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Harvesting tacit knowledge for composites workforce development

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"In baking, as in composites,
there are so many things that you can write in a book,
but there are many more that you learn by using your other senses"
Giuseppe Dell'Anno, 2022 [1].

Abstract
Explicit knowledge can often be shared through textbooks, technical papers, instruction manuals, guides, and videos. It is normally objective, logical and technical. However, tacit (implicit) knowledge is any information or skills that arise from personal and professional experiences. It is often subjective, cognitive and experiential. When an individual leaves an organisation, they can take intellectual property with them that could compromise future operations, unless that knowledge is harvested. This brief review considers how transient knowledge might be retained in an organisation.

Keywords: composites; manufacturing; tacit knowledge; workforce development

1 Introduction

In the early 1960s, there was an enormous push to accelerate technology development. United States (US) President John F Kennedy [2] pledged "we will go to the moon in this decade", while United Kingdom (UK) Prime Minister Harold Wilson [3] proposed that a new Britain would need to be forged in the *white heat* of scientific revolution. These initiatives prompted a significant increase in the employment of engineers, technologists and scientists over the following decades. However, after winning the 1979 General Election, Margaret Thatcher presided over changes that led to recession and rising unemployment with a long-term consequence for the technology industries (especially composites and nuclear engineering) of an ageing workforce. Those people who joined the sectors in the early days are now approaching or realising retirement. Their departure from the industry could lead to loss of tacit knowledge and in turn decelerate growth. Similar considerations apply where the workers move between employers.

The composites industry is challenged by a lack of standardisation and its foundations in, and reliance on, tacit experience [4]. Manufacturing development typically consists of process trials, development and simulation leading to knowledge and skills that will over time become tacit knowledge unless harvested from the individuals with that knowledge. Tacit knowledge locked in the heads of a few specialists, constrains innovation within a business. In 2014, Fabris and Poursatip [5] suggested that:

> "The current rate of knowledge transfer is not sufficient to sustain a vibrant composites industry. The growing disconnect between basic research and industrial practice and the prevailing magnitude of tacit composites manufacturing knowledge are two factors that impede effective knowledge transfer. Those focused on creating the fundamental knowledge often ignore or deprecate the application of that knowledge in practice. Equally, those focused on industrial practice fail to appreciate or are not aware of the fundamental knowledge that currently exists and has been commoditized into enabling tools".

Chatzimichali and Potter [6] highlighted the importance of knowledge transfer when developing a new technology, specifically in the composites industry. They stated that if new technology is integrated into a business without accompanying knowledge transfer, then the new technology will probably be treated as a 'black box' and hence not be used to its full potential:

> "Practices and rules developed very early in the history of composites, when the materials were new and untried, are still widely used across the breadth of composites applications despite the availability of new knowledge. This old mindset around composites is evident when we consider current production capability issues."

Leonard and Swap [7] predicted twenty years ago "… in the coming decade, because of demographic shifts, the so-called developed nations are about to face a large shortfall of leaders and managers": that prediction has been realised!

This paper considers the harvesting of tacit knowledge in the following sequence:

- §2 written knowledge, education and lifelong learning
- §3 current practice in harvesting tacit knowledge
- §4 harvesting tacit knowledge in the context of the composites sector
- §5 discussion
- §6 conclusions

2 Written knowledge

The Data, Information, Knowledge, (understanding), Wisdom (DIKW) pyramid represents each building block as a stepping-stone to a higher level [8]. Data is defined as an unorganised collection of results or facts. Information is data processed to remove errors then analysed to permit visualisation in categories or context: aggregation combines separate data sets, while validation ensures the data is accurate and relevant. Knowledge uncovers relationships and insights that are not explicit in the underlying information. Wisdom enables the knowledge and insights to inform proactive decision-making. Ackoff [8] makes a critical point: "*intelligence is the ability to increase efficiency; wisdom is the ability to increase effectiveness*". Critchley [9] suggests that "the gap between knowledge and wisdom is the very space of critical reflection".

Knowledge Management (KM) is the process for identification or creation / building, organisation / holding, mobilisation / sharing and application / using the knowledge base of an organisation. A key enabler of the process is ease of access to the compiled information. An optimised system should not only record what did work, but also should document where successful outcomes were not achieved especially if insights from the initial attempt(s) might inform alternative routes to success in the future. The *Journal of Trial & Error* aims to make public the lessons learnt from struggles in research. ISO30401:2018 [10] "sets requirements and provides guidelines for establishing, implementing, maintaining, reviewing and improving an effective management system for knowledge management in organizations".

Knowledge auditing and mapping [11-13], which might include directories of experts and inventories of equipment, can discover previously unknown relationships and gaps and facilitate interpersonal knowledge transfer. Nousala et al [14] saw a need for people to quickly identify the expert with the knowledge they need and to have confidence that this knowledge will be transferred to them. "Know-Who" is knowledge once removed [7].

Hansen et al [15] considered a situation where technicians were to be replaced by an 'expert system' guidance interface. The change failed because the system did not "capture the nuance and detail of face-to-face conversations".

Ghairi and Awad [16] considered that "the greatest factor in knowledge management is the sharing of tacit knowledge" and complain that work in this field often focusses only on content, rather than how best to communicate the material.

2.1 Education

Across the UK there are five stages of education: early years, primary, secondary, Further Education (FE) and Higher Education (HE). The latter two "tertiary" stages are not compulsory. FE is usually taught in Sixth-form, Further Education Colleges, adult- and community-learning institutions or by work-based learning. HE is normally taught in universities and can lead to Certificate of Higher Education (1 year FTE), Diploma of Higher Education (2 years FTE) or most often a degree (at least 3 years FTE). Students may stay on to achieve a postgraduate masters or doctorate qualification.

The HEFCE Catalyst Composites Curriculum Development project [17] sought to generate an industrially relevant and academically rigorous curriculum which could be deployed to tackle the significant skills gap in composites professionals. This was seen as vital for delivery of the UK National Composite Strategy to enable the industry to grow to the full potential forecast by the Composites Leadership Forum [18]. A Masters-level curriculum of short, industrially focused units was specified and a small number of trial units were developed.

2.2 Life-long Learning

Lifelong learning is the pursuit of additional education and the development of further skills beyond compulsory or formal education. When the learning is accredited, it is often referred to as Continuing Professional Development (CPD). CPD is a normal requirement for the maintenance of Charter status (*e.g.,* Chartered Engineer or Chartered Scientist).

The Perkins report [19] endorsed the idea that an increased supply of engineers would benefit the economy and that government, professional bodies and employers each have a role to play in realising that target. One recommendation was that adults should have "the opportunity to learn the latest techniques and approaches while learning in a vocational setting". The UK Government 2021 White Paper on Skills for Jobs [20] sought to deliver the equivalent of four years of post-18 education through a Lifelong Learning Entitlement to ensure everyone has access to education and training that will land them a "great job".

