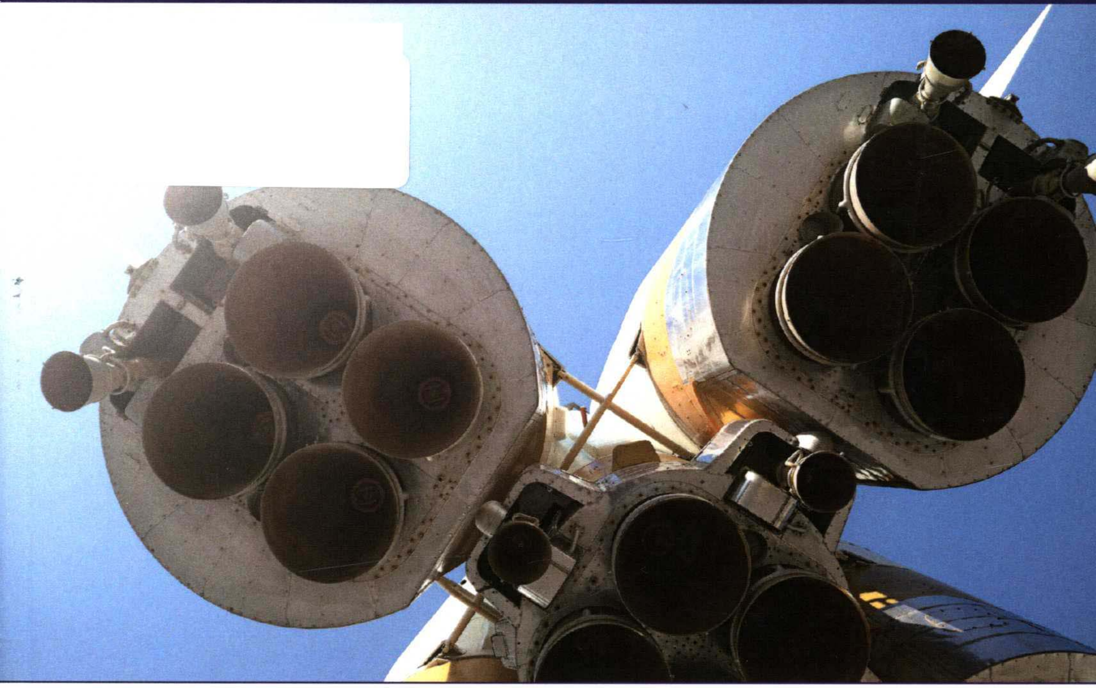

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# NOMENCLATURE

| | |
|---|---|
| CFRP | Carbon Fibre Reinforced Plastics |
| CFRTP | Carbon Fibre Reinforced Thermoplastic |
| CF/PPS | Carbon Fibre Reinforced Polyphenylene Sulphide |
| CAD | Computer Aided Design |
| CAM | Computer Aided Manufacturing |
| PLM | Product Lifecycle Management |
| FEM | Finite Element Method |
| FEA | Finite Element Analysis |
| APS | Assembly Process Simulation |
| PPR | Product, Process, Resources |
| DPM | Digital Process for Manufacturing |
| $T_g$ | Glass Transition Temperature |
| $T_m$ | Melting Temperature |
| $T_{c1}$ | First Crystallization Temperature |
| $T_{c2}$ | Second Crystallization Temperature |
| DoC | Degree of Crystallinity |
| SoC | Size of Crystal |
| CMM | Coordinate Measuring Machine |
| $V_f$ | Fibre Volume Fraction |
| $\rho$ | Density |
| $E$ | Young's Modulus |
| $G$ | Shear Modulus |
| $v$ | Poisson's Ratio |
| $\sigma$ | Normal Stress |

| | |
|---|---|
| $\tau$ | Shear Stress |
| $u$ | Displacement |
| $C$ | Stiffness Matrix |
| $\bar{C}$ | Transformed Stiffness Matrix |
| CTE / $\alpha$ | Coefficient of Thermal Expansion |
| $\Delta\theta_E$ | Change of Angle in Experiment Result |
| $\Delta\theta_S$ | Change of Angle in Simulation Result |

