A design process for the adoption of composite materials and supply chain reconfiguration supported by a software tool

Adrian E Coronado Mondragon*
Royal Holloway University of London, School of Management
Egham Hill, Egham, UK, TW20 0EX
adrian.coronado@rhul.ac.uk

Christian E Coronado Mondragon
School of Ocean Technology, Fisheries and Marine Institute of Memorial University of Newfoundland and Labrador, P.O. BOX 4920, St, John's, NLL, Canada
christian.coronado@mi.mun.ca

Paul J. Hogg
Royal Holloway University of London
Egham Hill, Egham, UK, TW20 0EX
paul.hogg@rhul.ac.uk

Nuria Rodríguez López
Organización de Empresas y Marketing
Universidad de Vigo, 32004 Ourese, Spain
nrl@uvigo.es

** corresponding author*

Abstract

Composite materials comprising fiber reinforced polymers (FRPs) possess advantageous properties that surpass that of traditional materials. The use of composite materials may give the opportunity to improve the technical specifications of a manufactured module and also impact the configuration of the supply chain. However, this represents a challenging decision-making process as various technologies are available for the manufacturing of composite materials. This paper proposes a design process based on the identification of the bill of materials of a component where the substitution of certain sub-assemblies using composite materials may result in the reduction of parts, operations and suppliers. The design process is supported by a customized software tool that generates a graphic representation of the bill of materials of the selected module, allowing users to choose a specific sub-assembly, select composite materials process types and identify potential suppliers from a database. An industry case involving the production of a module used in urban buses/long distance coach manufacturing is employed to illustrate the proposed design process. The software tool developed satisfactorily integrates the bill-of-materials and current product and process specifications with an existing costing engine and a populated database of potential composite materials suppliers. The approach presented in the paper can be used to address the lack of evaluation tools for using composite materials/carbon fiber.

Keywords: composite materials; design process; decision making; supply chain configuration/rationalization; manufacturing technology

1. Introduction

Recent developments in materials and technological innovations have enabled manufacturing organizations to attain technical achievements that were unthinkable few decades ago. The composite materials industry supports the development of innovative manufacturing products in several industries comprising aerospace, automotive, construction, marine, renewable energy, railway and sports among others. The composite materials industry is growing steadily in many locations around the world. According to JEC Group (Wilson, 2017) the global composites market amounted to some 10.8 million tons in 2016, representing a value of $82 billion with growth expected to be around 4% by volume and 5% by value by 2021 and creating a market of 12.0 million tons worth $103 billion. The expected global demand for carbon fiber will grow from 46,000 tons in 2011 to 140,000 tons by 2020 (Roberts, 2011).

Polymer matrix composites (PMCs), also known as fibre reinforced polymers (FRPs), consist of a matrix material, which is a polymer based resin, surrounding and supporting a reinforcement of some kind (typically fibers, particles or flakes). The resultant PMC has properties that are advantageous compared to those of either the matrix or the reinforcement when used on their own (Shakspeare and Smith, 2013).

These days the use of PMCs can be found in several state-of-the-art products, from aircraft, to motor vehicles, construction, windmill propellers, etc. For example, the latest generation of the BMW 7 series sedan introduced in 2016 carbon fiber reinforced plastic (CFRP) is found in the B- and C-pillars, in the roof bows, along the center tunnel, on the package tray, in the sills, and in a 9-foot arc that runs from the base of the A-pillar to the rear of the car along the roofline (Autoweek, April 21, 2015). The description from the manufacturer states body structure of the new car is 90 pounds lighter compared with the previous generation model.

The adoption of composites materials and in particular CFRP represents a major challenge to manufacturing organisations due to various technologies that can be adopted to manufacture composite materials, not to mention the implications it may have on the number of operations, lead times and eventually the configuration of the supply chain. To mitigate the challenges associated to the adoption of CFRP/composite materials, information and communication technology (ICT) can play a key role as it has already been the case in other industries. For example, in the textile industry Zülch et al., (2011) discussed that customers' needs should be realized through extensive automation concepts and integration of new resources and information technologies into the existing production systems. Furthermore, a similar situation might be taking place in the composite materials industry. ICT may play a major role in helping to configure the supply chains of end products that make use of composite materials. Prajogo and Olhager (2012) argue ICT plays a central role in supply chain management in three key aspects that cover the following:

- It allows firms to increase the volume and complexity of information which needs to be communicated with trading partners.
- It allows firms to provide real-time supply chain information, including inventory level, delivery status, and production planning and scheduling which enables firms to manage and control its supply chain activities.
- It facilitates the alignment of forecasting and scheduling of operations between firms and suppliers resulting in better inter-firms coordination.

Additionally we believe ICT can provide support to managers and decision makers on how to proceed with the rationalization of the supplier base based on the inherent advantages associated to composites materials. Indeed, the adoption of composite materials may bring opportunities to rationalize the supplier base and thus reconfiguring the supply network. In the view of Talluri et al. (2013) supply base rationalization can be seen as the process of determining what firms should be removed from a particular supply base and what firms should remain, which will eventually help to reduce the net number of suppliers a company needs to manage. The use of ICT to support the decision-making process about the adoption of composite materials fits well the future agenda towards the digitization of the manufacturing environment. Indeed, in the view of Oesterreich and Teuteberg (2016) Smart Production or Industrial Internet have been promoted by different actors to describe the trend towards digitization, automation and the increasing use of ICT in the manufacturing environment.

The aim of this work is twofold. First we want to identify the implications that the adoption of CFRP/composite materials may have in the number of operations and the configuration of the associated supply chain. Second, we want to develop an ICT-based design process for the adoption of composite materials that can be used as a reference leading to supply chain rationalization. The work undertaken was supported by the use of a customized software tool which was designed as part of an academic research project that focused on strengthening the composites supply chain. The tool has access to a UK-based composites capabilities database which works as a composites industry directory facilitating regular company updates. The next section discusses the nature of composite materials, the impact on manufacturing supply chains and the use of ICT as part of a design process that can be applied to composite materials.

2. The manufacturing of composite materials

It is well recognized choosing new materials and manufacturing technologies are part of the manufacturing strategy that permeates manufacturing organizations (Farooq and O'Brien, 2012). For manufacturing organisations the adoption of composite materials has strategic implications that impact their operations and supply chain. It is worth emphasizing that the composite materials industry is characterized for having flexible and innovative approaches to forming shapes, adapting processes and modifying materials. This can be seen as an opportunity but also as a key challenge. If we take the case of the metallurgy industry tolerances are well defined, but in composites that is not the case. In composite materials there are no standard manufacturing processes, nor are there standardized materials with defined or prescribed properties to select. As a result for any particular challenge there are frequently multiple solutions proposed that are technically viable, as typical processes used in the manufacture of composite materials include: *layup*, *filament winding*, *pultrusion* and *composite spray* to name just a few. Furthermore, these processes can be broken down into sub-processes comprising: *hand layup*, *automated tape layup*, *resin transfer moulding*, *liquid resin infusion*, *resin film infusion* and *hot ply forming*. Once a part has been manufactured it may go through different processes such as *curing*, *autoclave/oven*, *finishing* and *trimming*. A company has to choose the materials and consumables needed to manufacture the part required. Because different options are available, hence manufacturing organizations looking to adopt CFRP/composite materials need to make informed decisions about which specific solution they have to adopt in order to strengthen their own position within the supply chain.