3 Tacit knowledge

Tacit means understood or implied without being stated. Synonyms include implicit, inferred, interpreted, presumed, unexpressed, unspoken, or unvoiced. Tacit knowledge might include skills, experience, insight and judgement. Knowledge Harvesting (KH) is an integrated set of processes that permit the hidden insight of human expertise to be captured in a form that can be used by others. The challenges of KH are to identify where the tacit knowledge lies, to harvest the knowledge, and to create a format where it is easily transferred to those who need to know.

The concept of 'tacit knowledge' was introduced by Polanyi [21] in the book Personal Knowledge: Towards a Post-Critical Philosophy, where he suggested there was some knowledge that we could not articulate. Examples of tacit knowledge might include actions, behaviours, habits, instincts, intuitions, responses and routines. Dayasindhu [22] suggested a key issue is the problem of identifying the precise original tacit knowledge which should be transferred.

Leonard and Swap [7], citing Simon and Chase [23], suggested that "Most evidence suggests that it takes ten years of concentrated study and practice to become an expert (as opposed to merely competent)". They [7] further commented that "No amount of reading can substitute for building up the tacit dimensions of knowledge" and "What we think of as intuition is really swift pattern recognition, based on experience".

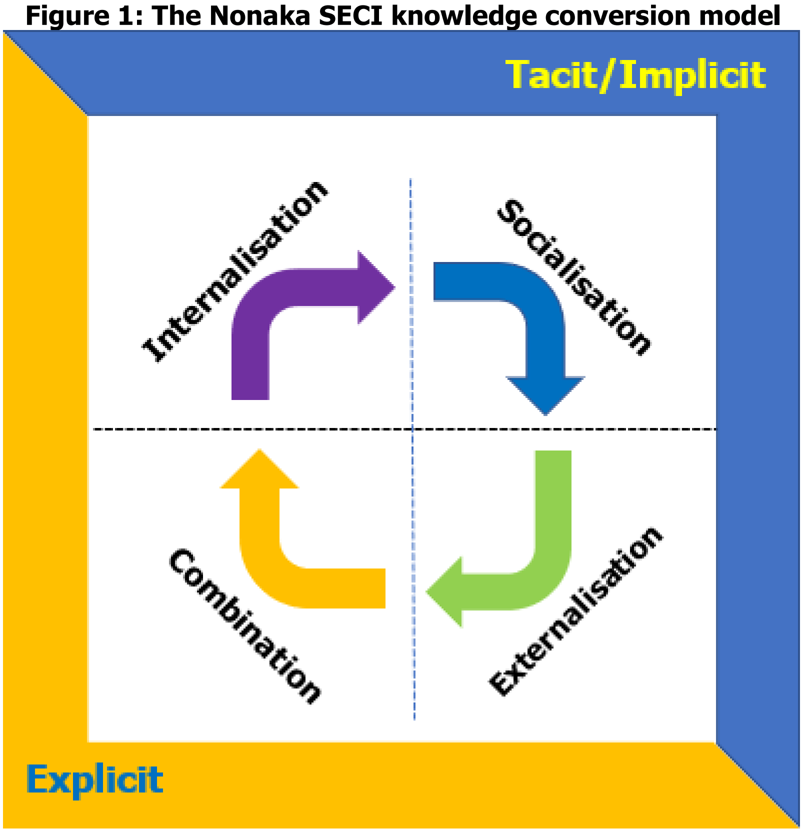
Foos et al [24] studied the factors influencing transfer of tacit knowledge between two partners in product development. They found that tacit knowledge transfer, content and process were "poorly understood". Three factors were identified that influenced the achievement of technology and tacit knowledge transfer expectations: trust, early involvement, and due diligence. Mahoney and Williams [25] identify that motivational barriers to knowledge transfer include resistance to change, turf protection, lack of economic incentives and interdivisional jealousy.

Szulanski [26] identified that further barriers to knowledge exchange included the underlying gap between the source and recipient, and the recipients lacking the experience to make effective use of the new ideas. Essential characteristics needed in the source are motivation and credibility. Davenport and Prusak [11] suggest that a person will only invest in the delivery of knowledge when there is something to be gained in return. That reciprocation may be as simple as the informed person asking questions that prompt new insights.

Bhagat et al [27] suggest that cultural context impacts patterns of knowledge transfer. They highlight the seminal importance of individualism versus collectivism, especially where they occur in combination with vertical and horizontal divisions.

The SECI (socialisation – externalisation – combination - internalisation) loop model (Figure 1) is the most common conceptual framework for understanding knowledge generation processes in organisations. Tacit knowledge is exchanged through shared experience [28, 29]. The knowledge is externalised as explicit concepts, images and written documents. The explicit data is then combined to become complex and systematic knowledge and then absorbed (internalised) by individuals as new tacit knowledge.

Figure 1: The Nonaka SECI knowledge conversion model



Nonaka and Konno [30] developed the Japanese concept of *ba* as a shared mental, physical and virtual space where knowledge is generated and shared. Individuals acquire tacit knowledge through their own experience or reflections on the experiences of other people. The four stages of *ba* map onto the SECI model: originating (socialisation), interacting (externalisation), cyber (combination) and exercising (internalisation).

Polanyi [21] and Leonard and Swap [7] recognised that the tacit knowledge within an organisation was embodied as experiences, skills and attitudes in the workforce (referred to as "deep smarts"). Leonard and Swap [7] created a scale for measuring the cultivation (stickiness) of knowledge transfer where high cultivation transfers rich knowledge (Figure 2).

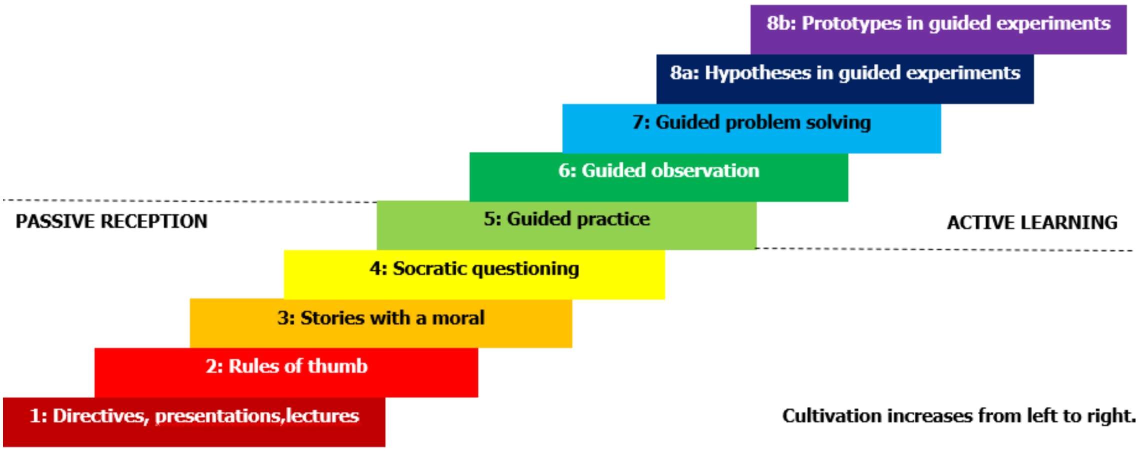


Figure 2: Scale for measuring the cultivation (stickiness) of knowledge transfer where high cultivation transfers rich knowledge, based on [7].

