EXPLORING THE SIGNIFICANCE OF IN-PROCESS KNOWLEDGE TO COMPOSITES DESIGN AND PRODUCTION

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Abstract

This work is an initial attempt to explore how knowledge generated during the fabrication of advanced composite components is relevant to their design and production. Despite their high performance applications their manufacture often relies on a manual process. The aim is to suggest mechanisms to integrate this knowledge to facilitate industry growth. A case study approach was taken to map the learning cycle during product innovation processes. The assumption was that a complete learning cycle leads to production efficiency. Differences in this process for a high performance product in an industrial environment and sculptures in an art fabricators' practice were investigated. It was found that the high performance composites industry has an incomplete learning cycle, with in-process knowledge not entering back into concept development. The art fabricators have a complete learning cycle; this has been attributed to their collaborative way of working and the knowledge generated by their material explorations. To complete the learning cycle in an industrial environment it has been suggested that tangible products are used to transfer knowledge about how the material is handled.

Keywords: Integrated product development, Knowledge management, Inclusive design, Composites, Tacit Knowledge

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1 INTRODUCTION

This work is exploring if and how tacit knowledge about how to handle a material enters a product innovation process in the composites industry. The industry currently has limited production rates and is looking to grow (Chatzimichali, 2014b and CLF, 2014). It has been suggested that for the industry to achieve growth (developing the supply chain and moving into emerging sectors) this tacit knowledge is required (Chatzimichali, 2013). This means capturing and organising it into an appropriate framework for exploitation. Understanding how to do this is currently unclear and is a subject of this research.

Here the aim is to understand if tacit knowledge from manufacturing enters the product innovation process. This is the first attempt to connect in process knowledge with mechanisms to facilitate growth, so the methods being used are being developed with the work. It is going to be demonstrated that the learning processes during the composite product innovation cycle are incomplete and explore the differences of an industrial process and art fabrication through this cycle.

Advanced composite materials find applications in high performance sectors (autosport, aerospace, defense) (CLF, 2013, CLF, 2014 and Lewis, 2013). Predominately advanced composites are made from engineered carbon and glass reinforcements pre-impregnated with resin to a certain predefined areal weight (prepreg). Despite their high performance applications their manufacture currently very often relies on manual processing (Bloom et al., 2013, Chatzimichali et al., 2013, Elkington et al., 2013). This research focuses on the manufacturing processes for these advanced composite materials.

The principal manufacturing process is called hand lay-up. It requires reinforcements to be formed to a mould by a laminator, i.e. the person doing the job. It largely relies on their tacit knowledge. The geometries that require forming are often complex, have multiple features and beyond the capabilities of their hands (Elkington et al., 2013). So to complete the forming the laminators make their own handheld tools, Figure 1 (Bloom et al., 2013 and Jones et al., 2014). These are fabricated ad hoc on the shop floor and despite being *"made for jobs"* they are not recognised or accommodated in the design process of a composites product, or by and large in the composites research community.

Another blocking factor for industry growth is the lack of composites design and manufacturing skills (Chatzimichali, 2014a). The sectors (aerospace and defense) that use composite materials are conservative and have been built designing with metals. Previously quality acceptance criteria have been developed using experience from metallic systems and these tolerances cannot be achieved with advanced composites leading to increased costs (Crowley et al, 2013). In the industries typically using advanced composites the associated cost issues can be absorbed and composites have been successfully integrated. To some degree as a material class of their own they are unexplored, composite products are often designed in a style that can be described as "*black aluminium"* due to geometrical similarities with metallic components (Tsai, 1993). Also any composites validation tools that are in house to companies are still based on conservative engineering rules. The initial codes of design practice that surround their use prevail and this is problematic (Potter, 2009) as there is a demand for the materials to move into less conservative industries (CLF, 2014). The sum output of this is that there are massive overhead costs that are limiting this transition.