2.1 The structure of the composites supply chain

Companies in the manufacturing industry are collaborating with suppliers and customers to achieve seamless integration of manufacturing and supply chains (Farooq and O'Brien, 2012). This applies to manufacturing organizations and their supply chains which integrate ''key business processes from end user through original suppliers that provides products, services, and information that add value for customers and other stakeholders'' (Lambert and Cooper, 2000). In order to understand the implications of adopting composite materials in manufacturing, we believe it is important to illustrate the structure characterizing the composite materials supply chain. Composite materials is a technology-driven industry with a supply chain comprising various echelon/stages. Figure 1 depicts a typical five-tier structure of the composites supply chain comprising raw materials, semi-finished materials, components, structures and Original Equipment Manufacturer (OEM).

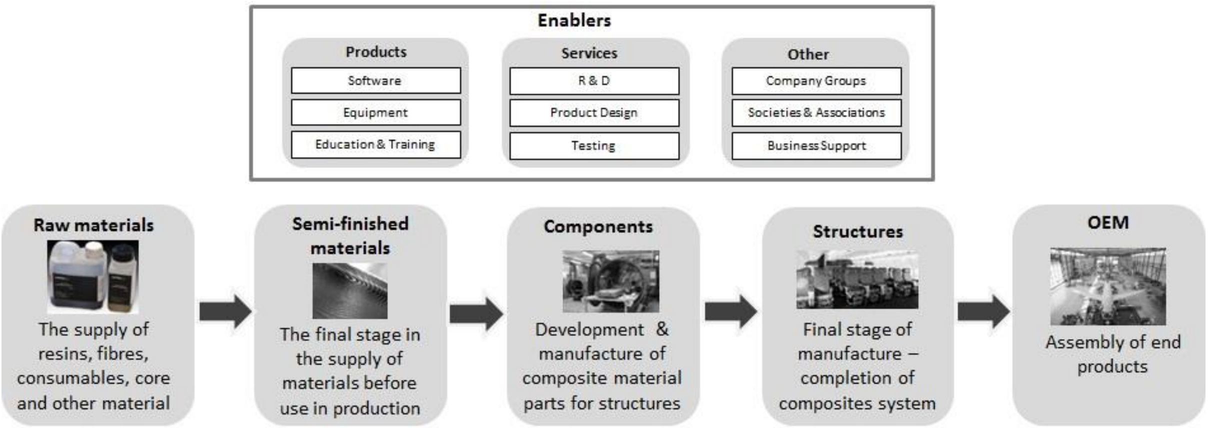


Figure 1. Depiction of the multi-tier composite materials supply chain

In figure 1, the tier associated with raw materials covers the supply of resins, fibers and core materials. Among the most important raw materials found include polyesters, epoxy resins, vinyl ester resins, phenolic resins, polyurethane and high value thermoplastics. Fibers comprise glass, carbon, aramid fiber and natural fiber. The tier associated to semi-finished materials includes the materials that go through processes such as '*prepreg*', pre-impregnated composite fibers which often take the form of a weave with a matrix material, usually epoxy. In '*prepregs'* the matrix is used to bond the fibers with other materials during production (the matrix requires cold storage because is only partially cured). Examples of semi-finished materials cover thermoset '*prepreg'*, thermoplastic '*prepreg'* and consolidated sheet/panels. In composite materials ply is a layer of a laminated material. Figure 2 depicts individual plies with fibre reinforcement. Here, composite laminates are made of stacking of plies with different angles of fibre reinforcement in directions of 0, 45, 90, -45 degrees.

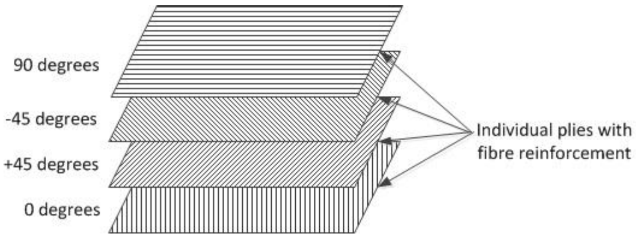


Figure 2. Stacking of individual plies into a composite laminate

The tier associated to components encompasses the development and manufacture of composite material parts. An example of components can be represented by the transmission tunnel of a motor vehicle made of carbon fiber. The tier associated to structures includes the manufacture of composite systems by joining several components such as the wing or fuselage of an aircraft. Enablers would be those companies that provide engineering services, tooling, training and business support to all suppliers in the composite materials supply chain. Going into more detail, enablers also comprise software, equipment, education and training, research and development, product design, testing, company groups, societies and associations. At the end of the chain there are OEMs who are responsible for manufacturing end products that will be delivered to the final customer. End products can include from planes, to cars, buses and long distance coaches, furniture used in railway stations, interiors in trains, renewable energy generation, sports gear and rescue and medical equipment among others. The adoption of CFRP/composite materials promises a major overhaul of manufacturing operations and the supply chain, hence there is a growing interest in using ICT tools to analyze to what extent adopting composite materials may affect the total number of operations and configuration of the supply network.

It is expected the composites supply chain will face significant challenges when it comes to making decisions about technology selection to produce components and structures required in the assembly and manufacturing of state-of-the-art end products. The case of the automotive sector is particularly important as in the foreseeable future the use of composite materials and in particular carbon fibre technology will become crucial for reducing vehicle weight and meet future Corporate Average Fuel Economy (CAFE) standards. Benefits of composite materials to automotive applications include reduced number of parts, reduction in tooling costs, good corrosion resistance and excellent crashworthiness properties among others (Shakspeare and Smith, 2013).

2.2 Use of ICT in supplier base reconfiguration/rationalization

The use of new technologies and processes may contribute to the growth and overextension of the supply network, hence the need to find ways to become leaner and reduce the size of the supplier base. ICT can play a role in assisting managers when it comes to making decisions pertaining the supplier base. Olhager and Prajogo (2012) based on the works by Li et al. (2005) provided a compelling case on it. They acknowledged that supply chain reconfiguration/rationalization is seen as an important component in the strategic partnership with suppliers as it refers to the practice of limiting the supplier base to a few strategic suppliers that can provide high quality and dependability. In fact benefits associated to supplier base reduction cover better market penetration (Chen and Paulraj, 2004), business growth (Narasimhan et al., 2001) and the formation of effective partnerships (Berger et al., 2004).

