technological and economic terms, this concept has the potential to be a long-term game changer for all rotor blade production throughout the wind power industry.
3.2.4 Engineering

To date, composites have been used only in a few niche applications in the engineering sector. In this industry, the trade-off between technical necessity and economic feasibility determines which materials are used. The required mechanical and physical properties of materials are two key aspects of technical necessity.

Mechanical properties refer to high stiffness linked to low weight. And this combination is precisely what makes high-strength fiber-reinforced composites attractive, especially for use in plants and machinery. Moreover, stiffness often plays a key part in long rolls. Required physical properties include a thermal coefficient of expansion close to zero and non-magnetic behavior.

Probably the most widespread application is the use of fiber composite rolls in fast-rotating machinery – in the paper and printing industry, for example. In such applications, the ratio of costs to the resultant added benefits is particularly attractive. Other examples of rotationally symmetric parts include rotors in synchronous motors with electrostatic bearings. For components of (fast-moving) handling systems, clamping chucks (to reduce weight), selective stiffening elements and many other niche applications, it is again the special mechanical and physical properties of materials that are crucial.

Typical series volumes for engineering applications run between 50 and 200 pieces per annum. In this industry, it is reasonable to regard volumes in excess of 1,000 pieces per year as large series, but series of such volume have so far rarely involved fiber composites.

In the long term, the sheer variety of applications bears considerable potential for fiber composites in the engineering industry. To begin with, however, growth will be slow due to an array of hard factors and the engineering industry’s conservative attitude towards new materials. The basic attitude – “We’ve always made it out of metal and it works fine” – is still apparent at many engineering companies. However, as global competition becomes fiercer, using fiber composites in the right places can open the door to new or improved functionality that keeps firms ahead of their competitors in China, for example.
3.3 Limiting factors and obstacles

Right now, the biggest obstacle to faster market penetration for high-strength fiber-reinforced composites – across all industries – is their significant extra cost relative to parts made from traditional materials (see section 2.3). From an economic perspective, the extra cost is only justifiable in applications that either yield corresponding savings over the entire lifecycle or that would not be feasible using conventional materials.

Having said that, target costs vary considerably from industry to industry. In aviation, paying several hundred euros to save an extra kilogram makes sense. In the automotive industry, however, costs must be reduced radically if fiber composites are to be able to compete with steel and aluminum in large series applications.

While the savings of around 30% expected between now and 2020 will increasingly drive the use of fiber composites in different industries, they will not lead to deployment in high-volume production such as in the automotive industry. According to industry insights, the cost of CFRP parts would have to be reduced by roughly 70% compared to 2010 levels in order for this to happen.

Besides the cost issue, further limitations exist (see Figure 17). One is that the recycling route for fiber composites (and for waste generated during production) has yet to be optimized. Scrap from continuous-fiber-reinforced textiles (in particular “offcuts” during the process of manufacturing parts) is already turned into lower-value semi-finished products. However, even this incurs substantial losses, as the non-woven materials that typically result from this process can only be used for parts subject to lower stress levels.

Unlike metal parts, the current state of technology allows CFRP and GFRP parts to be recycled only to a very limited extent, usually through thermal recovery. Unlike conventional materials such as steel and aluminum, fiber composites cannot be recycled for new high-grade products.

For GFRPs in particular, a mixed material and thermal recovery process has been developed in recent years. In this process, GFRP waste is comminuted and used as a raw material and fuel substitute for the production of cement bricks at a cement factory. The resins serve as combustible fuel, while the minerals contained in the glass can replace sand, for example. According to Holcim, 1,000 tons of GFRPs can substitute for up to 450 tons of coal, 200 tons of chalk, 200 tons of sand and 150 tons of aluminum oxide. While this process has established a viable recycling route, it is not yet as good as the extensive material recovery processes in place for metals.
Repairing fiber composite parts is another problem that has not yet been fully resolved. Damage in metal parts is usually relatively easy to repair (for example by replacing some of the damaged parts with "repair sheets" or by simply knocking parts back into shape), but remedies are not so simple as soon as fiber composites are involved. Instead, it is usually necessary either to replace entire components or to use special repair methods. Especially in the case of structural parts, however, repairs almost always lead to a loss of specific strength and stiffness because the fibers are interrupted. This has to be compensated for by additional layers. In aviation applications, this may be comparatively simple to do, while in automotive engineering implementing such kind of repair methods in practice would involve some difficulties, as the necessary expertise must be built up in repair shops first.

In this context, it is worth noting that it is often much more difficult to identify damage. While significant damage to metal parts is normally visible on the surface of the affected part, this is often not the case with fiber composites because the damage may actually occur inside the laminate. Such "delamination" can severely weaken the affected part without being apparent from the outside.

Especially in the case of carbon fiber, ensuring a reliable supply of material is yet another issue that must be addressed. Comparatively low demand compared to other construction materials has so far kept supply lines limited.
Except in times of economic crisis, available capacity is only slightly above current demand. Any sudden increase in demand would make it necessary to build up commensurate capacity first. One example of this process can be seen in SGL Automotive Carbon Fibers, a joint venture owned by SGL Carbon and BMW and founded for the sole purpose of supplying semi-finished carbon fiber products to the BMW Group. In phase one alone, a value of around USD 100 million was invested in the carbon fiber factory built in Moses Lake to create annual capacity of 3,000 tons.

Furthermore, there are a number of difficulties involved in attaching fiber composites to metal components. Production of durable joins that are suitable to cope with the relevant stresses and loads places exacting demands on bonding technology. In the long run, the hybridization of parts and the multi-material concepts touched on in section 2.4 will open up tremendous opportunities. Before that happens, however, the obstacles presented by bonding technologies must first be overcome step by step.

Despite these significant hurdles, an upbeat outlook is still reasonable at this point. None of the limitations described above are currently regarded as real "show stoppers". In all areas discussed, research and development work is currently seeking appropriate solution strategies. The cost aspect in particular still stands in the way of large series deployment in the short to medium term. However, thanks to the growing efforts of industry and research, further cost reductions will indeed be achieved up to and beyond 2020, driving deeper market penetration in the process.

### 3.4 Structure of demand and market model

By consolidating information about the current use of high-strength fiber composites, the principal market drivers and existing limiting factors, it is possible to forecast both demand and its underlying structure. As we saw in the analysis of demand in the relevant volume segments (section 3.2), large series (i.e. volumes of above 100,000 units per annum) will become established on a large scale only after 2020.

