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Design for Manufacture: Advancing Lamination Technologies towards Right First Time Every Time

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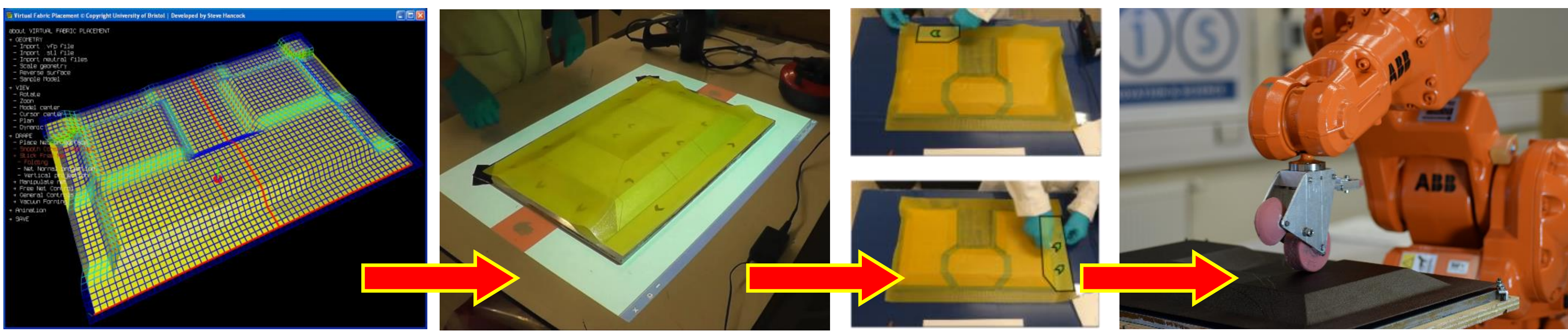

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Design for Manufacture

- The goal of DfM is to design a product that is easily and economically manufactured – implying that we can define “easily” and “economically” in meaningful ways and connect the two concepts together.

- The DfM literature talks about “optimising“ all the manufacturing functions to achieve the best outcomes, although it is not always clear how that can be made to work in practice.

- If we want to achieve a DfM capability we need an in-depth understanding of our processes.

Why study design rules?

- The "quality" and cost of composites products depends critically on the design process, BUT:
  - Manual processes still dominate the manufacturing of very many, if not most, composite products
  - The research base for manual processes has been at best underdeveloped and in some areas has been all but non-existent
  - We cannot move directly to automation from manual processes without first understanding them
  - We need to start by looking at the manual processes to be able to design well with them

Understanding manual processes

In the context of composites manufacturing the following processes are generally done manually

- Tool preparation and mould release application
- Preparation of reinforcement kits
- Lay-up for complex geometry parts
- Release film/bleed/breather/vacuum bag application for debulking and cure
- Autoclave or oven loading and unloading
- Demoulding
- Deflashing
- Initial post moulding inspection
- Transfer to metrology, NDE and further processing
- Traceability and paper trail

Even if AFP is used all the other processes may still be manual

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Understanding manual processes

Taking manual lay-up as an exemplar manual process;

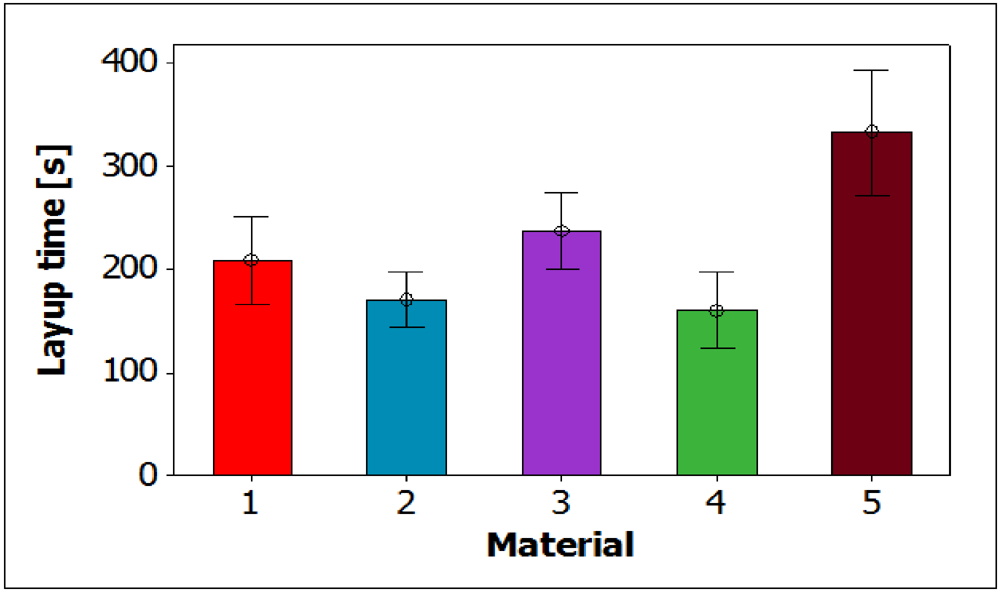
We need to develop a clear understanding of the rather complex interactions between:

- the materials being handled
- the tooling geometries being worked on
- the quality of the lay-up
- the time taken to achieve the lay-up
- laminator motivation and work quality

This information then all needs to be built into a knowledge base and fed back to support the design process

Materials impacts

Five slightly different materials have been laid down on a "standard" tool surface and the time taken to achieve the layup by experienced laminators has been measured.

