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Review of industrial manufacturing capacity for fibre-reinforced polymers as prospective structural components in Shipping Containers

Approximate cost, production methods and market drivers

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Cover Photo: Preparation for resin infusion of carbon-fibre walkway.

(Courtesy of Carlo Paulotto and Stefano Primi,
Acciona Infraestructuras, Spain)

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SUMMARY

It is estimated that in 2010 the world raw materials for fibre-reinforced composite market turnover was of the order of 6-10 Million tonnes with end-product value estimates in the range of €40 to 70 €Billion[1].

Fibre-reinforced composite materials offer a number of advantages over traditional materials. Indeed, the range of applications of modern composites has progressed exponentially in the last half century. Our dependence on them is such that many applications in the aerospace, naval, chemical, motor and general consumer commodities sector would be inconceivable without them. Although modern composites were initially developed for cost-insensitive military applications, improvements in manufacturing techniques and the development of lower-cost fibres means that nowadays composites are even used in some areas of the—highly price-conscious—structural and civil engineering sectors.

Two of the main drivers for this push are (i) composite materials' high structural efficiency (strength-to-weight ratio) and (ii) their corrosion resistance to a wide range of chemicals. However, perhaps just as important, is that the explosion in developments in modern materials science has coincided with the Information Technology revolution. Compare, for example, the wood-frame planes and electromechanical telephone exchanges at the start the 2nd World War to the multipurpose use of advanced composites in aeronautics and the computing capacity of our modern telephony. The combination of the structural manufacturing design flexibility of advanced composites and the wide variety of miniaturized sensor technologies opens up the possibility of developing structural components capable of providing more than one useful function in a manner that had, hitherto, not been possible before.

In this document we will analyse the manufacturing and techno-economic aspects that are perceived as key for determining the feasibility of commercially viable, mass-produced smart composite containers. The scope of this review is not to propose new technical solutions, but rather to paint a panorama of the key aspects that, with currently available technology, will define the backdrop for future commercial and policy developments.

This short review is a compendium of basic technological and market information, with the aim of providing an overview to assist the non-specialist in evaluating future R&D policy-developing criteria for the eventual development of tamper-evident, sea-faring, containers based on the use of composite materials technology. In short, the question is: can

[1] Based on figures of $50 Billion (1 Billion = one thousand million) and €68 Billion given by Lucintel, USA, and JEC Composites, France, respectively.

composites be used to manufacture commercially viable shipping containers; and, if so, what are the basic economic and technological constraints? In this report we provide the main baseline figures on the economics and manufacturing background of industrial composites.

WHAT IS A COMPOSITE MATERIAL?

Since their development just after WWII, fibre-reinforced composites (FRCs) have made considerable inroads into modern materials manufacturing and component production. FRCs have been used not just as substitutes for traditional materials in already-existing products, but in the development of new objects and devices; conceived and made possible only through the use of modern materials.

FRCs are only the latest manifestation of composite materials; indeed, humankind has been using them for millennia. Thus, for example, wood (a natural composite) and adobe (probably the first human-made composite) were some of the earliest tool-making and structural materials used by humankind.

Today we apply the term composites to a wide variety of compounds constituted by the combination of at least two distinct phases or material types. If one applies this definition in a strict sense, irrespective of dimension or scale, then just about every modern material that is not a homogeneous, single phase, substance would qualify: these include steels, metal alloys, concrete (reinforced and otherwise), mortar, wood, asphalt, and many more. However, here we refer to the most usual, modern-day, application of the term, meaning a compound substance obtained from the combination of two or more materials whose phases are distinct at the meso-scale (from a few microns up to the millimetres range). Scale, however, is not the only composite-defining criterion that distinguishes composites from other materials.

The most inherent quality of composites is their degree of heterogeneity, which often confers to them a complex range of both physical and chemical properties. Composites do ‘inherit’ properties from their constituent materials, but do so in a manner that is not governed by simple *rules of mixtures*. Most importantly, composites are highly directionally biased (or anisotropic); that is, they have different properties in differing directions.

The anisotropic properties of composites are a double–edged sword for, on the one hand, the designer can optimize in which direction to apply the desired properties (leaving out, and hence saving, material in the direction where said properties are not required), but on the other hand, makes the design process somewhat trickier because rarely can we design structures that require properties in only one direction.

Having made this distinction about scale and directionality, we can now restrict our subject matter to those composite materials made by combining some form of reinforcing fibre embedded within a matrix.

The key to understanding how composites work is to bear in mind that fibres, however strong, only work in tension —along the direction of their length— but are of little use in any other way unless they work together in fibre bundles, and especially when these are woven or draped —like clothing fabrics—in one or more directions. The job of structurally binding the fibres is done by the matrix which, although has rather poor reinforcing properties compared to the fibres, ensures that adjacent fibres stick to each other. Thus, fibres set in a hardened matrix constitute a composite material that can transmit an applied force in a very effective manner which, by themselves, the individual fibres and matrix materials cannot. Strictly speaking, composites are not materials; they are more like miniature structures, in the sense that they are the synthesis of combining two or more homogeneous material substances whose 'sum' is different from their apparent individual properties.

Another characteristic property of composite material structures that is often taken for granted is that both the material and the structure are created during the manufacturing process. What we mean by this is that as the fibres and matrix are combined and subsequently harden, they also generate the final manufactured object. For example when making reinforced concrete (also a composite), steel reinforcement bars, cement, sand etc., are combined and let to harden inside a formwork to take shape. The final structural element (a beam, a column etc.) is, in a sense, generated at the same time as the material (reinforced concrete). In the same manner, fibre-reinforced structures are generated at the same time as the formation of the composite laminate. This manufacturing method is in contrast to the manufacture of elements by deforming or joining an already-existing material into a final shape.

Large composite assemblies (for example complex pipe-and-vessel conduits used in the chemical industry) can be assembled from smaller sub-elements in the same way as is done for metallic or, most similarly, wooden structures. However, joining load-bearing composites requires quality-controlled procedures and experienced production staff.

Composite materials processing overview

Composite manufacturing technology is somewhat similar to cooking: satisfying products can be made for little effort; refined dishes with subtle aromas require great skill and technical knowledge. The best composite products balance the intuitive skills of artisanship with the precision of engineering.