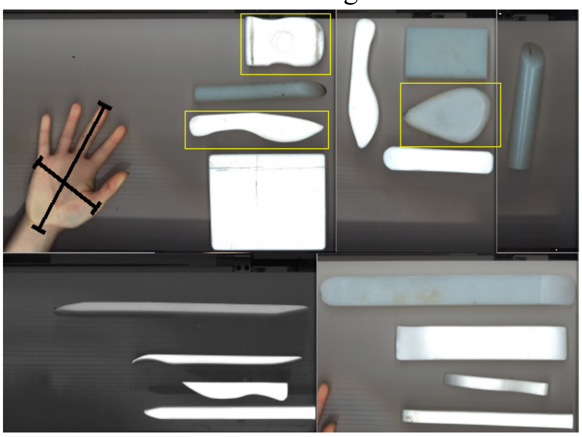

Figure 1. A complete set of tools belonging to an expert laminator. Highlighted are their three most popular ones. The dimensions on the hand are 165 mm and 95 mm. (Jones et al., 2014).

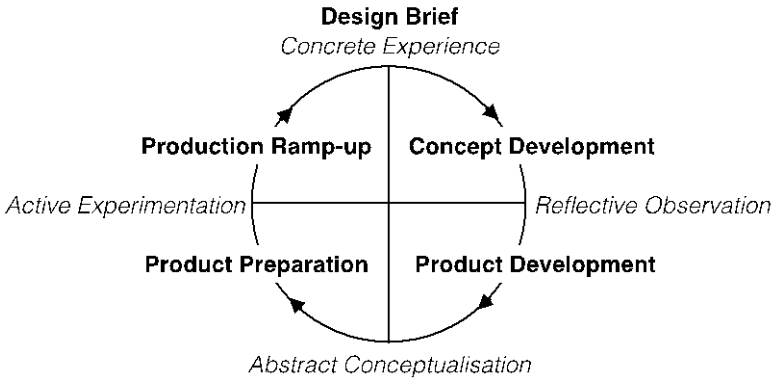

Figure 2. "Successive Phases of Product Innovation Process Mapped over (Learning) Stages (Kolb)". In italic text are the different learning stages, and in bold text are the different stages of the product innovation process. Taken from Smulders (2004).

In order to understand how material knowledge can enter the product innovation process a framework for how such transitions occur is required. Within this process different types of knowledge are used (tacit and explicit). Mental models are being used to explore these. The design-manufacturing interface is important because this is where the divide exists between the type of knowledge that is applied and generated.

Previous work at the interface between design and manufacturing by Smulders and Dorst (2007) suggests these two realms need to be bridged. This is challenging because typically the actors in either have different mental models due to their learning styles and the knowledge generated (Kim, 1993 and Smulders and Dorst, 2007). An actor's mental model is formed of explicit and tacit knowledge (Kim, 1993 and Smulders and Dorst, 2007). Bridging an interface requires either a collaborative mental model or for an individual to adopt a *"transitional mental model"* (Kim, 1993 and Smulders and Dorst, 2007).

A collaborative mental model requires an individual mental model to be explicit (Kim, 1993). Inter personal knowledge has become intra personal. Transferring tacit knowledge into explicit knowledge needs appropriate languages and tools that capture and communicate the richness of the knowledge involved (Kim, 1993). Previous research by Wood et al. (2009) had demonstrated the role of a designer for this purpose proposing interactive media channels to transfer knowledge.

A model mapping a product innovation process onto a Kolb learning cycle has been developed, Figure 2 (Kolb, 1984 and Smulders, 2004). The purpose was to suggest how different learning styles in different stages of product innovation could be accommodated (Smulders, 2004). This model allows us to identify where knowledge about handling materials gets generated and whether it transfers across the different realms of the process. For these reasons the model was selected for use in this work.

The composites industry has identified batch of one structures as an area for growth (CLF, 2014). Currently the laminators are using their own tacit knowledge to work out how to make a composite product, so it is thought that the implementation of the composite design is problem solved in the transition to manufacturing (Jones et al., 2014). Using this model differences in how first articles are produced can be explored. It is relevant for probing how for a batch of one scenario production efficiency can be realised. This work is assuming that a complete learning cycle leads to production efficiency. At least 70% of total project costs involving composites are committed by the end of concept and design development (NDIA, 2011), therefore the economic benefit of having a completed learning cycle is clear, and especially critical in small batch and batch of one environments where learning curve impacts are not available.