Even so, demand will increase significantly in all segments, driven by two major effects: Single-unit production or very small series (100 units per annum) will increasingly give way to small series (above 1,000 units per annum) and medium-sized series (above 10,000 units per annum). At the same time, the number of components made of high-strength fiber-reinforced composites will increase (see Figure 18).
The market forecast for continuous-fiber-reinforced composites shown in Figure 19 was formulated in light of the information and insights presented in the sections above. Between now and 2020, per-annum growth of 17% is anticipated for high-strength CFRPs, while GFRPs are expected to grow much more slowly at around 5% per annum. An assortment of market studies, reports and estimates prepared by relevant associations, institutions and companies (including AVK, Composites Forecasts and Consulting LLC, Industry Experts Publications, SGL Carbon and others) served as the basis for estimates of the current market size.

In the GFRP segment in particular, figures are usually published for the market as a whole (i.e. including both short- and long-fiber-reinforced materials). These figures were therefore adjusted on the basis of interviews with experts in order to identify the market size for continuous-fiber-reinforced composite parts only. To do so, estimates of continuous GFRPs as a proportion of the overall market volume were made separately for each relevant industry. Especially in the automotive/transportation, construction, consumer and electrical/electronics industries, these estimates significantly reduced the overall volume, because each of these sectors uses a substantial volume of short- and long-fiber-reinforced parts. In other industries, such as aviation, marine and wind power, continuous fibers account for the vast majority of manufactured GFRPs.
In the CFRP segment, distinguishing between the lengths of the fibers used is easier because almost all CFRPs are continuous. Cost considerations mean that it rarely makes sense to consciously deploy short-cut carbon fibers but usage of such fiber type is - among other reasons - driven by offcuts from processing semi-finished continuous fiber products fashioned into short or long fibers. Across all industries, short or long fibers account for no more than 10%. Compared to GFRPs, CFRP applications will in total remain a small niche in 2020, although their share will rise from less than 3% in 2011 to nearly 7% of the total market for high-strength fiber-reinforced composites.

Figure 19: Demand forecast for continuous-fiber-reinforced composites

Growth in demand for high-strength CFRPs will vary significantly from industry to industry. On top of the table is the automotive segment, the source of the strongest growth stimulus, which is expected to see an average annual growth rate of more than 30% until 2020. This industry is followed by wind power, whose 20% annual growth will be driven by the substitution of GFRPs in longer rotor blades, and the "Other" segment (including engineering), which will grow at a rate of 14% per annum. Aerospace too will be well into double figures as demand grows by 12% per annum. Only the sports segment will more or less stagnate, expanding by only 2% per annum.

By contrast, growth in demand for continuous GFRPs will be much more evenly spread across the various industries. Aerospace, automotive and transportation applications are forecasted to deliver the strongest growth of around 7% per annum through 2020. The slowest average annual growth rate – 3% – will be posted by the marine industry.
4. Industrialization of the production processes – Drivers, restrictions and potential standards

Growing demand for high-strength composites and the associated transition from small-scale to medium-sized series in the tens of thousands of units will raise questions and create new challenges for production technology across all industries. This section explores how cross-industry standards could emerge as a result. To this end, the new requirements and challenges themselves are first spelled out before we investigate and evaluate the suitability of existing production concepts and methods.

4.1 Requirements for series processes – Drivers of industrialization

As series volumes increase, production technology across the various industries must ensure that suitable plants are available and that productivity is adequate. At the same time, each individual industry must also face up to its own specific challenges (see Figure 20).

For automotive applications, cycle times must be shortened if the industry is to cope with increasing series volumes. It is especially important to reduce production costs and, hence, unit costs to improve fiber composites' competitive position with respect to metal parts and, in the long term, to help an increasing number of parts make the leap from the super-premium segment to other segments.

In aviation, and especially for short-haul aircraft, the cost aspect is becoming increasingly important, although other considerations – precision as well as stable and reliable processes – take precedence. On one hand, this is due to strict safety and regulatory requirements.

On the other, however, there is a distinct economic interest: Many parts in the aviation industry are quite large and, accordingly, very expensive. In light of the strict safety requirements, mistakes in the production process often lead to scrapping an entire part. Associated costs naturally explain why scrap rates must be kept as low as possible – hence the need for very stable processes. The need for precision derives from the combined requirements for as little weight and as much safety as possible. Only if production achieves a high level of precision, parts design can be taken to the limits while achieving required safety margins. Another aspect that is particularly important in aviation concerns the complexity of the geometry in general and the layer structures in particular. Even parts whose geometry is not especially complex (such as wing skins) generally feature complex layer structures with fibers running in many directions and varying wall thicknesses, i.e. changing cross sections.
The specific needs of the wind power industry are different from the two industries already examined. Apart from the huge dimensions of the rotor blades, the most important criterion is the cost of the production plants. As long as the rotor blades are still made using today’s most widespread technology from two half shells, the lengths of over 50 meters will remain a major obstacle to automation of the production process. Since presses of this size do not exist, vacuum-assisted infusion process will very likely remain the method of choice. Auxiliary automation solutions (to place dry semi-finished textile products, for instance) have already been developed but are not yet established on the market, probably because of the high cost of these systems. Partly on account of the sheer dimensions, they normally cost several millions of Euros. Usually, no business case can therefore be made for two reasons. First, the number of rotor blades made per plant is too low (series in the hundreds are the rule), so the cost of the plants can only be spread across a small number of parts. Second, the fact that the most time-consuming process is not placing the semi-finished textiles but curing the resin plays a major role. Logically, the added benefit of faster textile placement is relatively minor, because this alone is not sufficient to accelerate the overall cycle. At the present time, therefore, requirements in the wind power industry do not center primarily around fully automated placement systems, but focus rather on optimizing individual work steps and post-processing (e.g. trimming edges, grinding, etc.) through tailor-made, automation-assisted solutions.

Small-series production largely shapes requirements in the engineering sector: Automated solutions have to be flexible enough to adapt to the large number of variations in parts. Other requirements vary greatly from application to application, making it difficult to generalize.
Broadly speaking, it is reasonable to conclude that cost-effective production of larger unit volumes will be possible only through automation. With the exception of wind power, which requires special solutions, suitable concepts and methods must be developed that will enable the other industries to fulfill the requirements for series production.

4.2 Restrictions – Production concepts and production methods

4.2.1 Suitability of different production concepts

Before a suitable production method can be selected, it clearly makes sense to define the production concept. Figure 21 reflects the views expressed by the respondent engineering experts when asked which production processes they rate as well suited or highly suitable depending on series volume. For series of hundreds and thousands of units, the consensus (89% of responses) is that either entirely manual or semi-automated processes are the best option. Only 11% voted for manually linked fully automated process cells or fully linked lines. In both categories semi-automated manufacturing drew the most votes (46%). This concept involves automation support for work steps that were originally performed manually. Robots might be used to place prepregs in a form, for example. Superior reproducibility compared to fully manual set-ups make this approach sensible for small series too in cases where high reproducibility is essential. Up to series volumes of several thousands of units, respondents believe that less industrialized processes have the edge over both fully automated production cells and fully linked lines.