Herein we shall not provide an extensive taxonomy, but it is important to appreciate the disparate physical properties of composites' constituent materials and their processing characteristics. But first it is important to highlight some subtle differences in terminology:

- FRC: Fibre-reinforced composite.
- FRP: Fibre-reinforced polymer.

Broadly speaking, the term FRC is applied to any generic material compound made from a primary or reinforcing compound embedded in a matrix; this can take up many forms, ranging from papier-mâché to aerospace-grade carbon-fibre-reinforced Silicon Carbide (C/SiC). FRPs are the most common form of FRCs, where the matrix system is some form of polymer. Technically speaking, wood is a natural form of FRP, or perhaps one should say that FRPs are a synthetic form of wood. By far the most widely used varieties of FRP are glass-fibre-reinforced-polymers (GFRP). Other, but less commonly available, fibre feedstocks are Aramid and Carbon fibres; their approximate average cost are given in Table 1 and Figure 1. We can see that the cost range is subject to considerable variation depending on the specific type and finish of the fibre; thus prices for some special S-glass fibres can be as much as ten times those given for E-glass. Likewise, high modulus low strength (HMLS) carbon fibres can be considerably more expensive than their low modulus high strength (LMHS) counterparts. These figures are only indicative of raw fibre costs. The reinforcing material is usually further processed into tows to form bobbins, mats, or woven cloth, this extra processing may affect the final net fibre cost considerably.

There is a very broad range of polymer matrices, which, compounded by the multiple stoichiometric possibilities, results in a bewildering variety of matrix systems, so, as above, the prices given in Table 1 are an indicative average of wide band ranges. Typically, the polymer matrix represents at least 35% by volume of the finished product. The choice of matrix is fundamental to the final mechanical and other physical properties of the composite, and it also affects the final laminate cost—even for identical raw gross weight costs— because the polymer systems chosen can have very different production costs (rheology, process temperature etc).

In view of the fact that it is not just the constituent materials that define the final material properties, a further classification of composites is one that is based on the degree of quality assurance and processing costs which is therefore reflected in the price. These FRCs are referred to as Advanced Composites as opposed to standard, or 'commodity', composites.

Advanced Composites are typically used in the aerospace and high-end sectors of the automotive and goods markets (e.g. sports etc.). Although the use of carbon fibre is typical, the main criterion is the specification of strict performance and process control standards; so, for example, a wetlay-up composite using carbon fibre would not quality as an Advanced Composite, whereas a moulded glass-fibre autoclaved pre-preg component would. Furthermore, Advanced Composites usually have a very low percentage of voids in the resin system, they are typically produced under vacuum or high plate pressures, and they have higher thermal and dimensional stability than equivalent systems; all of which results in components with traceable specification mechanical and physical properties.

Raw Materials Cost:

From Table 1 it can be seen that the major resin system used for composite manufacture is Polyester, which is used in a wide range of applications in the marine, construction and automotive applications. Polyesters confer good mechanical properties at an acceptable cost. For applications where more demanding mechanical properties are called for, most manufacturers turn to epoxy resins; but epoxies, at more than double the cost, place a heavy burden on the final product cost.

Table 1 - Global shipments of raw materials used for composites manufacture[2]

	Type of material	Shipment 10^3 Tons	Shipment € Million	Average price €/kg
MATRIX (resin and other)	Polyester	1332	2785	2.1
	Epoxy	309	1360	4.4
	Vinyl Ester	65	238	3.7
	Phenolic	32	62	1.9
	Polyeurathane	74	215	2.9
	Thermoplastic Resin	1017	1852	1.8
	Fillers	337	126	0.4
	Other (pigments, etc)	133	931	7.0
FIBRES	Fibreglass	2570	4720	1.8
	Aramid	2	48	24.0
	Carbon	39	912	24.0
	Total	**5910**	**13,249**	**2.22**

In view of the cost-sensitivity of shipping containers, it is expected that polyesters will be the resin of choice –assuming all physical and chemical properties required are met; but there are more than just matrix polymers and fibres to consider when designing a composite. Whereas polyester (or, possibly, epoxy resins) will be used to manufacture the

[2] Based on data from *Growth Opportunities in Global Composites Industry 2011-2016*. Lucintel Report, February 2011 (Assuming average 2010 exchange rate of 1€=1.33$)

composite laminates themselves, a container wall could take the form of a sandwich panel, in which case either a foam or honeycomb core will be needed. An expanded filler polymer will be required for foam manufacture, and here, the resin of choice would most probably be an expanded form of polyurethane. Alternately the sandwich core could be made from aluminium or other (usually more expensive material such as impact–resistant aramid) honeycomb. However, it is not impossible to find acceptable quality cores made from resin-infused recycled paper, or other shredded fibres, wood and wood pulp, and cork at acceptable prices.

As regards fibres, one can expect that, aside from small quantities of carbon fibre, it is glass-fibre that will be the primary reinforcing material. However, it is noteworthy that although carbon fibre represents a small proportion of the overall trade by volume, the associated use of carbon fibre with the costlier Advanced Composite market increases its effective demand and hence its overall market share Figure 2.

The much less well-known, but highly prized, Aramid fibre, till now, has only been used in *niche* applications, primarily when good impact (or even ballistic) resistance is required. Although probably too expensive to be used substantially in container systems, it could find a use in key elements that are prone to being impact-damaged during standard container port and haulage manoeuvring procedures.