3.1 Dissemination

A number of organisations have published Good Practice Guides to disseminate best practice. The social media platforms are a repository of blogs and videos which document current practice. However, in the absence of moderation it is not trivial to separate best from bad practice.

3.2 An inclusive knowledge-sharing culture

An effective way to capture tacit knowledge is to share insights from current employees. Shared knowledge promotes team working and creates benefit for all stakeholders. Managers seeking to cut costs and boost productivity should try to harvest workers' subtle shortcuts and other tacit innovations but can be frustrated by the workers resistance to reveal their accumulated expertise [31].

Questions form a basis for connection, understanding and creativity. If you ask a question of one person, then you might get an appropriate answer. If you ask a question of ten people, then one of them may have the answer you really need. Sagan [32] said "There are naïve questions, tedious questions, ill-phrased questions, questions put after inadequate self-criticism. But every question is a cry to understand the world. There is no such thing as a dumb question".

Scott [33] describes the initial concept of a knowledge network as a 'sociogram', a map of social connections between individuals. A popular person, in sociometric concepts, is referred to as a 'star' due to the inward links surrounding them from admirers who aspire to be their friend. Networks may be an integrated community or sparse connections between separate cliques [33, 34]. Modularity is a measurement of the density of links inside cliques to links beyond the isolated silos (clique). Work done in cliques can result in duplication of effort. Blondel et al [34] used an iterative process to first identify nodes, then cliques, to develop high modularity partitions of networks.

3.3 Mentoring

In Homer's Odyssey, Mentor was a companion of Odysseus' son, Telemachus. Mentor guided and advised the son while remote from his home and family. Senior staff should become mentors to grow the skills, inform better decision making and create new perspectives on the life and career of their mentee(s). The mentor should leverage their experience to direct the career of the mentee for current and future life.

The full range of experiences a mentee wishes to develop may not be available from a single individual. One option is to set up a "composite mentor" using a few people who each embody one of the required broader skill-set characteristics. This use of "composite" with a parallel meaning has massively multiplied the number of hits when searching online!

3.4 Hands-on practical experience

The Master-Apprentice model is a long tradition (around eight centuries) when a youth would be taken into tutelage by a master craftsman or tradesman. The apprenticeship is normally associated with practical skills and trades but can be adapted for other situations.

An apprenticeship is employment where skills are developed by working alongside experienced staff. It is normally undertaken by individuals with better manual dexterity than theoretical capability at an early stage in their career. It provides substantial underpinning for career advancement which might lead to higher qualifications in due course.

Senge [35] observes that if an individual does not encounter the consequences of their decisions, they cannot learn from that experience.

3.5 Exit Interviews (EI)

Skilled and/or knowledgeable employees are the asset that generates success within an organisation. Knowledge loss on voluntary or involuntary employee exit has become a significant corporate risk. It is natural for ageing employees to take retirement, but where other staff leave early they should be interviewed to understand their reasons, especially where there might be an underlying systemic problem. The outcomes of an EI depend on the honesty and frankness of the departing employee. The departing employee should be free to follow their exit decision but should be encouraged to reveal tacit knowledge to enable a smooth transition into the role by the next incumbent.

Hendra and Allianto [36] used Knowledge Continuity Management (KCM) to define essential goal indicators for organisational strategy and operation. Four critical knowledge areas were identified to structure interviews: (i) operating data knowledge, (ii) key operational knowledge, (iii) basic operational knowledge, and (iv) background operational knowledge. Implementation of the KCM required development of a clear framework, identification and acquisition of both tacit and explicit knowledge, and transfer of acquired knowledge to other staff.

Massingham [37] set out to explore how to measure the impact of knowledge loss with a single case study in a public sector organisation using a critical realism paradigm. The negative consequences of knowledge loss were (i) low morale impacting productivity, (ii) capability gaps leading to strategic misalignment of the workforce, (iii) stakeholders unhappy with performance after resource cuts, (iv) inexperienced employees causing decreased work quantity and quality, (v) customers mistrust due to outputs not being used, (vi) learning costs leading to longer time to competence, and (vii) increased search cycle time slowing task completion. A lower impact was an increased sense of, and declining capacity to manage, risk associated with work activities. The lowest significant impact was knowledge loss that may never be filled over time. On a positive note, psychological contract and learning organisational capacity improved with appropriate knowledge management.

3.6 Simulation

Leonard and Swap [7] suggest that "simulations can help develop certain skills more efficiently than real experiences" and that "Simulation can effectively augment personal, direct experience with the real world. Simulations help develop receptors for new knowledge, build skills, and enable learners to practice with rare events, thus building an experience repertoire in a cost-effective, purposeful way. Simulation allows a learner to fail in an environment where there are no real consequences".

3.7 Artificial Intelligence (AI)

Artificial Intelligence (AI) may be defined as the use of computer systems to simulate intelligent human processes. The range of AI includes Expert Systems (ES), Machine Learning (ML), Machine Vision (MV), Natural Language Processing (NLP), Pattern Recognition (PR) and Speech Recognition (SP). Deep Learning (DL) is a subset of machine learning that uses artificial neural networks (ANN) to mimic the learning processes of the human brain.

ML enables engineers to create software (applications) that can draw conclusions similar to those derived from subsets of human tacit knowledge. Currently ML generates reliable shortcuts (empirical relationships) from big data that would be impractical for a human to independently analyse. ML does not yet incorporate the human cognitive powers (feelings or sense) that go beyond the analysed data subset.

Vocational training transmitted between teacher and student includes elements of unspecifiable tacit knowledge. That tacit knowledge will probably remain the preserve of human beings throughout the short- to medium-term future, but giving AI control of systems raises potential hopes and broader fears for the future of humankind. Rogan and Haselby [38] speculate that AI "will never assimilate tacit knowledge [so] humans must remain central to these systems, refining and extending the capabilities of AI systems" and that "robots that can range like humans across diverse tasks, wielding contextual nous enough to know which capability to deploy, remain the stuff of science fiction".

An AI management system standard, ISO/IEC 42001 [39], is due for publication soon. It mirrors ISO9001 for quality management [40], ISO 14001 for environmental management [41], ISO27001 for information security management [42] and ISO45001 for occupational health and safety management [43]. The standard will facilitate conformity assessment and certification to increase trust in the complex AI supply chain. Additional ISO documents address AI bias [44], governance [45], risk management [46], robustness [47], societal and ethical concerns [48], testing [49] and trustworthiness [50].