2 RESEARCH APPROACH

Themes of interest are how tacit knowledge from production moves into design and the impact of understanding how to handle a material at the concept development phase on design and production. With these themes a challenge is to identify measurable variables for the units of analysis (Yin, 2003). For this initial work proxies are being used.

To represent the movement of tacit knowledge the idea is to identify if the knowledge is intra or inter personal. It is assumed that if knowledge is interpersonal, tacit knowledge has been elicited and it can be communicated (Kim, 1993 and Rust et al., 2000).

For the impact of understanding how to handle a material the completeness of instructions, from the perspective of production, will be analysed. The assumption is that if during the generation of the manufacturing instructions there is a lack of understanding about how to handle the materials these instructions will be incomplete.

Figure 3 uses these variables to suggest an increase in production efficiency requires a move from intra to inter personal knowledge and to more complete manufacturing instructions. A case study approach is being used to build a map of the current situation in composites production (Siggelkow, 2007 and Eisenhardt, 1989).

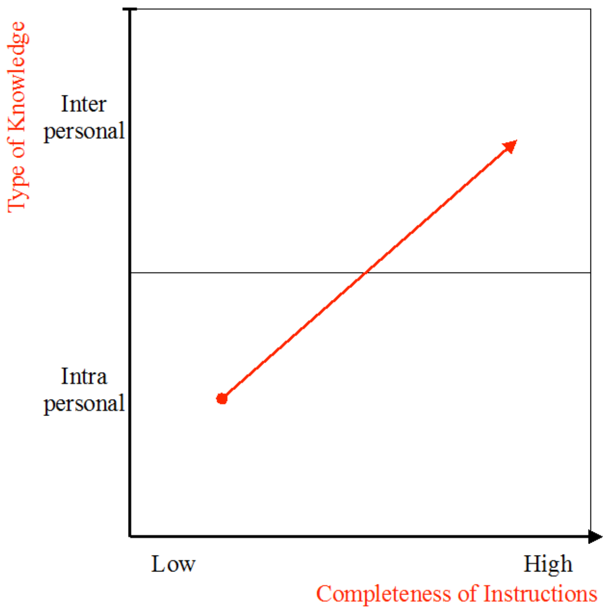

Figure 3. The units of analysis. The arrow highlights that for production efficiency complete instructions built of inter personal knowledge are required.

2.1 Pilot Study

Initially two case studies are being used: handheld tools in the composites industry and an art fabricators' practice. Personal manufacturing tools were selected to analyse a typical production process for a high performance composites product. It was important to consider who else handles these materials and what other products are made from them. The art fabricators were selected because they had worked with carbon reinforcements to make a bespoke sculpture. It is believed these cases are comparable because they have similar contexts; both are in a commercial environment and working on new product development. For case selection a theoretical replication approach was taken (Yin, 2003). The impact on the production process of differences in working environments, value systems and the nature of the products being fabricated can be investigated.

The two different systems are going to be analysed using the same model. In each case the production process for a composites product is going to be compared with the product innovation process learning cycle that is shown in Figure 2. This is to see where knowledge about forming material enters the product production process.

2.1.1 Manufacturing Tools

A latent observation from the shop floor of a composites production facility is the ubiquitous and unacknowledged role of personally manufactured tools in forming reinforcements. In their current form they are distinct to the composites industry. They demonstrate that despite having high performance application composites production is often a craft industry reliant on tacit knowledge (Bloom et al., 2013, Chatzimichali and Potter, 2013 and Elkington et al., 2013). It is assumed that the laminator's manufacturing tools are a physical representation of the laminator's tacit knowledge about forming reinforcements. The data used for analysis was collected during an initial exploration of their role (Jones at el., 2014). An experimental approach and semi-structured interviews with an expert laminator were used to capture the knowledge around their existence.