It is widely accepted the important role ICT plays in supply chain management. Prajogo and Olhager (2012) highlighted that the use of ICT in supply chain has received considerable attention with various technologies being introduced for Business-To-Business (B2B) communication, including web internet, B2B private (Ethernet), and EPOS (Electronic Point of Sale). Overall, ICT supports key processes in supply chains, including sourcing, procurement, and order fulfilment (Kehoe and Boughton, 2001). ICT can be useful when dealing with multi-criteria and the prioritization of the relative importance of certain characteristics. Talluri et al. (2013) identified several methods including analytical hierarchy process (AHP); analytical network process (ANP) and principal component analysis (PCA). For conceptual models the list identified by the researchers included interpretive structural modelling (ISM) and statistical models include conjoint analysis, fuzzy set theory and cluster analysis. Kemoe et al., (2014) developed a model that can be used in a wide ‘what-if’ design process. The model developed by the authors considered the evaluation of various flexibility configurations in multiple demand scenarios in order to choose the best option.

Given the importance of composite materials in modern manufacturing operations, in this work we want to explore the use of ICT to support a design process that can assist organisations in the adoption of composite materials. The next section presents the methodology considered for this research where an industry case is used to demonstrate whether the substitution of parts/components made of traditional materials with composites may lead to the reconfiguration and rationalization of the supply chain and the resulting reduction of activities.

2.3 Developments in design tools and supply chain involving the use of composites materials

In recent years, research in the area of composite materials has dedicated resources to investigate computer-assisted design, simulation and evaluation tools. Das et al. (2016) reviewed the work of various people in the area of tools for composite materials design. For example, the work by Ma (2011) investigated the cost modelling of aerospace composites manufacturing and the cost ramifications associated to design choices.

The review also highlighted the work by Van Gent and Kassapoglou (2013) about the adoption of cost models to guide design decisions involving the use of modular and custom parts. Das et al. (2016) indicated that in recent years OEMs have shifted design and manufacturing work toward their suppliers. Moreover, based on a limited survey focused on the supply and opportunities for application of carbon fibre composites in the USA, the authors highlighted that the lack of computer-assisted simulation and evaluation tools for carbon fiber advanced design affects growth and competitiveness of the industry.

3. Methodology

The methodology considered for this work takes into account elements of cradle-to-gate analysis used by Chua et al. (2015) in which they studied the manufacture of an upper wing skin of an idealized single aisle aircraft. This structure was manufactured from carbon fiber epoxy resin prepreg, using traditional hand layup and autoclave cure. In their work they followed guidelines of the Life Cycle Assessment (LCA) defined by the ISO14040 standard (2006). Key elements emphasized include of goal and scope definition; inventory analysis; impact assessment; and interpretation (Chua et al., 2015).

The approach used in this work follows a raw material-to-gate approach, where the identification of the bill materials of a component manufactured is used to build up the required new bill of materials using composite materials. In order to implement this approach, the researchers secured the participation of one European-based manufacturer of urban buses and long distance coaches with products exported to several markets around the world. The company director, the manufacturing and engineering managers and one key supplier participated in the study. The procedure employed for this research follows guidelines highlighted in the work by Seaman (1999), where visits to the participating sites were planned to obtain first-hand information from tours of specific facilities and services, interviews with individuals or groups, or observations of specific activities at the sites. Following the guidelines provided by Seaman (1999), site-visits and email exchanges were used to obtain reports, brochures, and examples of the products made available at the sites, also enabling the opportunity to obtain first-hand information about users or activities in a particular setting.

The justification for using an ICT tool for assisting supply chain management in the adoption of composite materials is based on the principles reviewed by Olhager and Prajogo (2012) and Prajogo and Olhager (2012) where the use of ICT supports key processes in supply chains, including: supplier evaluation, sourcing, procurement, and order fulfilment among others. In this research ICT is used as a support tool to assist in the adoption of composite materials in manufactured goods which may result in supplier-base reconfiguration/rationalization with the aim to limit the manufacturing supply base to a few strategic suppliers that can provide high quality and dependability.

This research comprised the development of an ICT tool, labelled ‘Comp-Fore’ (Cross sector modelling tool for strengthening supply chains by technology insertion), to assist in the design process for the adoption of composite materials in modules that go into end products. The tool may yield benefits such as visualization of the changes introduced, the generation of metrics followed by the possibility to choose suitable suppliers from a composites capabilities database.

We developed a design process which comprises the identification of the bill of materials (BOM) of a module used in a manufactured end product. Here it is necessary to breakdown the BOM in order to get all the details of sub-assemblies, parts and operations involved. This operation is supported by the Comp-Fore tool which is a web-based tool that allows users enter the BOM for a finished product and substitute sub-assemblies that use traditional materials with composite materials. The logic behind the design and operation of the Comp-Fore tool is presented in figure 3.