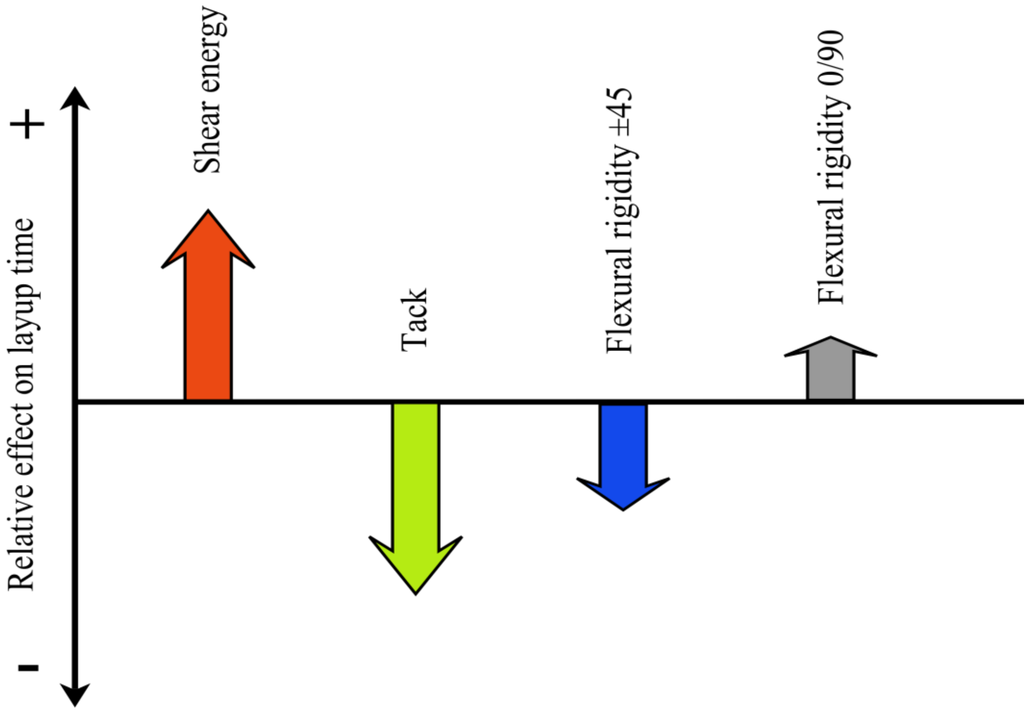


- All the materials were carbon fibre woven cloths with an epoxy matrix.
- Despite the materials being very similar the lay-up times could vary by a factor of two.

Materials impacts

We need to separate out the impacts of the different material properties that contribute to the differences in material performance.

Four interacting factors have been identified and the relationship between them has been investigated