2.1.2 Art Fabricators

The second case is an art fabrication practice formed by two sculptors with an expertise in casting resin. Rather than prevalent codes of practice, they used their knowledge of handling materials to form the carbon reinforcements to fabricate the one-off sculpture. The data used for analysis was collected from two semi-structured interviews with both the art fabricators together over the time period of a month.

3 RESULTS

For each case mechanisms for or artifacts that represent knowledge generation have been identified and analysed using the two units shown in Figure 3. The phase in the product development learning cycle where this occurs has been highlighted (Figures 4 – 6). The data has been structured in this way as a starting point for this topic of research but the subjective nature of these figures is highlighted.

3.1 Manufacturing Tools

Tools used for a manual task are according to Baber (2003) "cognitive artifacts" that are an "extension of the body" becoming both "part of the person and part of the task" (Vygotsky, 1928). Their use in the composites industry is an excellent example of this (Jones et al., 2014). The tools do not exist on the manufacturing instruction sheets (MIS) nominally controlling the manufacture of components; in creating tools the laminators are reacting to this lack of detail. The necessity of forming reinforcements to a mould geometry that is beyond the capability of their hands is the trigger for creating the tools.

A lack of information on the MIS about how laminators should actually form reinforcements also suggests that the tools help structure the layup task (Jones et al., 2014). That there is a gap in knowledge is not widely recognised or resolved. It is proposed the laminators generate their own knowledge for exploitation.

The act of making these tools is an example of a laminator's tacit knowledge; the role of these tools in knowledge generation is represented on the graph in Figure 4. The vertical line represents the development of a learning curve.

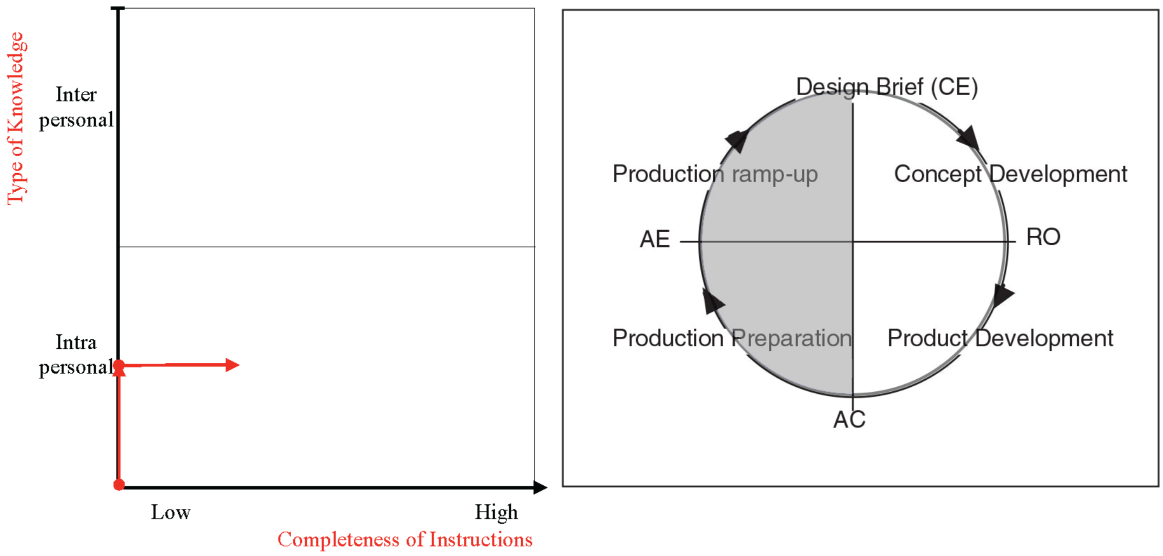

Figure 4. Manufacturing tools are a personal tool and increase the completeness of instructions. Where they exist in the process is highlighted in grey, showing an incomplete learning cycle.

The tools are not formally recognised in the design process as they *"are made for jobs"* on the shop floor. This means the learning cycle is not complete. The laminators' knowledge about how reinforcements can be handled is not entering back into the design process and concept development. Hence hindering the development of more complete MIS. In Figure 4 the grey area highlights this on the learning cycle.