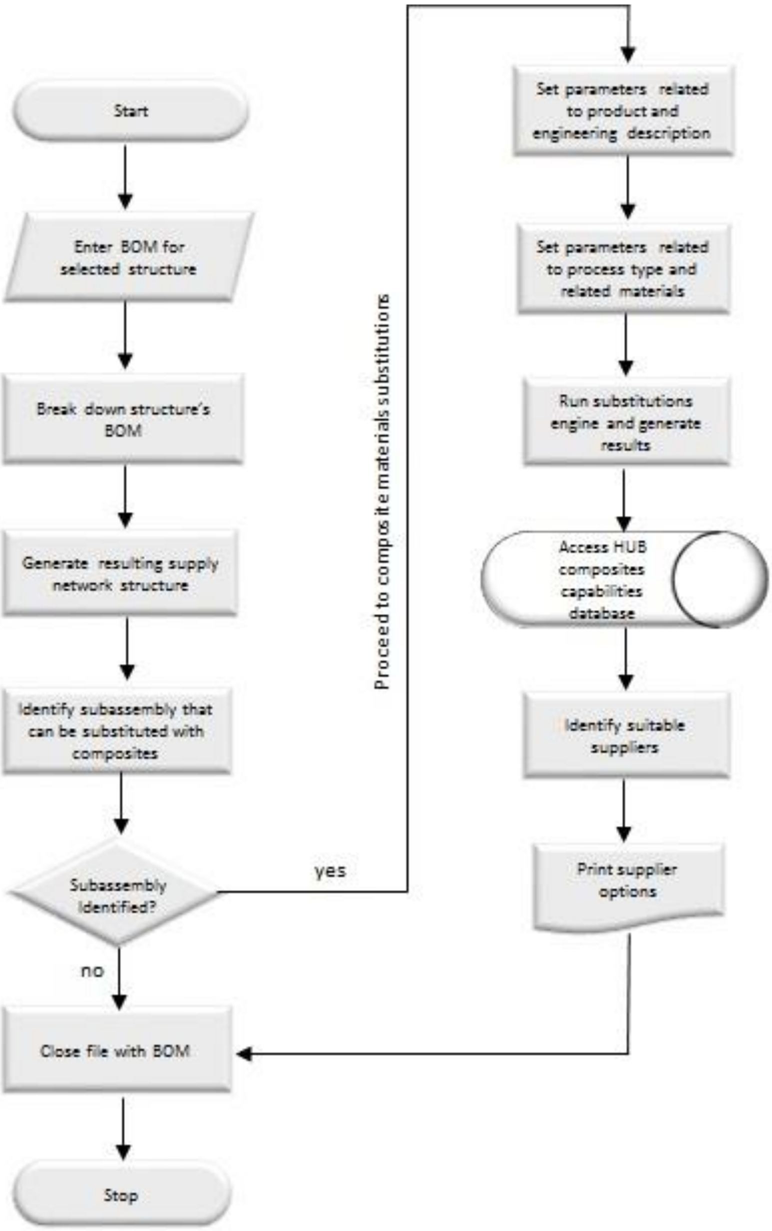


Figure 3. Flow diagram for the Comp-Fore tool

Following the logic presented in the diagram the user needs to enter the BOM for a selected module and this requires dissecting the structure of the BOM. Then the tool will generate a graphic representation of the supply network associated to that BOM. As a consequence this may facilitate the identification of a sub-assembly or sub-assemblies suitable for replacement using composite materials. Once a sub-assembly has been identified the next step is to define the parameters related to product and engineering description. There are eight major areas to consider when populating the parameters for composites calculations. These include: product description; engineering description; process type; material; process description; cure and manufacturing description. The parameters are sent to the costing calculation engine which will generate results including total cost/unit, material cost/unit, direct minutes/unit among others. The results from the costing tool can be matched to specialized suppliers who are registered in a composites capabilities database known as the Hub. These suppliers might be able of manufacturing the desired sub-assembly using composite materials.

4. Industry case presentation

The research undertaken comprised the participation of a European-based manufacturing company which produces urban buses and long distance coaches. The manufacturing of a bus/coach involves getting a chassis from manufacturers like MAN, Volvo, Scania among others and then a body is built onto the chassis. Among various models manufactured by the company, a distinctive urban bus model was selected for this study. The company produces 120 units of this model every year and the interior preparation is the last stage of the manufacturing process. The lead time from receiving a chassis to producing a finished bus ready to be delivered to the customer is 38 days. The body uses materials such as stainless steel, aluminum, polyester, adhesives, rivets, etc., however, the use of composite materials, in particular carbon fiber, is not present at the moment. The module chosen for this analysis is a panel comprising the interior engine hatch that facilitates the access to the engine. Key particularities of this module includes having good sound absorption and being able to withstand the temperatures of the engine bay. Figure 4 depicts the lead time associated to the manufacturing of the bus and the module being studied.

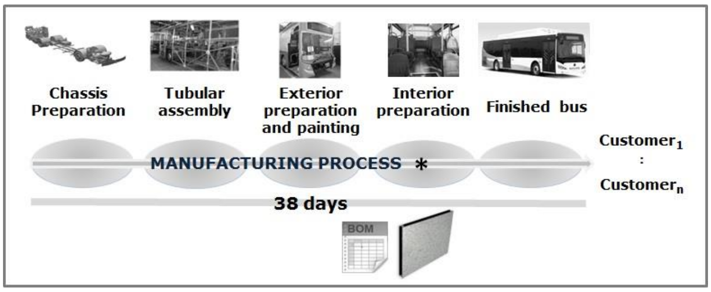


Figure 4. Diagram of the manufacturing stages of the component being investigated

4.1 Characteristics of the module investigated

An important part of the analysis of the feasibility of adopting composites materials requires breaking down the bill of materials (BOM) of the module studied to identify the potential substitution of materials like wood and metals with composites materials/carbon fibre. Table 1 shows the BOM for the module studied as specified by the manufacturer including the cost associated to each part.

The cost of the materials comprising the selected module excluding labor is €89 plus locally sourced screws, glue and aluminum frame. The suppliers of flooring materials, insulators 2, 3 and 4 are located more than 1000 km away. Suppliers of wood plate and insulator are located between 100 and 600 km. All the other suppliers are local. The cost of labor can be rated at €50 per hour. The operations associated to the assembly of the selected module are presented in table 2.

Bill of materials	**cost**
Flooring material (2/3 mm width)	€9
Wood plate (12 mm width)	€4
Insulator 1	€11
Insulator 2	€25
Insulator 4	€10
Insulator 3	€30
Self-tapping screws (16 units)	-
Polyester-based solvent glue (250 ml)	-
Aluminum frame	-

Table 1. Bill of materials for engine panel as specified by the manufacturer

Operations associated to this BOM (from bottom to top) – ***Estimated number of operations: 9***
Bore holes for self-tapping screws in insulators 1, 2 and 4
Attach insulator 1 to wood plate
Attach (glue) insulator 2 to insulator 1 already attached to wood plate.
Attach (glue and screw) insulator 4 to insulator 2 already attached to insulator 1.
Attach (glue) insulator 3 to insulator 4.
*Wait until glue has dried.
Cut flooring material to specified dimensions
Glue flooring material to wood plate.
*Wait until glue has dried.
Cut 4 parts making aluminium frame
Screw the aluminium frame to hatch
Insulator 1 (total parts: 2) – ***Estimated number of operations: 2***
Cut auto-adhesive aluminium film to measure.
Apply sealant.
Insulator 2 (total parts: 5) – ***Estimated number of operations: 9***
Cut glass fibre cover (twice).
Cut acoustic and thermal insulation layer (Fonoplast) (twice).
Cut to measure metallic sheet.
Attach glass fibre cover (1) to acoustic and thermal insulation layer (Fonoplast) (twice – assembly 1 & 2).
Attach metallic sheet to assembly 1.
Attach assembly 2 to metallic sheet already attached to assembly 1.
Insulator 3 (total parts: 2) – ***Estimated number of operations: 3***
Cut-to-measure polyurethane foam.
Cut auto-adhesive aluminium film.
Attach polyurethane foam to auto-adhesive aluminium foam.
Insulator 4 (total parts: 3) – ***Estimated number of operations: 5***
Sandwich made of three layers:
Cut-to-measure layer of thick, fire-retardant thermal insulator with aluminium sheet (twice – assembly 1 & 2)
Cut-to-measure layer in-the-middle heavy layer comprising stacked sheets made of elastomeric rubber EPDM type
Attach assembly 1 to in-the-middle layer.
Attach assembly 2 to in-the-middle heavy layer already attached to assembly 1.

Table 2. Operations performed in the assembly of the selected module

The identification of potential advantages in adopting composite materials to reduce the number of operations and reconfigure/rationalize the supply network for the module selected, required breaking down the BOM followed by the identification of the number of operations performed by first-tier suppliers making insulators 1, 2, 3 and 4. Although the BOM of the module investigated may look simple at first, once the BOM has been dissected it is possible to appreciate the complexity of it. For example, looking into the details: Insulator 1 is made of two parts (sealant and auto-adhesive aluminum film); Insulator 2 comprises five parts (two glass fibre covers, two acoustic and thermal insulation layers and one metallic sheet); Insulator 3 is made of two parts (polyurethane foam and auto-adhesive aluminum film) and Insulator 4 comprises three parts (two layers of thick, fire-retardant thermal insulator with aluminum sheet and one heavy layer comprising stacked sheets made of elastomeric rubber EPDM type). The total number of operations nested at the OEM (bus/coach manufacturer) level for the selected module is 28. Because of the proximity of this module to the engine bay, the life of it is limited to a span of about two years and then it will have to be replaced by a new one.