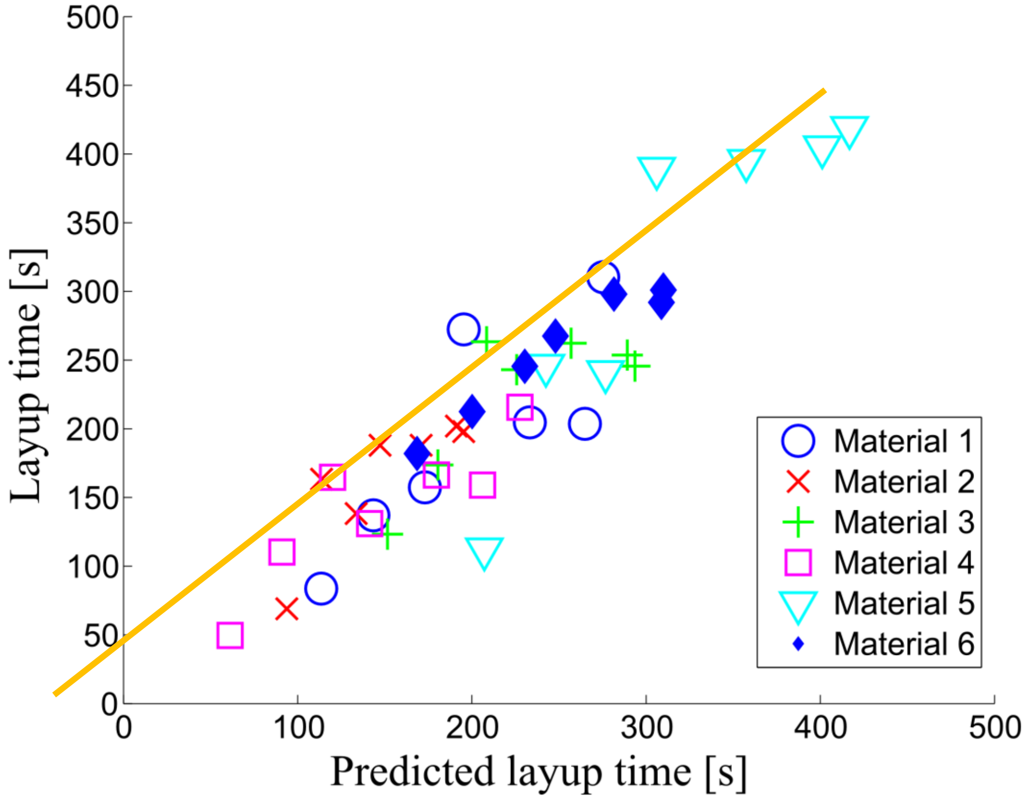
Materials impacts

Time to lay up = A + B(shear E) – C(Tack) + D(Flex 0/90) – E(Flex +/-45)

Constants A to E were estimated based on the data from materials 1-5.

Material 6 was a very different spread tow plain weave fabric prepreg, used to test the estimates.

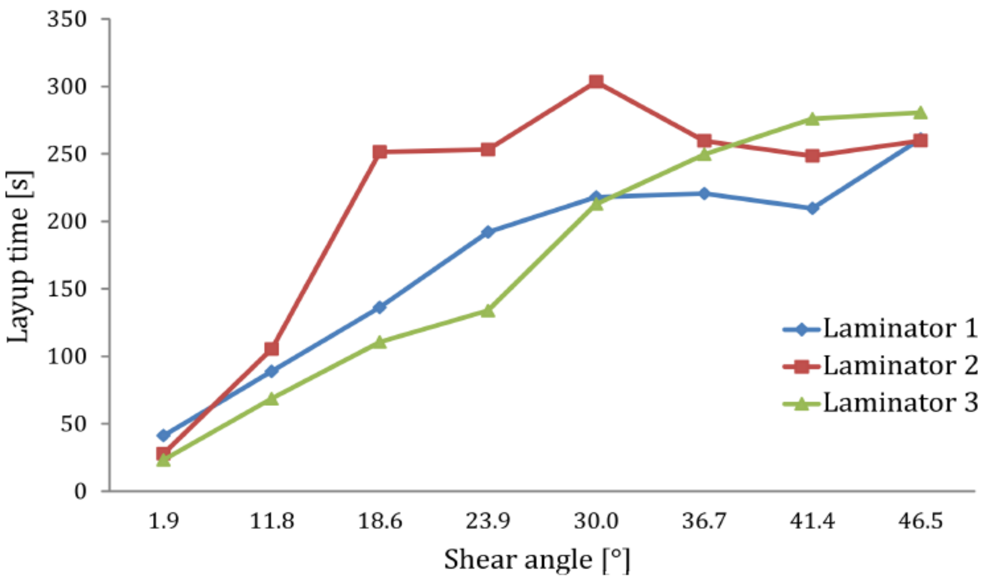
The fit to Material 6 is very good despite the significant differences in the prepregs' structure



Geometry Impacts

Experienced laminators were given a series of timed lay-up tasks over a graded set of tools with increasing ramp angles from 20° to 70°.

They were instructed to focus on achieving a “high quality” result.



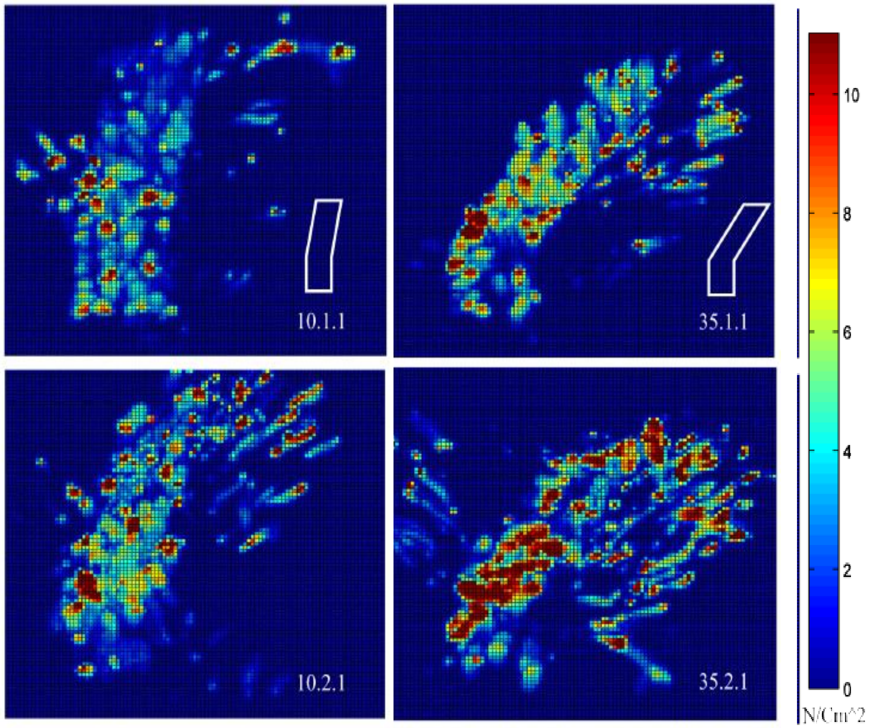
There is a very clear trend of significantly increased lay-up time as the ramp geometry increases in difficulty.