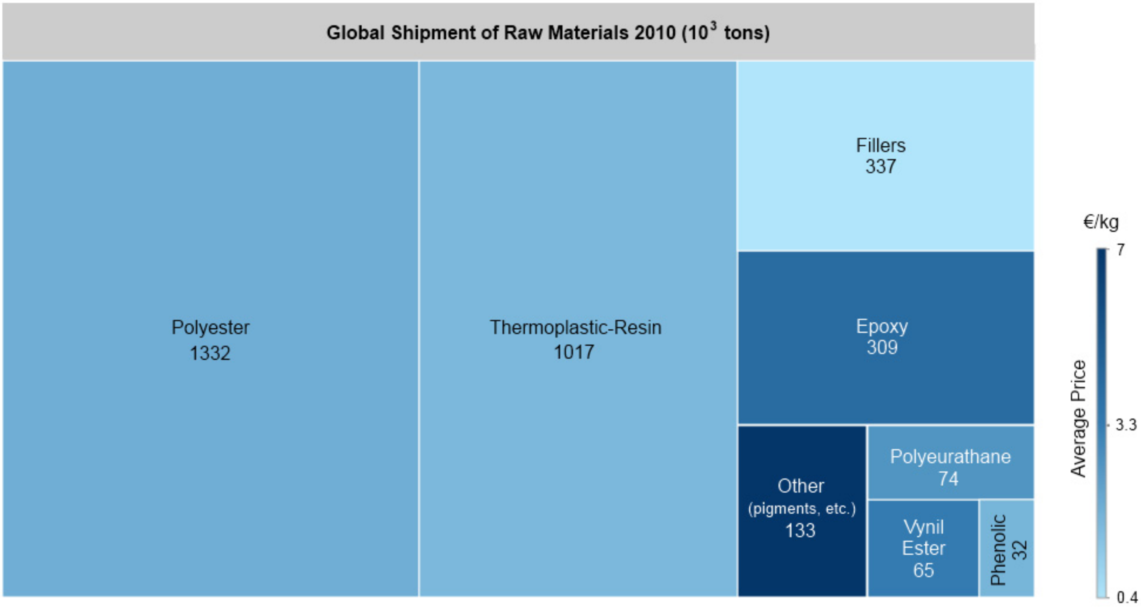

Figure 1 - Global shipments of raw materials (resins) used for composites manufacture[2].

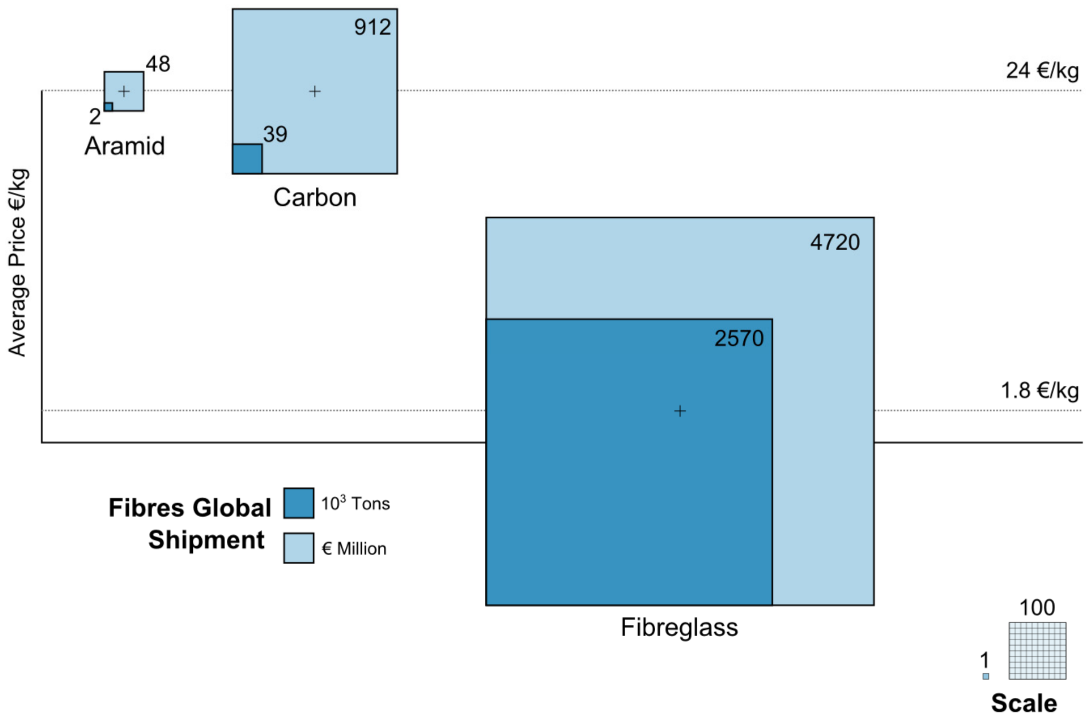

Figure 2 - Global shipments of raw materials (fibres) used for composites manufacture[2].

Basic Manufacturing Considerations:

FRPs are often presented to the non-specialist as somewhat exotic, lightweight, strong, materials manufactured in three varieties: glass, carbon, or aramid fibre composites. However, this oversimplification, at worst, can lead to potential design flaws, and, at best, presents composites in an unrealistic manner. To complicate matters further, the quality of the end product depends –sometimes just as much as the materials– on the manufacturing method used to produce it.
As is the case for any material production method, the quality assurance used for the manufacturing process as a whole, be it for manual or mass-produced items, can significantly affect the cost and mechanical properties of the end product. FRP composite manufacturing systems can be grouped in a variety of ways depending on feedstock and manufacturing processes; however, there are no hard and fast rules for composites production taxonomy. On the one hand we have that the manufacturing techniques can be divided into three main groups

(i) Moulded systems, where processing is conducted on a single or double-sided mould.
(ii) Continuous or semi continuous automated process such as filament winding, or pultrusion.
(iii) Laminated systems consisting of layers of dry or pre-impregnated sheets of fibre reinforcement.

Feedstock materials classification consists of two divisions for fibres based on their length:

- Short fibre
- Continuous fibre

Each of these can, in turn, be combined with two matrix divisions:

- Thermoset resins
- Thermoplastics

Although further divisions can be made for most of the classes above, all modern composites fit into some pairing or combination of the four classes above.

The manufacturing families for the various fibres resin types and methods are shown in Figure 3. Next we shall discuss some of these manufacturing processes in general terms, consider the context of their potential to be used to manufacture intermodal shipping containers, and examine the installed industrial FRC production capacity within the context of the world container fleet stock and manufacturing.