3.2 Art Fabricators

The data from the semi-structured interviews was used to identify mechanisms for generating knowledge. Two different mechanisms were identified, material exploration and the introduction of an artist's concept.

3.2.1 Material Exploration

The following quote demonstrates that the knowledge acquired from material exploration is distinct from testing and therefore is its own mechanism for knowledge generation. *"When you experiment (test) for a job you are blinkered. Tests might go off at a tangent but these are not relevant. With experiments you are not so focused on a point, [it's a] more organic way of working. When you start experimenting you notice [...] how material takes on its own structure. The experimentation and playing around makes [the] decision-making process easier for jobs. Gives you knowledge to draw on."*

The art fabricators *"still make time to experiment and play"* with materials. The role of *"experiments [to] help them to prepare mentally"* suggests that material exploration is connected to concept development. This process generates knowledge transitioning concept and fabrication. Allowing them to think through more complete instructions. The experience of producing a tangible result facilitates discussion about the knowledge generation, meaning intra personal knowledge becomes inter personal. On the graph in Figure 5 the role of material exploration is represented with an arrow.

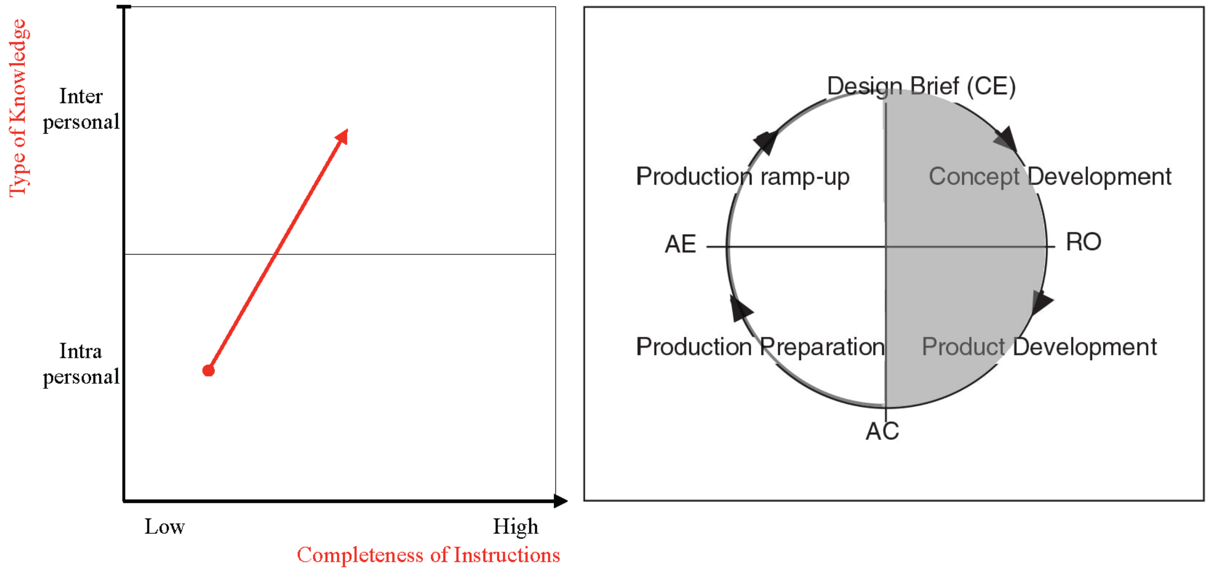

Figure 5. The role played by material exploration. The phases they exist at are highlighted in grey, showing the connection between material exploration and concept and product development.

The quotes *"playing is important, however picking up knowledge and knowing when to apply it is just as much a challenge and important. We are aiming to suggest things that are relevant and hopefully right for the job." And "researching materials, takes a lot of energy to play about with materials that is not funded. Idea that not just learning to accumulate knowledge, but how am I going to use it?"* connects concept and product development on the learning cycle (highlighted in grey on Figure 5). Suggesting there is a connection between material explorations and jobs. It also raises an important point about understanding how the art fabricators know when to exploit their knowledge.