Even small changes in ramp angles can have a big impact

Geometry impacts

To study the work done and relate it to the geometry we can look at the force reacted at the tool surface by the operator's hands as they shear the material into a predetermined shape.

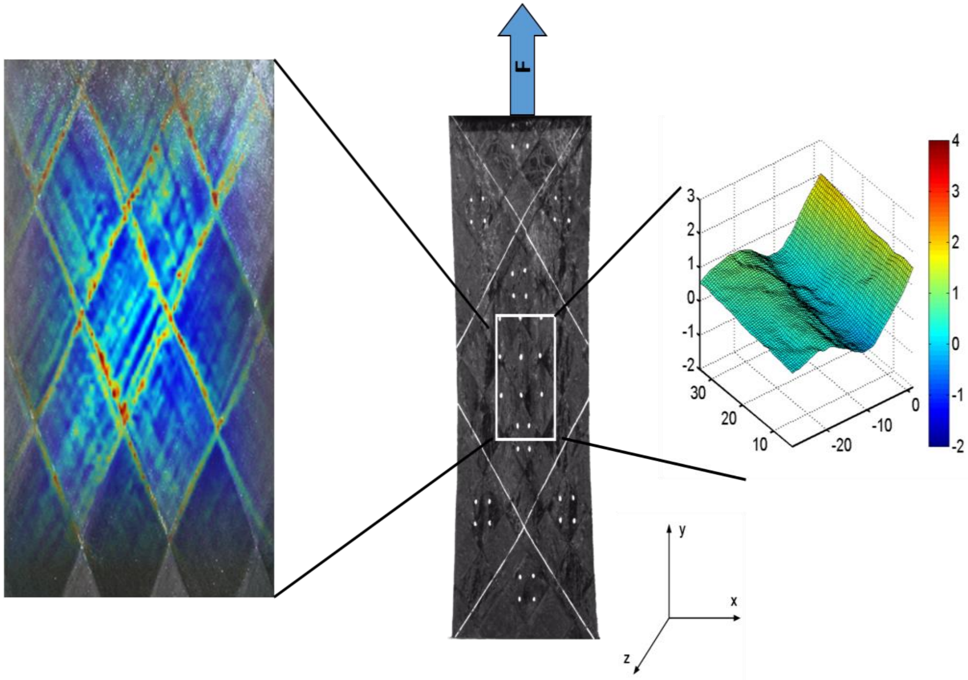
The pictures on the left are for a 10° shear and on the right for a 30° shear.



The images show all the tool/operator contacts, with the colours indicating force (red = high) for two different materials. The number and intensity of contacts is clearly different for the two different geometries (and for the different materials)

Quality impacts

The very thin spread tow based woven prepreg was relatively easy to lay up in terms of achieving the geometry but a larger proportion of the lay-up time was taken up by ensuring that the quality was adequate in terms of freedom from ply wrinkling.



To understand why that should be, we have to examine the fine detail of the materials deformation behaviour and the ease with which the prepreg buckles under load.

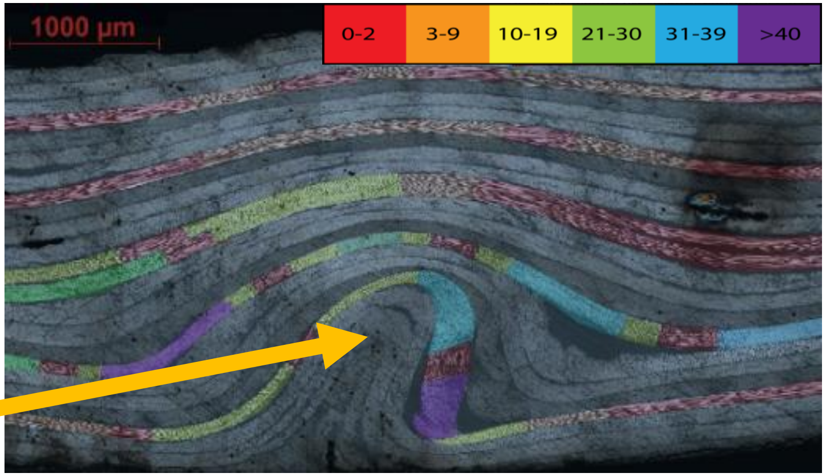
Quality Standards

- Quality standards and the associated Acceptance Criteria have a great and sometimes unacknowledged impact on Right First Time yields and overall quality costs.
- There are elements of common standards – for example for internal ply edge position accuracy requirements, that if applied as written, would probably lead to 100% shop reject rates. Fortunately they are also not detectable by NDE to the accuracy implied by the quality standard.
- The existence of quality standards that can neither be met in production nor detected by NDE is a measure of our failure to achieve concurrent design in composite parts.