As was to be expected, however, more heavily industrialized concepts receive far better ratings for series volumes of more than 10,000. Entirely manual manufacturing clearly has no further part to play at this end of the scale; and only 13% of respondents believe that semi-automated manufacturing is a suitable approach. By contrast, manually linked fully automated production cells attracted 44% of the votes and fully linked lines 43%. Once series volumes move up beyond 100,000, fully linked lines are the clear winners, commanding 71% of the vote, with production cells a long way off in second place (26%).

When interpreting these statements, it must be remembered that engineering companies are capable of providing heavily automated equipment whose substantially higher price tag naturally translates into greater potential sales revenues. The optimal level of automation has yet to be found for the various applications, however. This becomes particularly apparent when one looks at series of beyond 10,000 units. At this point, plant operators and OEMs tend to prefer manually linked automated production cells over the more expensive fully linked lines. Besides requiring less capital expenditure, the manually linked option also provides greater flexibility for many applications, as not every modification requires the reprogramming of the entire line.
Another benefit of production cells is that they can, if necessary, "grow together" later on to form a fully linked line if and when the level of automation is ramped up. Flexibility can thus be enabled by solutions that grow to keep pace with increasing series volumes.

For the series volumes of more than 10,000 that are expected to predominate up to 2020, manually linked fully automated lines of production cells appear to be the most likely production concept. Logically, therefore, industrialization should focus most strongly on this concept.

### 4.2.2 Suitability of different production methods

The second step is to ask which of the existing production methods are suitable both to meet industry-specific requirements and to cope with the necessary scale of industrialization. As a general statement, it must be noted that all the methods currently in use face challenges – and that many face the same challenges.

For all methods based on thermoset matrix materials, the curing time for the thermoset resin is one of the principal challenges. Even making certain allowances for pultrusion and winding methods, this parameter determines the cycle time and thus imposes limits on every method. This is especially true both for the curing of rotor blades for wind turbines and for the autoclave curing of airframe components for aircraft, as well as for the curing of parts manufactured using the RTM method.
In the latter case, current resins spend around 5 to 15 minutes in the press — far shorter than the several hours required by both of the other two methods mentioned. This step, however, is also the limiting factor in terms of overall cycle times for the RTM method since all other processes can be speeded up with the aid of suitable automation solutions. This is not the case for curing times, which are largely dependent on the resin’s material properties and can be accelerated by process control only to a limited extent.

Another challenge facing all methods is the need to ensure that manufactured parts are of the required quality. The quality of thin-walled metal parts, for example, can normally be verified by inspecting the surface. In the case of composite parts, however, defects inside the part constitute a significant risk factor. To preclude such risks, it is necessary either to fully inspect all parts after completion using non-destructive testing methods such as ultrasound, or to verify quality in some other way. Methods based on the impregnation of a dry semi-finished product pose particular problems on this score, primarily for two reasons. One is that the entire semi-finished product must be impregnated completely. The other is that the direction of the fibers must not be influenced in an uncontrolled manner by the injection process. While all structural parts are subject to exhaustive, end-to-end inspections in aviation, cost constraints mean that this is scarcely conceivable in other industries.

Another major challenge in prepreg-based methods begins well ahead of the part production process itself. To ensure that the resin does not cure prematurely, the semi-finished products must be kept cool during storage and transportation. As well as necessitating suitably equipped facilities, this process also devours a lot of energy and involves complex transportation logistics, all of which significantly influence the overall cost of the method. The need for curing in autoclaves likewise adds considerably to the overall costs, especially for large parts.

Besides the initial investment in suitably dimensioned autoclaves that can be controlled with extreme precision, the time this process takes (usually several hours) is ill-suited to the production of large series.

Moreover, all methods based not on the direct placement of individual fibers but on semi-finished textile products have the following drawback in common: Offcuts during the production of parts add up to a substantial volume of scrap (often as much as 30%). Offcuts can come from both dry semi-finished products (in cases where forms are cut from rolls of material) and prepreg materials. Dry fiber waste can be reused to some extent, but only in semi-finished products of inferior quality that no longer possess the full mechanical properties of the original material.
In the RTM process chain, the handling and accurate positioning of flexible semi-finished products is particularly difficult. Until the point at which the resin is injected and cured, dry semi-finished textile products that are both flexible and have uneven surfaces must be handled in several discrete steps. A reliable, high-speed handling process can be ensured only by using specialized systems based on needle or freeze grippers. However, with the technology that is currently available, this cannot yet be done at the handling speed commonly delivered by transfer lines for metal parts.

Besides these challenges, the suitability of production processes for particular engineering concepts plays a major role in determining methods that will be able to cope with larger series in future. Figure 22 provides a summarized estimate of the suitability of the methods described in section 2.2. To arrive at this estimate, the feasibility of automating the key steps in each method was analyzed. Demand for plant and equipment and achievable cycle times served as further significant evaluation criteria.

Prepreg placement, vacuum-assisted infusion and hand lamination methods appear to be primarily suitable for manual and semi-automated manufacturing. Conversely, it is barely conceivable to apply these methods for fully automated production cells, let alone for fully linked production lines. For these three methods, the automation of individual aspects (such as prepreg placement) is already the state of the art in many cases. However, further industrialization in the direction of fully automated production cells would seem scarcely feasible or sensible – for reasons relating to the size of parts, complexity issues and cycle times, for example.

**Figure 22: Estimated suitability of production methods for different production concepts**

<table>
<thead>
<tr>
<th></th>
<th>Manufacture</th>
<th>Semi-automated manufacture</th>
<th>Fully automated production cells</th>
<th>Fully linked production line</th>
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<tr>
<td>Prepreg placement</td>
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<tr>
<td>Vacuum assisted infusion</td>
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<td>Hand-lamination</td>
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<td>Placement of impregnated fibers</td>
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<td>Compression molding</td>
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<td>Resin-Transfer Molding (RTM)</td>
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<td>Pultrusion</td>
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<tr>
<td>Fiber-winding</td>
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</table>

1) With manual linking  2) Including curing in autoclave  3) Incl. organo sheets

Source: Expert interviews: desk research; Roland Berger
The placement of impregnated fibers in particular needs to be modeled in a semi-automated manufacturing scenario, because it is difficult to achieve the necessary precision and reproducibility when placing fibers in a form for a purely manual process. Even here, however, there are limits to how far the process can be industrialized. One reason is that placement takes a relatively long time: On top of the need for curing in an autoclave, this would tend to lead to very long cycle times.

The other methods – compression molding (including organo sheets), RTM methods, pultrusion and fiber-winding – are therefore much better suited to more heavily industrialized production concepts.

