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# Composite manufacturing supported by simulation

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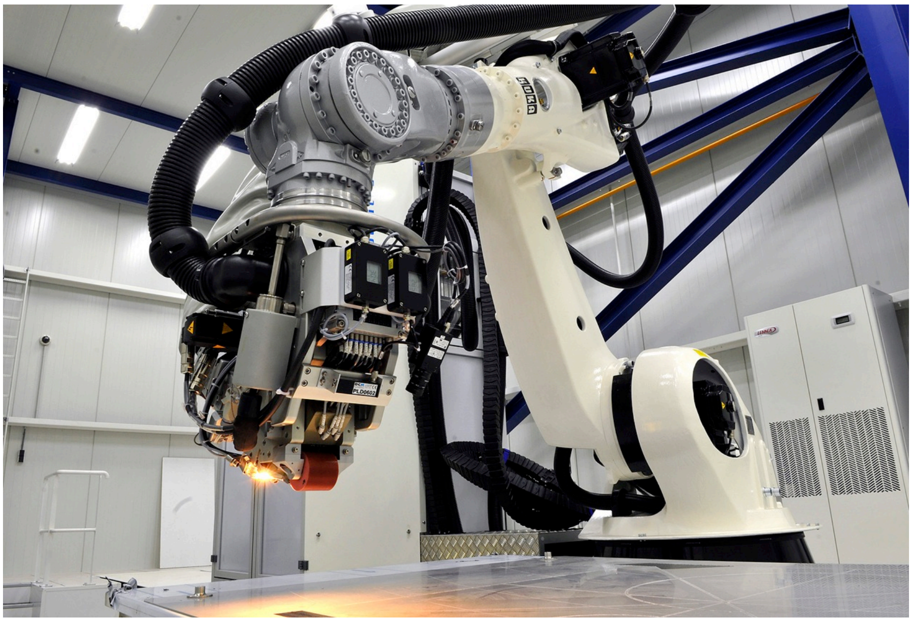

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## Problem area

Current computational tools enable analysis capabilities that include the manufacturing process of composite parts. By combining manufacturing parameters with material information in the simulation, the manufacturing and the design processes are combined in the so-called “virtual manufacturing”, which can support the production of “first time right” parts.

## Description of work

This paper presents an overview of the research performed at the Royal Netherlands Aerospace Centre (NLR) regarding virtual manufacturing of composite structures. Examples of manufacturing simulations are given, whose results are used to characterize the structural properties of the part(s) and to improve the

manufacturing process. Such experience ranges from using virtual manufacturing to support design and manufacturing of composite components, to the development of new virtual manufacturing models, both analytical and via finite element models. This knowledge has been developed via joint cooperation in several European projects.

## Results and conclusions

More projects are currently running to build on the existing knowledge and to expand into making more manufacturing processes “virtual”. In particular, the development of the NLR ACM Pilot Plan digital twin will enable the integration of the “real” and “virtual” worlds, further supporting the research of new composite materials and designs, while reducing development and certification lead time and cost.
Several challenges and opportunities are still open in this field of research. One of the most intriguing concerns the determination of the material properties of the virtually manufactured components and of the process parameters required to achieve pre-determined material properties. A fundamental step to fully implement virtual manufacturing solutions in support of development and certification activities is to develop a framework for the validation of virtual manufacturing models and results, as currently no clear virtual manufacturing test standard is available.

## Applicability

The models, tools and simulation skills developed can be applied to broad range of composite manufacturing applications.

**GENERAL NOTE**
This report is based on a presentation held at the SAMPE Europe, Nantes (France), 17th-19th September 2019.

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# Summary

Current computational tools enable to extend analysis capabilities to include the manufacturing process of composite parts. By combining manufacturing parameters with material information in the simulation, the manufacturing and the design processes are combined in the so-called “virtual manufacturing”, which can support the production of “first time right” parts. This paper presents an overview of the research performed at the Royal Netherlands Aerospace Centre (NLR) regarding virtual manufacturing of composite structures. Examples of manufacturing simulations are given, whose results are used to characterize the structural properties of the part(s) and to improve the manufacturing process. Indications of future developments are given, to improve the reliability of the virtual manufacturing simulations and to develop a digital twin framework.