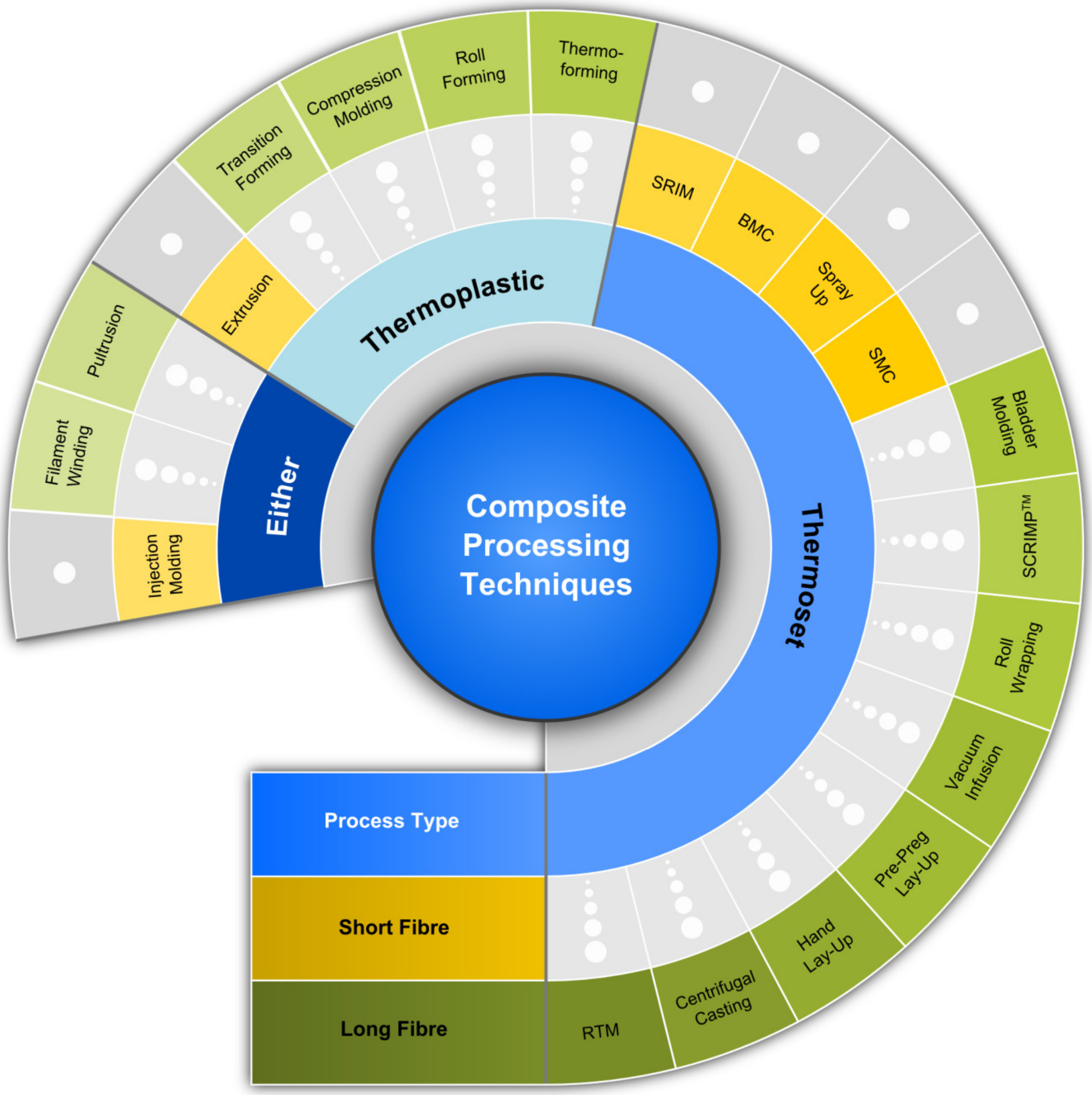

Figure 3 - Composites manufacturing common processes

(based on the information from *Fundamentals of Composites Manufacturing, Materials, Methods, and Applications* by A.Brent Strong, 2008 Society of Manufacturing Engineering)

Manufacturing Processes:

In principle, any number of methods are available for manufacturing composite shipping containers. In the first instance, containers can, in principle, be manufactured from sub-assemblies; so that each part can be tailored to the manufacturing process that best suits that specific component. The physical performance standards required for shipping containers, although demanding, are feasible for a wide range of FRCP manufacturing processes so long as the feedstock materials can meet those criteria. Another important reason is that many composite manufacturing processes were developed with the specific aim of optimising a process to meet the commercial and technical requirements (wherever it was thought that a part manufactured from FRPs would be most suitable). For example, the 'pultrusion' technique was specifically developed to suit the production of long structural and semi-structural profiles, and thus is cheaper than using more time-consuming methods (such as manual lay-up), even if the finished product were to look identical.

In terms of production capacity and potential for automation, both *Sheet Molding Compound* (SMC) and *Bulk Molding Compound* (BMC) processes have a combined production capacity of approximately 30% of all GFRP composites production in Europe. However, even though the production potential is high and SMC and BMC products are used where good surface finish is required (e.g. automotive etc) they usually do not exploit the best structural properties that can be attained from FRP composites. The reason for this is that, in general, it is difficult to control the reinforcing fibre orientation, more so in BMC, because the bulk material is composed of random chopped short fibres in a pre-cured bulk compound. Another drawback is that SMC and BMC production is not suited to large product sizes. Nevertheless, certain elements of composite containers could be considered using both these processes; for example small fixtures or components not subject to major loads.

An improvement in the quality of the laminate can be obtained by using the *Resin Transfer Moulding* (RTM) process. RTM represents about 10% of the EU composites manufacturing capacity. Even if in principle it is a relatively slow process, RTM can be used to manufacture quite large sections and, although a high level of capital equipment is needed (moulds and compression presses), the productivity potential is good. It could be possible to manufacture relatively cheap container walls using this method, perhaps in combination with a core material for the manufacture of sandwich panels that could also prove to be beneficial for transportation of temperature-sensitive products requiring good insulation.

Wherever good structural properties are needed, it is required to be able to manufacture the component in such a way as to best exploit the fibre alignment. There are two automated FRP manufacturing methods that can provide both the quality and manufacturing capacity at a reasonable cost, namely: *filament winding* and *pultrusion*.