Pultrusion and fiber-winding have something of a special status, as both are suitable only for largely symmetric parts, such as beams and pipes, and convex parts, such as tanks, etc. Neither method therefore plays any significant part in surface or complex structural parts. At the same time, both methods differ slightly from the other methods in terms of the actual production process: They essentially use just a single machine. Either a continuous beam or pipe is manufactured and afterwards cut to length, or a suitable length of fiber is wound around a core. This process is already heavily automated on a single machine in most cases. Accordingly, linkage and related questions are an issue only to a limited extent for these two methods.

This leaves us with two candidates that are particularly well suited to fully automated production cells: compression molding on the one hand and RTM (including derivatives such as wet pressing methods) on the other. Either method can achieve cycle times of just a few minutes and allows many process steps to be automated. Conversely, the large number of different equipment as presses, plastic processing machinery (mixers and injection units) and ovens required for such methods means that manufacturing concepts based on heavy manual involvement are scarcely economically feasible. Since both methods center around placing semi-finished products in a press, and since metal inserts can be added relatively easily, they also appear conducive to the production of hybrid components in the future.

4.3 Development path and standard processes

4.3.1 Potential development path

The key takeaways from what has been so far covered in regard to the industrialization of production processes for continuous-fiber-reinforced composites are the following:
> Series volumes of in the range of ten thousands of units are forecasted to predominate by 2020

> Fully automated production cells are better suited to these series volumes than fully linked lines, which should only be given precedence for series volumes of more than 100,000 units

> For concepts based on fully automated production cells, compression molding and RTM methods are best suited from a current perspective

> These two methods also appear to hold out the best prospects for the long-term future, as they will later permit automation to be increased in the direction of 100,000 unit volumes and as they are potentially well suited to the production of hybrid components

> While the two methods are subject to certain geometric restrictions (in particular with regard to the realizable size of parts), they are nevertheless suitable for a wide range of structural and surface components in many different industries

In light of these insights, what can be done now to ramp up the industrialization of production processes? Three development paths appear to be broadly suitable: the continued use of existing methods and equipment with little modification; the adaptation and optimization of existing methods and equipment; or the development of new methods and equipment from scratch. Figure 23 estimates the degree to which the engineering firms believe these three variants will be suitable going forward: 57% reckon that the adaptation/optimization option is much more suitable than development from scratch (28%) or simply using existing methods and equipment (15%).

Essentially, this reasoning is perfectly understandable: Merely continuing to use existing methods and equipment will lead not to the required degree of industrialization, but rather to stagnation. Potential cost reductions in the production process cannot therefore be realized along this path.

From a technological point of view, redeveloping all the machinery, equipment and methods would undoubtedly be the best option. The cost of development, however, would be excessive. Given the moderate market volume (see sections 3.4 and 5.3), it would not, for the foreseeable future, be possible to spread this cost across a large number of equipment.

The viable compromise left is to adapt and intelligently optimize the methods and machinery we have. This evolutionary strategy indeed holds out considerable potential for success. Virtually all of the respondent experts agree that the basic functionality of the individual methodological steps already in existence are essentially suitable for volume production.
Moreover, further potential can be exploited by optimizing the process as a whole and incrementally improving individual details. In light of limited R&D budgets, such an evolutionary approach will also be more efficient than redevelopment from scratch, because it will be significantly less expensive and may also allow direct synergies to be tapped with other business areas.

4.3.2 Potential standard processes

The question now is: What might the standard processes that evolve out of existing ones look like in the future?

It is not possible to give just one answer for all the possible process variants. We have therefore focused on the RTM and compression molding which, as we have seen, are believed to be particularly well suited to industrialization. Our point of departure is the process chain currently in place for either method.

Resin transfer molding (RTM)

For the RTM method (see Figure 24), the process chain begins with the use of textile production techniques to transform carbon or glass fiber into semi-finished products. Woven, warp knitted and multiaxial fabrics off the roll are the most common forms used today. Textile machinery is already used in a heavily automated process to produce these fabrics on an industrial scale and wind them on rolls. The majority of these semi-finished products are made by specialized providers of what are referred to as technical textiles, who act as suppliers to the component manufacturers.
The first step in the production of semi-finished textile products is unrolling the textiles supplied – sometimes in several superimposed layers – and cutting them to size.

In the next step, the trimmed forms are stacked, fixed with binder and placed in a mold. Preforms are then produced in a special preform press. Depending on the size and geometry of the part (i.e. if it is small and/or compact and has no large holes or openings), a single preform can be enough for the entire semi-finished product. In the case of large parts with complex geometries, several separate preforms are often used. BMW, for example, uses as many as nine small preforms for the side panels on the i3. The optimal split depends on a variety of parameters, such as drapability, offcuts, the mechanical demands placed on the end product, and so on.

The next step involves placing the preform(s) in the RTM tool/mold. Where several preforms are fitted together, it makes sense to use toolsets with just one upper part but several lower parts. In this way, the ability to maneuver the separate lower parts into the presses alternately means that preform placement can be swapped out to off-peak times. Alternatively, placement can be done in a simple "wooden" mold whose sole purpose is to ensure that the individual preforms are properly positioned. Suitable equipment must then be used to quickly move the resultant preform structure in its entirety into the RTM tool. In the case of hybrid parts, the corresponding hybrid components must also be placed in the tool, or long fibers must be added at this point.
Once the press has been closed, resin is injected and the curing process can begin.

After sufficient curing (normally after around 10 minutes using current processes), the RTM press is opened again and the raw part is removed and passed on for final processing. This can involve the machining of edges and, where appropriate, further mechanical processing steps. Machining methods such as milling and water cutting are used in most cases. In addition, any necessary surface treatment is performed to prepare for joining operations before the final, ready-to-fit part is complete.

As we saw earlier, R&D is currently tweaking at many different aspects, bringing evolutionary improvement to the overall process. Looking at the entire process chain that starts with the semi-finished product, four key areas of optimization potential have been identified. Taken together, these four areas could, on the basis of the existing process, lead to a fully industrialized RTM process for medium-sized series (see Figure 25).

Tailor-made textile production is the focus of attention at the start of the process chain. Ideally, using additional textile techniques such as braiding and stitching or combining different techniques should result in near-net-shape semi-finished textile products. Under certain circumstances, this can significantly reduce offcuts.
For simple geometries, it is also possible to eliminate at least part of the preforming process by placing cut-to-size and, ideally, tailor-made semi-finished products straight into the RTM tool. In connection with a suitably optimized part design, this can sometimes slash the cost of preforming.

End-to-end automation in the form of a production cell lends itself for infiltration, the core step in the whole process. In this step, every action – from inserting the preformed part/textiles to removing the raw part from the form (after curing) and placing it on the stack – can be fully automated.