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# CHAPTER 1 INTRODUCTION

Motivated by challenging economic and environmental conditions, the transport industry's unrelenting need to enhance the performance of commercial, military and personal transport systems is constantly driving the development of improved structural materials. Composites in general and carbon fibre reinforced plastics (CFRP) in particular, possess attractive properties such as improved structural performance and lower product weight when compared to their traditional metallic equivalents. For thermoplastic based composites, the fact that they can be reshaped or remoulded at elevated temperatures means that they can be formed using rapid production techniques, such as press thermoforming[1], and assembled[2] using resistance welding, induction welding or ultrasonic welding. Although carbon fibre reinforced thermoplastic (CFRTP) composites can have lower strength than their thermoset counterparts, the use of shim-less welding for their assembly, reuse at the end of service life and weight and cost benefits in service offer clear advantages over thermoset composites. Autoclave based manufacturing is still widely used to produce structural composite components in industry, but the fact that thermoplastics can be re-melted has led to the development of out-of-autoclave thermoforming manufacturing with a relatively low production cost. The thermoforming method can produce complex three-dimensional CFRTP components from a pre-consolidated laminate and voids or defects can be eliminated during the reconsolidation process and the processing time of thermoforming pre-consolidated CFRTP materials is in terms of minutes rather than the hours required to form thermosetting composites. This cost efficient thermoforming process for CFRTPs can manufacture small to medium-sized parts with relatively short production cycles, e.g. ribs for aircraft structures. The problem accompanying the advantages of composite thermoforming is how to produce large structural components using press forming and the process-induced deformation which can affect dimensional control of processed parts. Since poor dimensional control leads to increased cost in mould redesign and product assembly, or in critical cases, the need to scrap parts, methods for determining and managing these deformations need to be developed. Although the part shape variability could be rectified at the assembly stage using welding techniques, there will be other issues as the material is re-heated during welding as the performance of thermoplastic composites relies heavily on thermal history. In some circumstances, assembly can only be achieved using mechanical fasteners due to part thickness limits or the fact that disassembly is required for maintenance. Therefore the ability to achieve part geometry which is within tolerance requirements at the first article stage will benefit both bonding and mechanical fastening assembly methods.

As well as delivering key in-service performance requirements, modern material systems must also offer more sustainable solutions to their life cycle management, as shown in Figure 1.1[3]. This work is part of a broader program seeking to develop integrated, simulation methods which are capable of delivering whole life modelling methods in line with Figure 1.1, dealing specifically with material and part modelling relevant to the manufacturing and assembly aspects of the whole life model. The modelling strategy developed in this work is intended to support both mould design for part forming and tolerance definition for product assembly. Traditional approaches to product development and manufacturing planning can be time consuming even for established technologies, materials and processes[4, 5]. The interdependencies between design and manufacturing disciplines often result in inefficient, linear development processes where design changes at any stage can result in significant time and cost penalties. The way in which any complex engineering assembly is constructed is an important consideration as a product concept is developed. This takes on new significance when materials such as CFRPs are considered and their performance throughout the broader product lifecycle beyond manufacture, has to be taken into account. As CFRPs have not been in use for advanced structural applications for as long as their metallic equivalents, the generation, use and retention of knowledge related to these materials remains a challenge as historical data related to their performance and manufacturability is relatively limited. Knowledge of itself has become a significant asset to manufacturers and its management now plays a significant role in through life support. Digital manufacturing tools are now available which can support this role by determining electronically how an assembly needs to be designed and built. Although they use simultaneous or concurrent engineering concepts which can integrate disciplines and engineer new products, the utility of digital manufacturing platforms is limited by the absence of 'as manufactured' part forms and data in the simulation environment which could support functions such as tolerance allocation, digital build validation and tool fixture design. Design and process based knowledge gaps exist which are currently dealt with on a case by case basis, using trial and error techniques, requiring full scale prototyping and significant capital investment. Gaps also exist between simulation methods which focus in the design of single parts and the approach required to include multiple part assemblies in virtual product development including final assembly considerations. There is therefore a need for assembly process simulation methods which take account of complex material behaviours in order to use realistic composite geometries to support product and process development during design. Manufacturing planners would also be better informed thereby improving the likelihood of achieving tolerances as parts are formed and products are assembled. More significant dimensional non conformances can be addressed and possibly improved by considering alternative processing conditions or mould dimensions at the part forming stage.