4.2 Use of the Comp-Fore tool

The Comp-Fore tool was developed in the DRUPAL PHP-written open source web content management platform. The use of the Comp-Fore tool is linked to the Hub capabilities database, a composites industry database created in a format that facilitates regular updating. The aim is to ensure the model itself is sustainable and of long term value to the composites community. The URL address http://compfore.co.uk hosts the Comp-Fore tool. The Hub database collects information to support the UK composites industry and it acts as a free way to advertise companies and find other composites organizations. The Hub website is live at: http://www.compositesuk.co.uk/hub. The Hub database supports full search option includes material, equipment/software, manufacturer, service and advanced search. These two are free services.

When entering data into the software tool, the user has to define the tiers associated to each part comprising the BOM which allows to identify the hierarchy of the elements for that particular module. Once login into the Comp-Fore tool the user can click ‘Add BOM’ to start adding a BOM to the tool. The user can choose tier 0 to identify an OEM and tiers 1 and above for external suppliers with items grouped into sub-assemblies. A sub-assembly includes a limited number of items and operations. Once the BOM has been entered, the tool generates a diagram illustrating the resulting supply network for that module. Figure 5 shows a graphic representation of the supply network for the BOM and generated by the Comp-Fore tool.

Looking at the graphical representation of the BOM, the different tiers are represented using different geometric shapes. For example, a hexagon is used to represent the OEM level, a circle for first-tier suppliers and square for second-tier suppliers. Based on figure 4 and the details already presented in table 2 particular attention is given to sub-assemblies 1 and 2 and their related parts as these two together may be suitable for replacement with composite materials. Eventually the replacements of all these parts may result in a reconfigured/rationalized supply chain.

Once a sub-assembly suitable for substitution has been identified, a key important aspect to consider is the identification of the composites manufacturing process that will be required to make the desired components. As mentioned before methods available for manufacturing composite materials include: hand layup; automated tape layup; resin transfer molding; liquid resin infusion and resin film infusion among many others. Hand layup is a process associated to the manufacturing of flat surfaces which in this case it suits the characteristics of the panel comprising the interior hatch investigated in this case. The use of hand layup may make possible the replacement of sub-assembly 2 which comprises sub-assembly 1 and all its related parts.

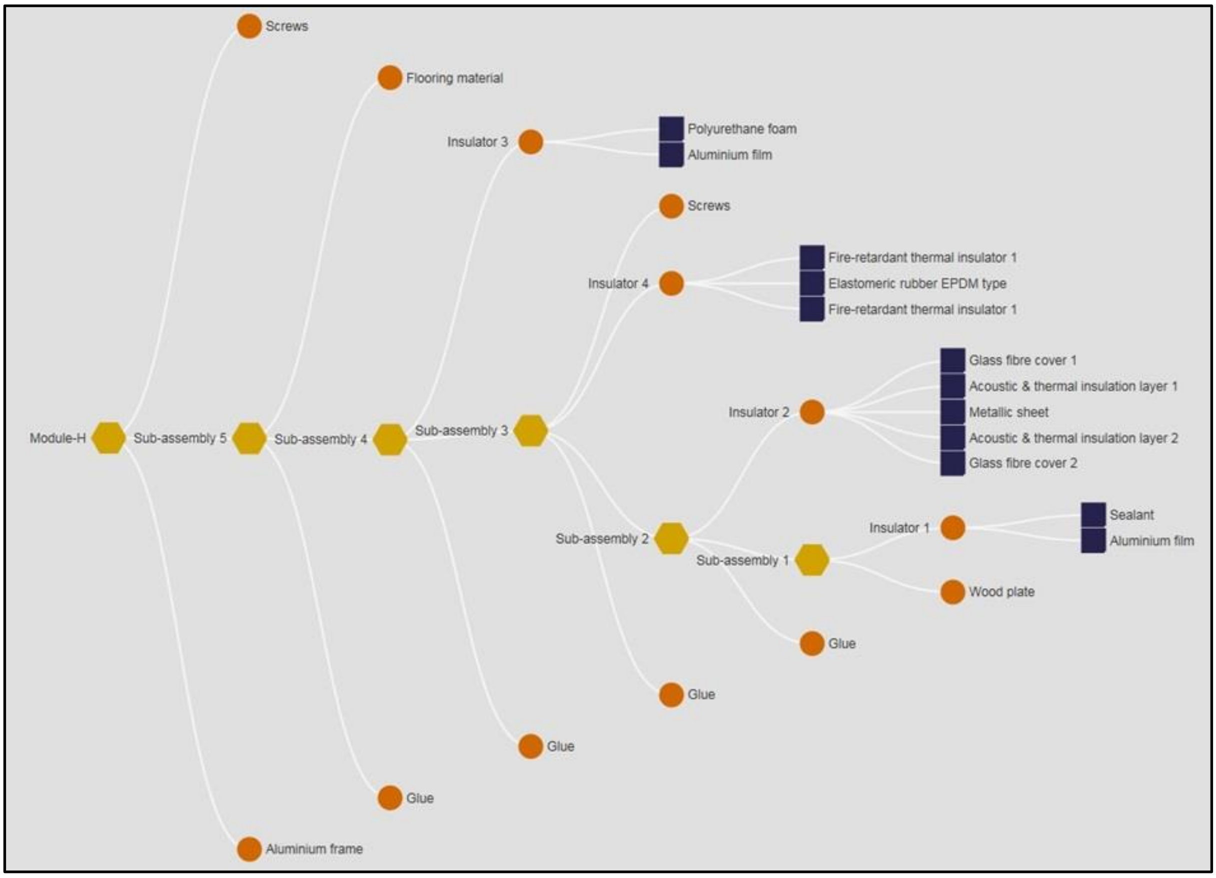


Figure 5. Graphic representation of the multi-tier supply chain generated by the Comp-Fore tool

4.3 Parameters used in the Comp-Fore tool

The Comp-Fore tool links itself to the “Detailed Composites” module offered by the SEER composites estimate costing engine (Galorath International, 2017) which is one of the most comprehensive composites calculation modules available to industry. SEER is an estimate costing engine adopted by leading organizations in various manufacturing sectors. Based on the functionality of the SEER composites estimate costing engine (Galorath International, 2017) once a sub assembly for substitution using composites has been identified, the user gets to choose from different options and parameters to start working on making a composites parts based on the specifications of the sub-assembly/sub-assemblies to be replaced. There are eight major areas to consider when populating the parameters for composites calculations: product description; engineering description; process type; material; process description; cure and manufacturing description. Table 3 shows the areas and parameters used in the Comp-Fore tool based on the Detailed Composites module of the SEER composites estimate costing engine (Galorath International, 2017).