Different aspects will also be optimized in the last link in the chain: Near-net-shape raw parts will reduce the need for final processing. In addition, alternative processing technologies such as CNC robots and (pulsed) laser technology have the potential to alter the final processing step.

**Compression molding**

Unlike the RTM method, the compression molding of thermoplastics (see Figure 26) is based not on dry semi-finished fiber products but on plate-shaped semi-finished products that are already composites combining the thermoplastic matrix and the fiber material in the form of a woven or multiaxial fabric. As a rule, these semi-finished products are manufactured in a continuous process on what are known as double-belt presses.

The first step in part production involves cutting these semi-finished products roughly to size and heating them in a special oven. Infrared ovens are often used, as they heat the products up very fast and facilitate very precise process control. Depending on the thermoplastic matrix material, a separate drying step may be necessary before cutting and heating.

**Figure 26: Current process: Compression molding of thermoplastics**

Source: Expert interviews; desk research; Roland Berger
Before the heating process, the roughly cut pieces are usually clamped in a device in which they first pass through the oven and are then transferred to the press. Depending on the specific technical implementation of the method, however, this step can be handled in different ways.

In the press, the heated semi-finished product is molded and then cooled down so that it can be removed from the mold as a raw part with a stable form.

Temperature control plays a vital role throughout the entire thermoplastic compression molding process chain: Parts of consistent quality can be produced only if the forming process is highly reproducible; and since the formability of the semi-finished product is heavily dependent on the temperature, it is imperative to control the temperature very precisely. Even minor delays in transferring the semi-finished product, for example, are enough to lead to overcooling. This in turn can alter formability and result in scrap.

The last step is the final processing of the part, just as in the RTM process. In this step, the edges of the part are machined in line with specifications and/or subjected to further mechanical processing steps.

As with the RTM process, thermoplastic compression molding also possesses substantial industrialization potential (see Figure 27). This more industrialized process is also referred to as organo sheet forming.

Figure 27: Potential fully industrialized process: Organo sheet forming

> Trimming of plate-shaped semi-finished parts to almost final contour:
  - Optimization of trimming waste
  - Saving of heating energy

> Combination with injection-molding tools, e.g., for back-injection molding of webs

> Elimination of finishing work by
  - Trimming inside compression tool
  - Injection-molding into final contour

Source: Expert interviews
The first step in the process chain is to cut the semi-finished products to a near-net shape. This step reduces offcuts and minimizes the energy needed for heating.

The most significant modification to this process concerns forming, however. Instead of merely forming the semi-finished product in a mold, this step is also combined with injection molding. To do so, forming takes place in an injection molding tool into which additional material can be injected immediately after initial forming. The additional material can be either pure thermoplastic or short and even long fibers can be added to reinforce the product. This combination can, for example, be used to add stiffening ribs that improve the mechanical properties of organo sheet parts that have a rather planar structure to meet the demands of certain load cases. Mounts or brackets, etc. can also be added to permit greater functional integration. In other words, this method almost automatically leads to the creation of hybrid components (see also Figure 12, at right).

For parts that are not too large, this method can combine heating equipment such as an infrared oven with a suitably modified injection molding machine and an appropriate handling system in relatively compact production cells. Given a suitable part design and the right circumstances, it can even be possible to injection-mold the final part, completely eliminating the need for any final mechanical processing.

The organo sheet forming and RTM process stand to gain very considerable benefits from the industrialization of production processes. In future, however, the other methods discussed above will still retain a certain status within the overall methodological landscape for the production of high-strength fiber-reinforced composite parts, although industrialization will gradually shift the contours of this landscape.

Pultrusion and fiber-winding are the ideal methods for beams and hollow parts and will maintain their current importance in the future. Especially in GFRP applications, both methods are already widespread and involve heavily automated processes that deliver cost-effective production.

RTM methods will remain the exception for structural and surface parts in excess of around 10 m², primarily because of the capital investment that would be needed to buy suitably dimensioned molding presses (and the lack of availability of such presses). This segment will therefore be serviced almost exclusively by vacuum infusion methods. Basic hand lamination methods will be an option only for very small series of under 100 units.
Conversely, it is logical to conclude that there will be no series of above 10,000 units in this segment. The exact design of the process chain for vacuum-assisted infusion can involve anything from traditional to semi-automated manufacturing, depending on the series volume.

However, there will be no fully automated production cells or fully linked lines. Prepreg-based methods are a special case. While they are still the method of choice in the aviation industry, their importance is expected to wane in the medium to long term. This decline is attributable above all to advances in the RTM methodology, which is already capable of achieving almost identical-quality parts. As development work continues, it is reasonable to assume that prepreg-based methods will no longer offer any compelling advantages in the medium term. In light of the drawbacks discussed above (the cooling chain, long cycle times, autoclaves, etc.), the aviation industry is working systematically to replace prepreg methods by other methods wherever possible.

That is not to say that prepreg methods will have disappeared completely from the process landscape by 2020. From a present perspective, however, it does mean that the future potential for this method must be rated as low to moderate.
5. The role of the engineering industry – Contributions, requirements profile and business potential

The clear trend toward the industrialization of production processes in the direction of medium-sized series volumes will open up significant medium-term business potential for the engineering industry. This section therefore examines the contributions that each segment of engineering can make to industrialized process chains. It also analyzes and evaluates the resultant business potential and the positioning that engineering companies can adopt.

5.1 Contributions of individual engineering segments to the industrialized production of high-strength composites

The engineering industry will play a key role in driving the ongoing industrialization of production processes for high-strength composites. Many different segments of the industry must play a part in bringing progress and improvement to different process chains (see Figure 28).

![Figure 28: Engineering industry's contribution to series processes for composites](image)

At least six different engineering disciplines play a part in RTM and compression molding methods, for example. Varied involvement begins as early as the production of semi-finished goods, for which textile machines and plastic (organo sheet) processing machines are needed.
Forming machines (usually presses), plastics processing machines (such as injection systems) and handling systems are then needed for the component production. Toolmakers too have a pivotal part to play as they produce the various molds and tools that are needed. Especially toward the end of the process chain, machine tools also come into play for final processing of the manufactured parts (additionally they may also be needed to cut textiles to size earlier in the process).

Fewer engineering segments tend to be involved in pultrusion and fiber winding methods. Pultrusion systems are classed as special-purpose machines, while toolmakers are needed to provide the necessary molds/tools, as well as handling systems for the finished parts. Compared to RTM and compression molding, however, both disciplines have a smaller part to play. This is because the molds that are needed are rather small, and because handling is usually only required when the raw parts are removed at the end of the process. This is where machine tools are called on once again to cut the pultruded continuous sections into parts of a defined length.