# Contents

# Abbreviations

| ACRONYM | DESCRIPTION |
|---|---|
| ACM | Automated Composite Manufacturing |
| CAE | Computer Assisted Engineering |
| CTE | Coefficient of Thermal Expansion |
| DNW | German-Dutch Wind Tunnels |
| DSC | Differential Scanning Calorimetry |
| NLR | Royal Netherlands Aerospace Centre |
| PEKK | Polyetherketoneketone |
| PPS | Polyphenylene sulfide |
| RTM | Resin Transfer Moulding |
| T | Temperature |
| TRL | Technology Readiness Level |

# 1 Introduction

The trend in present day computational simulation software is to extend the structural analysis capabilities to include simulation of the manufacturing process of composite parts. The idea behind this approach is that, by including manufacturing process and composite material parameters (e.g. curing temperature and chemical shrinkage) in the simulation, the design and manufacturing process can be configured beforehand to enable first time right products. In addition to this, by calculating the residual stresses occurring after manufacturing, more accurate predictions of structural properties can be made. This idea is not new; it had been discussed for over 40 years [1], since the first introduction of composite materials in different industries and the, coincidentally simultaneous, development of computers' computational power, which allowed the beginning of computer assisted engineering (CAE). Despite the clear benefits that integrating design, manufacturing and simulations would bring, achieving such integration is still not complete, due to the lacking of solid models representing manufacturing processes, but also, more in general, due to the difficulty of changing pre-existing "design" and "manufacturing" separate workflows into a "design for manufacture" workflow [1].

"Virtual manufacturing" is becoming an increasingly popular topic for research in support of first-time-right activities and in combination with the rising of digital twin architectures. The aerospace industry is particularly interested in virtual manufacturing and testing [2], seen as essential support to the certification of components stemming from new innovative technologies related to automated manufacturing and advanced lightweight designs and materials, while, at the same time, reducing development costs. The development and use of virtual manufacturing models require a thorough understanding of each stage of the manufacturing process, which can be achieved only by a close collaboration of experts in the field of composite materials and manufacturing and in the field of computational mechanics; such synergy is part of the research environment at NLR.

In this paper, the current work performed in the field of virtual manufacturing of composite structures at NLR is presented. Examples of predictive manufacturing simulation approaches are discussed, whose results are used to analyse the structural properties of the manufactured part and to improve the manufacturing process. Figure 1 provides an overview of the manufacturing processes investigated by NLR and presented in this paper. Section 2 presents the research performed on the simulation of the curing process and related distortions. Section 3 will give an overview of the simulation of the overbraiding process, while section 4 of the fibre placement process. Finally, an outlook of the future activities is given in section 5, collecting NLR's plans for future developments on the topic of virtual manufacturing.

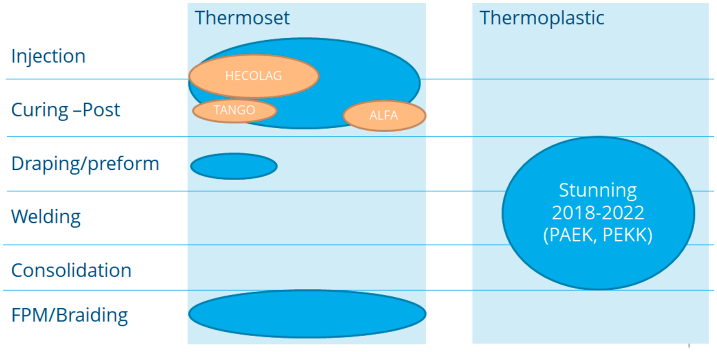

*Figure 1: Overview of NLR experience in modelling composite manufacturing and associated projects.*

# 2 Simulation of the curing process

During the manufacturing of composites the matrix material undergoes changes in temperature and/or phase, which result in volumetric changes in the composite material. Those volumetric changes generate size and shape deviations which are undesired when considering tolerances and assembly. The cooling down of the curing process is often captured by a thermal simulation using the materials thermal expansion coefficients (CTE). However this type of simulation does not include the phase changes of the material and for instance the chemical shrinkage of the resin. Therefore a cure method has been developed by NLR [3] (Figure 2), consisting of a thermal model to compute the temperature distribution during the cure cycle and of a mechanical model to compute the final product dimensions. For both models, user-subroutines have been implemented in Abaqus software, in which interaction with other structural parts, such as tooling, and further structural analyses can be taken into account.