Filament winding offers the possibility of manufacturing good quality laminates; however, there is a limitation to the curvatures that can be obtained from the filament winding process: it is ideal for producing cylindrical shells of revolution. In principle, non circular sections can also be manufactures as long as the curvature is positive on the outside of the tool. Filament winding could therefore be used for structural components such as container columns or beams.

Pultrusion is a highly industrialised process which can produce good quality FRP elements at competitive prices of, typically, €4/kg. This technique is ideally suited for the manufacture of longitudinal elements whose properties are preferentially aligned in the axis of loading. Elements that could be made in this manner include the primary column and perimeter beams.

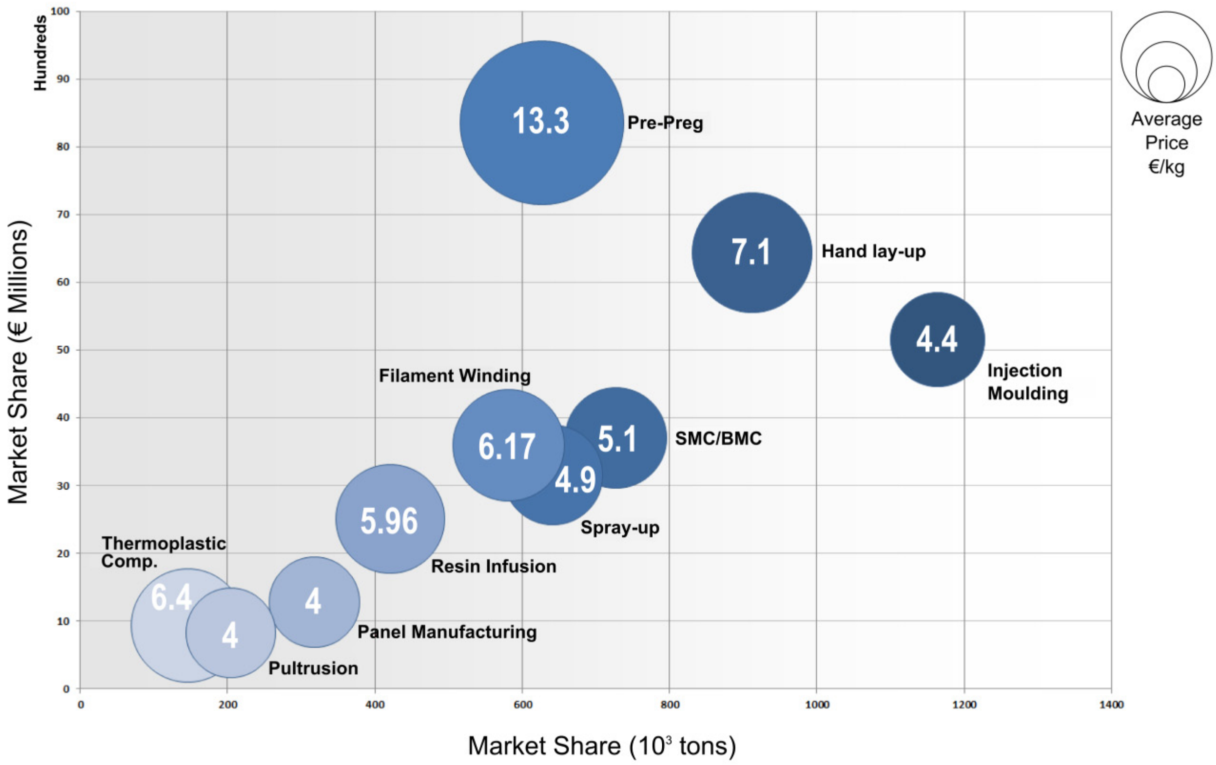

Figure 4 - World market share and value of end-product by composites manufacturing process[2]

In Table 2, Figure 4, we show the major manufacturing processes and their volume and market share of world production. In terms of capacity, of those listed, the most promising would appear to be Injection Moulding and Resin Infusion processes for the production of the container side panels (possible as a sandwich panel for both the flooring and walls). Typical end-product value for commercial production runs are of the order of 4-6€/kg. Both techniques have low-to-medium labour intensiveness and are therefore potentially commercially competitive in the European labour market. Product quality, although not as good as pre-preg panel manufacture, is acceptable for most load-carrying applications.

Table 2 - World market share and value of end-product by composites manufacturing process[2]

Process	Market Share *10^3 Tons*	Market share *€ Million*	Average price *€/kg*
Injection Moulding	1164	5159	4.4
Hand lay up	912	6436	7.1
SMC/BMC	727	3704	5.1
Spray-up	642	3161	4.9
Pre-preg	627	8357	13.3
Filament Winding	582	3593	6.17
Resin Infusion	421	2510	5.96
Panel manufacturing	318	1280	4.0
Pultrusion	205	825	4.0
Thermoplastic Comp.	146	936	6.4
Other	162	968	6.0
Total	**5906**	**36,929**	**6.25**

Although, in principle, all the methods shown in Table 2 could be used at various stages or for certain components, it is expected that low-cost manufacturing methods will dominate container manufacture. However, for key subcomponents, more expensive high-quality materials and methods (e.g. Pre-Preg) may make a contribution; for example by housing sensors or communication devices.

World Manufacturing Capacity and Markets

As mentioned earlier, when we manufacture an FRP element we also manufacture the FRP material itself. We also noted that there is a wide variety of FRP manufacturing methods that range from the manual to the fully automated. Given these aspects and the overheads incurred in the quality assurance chain for each technique, it is not surprising that a simple question like *"How much does FRP cost per kilo?"*, does not have a simple answer, but, typically, the lowest raw material costs for acceptable quality products are of the order of € 1.5-2/kg for glass-fibre reinforced polymers, whilst at the other extreme, the average price for LMHS carbon-fibre reinforced composites is of the order of €40/kg , and even considerably more for aerospace-grade HMLS carbon fiber. According to AVK[3] (the German Federation of Reinforce Plastics) the total production of GFRP in Europe in 2010 was of the order of one million tons, which, in turn, represents 90% of the entire fibre-reinforced composite market for Europe. The estimated production for the same year according to Lucintel[4] is of the order of 1.3 Million tons.