Although fiber winding machines are classed as textile machines, this process likewise requires the participation of other disciplines. Toolmakers have to make suitable molds/cores and the part handling systems; and machine tools may again be needed for final processing. (Since the finished parts are sometimes wound directly, machine tools are not classed as core elements here.)

At this point, it is very enlightening to look at what areas of expertise the various engineering companies already have and which they do not, or at least not to the same extent (see Figure 29).

Handling specialists have an in-depth knowledge of robotics and gripping technology (or at least one of these disciplines). Many also possess considerable systems expertise. What they lack with a view to the overall process, however, is often a knowledge of the core processes and machines, in particular the press and the plastics processing.

The situation is essentially similar for the producers of forming machines. They have a thorough understanding of vertical high-performance presses, as well as a certain level of handling skills in some cases. However, the vast majority of these companies has no knowledge of plastics processing machines. Conversely, the manufacturers of plastics processing machines only possess expertise in their chosen field (possibly complemented by some handling knowledge), but they know little or nothing about the high-precision, high-strength presses that are vital to the overall process.
The story is the same for the other players who participate in the process chain: Each focuses on its own specific aspect but has little or no knowledge of other core steps in the overall process. Specialists for textile machines devote themselves to the production of technical textiles but have little grasp of the other processes involved in component production. Some toolmakers possess vital expertise about tool design (although some merely manufacture to the specifications of the plant operator, who possesses the actual expertise). But even those that do have specialized knowledge are not sufficiently familiar with the wider processes around them. And even machine tools producers who make the machines and cutting tools for use in final processing (and, in some cases, to cut semi-finished products to size) tend to be sharply focused on their specific process steps, but are not sufficiently familiar with the rest of the process chain.

The situation is therefore that none of the parties involved has a full knowledge of every link in the process chain. Every player in the game therefore still has a lot of work to do. First and foremost, engineering companies must further optimize their own areas of expertise and align themselves with the demands of industrialized composite production. At the same time, however, they must learn about the interfaces between the individual links in the chain: There is still plenty room for optimization – from communication between individual machines and systems to continuous data flows from the engineering office to the handling system. End-to-end optimization of the series production process is another area whose vast potential is far from being fully exploited as things stand today.
5.2 Demands placed on engineering companies

What specific demands will therefore be placed on engineering companies in this context? In the interviews we conducted with industry experts, the OEMs and manufacturers of high-strength composite parts formulated a catalog of requirements (albeit with no claim to completeness) for the engineering industry.

Experts in the aviation industry, for example, often say they would "like to see engineering companies build up greater expertise in the production of CFRP parts". The former offer their assistance on material-specific issues (concept, calculation and design), although this is specifically linked to the demand "that engineering firms should also approach us [aircraft manufacturers] with their own ideas about production and suitable machinery". Rising cost pressures in the aviation industry are also behind the growing desire to make greater use of only slightly modified series production machines in place of the special-purpose machines that are generally much more expensive. Another demand is for engineering firms to become more involved in joint development projects.

Automotive OEMs assert slightly different demands, although all tend in a similar direction. "The engineering industry must itself be willing to invest some effort to transform existing concepts into technologies that are genuinely application-ready", is the general thrust. In the context of joint development projects, the call is explicitly for "patience and endurance" on the part of engineering firms, because demand for the equipment in question will grow only slowly. Regarding the concrete demand of production equipment, engineering companies are also urged to focus specifically on optimizing individual aspects that harbor considerable development potential (such as gripping technology and the handling of flexible parts). In the medium term, there is clearly also a keen interest in finding competent system partners who can provide suitable production systems for multiple operators. Only when this stage is reached, it will be possible to develop the technology at the necessary speed and reduce costs quickly enough.

The demands of the wind power industry differ more markedly from those discussed above: "Further automation is essentially desirable, yes, but we need tailor-made solutions that don't go over the top, that keep capital spending down." To this end, it appears sensible to initially focus rather on work steps that are less technologically sophisticated (such as milling, edge trimming and painting). On the other hand, industry experts are skeptical about the idea of using large, complex equipment to extensively automate textile placement processes, as the investment outlay would outweigh the current benefits.
While demands thus differ depending on the end customer segment, there are also some common features on which all the industries examined appear to agree:

> Engineering companies are expected to invest more in development in the directions discussed

> Further optimization is still needed in various areas of technology

> Since all development work has to be cost-effective, maximum automation is not always desirable

> Long-term development partnerships are being targeted

### 5.3 Business potential between now and 2020

German engineering companies' willingness to invest in the ongoing development and optimization of all this production equipment is contingent largely on expected business potential. Substantial R&D spending can be justified only by commensurate sales potential.

Based on forecast demand for high-strength fiber-reinforced composites (see Figure 19, page 34) and interviews with a large number of experts, we therefore crafted a market model in order to identify demand for automation systems for use in the manufacture of high-strength composites between now and 2020.

The key input variable for this model is growth in demand for continuous-fiber-reinforced parts. Since series production is the focus of the study, the model only includes equipment and machinery that is to be used in the context of at least semi-automated series production. Examples of items that do not belong in this category are molds that are deployed exclusively in manual processes (such as in the conventional production of rotor blades for wind turbines or in manually produced small series in the automotive segment). However, molds that are standard items for processes that are at least semi-automated are included in the model.

Drawing on experts' estimates, the first step was – for each industry and each material individually – to identify the share of annual market growth that involves at least semi-automated production equipment. The spectrum ranges from 10% for GFRPs for wind turbines to 80% for CFRPs for the automotive sector.
Based on the resultant quantities and further assumptions about the production capacity and cost of individual items of equipment/equipment components, we then calculated the market volume for production equipment as shown in Figure 30. The global market for high-strength composites will grow by just over 5% per annum (due to its market size, GFRP growth outweighs CFRP growth despite the latter’s higher growth rate, see Figure 19). However, growth of roughly 7% per annum is predicted through 2020 for production equipment. This slightly higher growth rate is essentially due to the increasing automation of processes that have been handled manually in the past. On the other hand, volume growth will be retarded slightly as production equipment becomes increasingly productive.

**Figure 30: Global demand for production equipment for high-strength composites**

*2011-2020 [EUR m]*

- **Semi-finished goods production**
  - 2011: 340
  - 2015e: 432
  - 2020e: 614

- **Component production**
  - 2011: 295
  - 2015e: 376
  - 2020e: 534

1) Only continuous-fiber-reinforced composites; tools are only considered in the context of automated plants
Source: Expert interviews; desk research; Roland Berger market model

The global market volume for equipment for the production of high-strength composites currently totals around EUR 340 million – a relatively low figure compared to other segments. Although this figure is expected to double worldwide to roughly EUR 600 million by 2020, that too will still be a fairly modest sum.