Area	Paremeters
Product Description	Quantity Per Next Higher Assembly; Production Quantity; Set-up Amortization Quantity (Optional); Tooling Amortization Quantity (Optional); Direct Hourly Labour Rate; Set-up Hourly Labour Rate and Production Experience/Optimization
Engineering Description	Part Complexity; Overall Length (mm); Shape/Dimensions (mm)
Process type	Process type; Core Operation 1; Additional Ply 1
Material	Prepreg Material Type; Tape Material Type; Material Cost Per Kg.; Roll/Tape Width (mm); Lightning Mesh; Material Utilization Factor
Process Description	Cutting Type; Cut Machine Efficiency Factor; Layup Type; Bagging/Tool closing; Operator Attendance Factor; Debulk; Debulk Interval; Hot ply forming; Ply Orientation
Bagging Material	Release Agent; Breather; Sealant Tape
Cure	Cure; Cure Method; Cure Temp. (°C); Final Cure Duration (min); Initial Temp. Cure Duration (min); Operator Attendance Factor; Heat-up Rate (°C/min); Cool-down Rate (°C/min)
Manufacturing Description	Set-up Complexity

Table 3. Areas and parameters considered for the Comp-Fore tool

A condensed description of each area and its parameters is shown in the next paragraphs.

In Product Description Set-up amortization quantity refers to the quantity of parts or assemblies over which the set-up (i.e. preparation of the machinery and the work area) will be amortized shared or divided. This is referred as the number of units in which a set-up is required as part of the production run (Galorath International, 2017). Tooling amortization quantity, represents an optional entry of an alternate amortization quantity for the production tooling (Galorath International, 2017). An assumption made is all of the tooling costs are amortized over the current production lot (entered in the Production Quantity parameter which by default is 1). If a value of zero is entered, the estimated tooling costs will be amortized over the current production quantity. The parameter production experience/optimization can be rated as Low, Nominal, High, Very High and Extra High. Low rating means little or no experience in the activities or processes considered. Nominal rating means the manufacturer is experienced to a medium degree in similar activities or processes. High refers to the manufacturer being experienced in the activities or processes considered. Very High means the manufacturer is highly experienced in the specified activities or processes and Extra High refers to the manufacturer being recognized as an industry leader in performing the specified process with a minimum of 10 years of experience.

The Engineering Description area encapsulates inputs related to the physical dimensions and complexity of the part that will be produced. Part complexity affects manufacturing time, for example, a flat panel made from plies is the simplest and least complex type of part that can be manufactured (Galorath International, 2017). The user can rate part complexity as Very Low, Low, Nominal, High and Very High.

In the Process Type area, the user can choose from five different composite process types including: Hand Lay Up (HLU), Automated Tape Layup (ATL), Resin Transfer Molding (RTM), Liquid Resin Infusion (LRI), and Resin Film Infusion (RFI). The parameter Additional Ply indicates whether plies used types include Peel Plies using prepreg material or dry fibre material. Peel plies using prepreg materials relate to bonding operations while peel plies using dry fibre material is normally used in drilling operations.

In the Materials area, the options available include: Prepreg Materials Type, comprising of either carbon, glass or aramid fiber which has been pre-impregnated with uncured resin (Galorath International, 2017). The selection of Tape Material Type is given in width sizes of 75, 100 and 150 mm.

In the area of Process Description the parameter Cutting Type includes values such as: None, Hand Cutting, Water Jet Cutting, Laser Cutting and Commercial Ultrasonic Cutter. The parameter referring to Cut Machine Efficiency Factor cover values that can fluctuate in percentages from 50% to 85%. Layup Type comprises the values of Manual and Automatic Pick & Place (moving materials using an operator or the use of robot/automation).

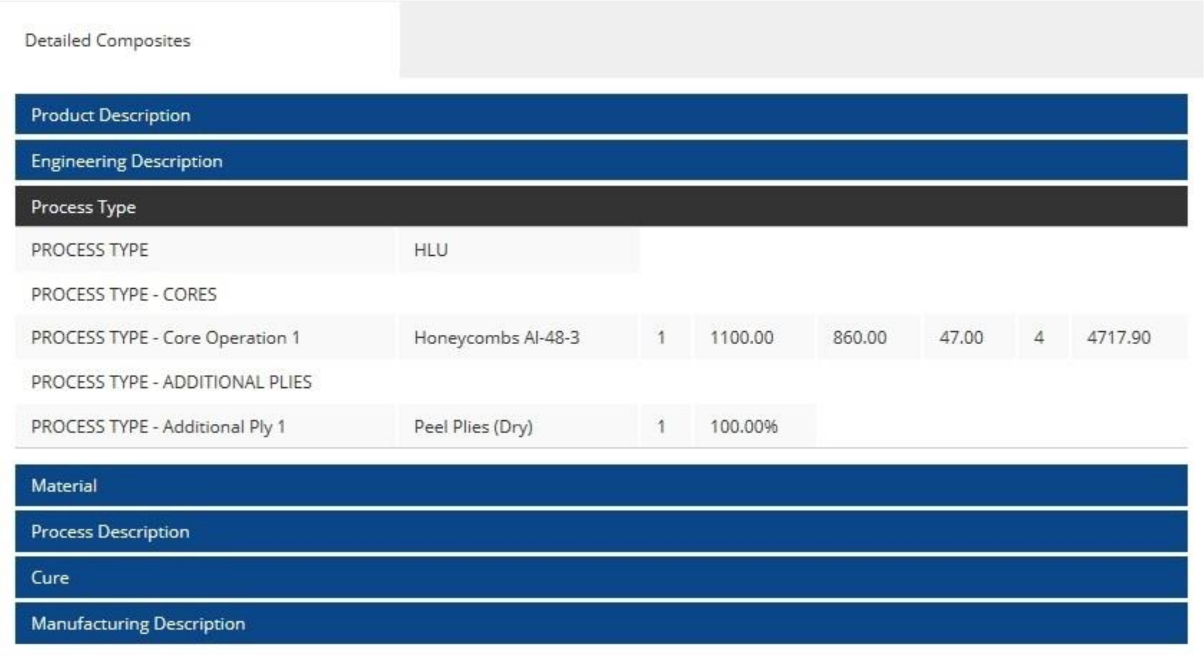
The Bagging Material area makes reference to Release Agent films used to prevent the composite part from adhering to tool surfaces (Galorath International, 2017). Regarding the Cure area, the value of Cure can be either Yes or No (Galorath International, 2017). If the value of Cure is Yes then the user needs to specify the parameters for Cure Temperature, Final Cure Duration, Initial Temperature Cure Duration, Operator Attendance Factor, and Heat-up Rate used by all processes.