4 Tacit knowledge for composites

The state-of-the-art for approaches to harvesting tacit knowledge have been reviewed in §3. This section will look at cases where those approaches have been applied to the composites sector.

4.1 Dissemination

Fabris et al [51] examined the transfer of university-based composites manufacturing science research and development (R&D) to small- and medium-sized enterprises (SME). They studied the technological and market uncertainties encountered by the companies during the commercialisation process, and how the uncertainties could be effectively managed. The study emphasised the importance of having a knowledge-based ecosystem in an industry dominated by tacit knowledge and the lack of standardisation.

Budwal et al [52] presented an outline route-map for a knowledge-based tool to assist textile fibre-reinforced composite product design. Various defects/variations inform knowledge capture which is then mapped to materials selection, process selection, tooling design or manufacture. An example is the mapping of defects/variations to knowledge capture then to design or manufacture in Budwal [53: Figure 7-19].

Best Practice Guides (BPG) or Good Practice Guides (GPG) compile the methods and evidence on a specific activity to guide future actions (selected list at Table 1). In the UK, Composites

UK (CUK), National Composites Network (NCN) and National Physical Laboratory (NPL) with others have published guides.

Table 1 Selected Best Practice Guides (BPG) or Good Practice Guides (GPG)

Source	Year	Ref.	Topic
NPL	2007	[54]	Absorption and diffusion of moisture in polymeric materials
Energy Institute	2021	[55]	Composite repairs
NPL	2005	[56]	Cure monitoring techniques for polymer composites, adhesives and coatings
NPL	2012	[57]	Deformation and damage in fibre-reinforced plastics
NCN	~~	[58]	Design tools for fibre reinforced polymer structures
SAMPE/BTG	~~	[59]	Design with composites
NPL	2021	[60]	Fatigue data for fibre-reinforced plastics
CUK	2019	[61]	Fire performance of fibre-reinforced polymer composites
CIRIA	2018	[62]	FRP Bridges - guidance for designers
CUK	2020	[63]	Joining of fibre-reinforced composites
NPL	2002	[64]	Machining of composites and specimen preparation
NPL	2021	[65]	Mechanical characterisations of 3D fibre-reinforced plastic composites
CUK/NCN	2023	[66]	Mould tooling for fibre-reinforced polymer composites.
NCN	~~	[67]	Non-Destructive Testing (NDT) of composite materials
BINDT	2015	[68]	Non-Destructive Testing (NDT) Guidance Document: an introduction to NDT common methods supported by lead employer document: AA050 Issue 2
Potter	2009	[69]	Origins of defects and variability in composites manufacture
NPL	2003	[70]	Qualification of composite materials
NCN	~~	[71]	Repair of fibre reinforced polymer structures
NPL	1998	[72]	Residual stress in polymeric mouldings
CUK	2022	[73]	Sustainability of Fibre Reinforced Plastics
Adams	2011	[74]	Tensile testing composites
NPL	2000	[75]	Thermal analysis techniques for composites and adhesives

Table 2: UBC Knowledge in Practice Center (KPC) resources [77]

Volume	Contents
A1	KPC home page
A2	Introduction to composites: the fundamentals of composite materials, and the systems approach to the design and manufacturing of composite materials
A3	Foundational knowledge: documents covering the governing science of composite materials design and manufacturing
A4	Systems knowledge: a science-based, systems level approach to tackle composite manufacturing problems
A5	Systems catalogue: the physical assets required in the manufacturing of composite parts
A6	Practice: guidance and step-by-step workflows on composite materials design and manufacturing
A7	Case studies: industrial projects performed by the Composites Research Network (CRN) and its academic and industry partners
A8	Perspectives: multimedia content and linking learning from the other volumes

The Composites Knowledge Network (CKN) Centre "empowers Canadian businesses with the knowledge they need to succeed" [76]. This network is federally funded by the Canadian Networks of Centres of Excellence (NCE) as a national not-for-profit organization hosted at The University of British Columbia (UBC). CKN connects industry with leading-edge technology through the Knowledge in Practice Centre (KPC) and Application + Impact (AIM) webinars and events. KPC is a resource for learning and applying scientific knowledge to the practice of composites manufacturing [77]. The KPC is an excellent selection of resources "for learning and applying scientific knowledge to the practice of composites manufacturing" (Table 2).

4.2 An inclusive knowledge-sharing culture

Pickard [78] used knowledge network diagrams to map who people within organisations contact for knowledge: who they go to with questions (asking/pull) or learn from (teaching/push). The diagrams have nodes (a person) connected by coloured lines where line thickness indicates the strength of the knowledge transfer. The plots (sociograms) indicate the robustness of knowledge transfer within the organisation. A complementary competence matrix was used as a sanity check on people's self-rating. Her analysis identified key individuals and potential breaks in the analysed network.

4.3 Mentoring

The UK National Composites Centre (NCC) in collaboration with the Composites UK (CUK) trade body ran a pilot mentoring scheme for small- to medium-sized enterprises (SME) in 2014 [79]. The pilot scheme sought both mentors and mentees in four topic areas to introduce the mentees to the world of composites: (i) health and safety, (ii) environment, (iii) technical and (iv) business improvement and innovation. All mentors were supported through the Institute of Enterprise and Entrepreneurs' certificated 'Introduction to Enterprise Mentoring' workshop. The NCC SME Affiliate Scheme provides technology breakfast meetings, hot desking, training and networking opportunities for SME [80].

UK Defence and Security Accelerator (DASA) introduced an Access to Mentoring and Finance (A2MF) scheme to provide the support and funding needed to take ideas to the next level [81]. The goal was to help companies become investment, market and supply chain ready.

The UK National Physical Laboratory (NPL) report "Increasing UK competitiveness by enhancing the composite materials regulatory infrastructure" produced in consultation with industry, was based on a cross-sector workshop organised on behalf of the Composites Leadership Forum (CLF) and on a review of relevant studies [82]. The recommendations sought to unlock the current regulatory barriers and increase the use of composite materials across the advanced manufacturing sector. The recommendations in the report included (a) acceleration of standardisation and publication of technical documentation to address identified gaps in the regulatory infrastructure, (b) design and implementation of a *digital tool and mentoring scheme* to help industry adopt and certify novel materials, and (c) the creation of an advanced materials assurance centre to integrate the materials supply chain and regulators as a central resource for access to trusted materials data.

The Wave-based Inspection for Damage Evaluation in structurally-Advanced composites (WIDEA: Horizon 2020 grant agreement 797034) project [83] generated a new wave-based structural health monitoring (SHM) system for the next generation of lightweight components. The academic profile and scientific experience of the researchers were enhanced by undertaking the research with two high-ranking representatives of their fields, alongside formal training and mentoring to provide "an outstanding content expertise in wave-based methods, structural health monitoring and modelling of lightweight composites".