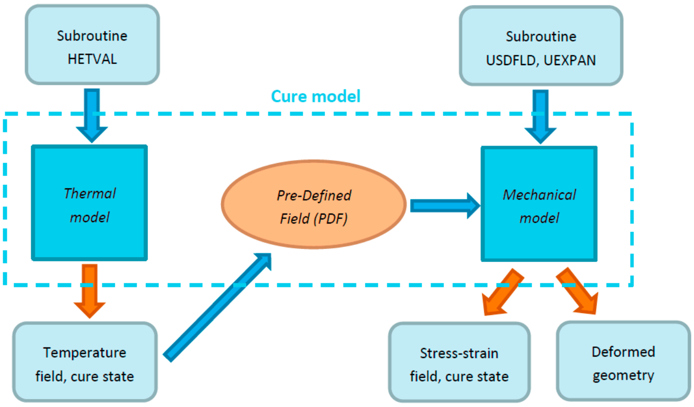

*Figure 2: Schematics of the curing model developed by NLR.*

The curing analysis has been newly developed using a sequential thermal and mechanical analysis to determine the residual stress and final deformation of the composite parts. In the curing simulation, the rate of cure is an important factor to capture during the cure simulation. Because of the forming of linkages during curing of the resin, an exothermic reaction develops. This can have an influence on the temperature in the mould. The curing model developed is as follows. The heat generated during the curing process is included in the formations as:

$$q(\alpha,T) = \rho \cdot Ht \cdot \frac{d\alpha}{dt} \cdot V_{mm} \qquad \text{Eq. 1}$$

Where $\rho$ is the density, $H_t$ is the enthalpy, $d\alpha/dt$ is the cure rate and $V_{mm}$ is the matrix volume fraction. The cure rate $d\alpha/dt$ is dependent on the actual cure state and the temperature:

$$\frac{d\alpha}{dt} = f(\alpha,T) \qquad \text{Eq. 2}$$

With $\alpha$ the cure state and $T$ the temperature of the resin. This can be extended by using two pre-exponential coefficients using the Arrhenius rate expressions:

$$K = Aexp\left(-\frac{Ea}{RT}\right) \qquad \text{Eq. 3}$$

Where *A* is pre-exponential coefficient, *Ea* is the activation energy, *R* is universal gas constant, and *T* is absolute temperature. The formulation by Hubert including auto-catalytic curing and diffusion factor is used in curing model [4]:

$$\frac{d\alpha}{dt} = K\frac{\alpha^m(1-\alpha)^n}{1+\exp(C(\alpha-(\alpha c0+\alpha ct\cdot T)))} \qquad \text{Eq. 4}$$

Where *T* is the absolute temperature, *m, n, C, αc0 and αcT* are fitting factors that have to be extracted from experimental values using Differential Scanning Calorimetry (DSC) measurements. When the curing process takes place, the glass transition temperature, *Tg,* increases. This can be described by the diBenedetto equation which is used in the subroutine to calculate *Tg* as an output.

$$\frac{T_g - T_{g0}}{T_{g\infty} - T_{g0}} = \frac{\lambda\alpha}{1-(1-\lambda)\alpha} \qquad \text{Eq. 5}$$

Here $T_{g0}$ and $T_{g\infty}$ are the glass transition temperatures of uncured and fully cured resin, $\alpha$ is defined as the degree of cure and $\lambda$ is a fit parameter between 0 and 1 for the specific resin.

In the mechanical model the stiffness of the material, and in particular the resin, is calculated using the USDFLD user subroutine, as factor of the temperature and the cure state. The strain in the model is calculated using the UEXPAN user subroutine in which four strain factors are computed: the elastic strain, the thermal strain, the chemical shrinkage strain and the creep strain. The thermal strain formulation is given in the following equation:

$$\Delta\varepsilon_{ij}^{therm} = \alpha(CTE)\Delta T \qquad \text{Eq. 6}$$

Where $\varepsilon_{ij}^{therm}$ is the thermal strain, which is dependent on the CTE values, and $\Delta T$ is the temperature difference.