The area of Manufacturing Description covers the parameter of Set-up Complexity which is about rating the sophistication of the manufacturing set-up (Galorath International, 2017). Here, the user can rate set-up complexity as Very Low, Low, Nominal, High and Very High. Very Low rating relates to standard fixtures, tools including manual insertion, placement, control and removal. Low rating relates to some custom designed holding fixtures and standard tools. Nominal rating refers to custom designed holding fixtures, tools and tool holders. High rating relates to numerically controlled machining, mechanized stock movement, tools, finished parts and tolerances which are computer controlled. Very High rating relates to fully automated CNC operation and automated feed of raw materials.

5. Results

As previously mentioned in section 4, the part being investigated has the shape of a panel with dimensions of 1100 mm in length and 860 mm in width. Overall, the complexity of the part is low. The direct hourly labour rate agreed is €58.52 and setup hourly labour rate is €62.94. The number of annual units produced is 120.

Process type is an important area for adopting composite materials. In process type the user can choose from five of the most common process types for manufacturing composites including: hand layup (HLU), automated tape layup (ATL), resin transfer moulding (RTM), liquid resin infusion (LRI) and resin film infusion (RFI). Also in the process option the user has the opportunity to specify the core materials to be used including honeycomb and populate other fields like quantity, length, width, thickness, vertices and cost. Figure 6 shows a screenshot of the Comp-Fore tool displaying the parameters entered into process types. Full details of all the parameters entered into the Comp-Fore tool for the panel comprising the interior engine hatch investigated in this work can be found in the appendix section. The material area of the Comp-Fore tool allows the user to choose the types of materials that better match the process type chosen to produce the desired part. Materials available to the user include up to 9 different types of *'prepregs'*.



PROCESS TYPE	HLU						
PROCESS TYPE - CORES							
PROCESS TYPE - Core Operation 1	Honeycombs Al-48-3	1	1100.00	860.00	47.00	4	4717.90
PROCESS TYPE - ADDITIONAL PLIES							
PROCESS TYPE - Additional Ply 1	Peel Plies (Dry)	1	100.00%				

Figure 6. Screen for process types available in the Comp-Fore tool

Once parameters had been defined for product description, engineering description, process type, material, process description, cure and manufacturing description, these are sent to the SEER composites estimate costing engine (Galorath International, 2017), processed and then sent back to the Comp-Fore tool which displays the results from the calculations. Table 4 shows the results of the calculations related to the adoption of composites in the manufacturing of the panel comprising the interior engine hatch investigated in this work. Calculations for a particular sub-assembly include: Total Labour Minutes/Unit, Total Cost/Unit, Set-Up Minutes/Unit, Direct Minutes/Unit, Inspection Minutes/Unit, Rework Minutes/Unit, Material Cost/Unit, Tooling Cost/Unit and Finished Weight.

Cost & Time	Detailed Composites
Total Labour Minutes/Unit	563.56
Total Cost/Unit	990.50
Set-Up Minutes/Unit	10.86
Direct Minutes/Unit	552.70
Inspection Minutes/Unit	0.00
Rework Minutes/Unit	0.00
Material Cost/Unit	440.04
Tooling Cost/Unit	0.00
Finished Weight	5.83

Table 4. Results of calculations for selected sub-assembly

The results from the analysis of replacing traditional materials used in sub-assemblies 1 and 2 with composites reveal some interesting facts, for example the total cost/unit is equal to €990.50 where the manufacturing times per unit is equal to 552.70 minutes. These results highlight one of the main disadvantages related to composite materials including costs and lead times. The use of composite materials can be 4 to 5 times higher compared to traditional materials. High cost per unit is directly linked to the costs of the material used in this case '*prepreg'* 8552 0.125x1200 mm in a process that uses Honeycomb material Al-48-3. Labor also represent a significant cost especially for the quoted rate for direct hourly labor at €58.52 and setup hourly labor rate at €62.94. Curing is an important activity related to the use of '*prepregs'* and which represents a bottleneck in itself. The parameters entered for curing comprise a final cure duration time of 120 minutes at a curing temperature of 170 ^{o}C. The use of hand layup (HLU) may result in inherent benefits such as minimum minutes required for inspection, rework and negligible costs for tooling. Although costs are still high, the aggregated operational benefits that can be achieved with composite materials may represent in the future a compelling business case.

For the interior hatch selected in this study the use of composites such as CFRP will increase durability, eliminating the need for replacements every two years. Interviews with the company director and managers showed that one of the key challenges is to identify composites substitutes that meet the technical specifications of the original materials. Decision making can become complex as some of the properties to consider when adopting composite materials may have to include density, stiffness, temperature resistance, etc.

In case composite materials are adopted, we can end up with a rationalized supply network by considering the reduction of parts related to sub-assemblies 1 and 2, this means a total of 9 parts including a total of 13 operations. Furthermore, it has been estimated that producing a carbon fiber flat panel using the hand layup process to replace sub-assemblies 1 and 2 and the use of glue and screws may result in a reduction of materials to approximately 3 parts and the number of operations to 4. This represents a significant reduction of approximately 6 parts and about 9 operations.

Once the tool generates the results from the calculations then it accesses the Hub composites capabilities database where it identifies suitable suppliers with the capabilities to manufacture the desired module based on the selected processes and materials. The list generated includes company name and address. Furthermore, the Comp-Fore tool allows a direct link to the Hub composites database showing full details such as a map with the location of the company, full business description and accreditations among others.

The module considered in this industry case is characterized for the use of one of the simplest geometries found in composite materials, the flat panel. Other components with more complex geometries will result in higher costs. For example a component/part with a concave shape will require an operator performing more operations involving the use of a mold. Ultimately, because the geometry is more complex than a flat panel hence, costs will be higher. Nonetheless, the same logic presented in figure 3 has be followed.

6. Conclusions

In this work a customized web-based tool, Comp-Fore, was developed to support a design process about supporting the adoption of composite materials in the manufacturing industry. Using an industry case involving the manufacturing of urban buses and long distance coaches this work demonstrated the feasibility of achieving operational improvements by adopting composite materials to substitute traditional materials in the production of certain sub-assemblies.

The composite materials industry and in particular CFRP is expected to become an important supplier to many industries such as aerospace, automotive, construction, marine, oil and gas, rail, sports gear, medical equipment and renewable energy to mention just a few. Still the adoption of composite materials represents a challenging solution for most applications. Hence the use of customized ICT tools like Comp-Fore can be helpful.

Composite materials/CFRP may represent a more expensive solution compared to traditional materials, however manufacturing organizations may end up adopting and finding it an attractive proposition on condition of reducing the number of operations and simplification of the supplier network. Although the switch to composite materials still represents an expensive option, advantages to the manufacturing industry may include the reduction of lead times, the deployment of workers in activities other than assembly, the reduction in the complexity of its supply chain, the selection of suppliers closer to the production site and the rationalisation in the number of suppliers. In the future it may be possible to reduce costs and achieve economies of scale if a standard size of interior hatch is adopted along the various products offered by the manufacturer, so instead of 120 units there may be annual demand of 400 or 500 units.