The US Women in the Composites Industry network helps to "develop and improve skill sets, stay on top of the latest industry trends, keep a pulse on the job market, meet prospective mentors, partners, and clients, and gain access to the necessary resources to foster career development" [84].

National Composites Centre (NCC) in collaboration with Mentor Digital developed an innovative e-learning solution with the Umbraco Content Management System (CMS) as a base, and they won the 2021 Umbraco 'Best Custom Solution' award for extension to a bespoke, modern and professional, engaging and interactive e-learning platform [85].

4.4 Hands-on practical experience

Jones et al [86] explored how knowledge generated during the fabrication of advanced composite components could be integrated into design and production to facilitate industry growth. They used a case study approach to map the learning cycle during product innovation with an assumption that a complete learning cycle would lead to production efficiency. Integration of the laminators' tacit knowledge into concept development is required for production efficiency.

Jones et al [87, 88] observed that laminators used handmade and personally owned tools on the production shop floor to get the reinforcement fabrics to conform to the mould tool. The combined aspects of various individually-created tools were integrated to design "The Dibber".

The earlier work on material conformation and composite manufacture has been leveraged to provide an interactive, digital learning program, LayupRITE [89], delivered using Augmented Reality (AR). The system aims to (i) train laminators effectively and repeatably, (ii) teach the underlying skills and knowledge of layup, (iii) provide a record of the training done, and (iv) increase the rate at which laminators can be trained.

Accurate ply placement is essential in the manufacture of high-cost, high-performance composite components. Templates or specialised support systems are integral to monitoring ply sequence and orientation for quality assurance. Blake [90] reviewed the use of laser guidance for positioning of each lamina of a composite. Such et al [91] developed an optical projection system to display a predetermined and unambiguous instruction set close to the area of lamination, and claimed the system presents better information than laser alignment systems. The PlyMatch (Ply Placement Visual Control System) [92] displays a live video screen image of the operator interacting with the composite ply assembly overlaid with a computer-generated image of the structure to assist alignment of the reinforcement.

Gandhi et al [93] sought to develop a detailed high-fidelity knowledge base to map material, component and defect configurations to the capability and limitations of three non-destructive testing (NDT) detection methods (ultrasonics, thermography and shearography) for composite material products. Tacit knowledge was captured in a capability matrix to provide NDT operators/engineers with explicit, validated applicability data to inform the selection of appropriate test methods.

Hoskins [94], considering 3D printing for artists, designers and makers, found that adoption of new technology can create work dictated and limited by the simple constraints of the process, and is not simply a matter of detailing scientific or engineering advances. Case studies of leading designer makers show skill and technical expertise that reveal the "spread and problems of the technology over a number of diverse disciplines".

Recognition of specific textile reinforcement styles normally requires a trained human eye. Piasecki and Summerscales [95] presented a novel system that might be implemented within a composites manufacturing quality system to ensure use of the correct fabric. Images were acquired using a high-resolution scanner, converted into binary, then analysed using ImageJ/FracLac software [96, 97] and quantified as a single real number: the Fractal Dimension (FD). The system returned a distinct FD value for each of three carbon fibre reinforcement fabrics (300 gsm plain weave, 320 gsm single-tow twill and 375 gsm double-tow twill) in the undeformed condition and when sheared up to 30° (the locking angle).

4.5 Exit Interviews (EI)

The CKN at UBC [98] interviewed Professor Emeritus Kevin Potter at the University of Bristol about his experiences and perspectives on manufacturing with composite materials. The interview is online albeit subject to sign-up or log-in.

4.6 Simulation

The University of Plymouth teaches a unique undergraduate course with a significant composites element (40 of 120 credits at Stage 4, plus an honours project). In Semester One, students have a course on design and manufacture of monolithic composite materials. In Semester Two, the students (a) choose a component, (b) create a product design specification, (c) generate a design, (d) manufacture a mould tool, (e) manufacture the prototype, and (f) test against the original specification. The component may be a composite structure (laminate or sandwich), so laminate analysis and finite element modelling are developed in parallel with the work. The practical work increases the personal skill set. The honours-level marks from the assignment relate to the extent of critical thinking around the design and manufacture. Course staff take the role of the customer for the studied component and undertake regular reviews of the progress of the project. Access to the "expert" staff can often provide short-cuts to appropriate routes forward through interrogation of the staff tacit knowledge.

4.7 Artificial Intelligence (AI) in the composites context

The role which AI has taken so far in the context of DIKW for fibre-reinforced composite materials has been the conversion of Data into Information. The development of Knowledge may be some ten years in the future, and AI fully realising Wisdom may be a quarter of a century away. Fore-sighting at this level is rarely accurate!

The use of AI for fibre composites has been reviewed by Pattnaik et al [99], Qiu and Yang [100], Nelon et al [101] and Cassola et al [102]. AI in the context of composites can potentially analyse a broad range of text (and other sources) and provide guidance on (a) where common approaches have been adopted by the sector and a general consensus has emerged, and (b) potential new directions for optimisation of products and processes. The implementation of AI is developing rapidly and work reported so far for composites includes:

- predictions of the macroscopic stiffness and yield strength of a unidirectional composite loaded in the transverse plane [103].
- a case study on autoclave cure processes for carbon epoxy prepreg [104]
- an *a priori* algorithm for the prediction of properties of natural fibre composites [105].
- prediction of stress field maps for composite cross-sections with a fixed number of fibres and varying spatial configurations [106].
- modelling of stress concentrations in unidirectional fibre composites [107].
- characterisation of glass fibre epoxy or biocomposites based on fibre optic sensor acoustic emission signals [108].
- a gene expression predictive model for creep behaviour of composite materials [109].

5 Discussion

This review was conducted to establish how tacit knowledge might be harvested for the benefit of the composites community. In the absence of personal engagement with the techniques (Table 3), speculation on the potential advantages/disadvantages of the different knowledge transfer methods listed in §3 and §4 may bias how the ideas might be applied. Such insight is expected to arise sooner by sharing, rather than withholding, these ideas as so little work has been done to date.

Table 3: Some advantages and disadvantages of potential routes to harvesting tacit knowledge.

Technique	Advantage	Disadvantage
Dissemination	Ready availability of texts, videos, etc. Self-paced learning.	Errors in the resource. Quality of resources. Availability of formats for disabled users.
Knowledge sharing culture	Access to the expert. Ability to directly question. Pre-empts exit interview knowledge transfer.	Working hours only. Conscious and unconscious bias.
Mentoring	Access to the expert. Ability to directly question. Aligns mentee to company culture. A resource for the mentee. Pre-empts exit interview knowledge transfer.	Working hours only. Conscious and unconscious bias. Personality clashes. Overloaded/frustrated mentor.
Hands on experience	Holistic experience. Build motor skills.	Working hours only. Broad risk assessment needed. Over-simplified examples. Over casual supervision.
Exit interviews	Retention of knowledge that would otherwise escape. Insight into distress, concern and discontent within the company without fear of reprisal.	Time limited by retirement. Tensions around reasons for departure. Time-expired information received too late. Managers afraid of receiving feedback.
Simulation	Ability to directly question during hands-on simulation. Insight into relevant variables. 24/7 implementation of computer simulation.	Task specific. Constrained by rules used for model creation. Computer simulation may encourage higher risk activity.
Artificial intelligence	24/7 implementation. Handles massive data sets. Faster decisions.	Implementation and running costs. Server energy consumption and consequent environmental impacts. Need to understand underlying assumptions. Limitations of the training dataset. Currently limited innovation and creativity. Compassion and kindness cannot be programmed.