To put these figures in perspective, we would explicitly reiterate that they are limited exclusively to production equipment for high-strength composite parts, i.e. they do not include production equipment for short- or long-fiber-reinforced parts. At the same time, some of the equipment components that are included (relating to molds, plastics processing machines and handling systems, for example) are also used in the latter market segments.
When speaking of such volumes, it makes sense also to briefly examine the reliability of the forecasts involved. Product development cycles have widely differing time frames in the various industries analyzed. Development cycles in the automotive sector tend to extend over about three years, for example, while the aviation industry needs at least ten years to develop a new commercial aircraft. In the latter industry, however, a large number of aircraft have already been ordered before even one has been produced. As a result, the utilization of production capacity can be planned with very considerable certainty for years at a time.

Accordingly, forecasts of the machinery and equipment that will be needed to produce suitable fiber composite parts in the aviation industry beyond 2020 are significantly more reliable than is possible in the automotive industry, for example. This factor can play a major role in influencing companies’ willingness to engage in industry-specific development. All in all, the German engineering industry’s current activities with regard to production systems for high-strength composites can only be assessed as rather modest. Although the tendency is to see substantial growth prospects for production equipment in this market segment, the allocation of development budgets is not overwhelming (see Figure 31).

Figure 31: Business activity of the German engineering industry

58% of the respondent engineering experts in our study rate relevant growth opportunities as high or very high. Only 3% anticipate low growth prospects.
Nevertheless, the willingness to shoulder commensurate risks is less pronounced than it is for the core products and technologies of the companies concerned. When it comes to their core products, 78% of companies demonstrate a high or rather high willingness to invest up front in the form of development work. By contrast, only 39% of companies are prepared to take this risk in relation to composites. Indeed, one third of companies explicitly state that they have a low or rather low willingness to invest on this front.

These findings show that many players in the engineering industry are currently settling for a wait-and-see attitude with regard to production equipment for high-strength composites. The majority of German engineering firms does not rate the anticipated potential highly enough to justify allocating substantial R&D budgets to this market segment.

5.4 Need for action and how German engineering can position itself

Necessary actions and sensible options for positioning the German engineering sector on the market for production systems for high-strength composite parts can be derived from the discussion and deliberations so far. Let us summarize the insights we have gained:

> No engineering company currently has all the skills that are needed for the industrialization of RTM and/or compression molding processes

> Nobody has all the necessary interdisciplinary systems expertise and matching references – which makes it difficult to offer end-to-end solutions from a single source

> Despite its limited volume today, the overall market for production systems for high-strength composite parts exhibits solid growth and holds out additional medium- to long-term potential through hybridization

> However, since these production systems are not part of the relevant engineering firms’ core business, only limited R&D budgets are available. Accordingly, ongoing development must take the form of evolution on the basis of existing equipment

> It must be the aim to facilitate a flow of technology across operators in order to speed up innovation and thereby lower production costs

So what does all this mean for the positioning of German engineering companies with regard to production systems for high-strength fiber-reinforced composites?
Given the sheer multiplicity of engineering firms that play a part in the process chain, no overall "system leader" is readily apparent. None of the market players stands out because of its added value. From a present perspective, therefore, it seems to be very difficult for any player to organically achieve a position of system leadership (i.e. using only its own resources). In the interests of rapid technological development, customers/OEMs thus see intercompany cooperation as imperative if the challenges ahead are to be mastered.

Three different types of cooperation could lead to the development of the required equipment (see Figure 32). In the first of these variants, the operator is both system leader and coordinator. The various engineering disciplines would then contribute components in line with their areas of expertise.

**Figure 32: Potential types of cooperation**

1) Plastics-processing machines (e.g. injection unit, etc.)
   Source: Roland Berger

The second conceivable variant would involve cooperation between different engineering companies that each play a significant role in the process chain and that thus team up to form a consortium. In respect of operators, this consortium would take on the role of system provider (prime contractor).
The manufacturers of presses, plastics processing machines and handling systems in particular would lend themselves to participation in this undertaking. Other necessary elements could then be sourced with third parties.

The third alternative would involve M&A activities that allow engineering companies to acquire skills and expertise through selected acquisitions in order to be able to offer end-to-end solutions from one source.

Many different criteria must be examined in order to assess these different options. Figure 33 thus summarizes the findings of an analysis of the following key criteria: investment need/development budget, synergies, the speed of innovation, the coordination effort involved and the adopted know-how position.

Regarding the required investment volume, engineering companies take a positive view of both the operator solution and the option of cooperation between several firms. The former would involve only very minor capital spending on the part of the engineering firms themselves, while the latter would allow the burden of investment to be spread across several shoulders. Not so the M&A option, which would necessitate heavy spending as more than one acquisition will be needed in most cases to optimally top up a company’s own portfolio of expertise.

A similar view can be taken of synergies: The operator and cooperation-based solutions should normally allow engineering companies to exploit synergies between composite-specific activities and their core business. For example, slight modification may be enough to adapt some of the systems developed in the context of core business for use in composite production. Alternatively, scale effects too can be put to good use. Conversely, substantial dis-synergies are probable in the case of M&A activities, as carving an engineering company’s composite activities out to form a new entity eliminates any possible synergies with core business at a stroke.
In terms of the speed of innovation, the operator solution is significantly inferior than either of the other two solutions. Experience in other fields of technology shows that technology transfer between operators is needed to drive rapid development. On this score, close cooperation between engineering firms can be recommended as strongly as M&A activities that would bring all the necessary skills together under one roof.

Regarding the coordination effort involved, engineering companies would logically prefer the operator model, since the whole burden of coordination must be carried by the operator in this case. On the other hand, this issue constitutes the biggest barrier to cooperation between different engineering firms, as getting this kind of intercompany cooperation off the ground in the German engineering industry is a truly challenging task. M&A activities will also necessarily involve a certain amount of coordination effort as new business units have to be integrated.

One final consideration is that the know-how position of German engineering companies is one major reason why these firms take a dim view of the operator model in particular. If they commit to such a model, engineering
firms have no chance of cultivating a knowledge of the entire process in house. Instead, they position themselves merely as suppliers of individual subsystems. By contrast, the other two forms of cooperation significantly reinforce engineering firms’ know-how position by allowing them either to share end-to-end system competency or to accumulate it under one roof.

Ultimately, the operator model leaves engineering companies in a rather passive role in which they serve solely as suppliers of individual plant components. Their influence on overall technological development is thus largely limited to their own component and remains modest at best. Especially in view of the long-term global potential that exists, it is therefore worth asking whether this model really holds out any promise of success for the engineering industry. Any company that wants to become a global leader in this field has no choice but to cultivate its own system competency in the medium to long term. On markets outside Europe in particular, demand for turnkey plant from a single source is a given, irrespective of the specific production technology involved. And the same principle applies all the more for complex processes that interlink multiple technologies and thus require considerable expertise.