Verification of this approach has been performed first using L-shapes coupons in the EU LOCOMACHS project [4].

## 2.1 Curing simulation applications: distortions

The method described in the previous section has been used for the evaluation of distortions in large composite aerospace parts. Distortions in geometrical dimensions of composite components can result in mismatch during assembly of the final structure. Composites are much less forgiving for such geometrical mismatches than their metal counterparts, as they require a higher manufacturing tolerance. Therefore, making the manufacturing process more robust is important in order to achieve a higher product quality. In addition to this, there are a wide variety of design and manufacturing factors that can potentially affect the curing processes and lead to distortions. By predicting the possible distortions during and after the manufacturing, it is possible to modify the design prior to the actual manufacturing of a part, in order to account for their effect.

An application of such approach is executed within the MAAXIMUS European project (Figure 3) [3]. In this project, optimized grid structures are designed for aircraft fuselage sections and wing-box sections and detailed analyses and comparisons with test results are performed. Grid stiffening is a process in which local thick unidirectional sections (called ribs) are co-cured within the laminate. The connection between skin and grid the interface is critical due to the change in stiffness and the large a-symmetry of the laminate; this may cause considerable thermal stress at the interface between the skin sections and the ribs itself, large distortions and/or warping of the structure during curing and after the release. In the MAAXIMUS project, numerical methods predicting interface damage and curing behaviour of the grid structure have been applied to different manufacturing concepts, including combined skin and grid co-curing and separate grid curing. By modelling the curing process, specific challenges for the manufacturing of grid-skin interfaces have been investigated and the best design concept could be identified prior to actual manufacturing.

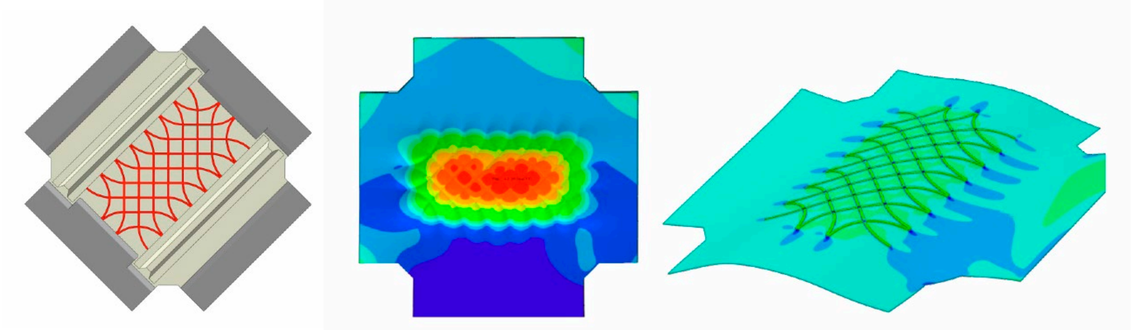

*Figure 3: Optimized grid structure designed in the MAAXIMUS: model (left) and results of the curing simulation with the out of plane deformation and maximum principal strains for the co-cured panel concept (right) [3].*

The deterministic model described in section 2 has also been used in the TANGO European project (Figure 4) [5]; in this project Z-shaped composite frames for a non-circular composite aircraft fuselage have been developed and are shown in Figure 4. Due to residual stresses build-up during the autoclave process, distortions, such as spring-in and warpage, can be present in the final product geometry. For the TANGO frames the spring-in is the main distortion. Spring-in is caused by differential thermal expansion between fibres and matrix and by the evolution of mechanical properties of the resin during processing; therefore, spring-in strongly depends on the timing of events during curing. The spring-in angle α characterizes the variability in the “spring-in effect” and can be corrected on average by adjustments made to the mould. This compensation angle has been determined via finite element model and applied to a small resin transfer moulding (RTM) section of the composite frame. The resulting TANGO frame mould has a spring-in compensation angle of 1.2°, i.e. the right angle of the mould is 91.2°, instead of 90°.