6 Conclusion

Tacit knowledge is often understood or implied without being stated. Personnel in the composites industry acquire tacit knowledge over the duration of their careers and may compromise a company if they depart without passing the knowledge to the next generation. This review has considered how the knowledge transfer might be achieved to ensure continuous workforce development. Successful implementation of these ideas should permit the sector to prosper. The composites community should seek to implement the ideas as appropriate to each specific context, and disseminate their successes, and failures, as formal publications or best practice guides.

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References

1. Dell'Anno G. Making cakes and composites, Meet the Maker podcast episode at 24:19-24:30, September 2022.
2. Kennedy JF. Address at Rice University on the nation's space effort, accessed 16 February 2024.
3. Johnston G. Harold Wilson's 1963 pledge to harness the white heat of a scientific revolution H Wilson, British Library Sound and Vison Blog, 02 October 2023, accessed 16 February 2024.
4. Stojkovic M, Butt J. Industry 4.0 implementation framework for the composite manufacturing industry, Journal of Composites Science 2022;6(9):258.
5. Fabris J, Poursatip A. Knowledge in Practice: the next step in reducing risk in composites manufacturing and design, Proceedings of the 10th Joint Canada-Japan Workshop on Composites, Vancouver ~ Canada, August 2014. Design, Manufacture and Applications of Composites 2014, DEStech Publications, 2015. ISBN 978-1-60595-169-0.
6. Chatzimichali AP, Potter K. Building material capabilities: a socio-technical analysis of composite product development and manufacturing strategy, International Journal of Markets and Business Systems 2015;1(3):196-216.
7. Leonard D, Swap W. Deep smarts: How to cultivate and transfer enduring business wisdom, Harvard Business School Press, 2005. ISBN 978-1-59139528-7.
8. Ackoff RL. From data to wisdom, Journal of Applied Systems Analysis 1989;16:3-9.
9. Critchley S. Continental Philosophy,: a very short introduction, Oxford University Press, Oxford, 2001. ISBN 978-0-19-285359-2.
10. Anon., ISO 30401:2018 Knowledge management systems – Requirements, International Organization for Standardization, Geneva ~ Switzerland, 2018. ISBN 978-0-539-12673-0.

11. Davenport TH, Prusak L. Working Knowledge: how organizations manage what they know, Harvard Business School Press, 1998. ISBN 978-1-578-51301-7.
12. Barnard Y, Rothe A, Knowledge Management in engineering: supporting analysis and design processes in innovative industries, in Cunningham P, Cunningham M, Fatelnig P (editors), Building the Knowledge Economy: issues, applications, case studies, IOS Press, Amsterdam, 2003, p.931-938. ISBN 978-1-58603-379-8.
13. Burnett S, Williams D, Grinnall A. The strategic role of knowledge auditing and mapping: an organisational case study, Knowledge and Process Management: The Journal of Corporate Transformation 2013;20(3):161-176.
14. Nousala S, Miles A, Kilpatrick B, Hall WP. Building knowledge sharing communities using team expertise access maps, International Journal of Business and Systems Research 2009:3(3):279-296.
15. Hansen MT, Nohria N, Tierney TJ. What's your strategy for managing knowledge?, Harvard Business Review 1999;72(2):106-116.
16. Ghaziri H, Awad E. Is there a future for knowledge management?, Journal of Information Technology Management 2005;XVI(1):31-38.
17. Pickard LR, Potter K, Summerscales J, Graham-Jones J, Taylor A, Rusnáková S, Wisnom M. Composites Curriculum Development: tackling the skills gap in UK advanced composites, University of Bristol and University of Plymouth, 31 August 2019.
18. Anon., Lightening the Load: the 2016 UK Composites Strategy, Composites Leadership Forum /Composites UK, Hemel Hempstead ~ United Kingdom, 2016.
19. Perkins J. Review of Engineering Skills, URN BIS/13/1269, Department for Business Innovation and Skills, London, November 2013.
20. Skills for jobs: lifelong learning for opportunity and growth, Department for Education policy paper CP338, January 2021. ISBN 978-1-5286-2347-6.
21. Polanyi M. Personal Knowledge: towards a post-critical philosophy, First edition, The University of Chicago Press, Chicago and Routledge and Kegan Paul, London, 1958. Second edition, University of Chicago Press, 2015. ISBN 978-0-226-23262-1.
22. Dayasindhu N. Embeddedness, knowledge transfer, industry clusters and global competitiveness: a case study of the Indian software industry, Technovation 2002;22(9):551-560.
23. Simon HA, Chase WG. Skill in chess, American Scientist 1973;61(4):394-403.
24. Foos T, Schum G, Rothenberg S., Tacit knowledge transfer and the knowledge disconnect, Journal of Knowledge Management 2006;10(1):6-18.
25. Mahoney JT, Williams C. Reviewed Work: Sticky Knowledge: Barriers to Knowing in the Firm by Gabriel Szulanski, The Academy of Management Review 2003:28(4):679-681.
26. Szulanski G. Sticky Knowledge: barriers to knowing in the firm, Sage Publications, December 2002. ISBN: 978-0-76196-143-7.
27. Bhagat RS, Kedia BL, Harveston PD, Triandis HC. Cultural variations in the cross-border transfer of organizational knowledge: an integrative framework, Academy of Management Review 2002;27(2):204-221.
28. Nonaka I. A dynamic theory of organizational knowledge creation, Organization Science 1994;5(1):14-37.
29. Farnese ML, Barbieri B, Chirumbolo A, Patriotta G. Managing knowledge in organizations: a Nonaka's SECI model operationalization, Frontiers in Psychology 2019;10:2730.
30. Nonaka I, Konno N. The concept of "ba": building a foundation for knowledge creation, California Management Review 1998;40(3):40-54.
31. Aeppel T. On factory floors, top workers hide know-how from managers, The Wall Street Journal, 1 July 2002.
32. Sagan C. The Demon-Haunted World: science as a candle in the dark, Headline, London, 1996. ISBN 978-0-74727-745-3.
33. Scott J. Social network analysis ~ third edition. Sage Publications Ltd, 1991.