In assuming an active role, that is cooperation or launch of some form of “German Composite Production Systems AG” on the back of M&A activities, the German engineering industry would undoubtedly enhance its position in the market, improving its chances of success in the long term.

Alongside these “major” strategic considerations, many complementary measures can be implemented to expedite the industrialization of production processes for high-strength fiber-reinforced composite parts (see Figure 34). From the perspective of engineering companies, closer cooperation with OEMs/end customers would be a particularly good move in this regard.

Nearly 90% of the respondent engineering firms in our study cited more detailed requests from and development partnerships with OEMs as an essential precondition to ramp up production of equipment for high-strength composites. 70% were also in favor of joint R&D activities preceding competition in the market. This view undoubtedly reflects the understanding that fundamental development potential remains to be tapped at many links in the entire process chain. A number of activities are already underway on this score – For example in Bavaria’s regional MAI Carbon cluster.
Industry experts are generally ambivalent about the benefits of networking events, government-backed economic development and education and training initiatives. Many players do see networking events as a very good way to familiarize themselves with the material, glean initial knowledge and establish contact both with other engineering firms and with OEMs. They are thus an important way to prepare the ground – but are not enough to significantly boost the activities of the individual player.

Economic development and education initiatives too are generally seen as a good thing: Roughly half of the respondents expects such activities to add value directly. The other half, however, fails to see where this value is added, for example because the process of applying for subsidies is too complex, or because companies do not believe that they will benefit directly from education initiatives.

A substantial majority sees activities to define norms and standards as unsuitable – again probably because the direct influence this might have on the individual company is difficult to grasp.
6. Outlook – Medium and long-term perspective

What conclusions can we draw from the findings of the preceding sections? What do the medium- and long-term prospects look like for the composite activities of German engineering companies?

The first core conclusion is that demand for high-strength fiber-reinforced composite parts is increasing across all industries and will translate into solid market growth between now and 2020. Demand is driven by an increasing focus on lightweight construction. Carbon fiber-reinforced parts in particular will stand out with growth rates well into double digit figures. Growing demand is apparent across a range of industries: While the automotive, aviation and wind power sectors will initially be the main drivers of volume, significant potential also exists in several engineering niches.

To cope with the increasing demand that accompanies growing series volumes, it will be necessary to build more production plants. Yet the required industrialization of production processes has only just begun: The RTM method and the thermoforming or organo sheet forming processes still have substantial potential for industrialization and will remain suitable for the series production of structural and surface parts in the long term.

It is reasonable to expect process costs to drop by 40% between now and 2020, while fiber costs are likely to decline by around 20%. An overall reduction of about 30% in the cost of components is thus expected.

If this goal is to be met, many different technologies must be improved and optimized in line with the specific requirements of the semi-automated production of composite parts. This will involve the development and testing of completely new, innovative components for the prefabrication of tailor-made semi-finished goods. It will also require the refinement and adjustment of existing components and the build-up of process-specific experience and knowledge with regard to the optimal process design/parameters for individual fiber/matrix combinations, part geometries and part designs. In addition, a knowledge of the design and integration of the entire series production system based on the RTM and thermoforming process must be built up from scratch.
Those engineering companies that play a part in this early phase have the chance to gain knowhow leadership. Especially in the areas of system design, systems integration and process alignment, they will be able to accumulate experience that will be hard to copy in the future. This fact alone will help them protect their leadership position in the long term. In other words, the market-leading places in the engineering of composite production systems are filled now.

Individual engineering companies must therefore quickly decide whether they want a share in the market, and if so, what role they plan to assume. Those companies that are willing and able to fund a protracted startup phase in this line of business must follow this path systematically and determinedly. This decision will involve launching specific new development and improvement projects, deploying these technologies and products in as many and varied pilot installations as possible, cooperating actively both with other engineering companies and operators, and – where appropriate – actively striving for a position of system leadership.

In the long run – i.e. in the period after 2020 – a significant increase is expected in the market volume for composite components and the corresponding production systems. Coupled with superior series production processes, further cost reductions and improvements in the performance of fibers and matrix materials will continue to drive down the cost of the finished components. At the same time, the significant experience gained in the design of composite parts in combination with sophisticated testing and simulation methods will drive down costs further. In the long term, high-strength fiber-reinforced composite parts will therefore successfully compete with established materials in more and more applications.

Given the development of suitable multi-material concepts, one key driver of growth is likely to be the hybridization of composite parts. The intelligent use of continuous fibers for reinforcement purposes only in areas where their mechanical strengths are fully exploited and a combination with lower-cost materials such as short-fiber-reinforced plastics or metals will drive the variety of hybrid parts with attractive cost profiles. This will also open up a broad spectrum of new application opportunities, some of which will feature completely new components and end product designs. As suitable design guidelines and simulation methods are fleshed out, this will in turn create the conditions for dramatic growth in the composites market.
Many hybrid parts can be manufactured using the same series processes as pure composite parts. This fact therefore opens up a substantially broader array of potential applications for RTM and thermoforming series processes, which require only minor adjustment or modification for this type of parts. Demand will leap as a result. Any investment in developing and ramping up the underlying technologies will therefore be well spent money.

It follows that engineering companies that invest now in this area of technology and application will, after 2020, be excellently positioned to participate in far more rapid market growth. However, this also means that decisions taken now in regard to market entry must be based on a suitable long-term strategic perspective of the company’s role in the market for production systems for composite parts.

The pivotal question is whether a company wishes to position itself as a systems provider/integrator or as a component specialist. As in other areas of application such as car body assembly and painting, system providers specializing in the manufacture of composite production systems are likely to emerge in the medium to long term. Some of these providers will still manufacture certain key components in-house. Others will operate as pure systems integrators, combining components and units that they source on the market to assemble tailor-made production systems, which they then hand over – effectively as turnkey solutions – to the operator.

Many German engineering firms are currently pressing ahead with the development of individual technologies and specific components. Up to now, however, little knowledge has yet been accumulated and little market activity is therefore observable in systems integration for entire production plant. Operators – primarily the big automotive OEMs – are currently plugging the gap. However, this arrangement is more of an interim workaround than an optimal long-term solution. Hence, there is still plenty of room for companies to clearly position themselves as providers of end-to-end systems, even if a position as a pure-play component specialist is likely to be more attractive in many cases. At all costs, it is vital to avoid trying to do both: Experience shows that such strategies almost inevitably lead to a loss of focus, causing valuable investments and resources to be squandered without any sustainable benefit.
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Perspectives for the German engineering industry

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