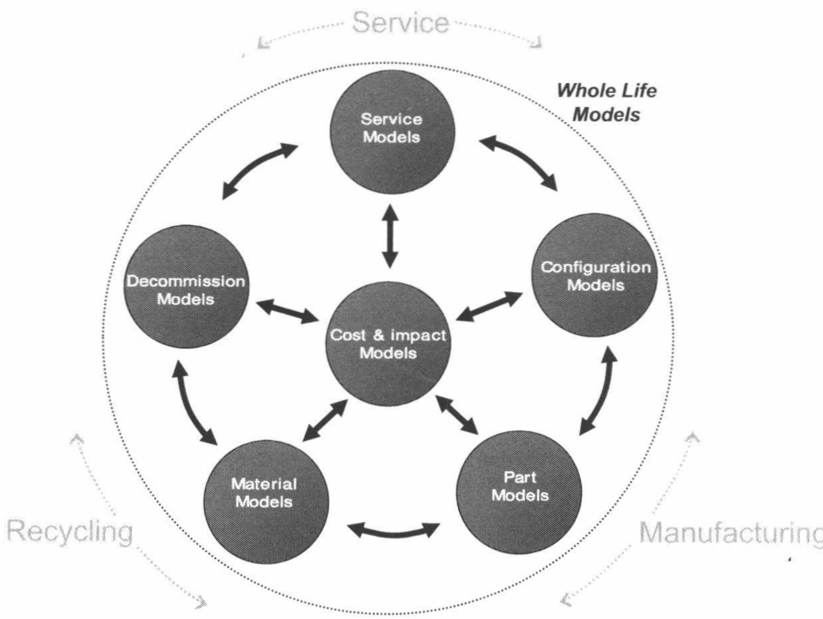


**Figure 1.1 Whole Life Modelling of Composite Systems for Use in Sustainable Transport Systems[3]**

The fundamental motivation for this research therefore comes from this growing need to develop and integrate predictive methods for CFRTP composites' manufacturing and assembly in a digital manufacturing environment to promote more sustainable solutions for advanced material applications in future transport systems. Furthermore, the function of digital manufacturing, to simulate and validate the product manufacturability, is based on the prerequisite that the digital models run in the software systems are in accordance with realistic virtual part forms. Given that the typical difficulty with composite part manufacturing is process induced shape variation, there is a need for manufacturing simulation which can support mould design using predictive methods and assembly process simulation which use realistic composite geometries for design purposes and component build validation during assembly planning. As well as FE based shape prediction of composite parts, theoretical analyses of the factors causing deformation and effective solutions will also be studied to support the utilization of digital manufacturing for composite material's forming and assembly simulation.

The chief objective of this work is to cover the current gap between conventional part design methods and final assembly simulation platforms for CFRTP components allowing for realistic, 'as manufactured' part geometries and the methods used to recover their 'as designed' forms prior to or during assembly. A successful research outcome will be dependent on addressing the design, manufacture and assembly of CFRTP structures across a range of engineering disciplines from design to production. This will only be possible through the integration and management of inter disciplinary activities within a digital manufacturing framework using a method which promotes concurrency.

An additional layer of simulation methods is defined, validated and integrated within a digital manufacturing framework to enable CFRTP part form prediction[6-10], as shown in Figure 1.2. Currently the designed CAD model for composite parts will not directly deliver realistic part forms to manufacturing disciplines. Process simulation and deformation prediction, form the core of the extra layer, which is required to predict the real part geometry. To improve the reliability of the simulation, corresponding validation experiments are carried out to compare the simulated outcomes with experimental results. Press thermoforming process experiments are designed to produce CFRTP parts which are used to determine actual deformation behaviours and validate prediction methods. After the deformed part shape is predicted, the next step is to determine the variant is acceptable or not according to tolerance requirement of design intent. Processing revision, fixture correction, shimming and tool redesign, are tried to solve the mismatch between post-processed part shape and design desired one. Both the benefits of digital manufacturing and advanced composite materials can be exploited using this approach resulting in a reduction in the learning curve as the application of advanced composite materials increases in transport applications.