Given that nearly 99 % of the world production by weight (but, as we shall see not by cost) is in glass fibre, we can consider the values given above as indicative of the current capacity in Europe to manufacture composites. We shall later analyse which methods and materials (fibres and resins) account for this amount and which of these methods will be most appropriate for the manufacture of composite containers.

We can compare the prices and figures for glass-fibre products given above to an estimated world production of the order of 50,000 tons of carbon-fibre reinforced composites (based on the 27,000 tons of carbon fibre tow produced annually in 2009[5]). It is estimated by AVK that the production in 2010 was therefore equivalent to that of 2008 following the drastic downturn in production of 2009. Lucintel[4] gives a figure closer to 75,000 tons which, although 50% higher than the AVK estimate, nevertheless makes carbon fibre production by weight tiny compared to glass.

Advanced composites represent only 1.5 % of the total composite market by weight, but they account for over 20% if the net market value. It is expected that with the advent of the next generation of jet airliners, the demand, and hence total market share, of advanced composites is set to increase.

Although shipping containers could not possibly support the costs of using advanced composites, certain key elements (perhaps linked to energy harvesting components and sensor networks) would require the use of these materials.

Even if it is improbable that –other than for niche applications– the production of composite shipping containers will be based on the use of carbon fibre composites, it is not to be discounted that for certain critical elements (especially where low weight and strength are required), it would seem apparent that, based on the current costs/kg of finished

[3] *Composites Market Report: Market Developments, Challenges, and Chances, September 2010*.

[4] Growth *Opportunities in Global Composites Industry 2011-2016*. Lucintel Report, February 2011.

[5] Reinforced plastics, '*Carbon recycling: a soluble problem*', May issue 2009.

composite components, glass-fibre composites will be the material of choice in the development of shipping containers (should this become economically and technically feasible). Manufacturers of such containers would probably find themselves competing for resources with other manufacturers in the Transportation and Construction sectors.

HOW MANY CONTAINER UNITS ARE THERE?

The annual replacement of the container fleet in 2009 stood at approximately 1.35 million containers[6]. If it were possible to manufacture ISO-compliant containers made from FRP, and assuming that each FRP container would have a weight of 1.5 tons, this would require a total manufacturing capacity greater than that of all the EU's production for all types FRP products. Even 1% of the replacement fleet would still imply of the order of 20,000-25,000 ton of extra FRP capacity; however, because most of these would have to be made using resin infusion, panel manufacturing or filament winding methods, a conservative guess would mean that a 1% share of the market would require an increase of the order of 20% of current EU manufacturing capacity for these techniques. This represents both a great challenge and great opportunity for the EU composites industry.

Just to put these figures into world market context, the composites consumption in the wind energy market (blades and nacelles) of the People's Republic of China (PRC) was approximately 220,000 tons in 2010 and is expected to reach 250,000 tons by 2016[7]. The PRC is now not just one of the biggest consumers of composites, it is now one of the biggest producers of glass-fibre with the Jushi Group (owned by China Composites) producing 900,000 tons[8] of fibre glass —much of which is exported for the consumer product market all over the world. One can contrast this with the situation in 1998 when the total production of glass fibre in China was just under 200,000 tons (Source reinforced Plastics July/August 2006), whereas in 2010 the total reached 1.5 Million tons.

If we examine Table 3, we can see that the global raw material shipment value in 2010 was of the order of €13 Billion of which Asia (primarily China) represents nearly €5 Billion. Although the production of composites in the PRC is still, mostly, consumer-product grade, using hand layup and open-mould processes, the production of higher quality products has been increasing significantly since 2006. This is primarily linked to its

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[6] World Shipping Council: http://www.worldshipping.org/about-the-industry/global-trade/trade-statistics

[7] Composites Week, No. 22, Vol. 13, May 31, 2011. Lucintel Newsletter.

[8] Reinforced Plastics, '*Jushi spearheads growth of China's fiberglass industry*'. November 2006

burgeoning aerospace industry and the exponential use of composites in the wind power market: the PRC is now the world leader in wind turbine installation capacity. A decade ago the PRC was just seen as a low-cost production base, it is now able to compete with Europe and North America in the development of quality end-products. For the case of composite containers, therefore, it is clear that China will find itself in a privileged position to take up any technology development and implement it on a low cost production platform (unless products are protected by policy or rights laws enforced at local market level).

Table 3 - Shipments of raw materials by region[2].

Region	Shipment (10^3 Tons)	Shipment € Million	Average price €/kg
Asia	2434	4870	2
Europe	1334	3200	2.4
N. America	1848	4490	2.4
Rest-of-world	290	588	2
Total	**5906**	**13,148**	**2.2**

The market in North America, which is now the second biggest, has suffered most from the Economic downturn in the USA (down from about 2.5 million tons in 2005). The biggest shortfalls come from the automotive and construction sectors which were the main markets in the USA. However, there is a trend for FRP products to find new applications based on a strong collaboration with academia; for example the application of FRPs to bridge repair and seismic retrofit is spearheaded by a number of federal highway programs.

The European composites market also appears to have suffered lately, although somewhat less than the North American. Production in 2005 stood at approximately 1.6 million tons, perhaps protected by the strong investment in Wind Energy which continued to grow during the period 2005-2010.

This trend, in view of the recession in Europe and North America and the continued growth in Asia, is probably set to continue. In view of the potential of these growing markets it would seem that European products (in this case shipping containers) will only be able to compete on the basis of providing more advanced technology. However, said technology must still conform to the fact that containers are a highly price-sensitive product, and that 'SMART' containers with 'bells and whistles' will only sell if they are making money for their buyer or are imposed by security-related legislation.

As can be seen from Table 4**,** no single market segment accounts for FRP composites production: this testifies to the flexibility of these materials to penetrate nearly all technological areas. One of the most lucrative applications of composites is in the Aerospace market which, with only a tiny share of the market by volume , accounts for over 10% of the raw material cost and about 15% in terms of end-product market value. However, the sectors that could be most closely linked to shipping containers manufacture (and hence compete for resources) are the construction and transportation markets.

Table 4 - Global shipment of raw materials by main market segments[2].