3.2.2 Artist's Concept

The art fabricators role is to take an artist's concept from having no instructions on how it will materialise *"people don't know what they want"* to a plan, *"don't buy anything or do anything until we know what going to do or have a strategy for a project"*. The fact that they *"suggest and propose to make artists aware of the possibilities"* shows this process is not-linear and iterative conversation that is linked to concept development. For ease in Figure 6 the pathway has been represented in a linear format, as its exact route is not known. It has been suggested by Hall (2011) that there is a relationship between a non-linear and iterative way of working with a willingness and ability to probe existing boundaries, leading to a higher level of innovation.

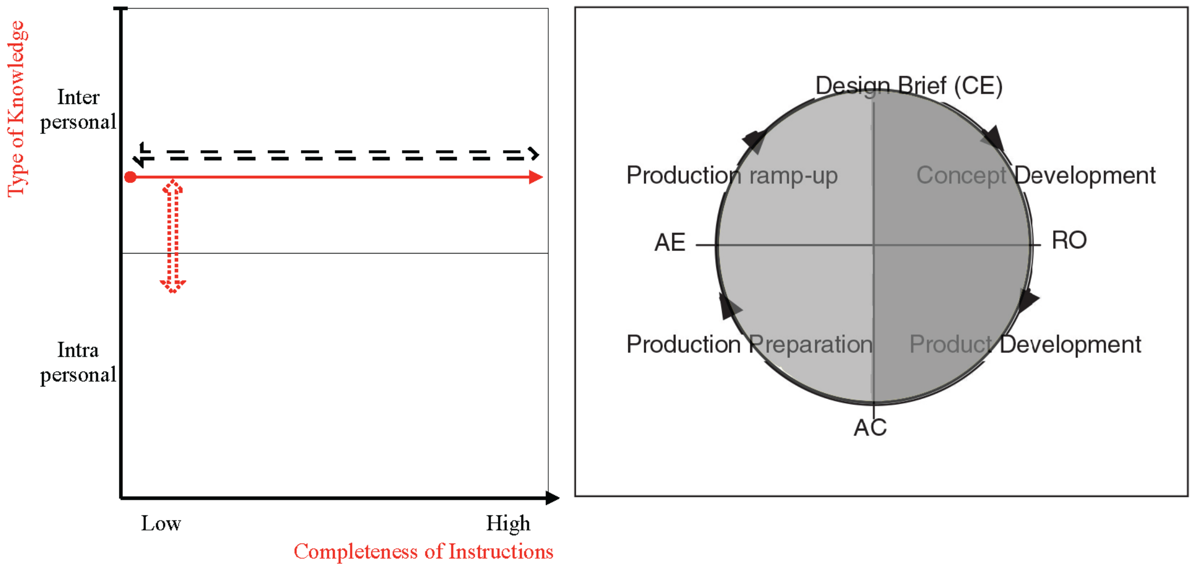

Figure 6. How a job progresses after the introduction of an artist's concept, at the design brief stage. The solid line represents the generation of fabrication instructions, the dashed line that it's an iterative process and the dotted line suggests possible movement between inter and intra personal knowledge. The darker grey highlight in the concept and product development phases shows the relationship between material exploration and delivering the job.

This quote demonstrates the interpersonal level of this conceptual and iterative development, *"thought experiments, **work backwards**, how do we get to what we want? Lots of different ways of doing it. Discuss different ways that could make it, between each other and an interaction with the artist".* The movement between an intra and inter personal way of working was not discovered; its potential is represented with a dotted line in Figure 6.

The introduction of an artist's concept is at the design brief stage. The art fabricators stated that *"extracting requirements is one of the main things that we do"* and *"making is just a small part [...] two way discussion between design and requirements.* They perceived that the artists *"don't understand the process by which it is going to be made so they have no idea of what is a realistic expectation rather "I am hoping it is going to look like this" [...] part of our job is understanding the expectations of the artist".* Using their knowledge from material experiments the fabricators expertise also lies in mediating between concept and product development. For the job where they worked with carbon reinforcements, the artist stipulated the material choice once they were aware that the fabricators were working with it. Whilst the art fabricators are not in control of material choice, a part of their job is to match requirements with material selection and this is not a possibility for laminators. For jobs the knowledge base from material experiments is exploited, represented by the darker highlight in the learning cycle (Figure 6).