Quality Standards

We need to set acceptance and quality standards based on evidence of likely impacts on in-service performance

This is obviously an unacceptable fibre wrinkling defect anywhere.



Is this an unacceptable defect?

- In a highly stressed area?
- In a low stress area?
- If the effect of failure is minimal?

Many design approaches don’t discriminate between the 3 cases

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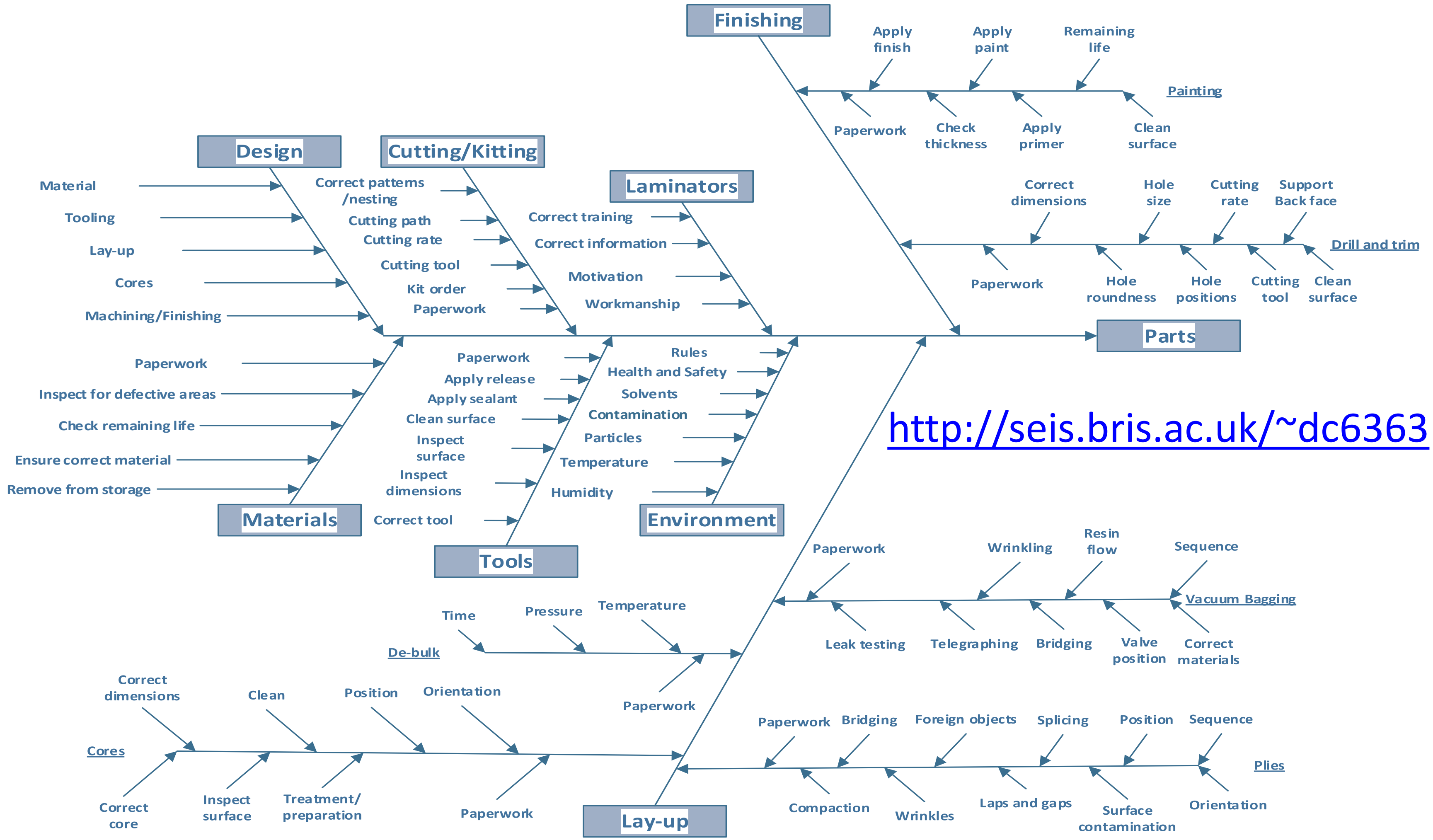
Impacts on Quality



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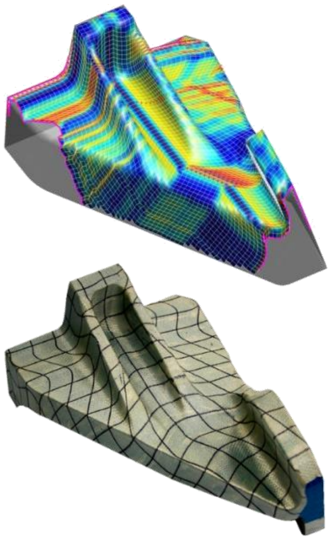
In-process inspection (IPI)

Our standard NDT techniques are of very little use during in-process inspection, when what we want to do is to predict from a knowledge of the current state of a lay-up what the final quality of the component will be at the end of processing.