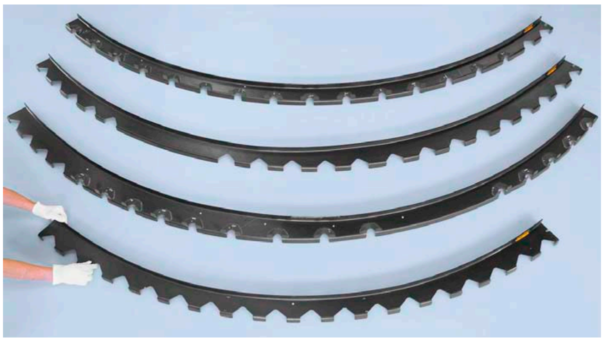

*Figure 4: Frame designed within the TANGO project [5].*

Besides accounting for spring-in in the design of the mould, the determination and characterization of the most important scatter sources affecting spring-in angle has been investigated. Reduction of the amount of scatter is important to make the manufacturing process more robust and achieve a higher product quality. In TANGO, the curing model has been applied in the probabilistic analyses developed to examine the influence of the various scatter sources on the scatter in the product dimensions of the composite part. Assessing the impact of scatter factors via simulation helps reducing the costs involved in an experimental programme and allowing to assess the impact of parameters which are difficult, or even impossible, to measure (e.g. volumetric chemical shrinkage in rubber or glassy state, heat generated during curing process or coefficient of thermal expansion at glassy state).

# 3 Simulation of overbraiding process

Overbraiding is the iterative braiding of dry fibre yarns over a mandrel. The dry fibres are subsequently impregnated with resin to produce semi-finished products (Figure 5). Overbraiding is used in the manufacturing of high-quality, lightweight, complex-shaped, hollow composite structural components. The shape of the structure can affect the distribution of the fibre layers and, in turn, alter the material properties of the entire composite structure. Therefore, the manufacturing process still relies on trial runs to determine the correct settings of the braiding machine. These tests are costly in terms of both labour and material. In the OBODAS project [6] (Figure 5), the need for trials runs has been investigated by determining the settings of the overbraiding machine a priori, through simulation of the overbraiding process and optimisation of the process for specific design requirements. The input for the simulation includes the geometry of the mandrel, the braiding material characteristics, the overbraiding machine parameters, and the target design parameters, such as fibre orientations. The output of the simulation comprises a model of the over braided product available for inspection by the engineer, an optional video animation of the overbraiding process, and the applicable machine program readily available for uploading to the overbraiding machine.

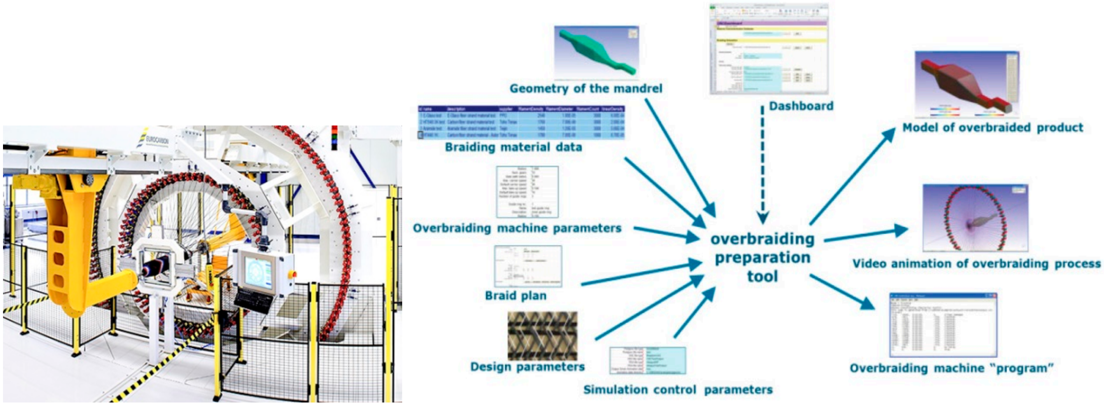

*Figure 5: Overbraiding machine at NLR (left) and context of the overbraiding simulation tool (right, [6]).*

Predictions of the braiding process and of the resulting fibre angles and fibre offsets in the product are currently ongoing work. The predictions are currently demonstrated for a four yarns braiding process (shown in Figure 6), which will be extended in the future to braids and tri-axial braids. Differently than in OBODAS, the approach is modelled in Abaqus software. The composite yarns are fed onto the moving mandrel and between all parts, including the yarns, a contact formulation is defined, which allows for modelling the undulations in the braids.