Market Segment	Raw Shipment 10^3 Tons	Raw Shipment € Million	End-product € Million	Average price €/kg
Transportation	1261	2010	5100	1.6
Marine	198	348	600	1.75
Wind Energy	400	1513	3600	3.8
Aerospace	22	1458	5200	67.0
Pipe &Tank	842	1537	4400	1.8
Construction	1459	2310	6100	1.6
Electric & Electronic	1090	2764	8300	2.5
Consumer Goods	375	802	2200	2.1
Other	258	408	1400	1.6
Total	**5905**	**13,150**	**36,900**	**2.22**

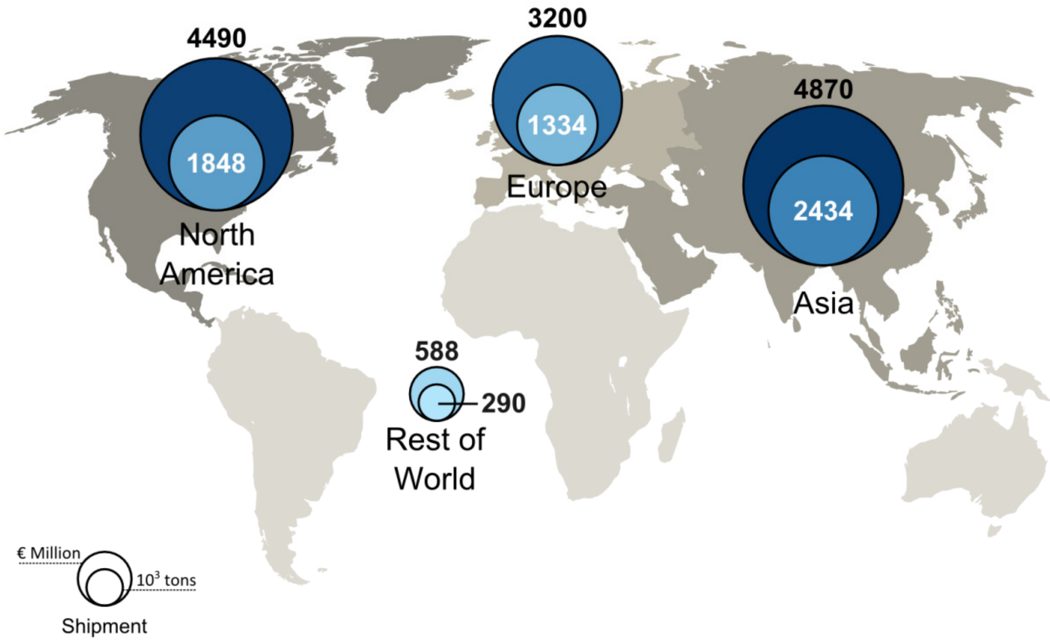

Figure 5 – Shipments of raw materials by region[2].

Although FRPs are heavily used in the construction sector, historically their applications have not been as major load-bearing elements; however, following on from significant research developments in the civil engineering field, these materials have increasingly been used as major structural components for retrofitting and reinforcing existing structures. In fact, for these load-bearing applications, it is often the case that carbon fibre is used as the major reinforcing element. Thus, even in the very competitive, price-conscious, construction market, a high cost fibre has been adapted to suit the application due to its low weight, high strength, and corrosion resistance.

In the transportation sector, FRP composites are used primarily as semi-structural components, such as lorry trailers, and non-structural shells for bodywork and interiors. Their primary role is to reduce weight and provide good corrosion resistance.

In many ways these fields of application require the four main criteria needed for a shipping container, strength, lightness, corrosion resistance and cost.

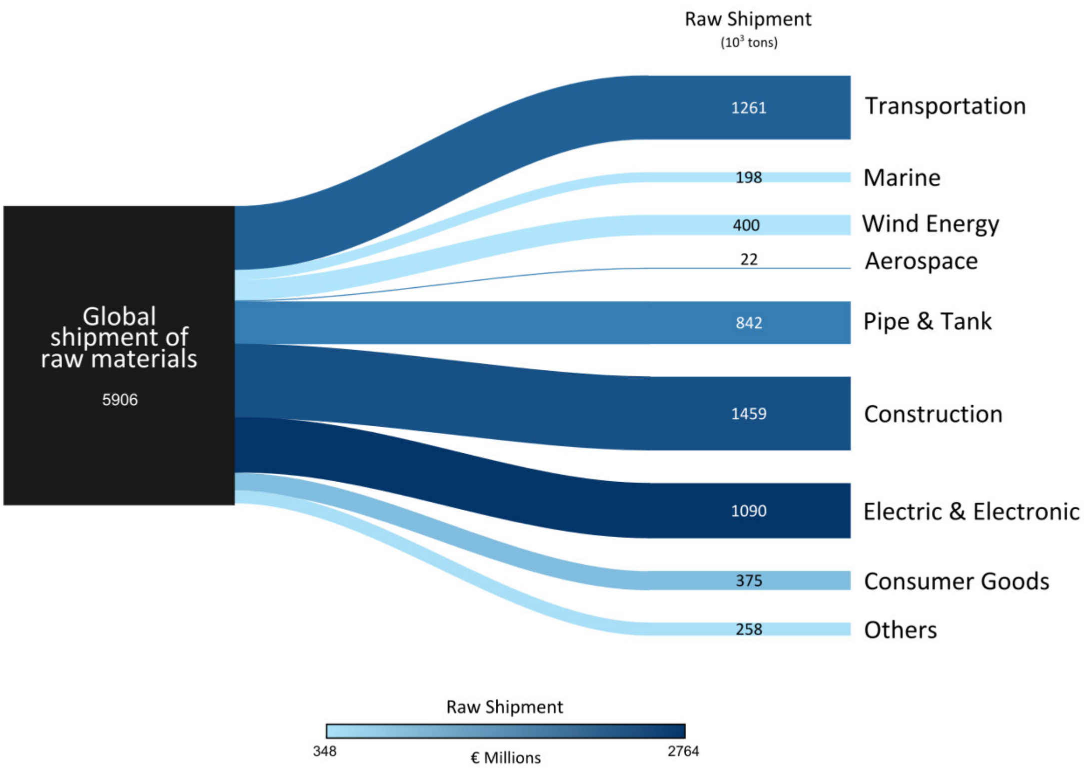

Figure 6 - Global Shipment of Raw Materials by Main Market Segments[2].

