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

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A B S T R A C T

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.

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 & 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, 2015). The description from the manufacturer states body structure of the new car is 90 lb 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

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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, Koruca, and Börkircher (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, DeCampos, and Hult (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 & 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 & 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 & 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 are a technology-driven industry with a supply chain comprising various echelon/stages. Fig. 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).

In Fig. 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. Fig. 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°.

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