- We want to be able to identify:
  - Lay-ups that will bridge or wrinkle during cure (which can also contribute to high voidage)
  - Fibre directions outside of specification
  - Ply edge positions
  - Gaps and overlaps in AFP
  - Foreign materials such as backing paper or rulers



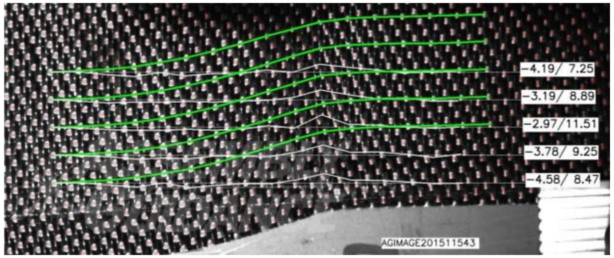
- We are largely looking at ply geometry rather than traditional quality indicators

IPI possible methods

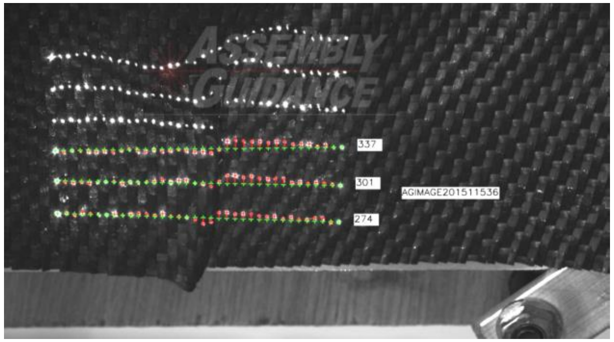
- Some combination of image analysis and surface metrology seems to be the best way to make progress
- Our materials can be sticky, black, matt and fuzzy, or specular reflectors. These are not ideal characteristics for either image analysis or surface metrology.
- Whatever process is used needs to integrate seamlessly into current practices without adding any significant delays to total manufacture times
- Some initial trials do look promising

IPI possible methods

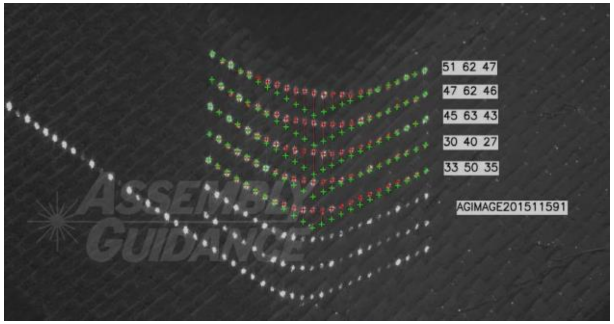
1. Automated tracking of changes in fibre direction due to drape in lay-up