34. Blondel VD, Guillaume J-L, Lambiotte R,Lefebvre E. Fast unfolding of communities in large networks, Journal of Statistical Mechanics: Theory and Experiment 2008:P10008.
35. Senge PM. The Fifth Discipline: the art & practice of the learning organization, Random House Business Books, 1990/2006. ISBN 978-0-385-51725-6.
36. Hendra, Allianto H. Applying knowledge continuity management in non-profit organization (NPO), IEEE Xplore® International Conference on Information Management and Technology (ICIMTech), Bandung ~ Indonesia, 16-18 November 2016, p.41-46.
37. Massingham PM. Measuring the impact of knowledge loss: a longitudinal study, Journal of Knowledge Management 2018;22(4):721-758.
38. Rogan T, Haselby S. Know-how: market systems have made better use of more information than economic planners. What if AI and machine learning changed that?, 25 March 2019, accessed on 16 February 2024.
39. ISO/IEC 42001: 2023, Information technology - Artificial intelligence - Management system, International Organization for Standards, Geneva ~ Switzerland. ISBN 978-0-539-15269-2.
40. ISO 9001:2015, Quality management systems - Requirements, International Organization for Standards, Geneva ~ Switzerland.
41. ISO 14001:2015, Environmental management systems - Requirements with guidance for use, International Organization for Standards, Geneva ~ Switzerland.
42. ISO/IEC 27001:2022, Information security, cybersecurity and privacy protection - Information security management systems - Requirements, International Organization for Standards, Geneva ~ Switzerland.
43. ISO 45001:2018, Occupational health and safety management systems - Requirements with guidance for use, International Organization for Standards, Geneva ~ Switzerland.
44. PD ISO/IEC TR 24027:2021, Information technology - Artificial intelligence (AI) - Bias in AI systems and AI aided decision making, International Organization for Standards, Geneva ~ Switzerland.
45. BS ISO/IEC 38507:2022, Information technology - Governance of IT - Governance implications of the use of artificial intelligence by organizations, International Organization for Standards, Geneva ~ Switzerland.
46. BS ISO/IEC 23894:2023, Information technology - Artificial intelligence - Guidance on risk management, International Organization for Standards, Geneva ~ Switzerland.
47. ISO/IEC TR 24029-1:2021, Artificial Intelligence (AI) - Assessment of the robustness of neural networks - Part 1: Overview, International Organization for Standards, Geneva ~ Switzerland.
48. PD ISO/IEC TR 24368:2022, Information technology - Artificial intelligence - Overview of ethical and societal concerns, International Organization for Standards, Geneva ~ Switzerland.
49. BS ISO/IEC 23053:2022, Framework for Artificial Intelligence (AI) Systems Using Machine Learning (ML), International Organization for Standards, Geneva ~ Switzerland.
50. PD ISO/IEC TR 24028:2020, Information technology - Artificial intelligence - Overview of trustworthiness in artificial intelligence, International Organization for Standards, Geneva ~ Switzerland.
51. Fabris J, Roughley D, Poursartip A, Maine E. Managing the technological and market uncertainty of composites innovation: a case study of composites manufacturers in Western Canada and interventions by a translational research centre, Translational Materials Research 2017;4(4):046001.
52. Budwal N, Kasper K, Goeing J, Ward C. Developing knowledge-based systems for the cost-effective product design of high performance textile fibre-reinforced composites, The Composites Advanced Material Expo (CAMX), SAMPE, Dallas TX ~ United States of America, 19-21 October 2021.
53. Budwal N. Developing design and manufacturing capability towards cost-effective textile reinforced and complex geometry composite structures, Engineering Doctorate (EngD) thesis, University of Bristol, 21 March 2023.

54. Duncan BC, Broughton WR. Absorption and diffusion of moisture in polymeric materials, National Physical Laboratory Good Practice Guide (GPG102), 2007.
55. Johnson D, Blackburn M, Stewart C. Management of engineered composite repairs: end user good practice guide, Energy Institute, London, 2021. ISBN 978-1-78725-300-1.
56. Lodeiro ML, Broughton WR. Cure monitoring techniques for polymer composites, adhesives and coatings, National Physical Laboratory Good Practice Guide (GPG75), 2005.
57. Broughton WR, Gower MRL, Lodeiro MJ, Shaw RM. Monitoring deformation and damage in fibre-reinforced plastics, National Physical Laboratory Good Practice Guide (GPG123), 2012.
58. Meunier M,Knibbs S. Design tools for fibre reinforced polymer structures, National Composites Network Best Practice Guide, no date, accessed 16 February 2024.
59. Beckwith S. Designing with Composites: suggested "Best Practices" rules, accessed 16 February 2024.
60. Broughton WR, Gower MRL, Lodeiro MJ, Shaw RM. Generation and assessment of fatigue data for fibre-reinforced plastics, National Physical Laboratory Good Practice Guide (GPG115), 2021.
61. Royle T, Keen N, Job S. Fire performance of fibre-reinforced polymer composites, Composites UK Good Practice Guide, 2019.
62. Mottram JT, Henderson J (editors). Fibre-reinforced polymer bridges – guidance for designers, CIRIA, 2018. ISBN: 978-0-86017-794-4.
63. Worrall C, Kellar E, Vacogne C (edited by Job S). Joining of fibre-reinforced composites, Composites UK Limited, January 2020.
64. Davies A, Foreman A, Shaw R, Sims G, Fibre reinforced plastic composites – machining of composites and specimen preparation, National Physical Laboratory Good Practice Guide (GPG38), 2002.
65. Poole M, Gower M. Mechanical characterisations of 3D fibre-reinforced plastic composites, National Physical Laboratory Good Practice Guide (GPG151), 2021.
66. Keen N, Bland R, Job S, Mould Tooling for fibre-reinforced polymer composites - a good practice guide, Composites UK/National Composites Centre, 13 July 2023.
67. Kapadia A. Non-destructive testing of composite materials, National Composites Network Best Practice Guide, no date, accessed 16 February 2024.
68. Anon., Non-Destructive Testing (NDT) – Guidance Document: an introduction to NDT common methods supported by lead employer document: AA050 Issue 2, Rolls-Royce and British Institute of Non-Destructive Testing, November 2015.
69. Potter KD. Understanding the origins of defects and variability in composites manufacture, 17th International Conference on Composite Materials (ICCM-17), Edinburgh, 27-31 July 2009.
70. Gower M, Sims G. Fibre-Reinforced plastic composites - qualification of composite materials, National Physical Laboratory Good Practice Guide (GPG64), 2003.
71. Halliwell S. Repair of fibre reinforced polymer (FRP) structures, National Composites Network, no date, accessed 16 February 2024.
72. Turnbull A, Maxwell T, Pillai S, White J. Residual stress in polymeric mouldings, National Physical Laboratory Good Practice Guide (GPG10), 1998.
73. Fitzgerald A, Parsons S, Forsyth M, Job S, Keen N. The sustainability of fibre-reinforced polymer composites, Composites UK Limited Good Practice Guide, 2022.
74. Adams D. Tabbing composite test specimens: when and why, High-Performance Composites, March 2011, 19(3).
75. Mulligan DR, Gnaniah S, Sims G. Thermal Analysis Techniques for Composites and Adhesives (Second Edition), National Physical Laboratory Good Practice Guide (GPG 62), Teddington, 2000.
76. Anon., Empowering Canadian businesses with the knowledge they need to succeed, 2021, accessed 16 February 2024.
77. Anon., CKN Knowledge in Practice Centre, 2022, accessed 16 February 2024.
78. Pickard LR. Towards efficient composites manufacture through in-process monitoring and knowledge management, PhD thesis, University of Bristol, May 2019.
79. Anon., BIS-sponsored mentor challenge fund, accessed 16 February 2024.