Academic projects like Comp-Fore can be used as a tool to see what are the implications resulting from the adoption of composite materials. Using the tool the user can generate estimates and suggest processes based on parameters of dimensions and shape and also source appropriate suppliers from the UK Composites Hub database. The adoption of composite materials may become more complicated given the challenges faced by the industry such as the lack of staff with the right skills, the absence of standardized manufacturing processes and the possibility of having multiple solutions technically viable among others.

References

Autoweek, 2015. Carbon core: 2016 BMW 7-series gets carbon-fibre implants. April 21. http://autoweek.com/article/car-news/carbon-core-2016-bmw-7-series-gets-carbon-fibre-implants#ixzz3kU14HLVD

Berger, P.D., Gerstenfeld, A. and Zeng, A.Z., 2004. How many suppliers are best? A decision-analysis approach Omega. *The International Journal of Management Science*, 32 (1), 9–15.

Chen, J.J. and Paulraj, A., 2004. Understanding supply chain management: critical research and a theoretical framework. *International Journal of Production Research*, 42 (1):131–63.

Chua, M. H., Smyth, B.M., Murphy, A. and Butterfield, J., 2015. Understanding aerospace composite components' supply chain carbon emissions. Paper presented at Irish Manufacturing Conference, IMC32, Belfast, United Kingdom.

Das, S., Warren, J., West, D. and Schexnayder, S. M., 2016. Global Carbon Fiber Composites Supply Chain Competitiveness Analysis. Energy and Transportation Science Division, Oak Ridge National Laboratory. Technical Report ORNL/SR-2016/100 | NREL/TP-6A50-66071.

Farooq, S. and O'Brien C. 2012. A technology selection framework for integrating manufacturing within a supply chain. *International Journal of Production Research*. 50(11), 2987-3010.

Galorath International, 2017. SEER manufacturing costing tool.

ISO 14040, 2006. Environmental management – Life cycle assessment – Principles and framework, International Organization for Standardization, Switzerland.

Kehoe, D.F. and Boughton, N.J., 2001. New paradigms in planning and control across manufacturing supply chains. *International Journal of Operations & Production Management*, 21 (5/6), 582–593.

Lambert, D. M. and Cooper, M. C., 2000. Issues in supply chain management". *Industrial Marketing Management*, 29 (1), 65-83.

Li, S., Rao, S.S., Ragu-Nathan, T.S. and Ragu-Nathan, B., 2005. Development and validation of a measurement instrument for studying supply chain management practices. *Journal of Operations Management*, 23 (6), 618–41.

Ma, W. 2011. Cost Modelling for Manufacturing of Aerospace Composites. MS Thesis, Cranfield University, Bedford.

Narasimhan R, Talluri S and Mendez D., 2001. Supplier evaluation and rationalization via data envelopment analysis: an empirical examination. *Journal of Supply Chain Management*, 37 (3), 28–37.

Olhager, J. and Prajogo, D., 2012. The impact of manufacturing and supply chain improvement initiatives: A survey comparing make-to-order and make-to-stock firms. *Omega*, 40, 159–165.

Oesterreich, T.D. and Teuteberg, F., 2016. Understanding the implications of digitisation and automation in the context of Industry 4.0: A triangulation approach and elements of a research agenda for the construction industry. *Computers in Industry*, 83, 121–139.

Prajogo, D. and Olhager, J., 2012. Supply chain integration and performance: The effects of long-term relationships, information technology and sharing, and logistics integration. *International Journal of Production Economics*, 135, 514–522.

Roberts, T., 2011. The Carbon Fibre Worldwide 2011-2020: An evaluation of current markets and future supply and demand Location. *Materials technology publications*. Watford:UK.

Seaman, C., 1999. Qualitative Methods in Empirical Studies of Software Engineering. *IEEE Transactions on Software Engineering*, 25 (4), 557-572.

Shakspeare, P. and Smith, F., 2013. UK Composites 2013. A Study into the Status, Opportunities and Direction for the UK Composites Industry, *Composites Leadership Forum, Department for Business, Innovation & Skills*, UK: London.

Talluri, S., DeCampos, H.A. and Hult, G.T.M., 2013. Supplier Rationalization: A Sourcing Decision Model. Decision Sciences, 44 (1), February, 57-86.

Van Gent, I., and Kassapoglou, C. 2013. Cost-Weight Trades for Modular Composite Structures. Structural and Multidisciplinary Optimization 2014 (49), 931–952.

Wilson, A., 2017. Edging to Industry 4.0 at JEC World, March. http://www.insidecomposites.com/edging-to-industry-40-at-jec-world/#sthash.nMAUXJnH.dpuf

Zülch, G., Koruca, H.B. and Börkircher, M., 2011. Simulation-supported change process for product customization – A case study in a garment company. Computers in Industry 62 (2011) 568–577.

Appendix

Sub-assembly

Detailed Composites

Product Description

Quantity Per Next Higher Assembly	1		
Production Quantity	120		
Set-up Amortization Quantity (Optional)	10		
Tooling Amort. Quantity (Optional)	0		
Direct Hourly Labor Rate	58.52		
Setup Hourly Labor Rate	62.94		
Production Experience/Optimization	Hi	Hi+	Vhi

Engineering Description

Part Complexity	Low	Low	Low
Overall Length (mm)	1100.00	1100.00	1100.00
Shape/Dimensions (mm)	Panel	860.00	3.00

Process Type

Process type	HLU						
Core Operation 1	Honeycombs Al-48-3	1	1100.00	860.00	47.00	4	4717.90
Additional Ply 1	Peel Plies (Dry)	1	100.00%				

Material

Prepreg Material Type	Prepreg 8552 0.125x1200mm		
Tape Material Type	8552 (0.25x75mm)		
Material Cost Per Kg.	36.25		
Roll/Tape Width (mm)	1200.00		
Lightning Mesh	NO		
Material Utilization Factor	1.00	1.00	1.00

Process Description

Cutting Type	ultrasonic cutter

Cut Machine Efficiency Factor	90.00%	90.00%	90.00%
Layup Type	Auto. Pick & Place		
BAGGING/TOOL CLOSING	YES		
Operator Attendance Factor	5.00%	5.00%	5.00%
Debulk	NO		
Debulk Interval	4		
HOT PLY FORMING	NO		
Ply Orientation	25.00%	25.00%	
CONSUMABLES	NO		
Bagging Material	Fromocene Unembossed		
Release Agent	PTFE Release Fabric		
Breather	NW153 Medium weight fabric		
Sealant Tape	Tacky Tape SM5144		

Cure

CURE	YES		
Cure Method	Oven		
Cure Temp. (°C)	170.00		
Final Cure Duration (min)	120.00	120.00	120.00
Initial Temp. Cure Duration (min)	60.00	60.00	60.00
Operator Attendance Factor	5.00	5.00	5.00
Heat-up Rate (°C/min)	2.00		
Cool-down Rate (°C/min)	3.00		

Manufacturing Description

Set-up Complexity	Low	Low	Low