Knowledge acquired from jobs *"may not be relevant to this project but another one"* demonstrates the fluid nature with which the art fabricators approach the application of their knowledge. This allows them to shuttle between production and concept development, and complete the learning cycle as shown by the lighter highlight on Figure 6.

4 DISCUSSION

4.1 Using Manufacturing Tools to Integrate a Laminator's In-process Knowledge into the Design Process

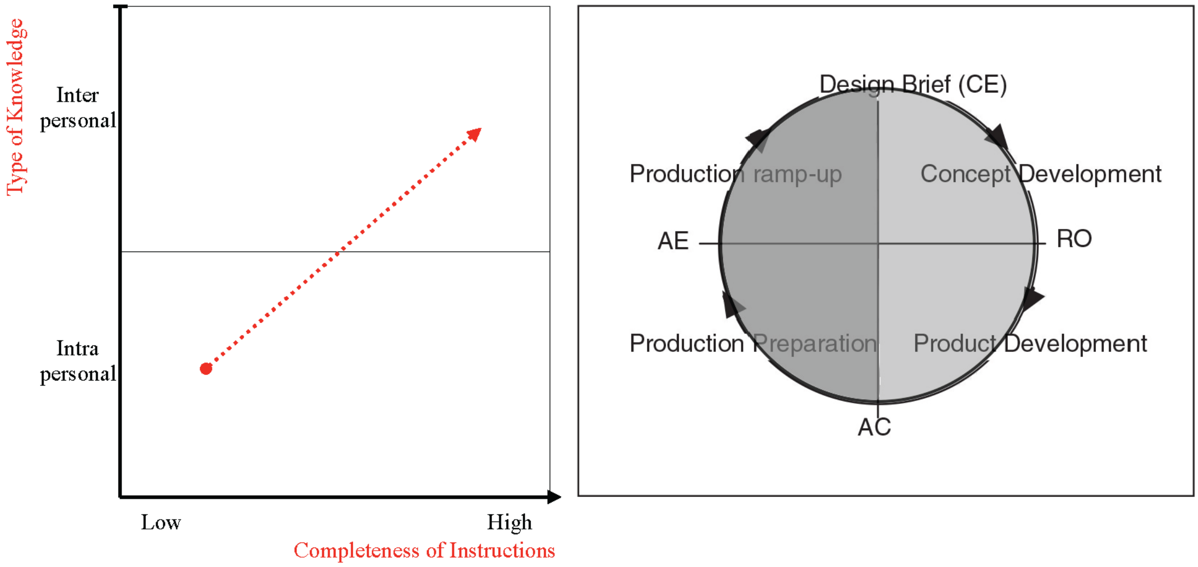

Figure 7. An intervention using manufacturing tools to complete the learning cycle and facilitate production efficiency. To achieve this the lighter highlights represents where they would have to intervene in the product innovation process; their current contribution is the darker highlight.

Production efficiency requires a laminator's knowledge to be elicited (Chatzimichali, 2013). Previous research by Kim (1993) and Rust et al. (2000) has stated the value of artifacts and tools to capture and subsequently transfer tacit knowledge. Moving the handheld tools across the intra-inter personal interface is a mechanism to elicit and transfer their knowledge. It can then be integrated into the design process for composite products. Formalising and standardising the currently personally manufactured tools underlines the general lack of detailed instructions for the layup task; and by providing a standardised way that the lay-up tasks can be implemented insists that the current shortcomings be addressed. The idea is to use the standardised dibber tool design to bridge design and manufacturing allowing design for manufacture through the application of a tangible product. Another aspect of composites manufacture where this approach is applicable is in vacuum bag design, which requires a separate study.

In Figure 7 the impact of displacing the manufacturing tools has been demonstrated. From their current position (dot) the pathway is shown in a dotted line, as the exact route is not known. To facilitate this displacement and complete the learning cycle it is suggested that the tools have to intervene at the product's concept development stage (the lighter highlight on the learning cycle in Figure 7). The outcome should be production efficiency for feedback loops in the learning cycle.