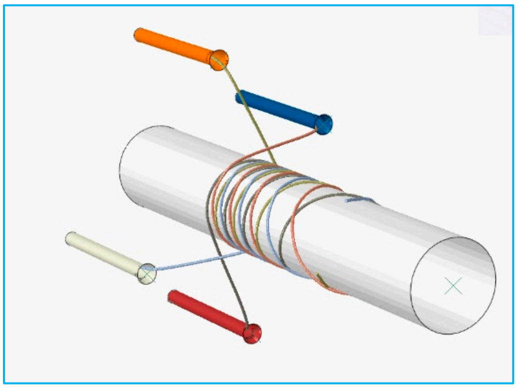

*Figure 6: Finite element dynamic simulation of the overbraiding process by NLR.*

# 4 Simulation of fibre placement process

Another current research topic in the field of virtual manufacturing includes simulation of the fibre placement process, in order to predict the behaviour of the composite tow during placement. Fibre placement automated facilities are gaining popularity in the composite industry (Figure 7) as they enable shorter production lead times and faster lay-up rates, combined with the capability to process different composite materials and to make virtually any type of object, including large ones with complex shapes and a higher TRL level. However, this manufacturing process is critical during the placement of the tows on the mould; those manufacturing issues are influenced by temperature, tack of the material, steering of the tow fibres and cutting of the tows. Apart from multibody dynamics models, limited insight of the fibre placement behaviour and related predictions are available.

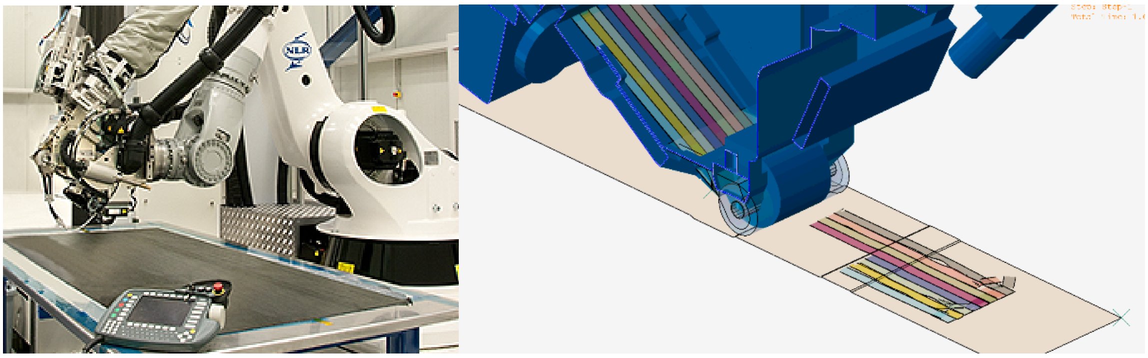

*Figure 7: Fibre placement facility at NLR and tow head simulation.*

The simulation approach developed at NLR focuses on the fibre placement head and it includes most parameters affecting its behaviour. The eight tows are fed into the fibre placement head where they contact with the roller and the mould. A tack level is defined using cohesive definitions to control the tack behaviour and allow for the tows to stick. The fibre placement head then moves forward, the roller presses the tow on the mould and pulls the tows from the feeder. In the model, cutting knives are located before the roller and, by incorporating material damage and failure models, the cutting of individual tows can be simulated. In this way different scenarios can be evaluated, including fibre steering effects, ramp zones and cutting effects.

# 5 Future developments

The field of virtual manufacturing is constantly evolving, as an independent topic for research, but also as support activity for other research projects. In this section an overview of future developments is given. Such developments cover the topics of induction welding for thermoplastics composites, simulation of the draping process, and development of digital twin architecture.

In the STUNNING European project, a 180° full scale multi-functional integrated thermoplastic fuselage shell will be designed, developed and manufactured, including cabin and cargo floor structure and relevant main interior and system elements. In the project, NLR will consider advanced design principles, materials and processes for the design of a thermoplastic fuselage skin. Simulations of the fibre placement process and of the induction welding as joining method will be investigated, in order to reduce manufacturing costs and assembly times and increase production rates.