2. Automated detection of drape induced fibre wrinkling

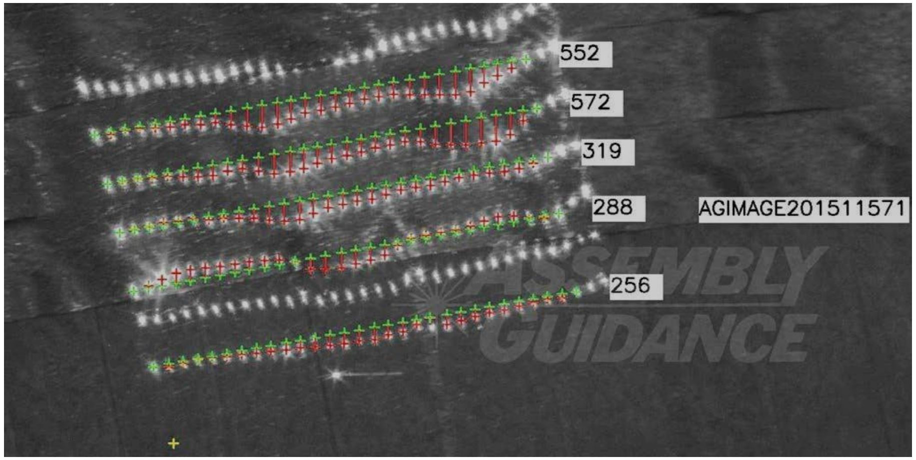


3. Automated detection of bridging in a corner radius

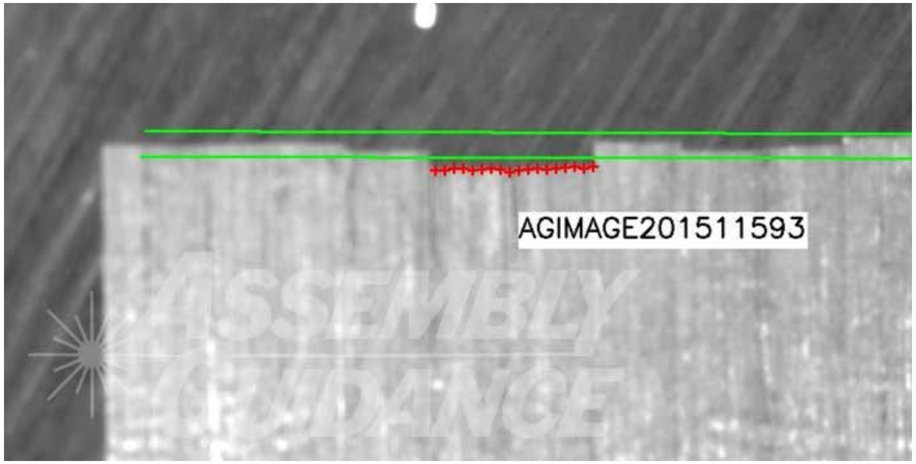


IPI possible methods

1. Automated detection of surface wrinkling due to tape steering in AFP



2. Automated detection of ply drop edge position in AFP



Factory Operations

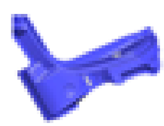
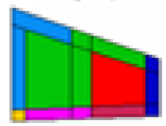
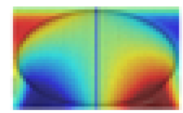
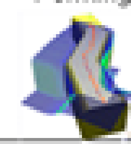
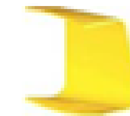
- Whatever manufacturing and IPI processes are being used, how they are implemented and integrated into the production flow is a key determinant of the plant efficiency and how costs build up through manufacturing
- We are only just beginning to be able to capture data on these issues with tools such as Value Stream Mapping and Process Failure Mode and Effect analyses
- The data will help us to understand how to optimise the part design to ease its way into production and provide another level to the understanding of DfM

Costing

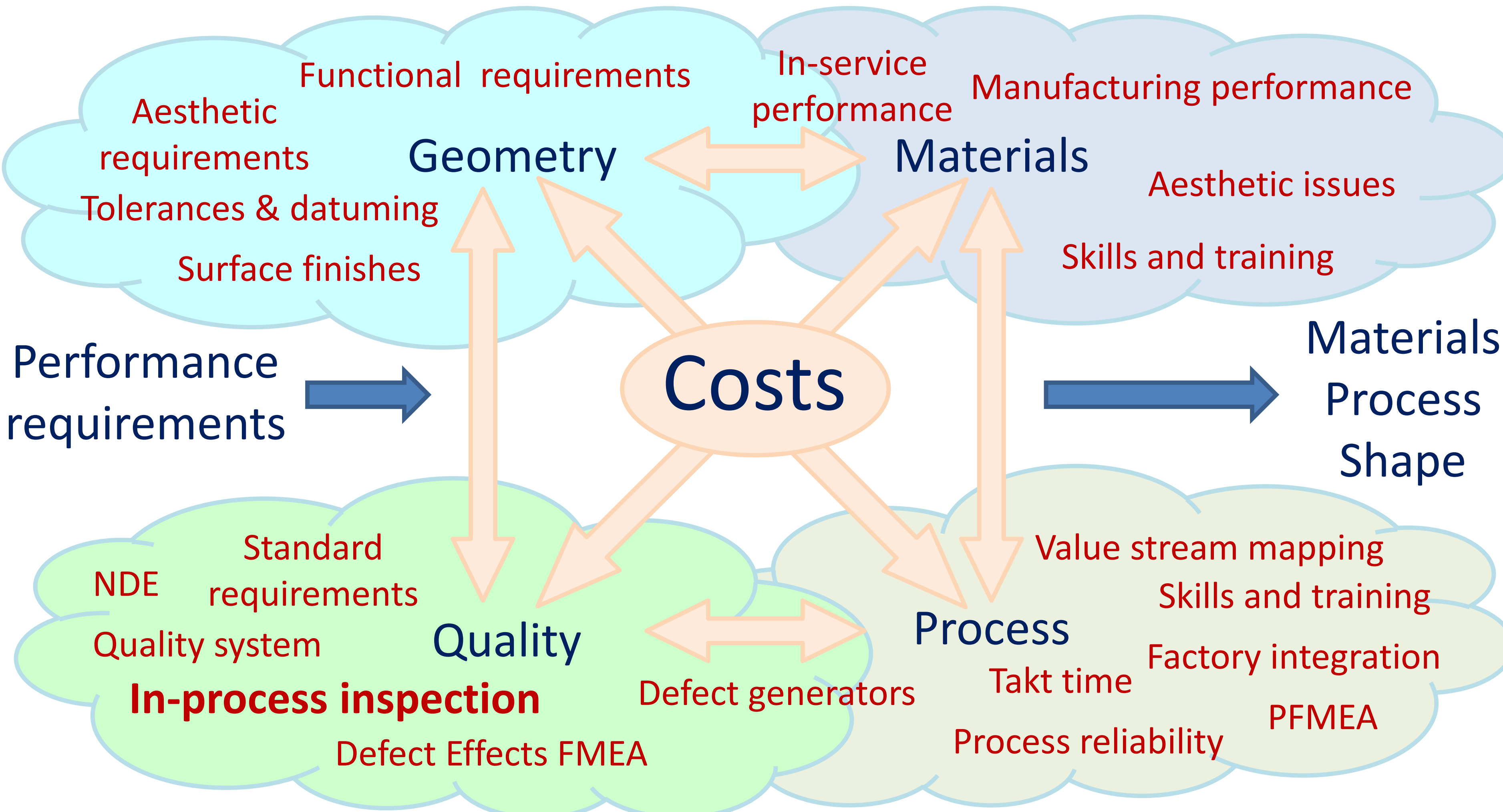
- Costing models essentially rely on past experience to guide the estimation of labour time in various tasks, even if a detailed bottom-up approach is being used.
- We have seen that:
  - Changing the grade of prepreg can change labour costs by a factor of two.
  - Changing the details of tool geometry can make at least as much impact
  - Changing acceptance criteria also impacts both directly and indirectly on costs
  - Design details can also impact on production flows at the factory level
- Much of this is missing from traditional costing models