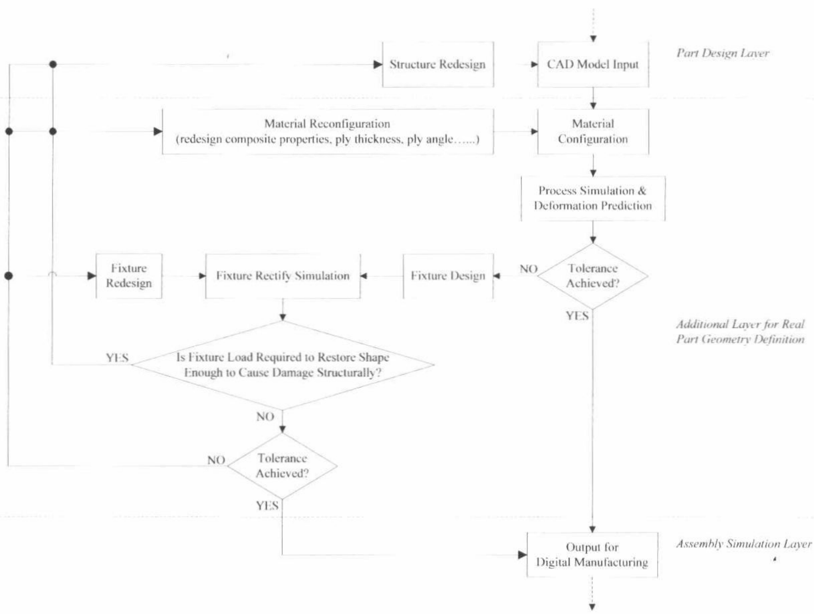


**Figure 1.2 Proposed Methodology for Composite Component Shape Prediction**

# CHAPTER 2 LITERATURE REVIEW

This chapter presents a review of available literature covering the main topic areas which are relevant to the main project aim which is:

'to advance the state of the art in manufacturing process simulation for CFRTP components to predict and understand material behaviours and component forms during thermoforming manufacturing in order to drive more realistic assembly simulations using digital manufacturing tools'.

The content of this section was chosen by using the analysis and synthesis method shown in Figure 2.1.

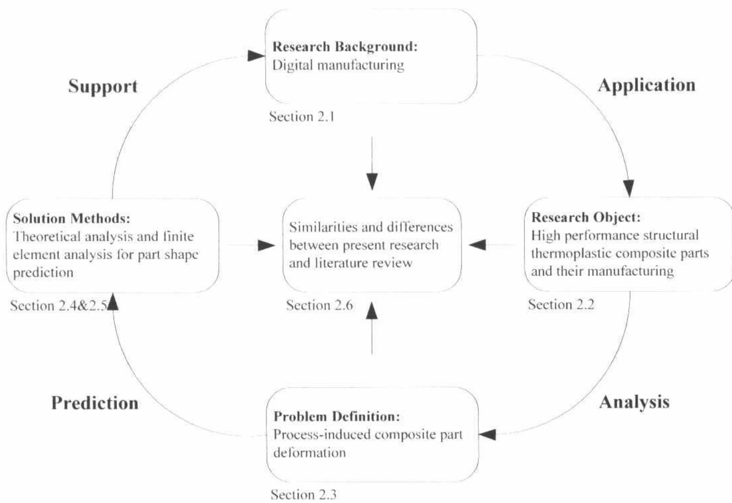


**Figure 2.1 Approach to Literature Review Used in This Book**

Individual sections are organized using the sequence of problem definition, analysis and solution. Because this work is to apply digital manufacturing methods on composite components, this chapter starts with a review of the literature on digital manufacturing. Then it presents a review