For the handheld tools to act as a knowledge transfer mechanism, the design of a tool has to be shifted forward to concept development. To be feasible this requires investigating the concept of geometry matching between a mould and a tool, so their engineering can be coupled at the design stage. This is currently the subject of future work, and it is not known what properties need to be considered. However a suggestion of required information is presented in Figure 8. Further work will be focused on defining the limits of the design freedom based off an experimental scoping of these properties. This approach provokes questions around a predictive tool being delivered and how knowledge can be used to inform use of this tool. It has been found before that selection is a process that requires more than analysis, challenging an over reliance on merely simulating it (Johnson and Ashby, 2002).

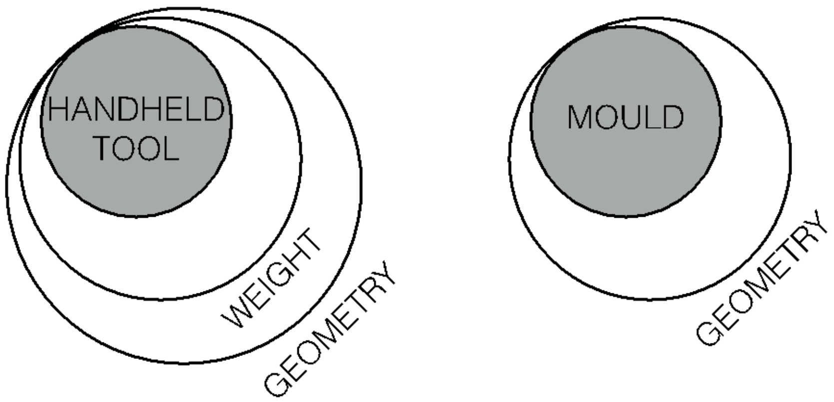

Figure 8. Exploring the concept of geometry matching between a mould and a tool requires investigating the displayed properties.

The results have represented pathways for knowledge generation. What influences these pathways needs to be better understood. This is a considerable new set of challenges because it involves both social (ways of working, value systems and cultures) and production structures (product value and volume). It is important to comprehend this set of requirements because it is anticipated integrating knowledge will result in challenging current behaviours and structures.

4.2 Using Material Exploration to Generate Knowledge for Conceptual Development

The art fabricators demonstrated the value of using material exploration to generate a collaborative knowledge base for concept development and complete learning cycles leading to production efficiency. It is believed that this material exploration does not exist in the majority of the composites industry. However examples of this can be found in a research context (Bloom et al., 2013). Possibilities for why this is the case could be differences in a product's functional requirements, educational backgrounds or a company's philosophy. It is also believed the artist's ability to live with risk whilst probing boundaries plays a part here.

This suggests during concept development channels and forms of communication that exist with the current industry structure need to be developed or challenged (Manzini, 1986 and Smulders et al., 2008). The question of how to introduce this collaborative and explorative way of working remains unclear but another mechanism to generate knowledge could lead to novel concepts (Hatchuel and Weil, 2003). As the industry is looking to grow it is surely worth considering alternative modes of materials investigation and the artist's as well as the engineer's concepts of "experimentation".

5 CONCLUSIONS

This work is an initial and unique attempt to investigate how in-process knowledge about handling materials is of relevance to design and production in the composites industry. The intention is to make suggestions that enable industry growth. In this initial study it has been shown that in a typical high performance product innovation process there is an incomplete learning cycle. For production efficiency integration of a laminators tacit knowledge into conceptual development is required. It is suggested that the handheld tools used for forming reinforcements could be used as the first of many knowledge transfer mechanisms. It has also been shown that material explorations play a role in realising a complete learning cycle. This has been attributed to both the generation of a knowledge base and a collaborative way of working. It has been suggested that different communication channels are required to nurture its value in an environment creating products with different functions. Future work is aimed at prototyping these suggestions to ensure they are viable solutions to the challenges faced by the composites industry.

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