80. Anon., SME Affiliate Scheme, accessed 16 February 2024.
81. Anon., Introducing the Access to Mentoring & Finance Team (A2MF), 2021, accessed 16 February 2024.
82. Anon., Enhancing the composite materials regulatory infrastructure, 2022, accessed 16 February 2024.
83. Anon., Wave-based Inspection for Damage Evaluation in structurally-Advanced composites, EU Cordis, accessed 16 February 2024.
84. Offner M. Welcome to an exclusive Composites industry group ... just for you, Women in the Composites Industry, 2021, accessed 16 February 2024.
85. Anon., NCC partners with Mentor Digital to win 'Best Custom Solution' at the 2021 Umbraco Awards, accessed 16 February 2024.
86. Jones HV, Chatzimichali A, Potter K, Ward C. Exploring the significance of in-process knowledge to composites design and production, Proceedings of the 20th International Conference on Engineering Design (ICED15), Milan ~ Italy, 27-30 July 2015, accessed 16 February 2024.
87. Jones H, Chatzimichali A, Middleton R, Potter K, Ward C. Exploring the significance of in-process knowledge to composite design and production, ACCIS CDT Conference, Bristol, 2015, accessed 18 February 2023 (no longer online).
88. Jones HV, Chatzimichali A, Potter K, Ward C. Exploring the significance of in-process knowledge to composites design and production, Proc. 20th International Conference on Engineering Design (ICED15), Milan ~ Italy, 27-30 July 2015.
89. Anon., LayupRITE: augmenting composites layup training, University of Bristol webpage, accessed 16 February 2024.
90. Blake S, Laser guidance for hand laid composites: past, present and future, Composites '97 Manufacturing and Tooling, Society of Manufacturing Engineers, Anaheim CA ~ United States of America, 20-22 January 1997, accessed 16 February 2024.
91. Such M, Ward C, Hutabarat W, Tiwari A. Intelligent composite layup by the application of low cost tracking and projection technologies, 8th International Conference on Digital Enterprise Technology (DET 2014), Stuttgart ~ Germany, 25-28 March 2014. ISBN 978-1-6343-9765-0. Procedia CIRP 2014;25:122-131.
92. Anon., Ply Placement Technology, accessed 16 February 2024.
93. Gandhi N, Rose R, Croxford A, Ward C, Developing a high-fidelity knowledge base for non-destructive testing and composite material products: a review, 58th Annual British Conference of Non-Destructive Testing, BINDT, Telford, 3-5 September 2019, accessed 16 February 2024.
94. Hoskins S. Issues of tacit knowledge within 3D printing for artists, designers and makers, Proceedings of the Digital Fabrication and Digital Printing (NIP30) Conference, Philadephia PA ~ United States of America, 7-11 September 2014, 30, p.426-431. ISBN 978-1-5108-1438-7. ResearchGate.
95. Piasecki D, Summerscales J. Characterisation of reinforcement fabrics by fractal dimension, Europe Conference 2018, Society for the Advancement of Materials and Process Engineering (SAMPE), Southampton ~ United Kingdom, 11-13 September 2018.
96. Anon., ImageJ: image processing and analysis in Java, accessed 16 February 2024.
97. Karperien A. Fractal Dimension and Lacunarity (FracLac), 2011, accessed 16 February 2024.
98. CKN. Interviews - A133, Composites Knowledge Network, 5 March 2021, accessed 16 February 2024.
99. Pattnaik P, Sharma A, Choudhary M, Singh V, Agarwal P, Kukshal K. Role of machine learning in the field of fiber reinforced polymer composites: a preliminary discussion, Materials Today: Proceedings 2021;44(6):4703-4708.
100. Qiu C, Yang J. Machine Learning Applications in Composites: manufacturing, design, and characterization, Chapter 4 in Y An (editor); Machine Learning in Materials Informatics:

Methods and Applications (ACS Symposium Series v1416), American Chemical Society, 2022, p.65-85. ISBN 978-0-84129-763-0.

101. Nelon C, Myers O, Hall A. The intersection of damage evaluation of fiber-reinforced composite materials with machine learning: a review, Journal of Composite Materials 2022:56(9):1417-1452.
102. Cassola S, Duhovic M, Schmidt T, May D, Machine learning for polymer composites process simulation: a review, Composites Part B: Engineering 2022;246:110208.
103. Pathan MV, Ponnusami SA, Pathan J, Pitisongsawat R, Erice B, Petrinic N, Tagarielli VL. Predictions of the mechanical properties of unidirectional fibre composites by supervised machine learning, Scientific Reports 2019;9:13964.
104. Crawford B, Sourki R, Khayyam H, Milani AS. A machine learning framework with dataset-knowledgeability pre-assessment and a local decision-boundary crispness score: an industry 4.0-based case study on composite autoclave manufacturing, Computers in Industry 2021;132:103510.
105. Balasundaram R, Sathiya Devi S, Sakthi Balan G. Machine learning approaches for prediction of properties of natural fiber composites: apriori algorithm, Australian Journal of Mechanical Engineering 2023;21(5):1790-1805.
106. Bhaduri A, Gupta A, Graham-Brady L. Stress field prediction in fiber-reinforced composite materials using a deep learning approach, Composites Part B: Engineering 2022;238:109879.
107. Choi J-H, Na W, Yu W-R. Machine learning-assisted modelling of stress concentration factor of unidirectional fiber composites for predicting their tensile strength, Modelling and Simulation in Materials Science and Engineering 2023;31(2):025001.
108. Kek T, Potočnik P, Misson M, Bergant Z, Sorgente M, Govekar E, Šturm R. Characterization of biocomposites and glass fiber epoxy composites based on acoustic emission signals, deep feature extraction, and machine learning, Sensors 2022;22(18):6886.
109. Tan H, Zhu S, Yan S, Wen P. Predictive model for creep behavior of composite materials using gene expression programming, Applied Composite Materials 2023;30:1003-1030.
110. Jupp, S. Knowledge management and knowledge loss at Oakmount Controls, BEng (honours) Mechanical Engineering project report, 2020.