In CleanSky2 ALFA European project, a demonstrator of a full-scale natural laminar flow horizontal tail-plane will be developed, designed and manufactured. With respect to virtual manufacturing NLR focuses on the simulation of the manufacturing processes (RTM technology (single sided tool) and autoclave technology) for the leading edge as one of the required developments to achieve the compliance with the stringent natural laminar flow requirements for the step/gap between leading edge and torsion box.

Challenges connected to the simulation of the draping process are being investigated at NLR, mainly using the ESI PAM-Composites software. The current focus is to model the compression moulding process for thermoplastic composites such as carbon fibre PPS and PEKK. Also draping of carbon fabric layers to create the preform (dry fibre) for the RTM process is investigated.

Another topic extensively investigated in NLR is the simulation and modelling of model the resin transfer moulding (RTM) injection process. The purpose of this activity is to be able to design a design faster and with less risk RTM moulds and RTM products. Several projects are currently ongoing, considering applications of RTM to landing gears, repairs and multifunctional composite aero-structures.

NLR is currently developing a digital twin of several facilities in its own Automated Composite Manufacturing (ACM) Pilot Plant (Figure 8). The entire project will include digital twins of the resin transfer moulding (RTM) process, of the induction welding process, and of the overbraiding process. In first instance, the project is focusing on developing digital twins of the equipment used in the above mentioned processes, with the goal of remote equipment monitoring and predictive maintenance of the equipment itself. The overall virtual architecture is set up around real-time simulation software (EuroSim [7]) in combination with big data and data analysis (Machine Learning, Deep learning) methodologies. Currently the focus is on ensuring real-time communication with the equipment and each component in it, in order to monitor the process, to receive indications of (upcoming) malfunctioning, and to suggest corrective actions or need for maintenance. One of the goals is predictive maintenance of the equipment, to minimize the down-time of each piece of equipment and to avoid that a minor malfunction could cause a larger damage or impact the on-going manufacturing process. At a later stage, coupling of the digital twins of the machines with virtual manufacturing simulations of the corresponding processes will be used for process preparations and validation.

*Figure 8: NLR Automated Composite Manufacturing (ACM) Pilot Plant.*

# 6 Conclusions

In this paper, an overview of the broad experience developed by NLR in the field of virtual manufacturing has been presented. Such experience ranges from using virtual manufacturing to support design and manufacturing of composite components, to the development of new virtual manufacturing models, both analytical and via finite element models. This knowledge has been developed via joint cooperation in several European projects.

More projects are currently running to build on the existing knowledge and to expand into making more manufacturing processes “virtual”. In particular, the development of the NLR ACM Pilot Plan digital twin will enable the integration of the “real” and “virtual” worlds, further supporting the research of new composite materials and designs, while reducing development and certification lead time and cost.

Several challenges and opportunities are still open in this field of research. One of the most intriguing concerns the determination of the material properties of the virtually manufactured components and of the process parameters required to achieve pre-determined material properties. A fundamental step to fully implement virtual manufacturing solutions in support of development and certification activities is to develop a framework for the validation of virtual manufacturing models and results, as currently no clear virtual manufacturing test standard is available.

# 7 Acknowledgements

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# 8 References

1. K. Potter, “Towards a design for manufacture capability in composites – tying together manufacturing research to maximise impact”, ACCIS Annual Conference 2013.
2. R. J. D’Mello, M. Maiarù and A. M. Waas, Virtual manufacturing of composite aerostructures, The Aeronautical Journal January 2016 Volume 120 No 1223 pp 61–81.
3. W.M. van den Brink, W.J. Vankan, G. van de Vrie, Manufacturing process simulation and structural evaluation of grid stiffened composite structures, NLR-TP-2014-442, 2015.
4. J.M. Muller, W.M. van der Brink, Comparison of integrated rib stiffened and L-blade stiffened composite panels manufactured using simple tooling methods, NLR-TP-2016-201, 2016.
5. F.P. Grooteman, Inverse probabilistic analyses of composite part distortion, NLR-TP-2015-303, 2015.
6. E.H. Baalbergen, S. Voskamp, A.A. ten Dam, W. Gerrits, Innovating the overbraiding design process to optimise the development of composite aircraft structural components, NLR-TP-2012-498, 2012.
7. www.eurosim.nl

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