Concluding Remarks

FRPs have made inroads into nearly all branches of engineering production; however, in most cases, composites were not originally the primary material of choice in the design process. It is often the case that FRPs are used to substitute a standard material for reasons of weight or corrosion resistance; for example, the original (usually metallic) materials used for the primary components in the wind-energy, aerospace, pressure vessel and piping industries are now often made from FRPs. Even for the safety-conscious civil engineering market, the efforts of academic and private research programmes promoting these materials has paid off in their use as primary load-bearing structures like highway bridges (although a number of such projects have a strong element of marketing and serve as demonstration of the constructor's and designers high-tech capabilities, rather than to meet strict commercial viability).

Nevertheless, it is clear that, given their higher cost compared to standard materials, composites will not be used unless the design engineer can prove they are cheaper for the job required, either through better use of structural material properties, immediate gains in corrosion resistance, weight-saving, or by providing some unique combination of intrinsic properties such as radar-transparency with impact resistance.

Whereas it is true that composites could find more applications if designers knew how to make better use of their rich set of physico-chemical properties, the fact remains that their cost and certain physical weaknesses, such as creep and fire-resistance, make them poor candidates for certain structural applications.

FRPs' competitiveness is even further reduced when trying to dislodge a highly locked-in product, such as steel containers. The size, loading distribution, even the shape, of shipping containers has, essentially, remained the same for fifty years; and although certain variations and add-ons (such as advanced refrigeration) have been introduced, shipping containers are well suited to steel manufacture. Steel is a wonderfully versatile material whose few weaknesses can be offset by its many strengths: it's cheap, it can be joined easily, it can be recycled, it can rely on internationally accepted design and material quality standards. Why bother substituting it? If there is a case to be made for another material that is not steel, then why FRP composites? These are hard questions we should strive to answer.

An often-used argument proposed for using composites instead of metals is to quote two key properties: light weight and better corrosion resistance. The benefits of both these properties are apparent whenever the extra cost of these materials is easily recouped to the benefit of the end-user (for example, savings in fuel costs); however, FRPs lose their shine if the costing and time to fruition of these benefits are not well defined. So when it is claimed, for example, that because composites are lighter they will save on logistics costs of container movements, the buyer will expect some quantification of this claim, or otherwise the argument will not be convincing. Whereas it is true that a composite container is lighter and requires less fuel to transport it, the saving in fuel costs over the lifetime of a container are not well defined. Thus, if a container costs two or even three times more than a steel one, how is the money to be recouped and who, in the complex supply chain, recovers the benefit? Likewise, FRP containers can sustain corrosive environments, but that comes at a higher price than one made from steel. Will this price be enough to offset the costs of painting a steel container or increase its lifetime? Perhaps, but the answers to these questions are easy to quantify and, for this reason, it is doubtful that a shipper, or logistics company will risk the extra capital investment until a credible saving is provided.

The use of FRCs to manufacture containers is not new. As early as the 1990's there were attempts in the USA to introduce composite containers into the market. Clearly, these have not yet made any major inroads into this sector. However, a number of economic, social and technological changes have occurred since then.

Recently a new design criterion has been brought to the forefront of container design that could make FRPs a better option: Security. If it can be shown that, after meeting all the structural safety standards, FRP containers can be fitted with devices that can ensure equal, or better, protection against tampering, then FRP containers have a chance of competing with steel; but only if sufficient evidence can be provided that they will be cheaper or generate extra revenue by providing a collateral service.

Another new design criterion that has become fundamental to any engineering design is sustainability and environmental concerns. In these two areas FRPs start as underdogs: most FRPs matrices (which make up 30-50% of weight) rely on 100% fossil-fuel-based chemicals, and their fibres are very energy-intensive to produce. To make matters worse, one of their key benefits, namely corrosion resistance, becomes an environmental handicap as they neither degrade in harmony with the environment, nor can they be easily recycled to make new composite laminates. Thermoplastics are easier to recycle, but their poor creep resistance and higher initial cost practically exclude them from the container market. Steel, on the other hand, is not only easily recycled (although energy intensive) but can fetch significant re-sale prices in order to recoup some of the initial outlay. Unless new environmentally-friendly matrix systems and fibres are invented, or worth-while FRP recycling methods developed to their full potential, FRPs will not earn an eco-friendly tag.

Because, to date, there are still many practical engineering design problems yet to be solved, and because the volatility of the shipping container market undermines the purported long-term benefits of using FRPs, it is not an easy task to perform a cost-benefit analysis that could unequivocally convince the industry that FRP containers are a viable, general purpose, product for their market.

Irrespective of the arguments above, there is a clear need for shipping containers that are not only lighter, but that can also reduce the world-wide volume movement of empty containers resulting from trade imbalance and ineffective logistic practices. Finally, there is also a need to ensure that the potential for containers to be used for transporting illicit cargo is reduced. For all of these issues, a solution is sought for a light-weight — perhaps variable volume— container, fitted with embedded sensors to provide continuous information on its location and security status. Such a container could reduce unnecessary transport costs and CO_2 emissions by optimising the logistics chain; indeed, the humble 'box' could, one day, be integrated into the, much touted, Internet of Things.

Within this context, composites still have a chance of entering the container shipping container market, but only when (i) new matrix materials are found that are cheap, strong, creep resistant and easily recyclable, (ii) they are fitted with versatile, affordable information-gathering systems.

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Abstract

In this document we will analyse the manufacturing and techno-economic aspects that are perceived as key for determining the feasibility of commercially viable, mass-produced smart composite containers. The scope is not to propose new technical solutions, but rather to paint a panorama of the key aspects that, with currently available technology, will define the backdrop for future commercial and policy developments.
This short review is an amalgam of materials-property and market information, whose aim is to provide an overview to assist the non-specialist in evaluating future R&D policy-developing criteria for the eventual development of tamper-evident, sea-faring, containers based on the use of composite materials technology.

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