The Design Process now

The conventional composites design flow is sketched below. It is difficult for manufacturing details to impact strongly in the most critical conceptual design phase where >70% of the final product production costs are fixed.

	Manage	Component design				Process design		
	Costing	Materials	CAD	Lay-up	FE Analysis	Forming	Distortions	Molding
Tool Module								
Conceptual design	Materials process & selection	Selection	Concept	Zones	Preliminary	Formability	Acceptability	Practicality
Detailed design	Process optimisation	Modeling & characterisation	Details	Optimisation	Detailed static linear dynamic non-linear	Fibre/ fabric topology	Assembly forces & residual stresses	Tooling design
Manufacture	Process control	Specification	Specification	Specification	Check	Manual/ machine instruction	Check & verification	Tooling design

Conceptual Design Process



Conceptual Design Process

- Everything feeds into everything else
- There is nothing that can be taken in isolation
- A linear process is not compatible with the levels of interactions between different factors
- Attempting to accommodate all these factors concurrently may also not be realistic as there's too much detail to process in parallel
- Iteration will be needed around a loop from requirements through geometry to materials, process, quality and cost, bringing to bear each element of the knowledge bases at each stage.
- Starting the loops at different points can help to generate some creative tension and avoid prematurely fixing on an adequate but non-optimal design.

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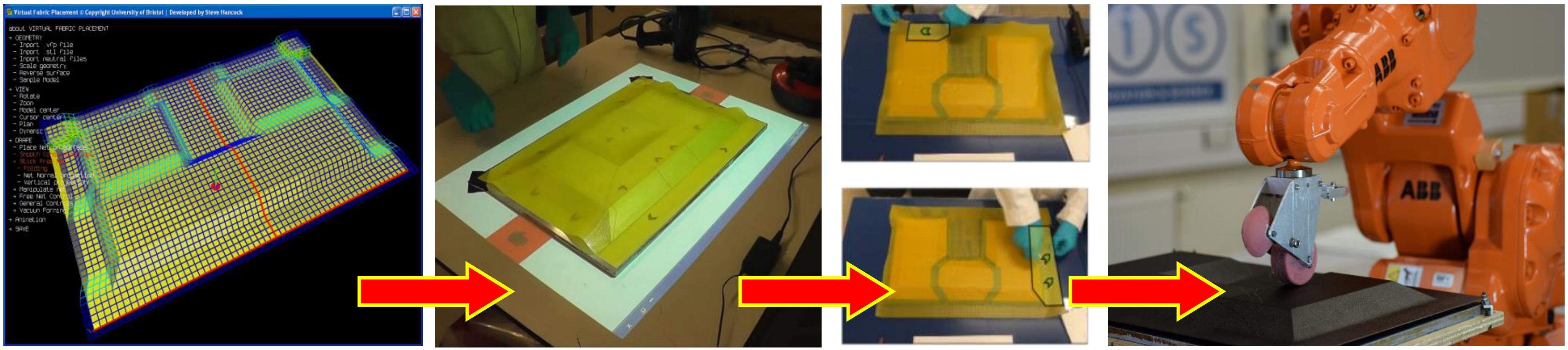
Conclusions

- We have made significant progress across a number of areas to understand the interactions between the many different factors in composites manufacture using largely manual processes

- The next step is to extend that understanding and embed the knowledge base in tool sets that can support each stage of the composites design process – with the most important stage being the conceptual phase

- To complete the development we need to develop in-process inspection tools, methods and standards that work "with the grain" of manufacture to deliver right first time every time.



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