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Article:

Henry, P., Vazirian, M. and Westland, S. (2026) Trust in Color: Supporting the Digital Transformation of Textile Printing for Fashion and Apparel Industries. *Fashion Practice*, 18 (2). pp. 367-390. ISSN: 1756-9370

<https://doi.org/10.1080/17569370.2025.2610226>

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Trust in Colour: Supporting the Digital Transformation of Textile Printing for Fashion and Apparel Industries

Phil Henry, Marjan Vazirian, & Stephen Westland

Abstract:

This responsive R&D Future Fashion Factory funded project supported a collaboration between Burberry and the University of Leeds to explore digital-colour and data-driven design workflows, evaluating their effectiveness within contemporary Fashion and Textiles supply-chains. In principle, data-driven approaches prioritize decisions based on technical processes and data analysis over individual experience or personal intuition with the aim being to produce the right product. The study incorporates perspectives from the design and technology interface to assess the reliability of technical colour-judgments. It considers how trust in measured colour-decisions impacts on the Digital Transformation objectives of streamlining processes, improving business efficiency, and delivering on sustainability goals through digitally driven manufacturing processes. Reliable colour accuracy and consistency can be fundamental in the assessment and successful integration of digital design workflows.

The implications of this innovative research are positioned within the broader context of industry transformation and the urgent need to make sustainable progress in the reform of traditional Fashion & Textile manufacturing. The opportunities it presents are closely aligned with the growing demand for compliance in meeting international legislation, the mandate for transparent reductions in CO₂ emissions, material waste, and the adoption of low-impact manufacturing practices.

Colour, although recognised as integral to the creative design process, is seldom mentioned as a factor influencing successful Digital Transformation. This is perhaps reasonable considering the maturity of colour-measurement technologies and their integration with established CAD-software, both analogue and digital manufacturing. A systematic evolution of the scientific instruments and routines used to measure colour, spectrophotometry and calibration routines, has been conducted assessing reliability for absolute, quantitative, and reproducible colour measurement. Experimental results raise questions regarding the complexities of technical-protocols revealing both scope for human-error and potential drifts in machine accuracy.

At this initial scoping stage, the primary objective is to deepen our understanding of the complexities and challenges inherent in digital colour workflows. This includes identifying existing skill gaps and exploring opportunities for upskilling that can be effectively addressed through targeted education and training initiatives.

It is widely recognized that embedding industry-relevant skills into fashion and textiles education promotes positive change through broader sustainable development (Briggs-Goode and Hardaker, 2025). Almond and Rainton (2025) evaluated how Future Fashion

Factory success stories utilising Industry 4.0 digital textile innovations are enhancing the design and creation of fashion and textile products.

In the longer term, this investigation holds significant potential to contribute to the reduction of CO₂ emissions and material waste. By enabling accurate, first-time-right colour decisions, it can reduce the need for costly sampling and fabric batch approval processes, thereby supporting more efficient, data-informed digital manufacturing practices.

KEYWORDS:

Technical Colour Accuracy, AI Innovation, Printed Textiles, Sustainable Fashion Supply Chain, Design Education, Digital Skills.

Introduction

The Fashion and Textiles (F&T) industry is currently on the precipice of a revolution as advances in AI, robotics and automation have the potential to transform manufacturing practices, supply chains and retail experience. The textile industry is not alone in facing this transformation of course. A key factor in the rate at which effective change can occur is in digitisation of information. Such digital information is a requirement for use by machine learning models and digital colour information is particularly vital in the case of F&T industries. The digital revolution represents an opportunity to deliver positive change for the F&T industry. If successfully implemented into the supply chain it may provide a means to reform both the perception and the reality of pollution, waste and over-consumption embedded in traditional manufacturing (Nobile et al, 2021). The adoption and integration of innovative digital technologies and faster more intelligent business models are positioned as key in delivering sustainable gains by dematerialisation of resource-intensive production (Casciani, 2022). The need for new systems embedded with holistic system-wide understanding and alongside transitional strategies that streamline cooperation between design and manufacturing in the delivery of creative value is an established objective (Niinimäki, 2020). Stronger Corporate Social Responsibility (CSR) driven by new legislation and a need for transparency, is seen as the route to achieve the goal of a carbon-neutral F&T industry by 2050 (Virta and Riikka, 2021). Indeed, the more imminent goal of Net Zero energy transition by 2030 may be at risk if companies are resistant to the adoption of new innovations (Talwar, 2023).

A key motivation for this on-going research is to better understand the scope of opportunity and impact, and to improve and streamline colour efficiencies with innovative big data technologies in line with F&T industry sustainable agendas (Heim, 2022). This paper describes an industry-led collaboration between Burberry and the University of Leeds that investigated how colour can be digitally communicated in contemporary workflows. The project was motivated by the understanding that for digital information to be useful it must be trusted. This collaborative project investigated the potential of AI technologies to improve confidence in creative colour decision-making. The objective was to enhance the reliability of digital

colour assessment technologies to deliver trusted right-first-time colour data. Balanced with this is the wider aim for improved levels of problem understanding, to clarify and disseminate greater recognition of challenges in colour communication that are less widely appreciated but nevertheless deep-rooted. The need to upskill the workforce to fully exploit the potential of digital systems is discussed in terms of common gaps in colour knowledge.

The aesthetic qualities of colour are recognised as a fundamental element of F&T design processes; a creative starting point that reflects the mood of a new season or collection (Ruppert-Stroescu and Hawley, 2014). The ‘right’ colour is an established commercial driver in signalling a product’s value to the market and equally established as a strategic marketing component in maintaining brand recognition (Kauppinen-Räsänen and Luomala, 2020). The colours of F&T products are known to be a key consideration in consumer assessment of material quality and the visual appraisal of a product’s intrinsic values (Kumah, 2019). In summary, colour is widely recognised as a trigger for driving purchasing decisions (Yu et al., 2021). Yet despite the obvious importance of the colour of designs or products, many decisions about colour are considered to be creative or even subjective in nature. Decisions are often based more on the designer’s intuition and experience rather than tangible metrics relating to consumer demand, textile material properties, or supply chain realities (Lee et al., 2019). In between these very different values systems and unsurprisingly fluid commercial priorities, colour quality control procedures have benefited from the integration of advanced digital colour measurement devices.

Colour measurement devices (colorimeters, spectrophotometers and, more recently, imaging systems) are used to support or eliminate subjective colour decisions and to efficiently optimise accurate assessment of colour pass/fail decisions. Spectrophotometers are designed to approximate how the human eye evaluates colours, but via objective results rather than subjective evaluation.

At first glance it may seem that the wide-spread use of these measurement devices makes colour one of the easiest pieces of information to digitise. Yet in reality, many elements of digital colour workflows are delayed by interdepartmental tensions, different priorities for colour delivery, and (crucially) by the plethora of different instruments being used within the same supply chain. Whilst technical protocols still hold undisputed advantages over human visual assessment, different devices, manufacturers and models are known to have varying performances metrics (Luo et al., 2016). There are also subtleties to the measurement procedures that can be impacted by user-based techniques (Qiu et al., 2021). Variations in measurement geometry (the difference, for example, between a sphere-based device and a 0/45° device) can make the data dependent upon the device or model being used (Milić et al., 2023). This leads to lack of trust in colour measurement which is only made worse by lack of technical understanding of the process within the workforce. Colour is an inherently multi-disciplinary subject that is often taught badly in schools, colleges and even in Higher Education (Csillag et al., 2018).

The discursive dialogue in the following sections is founded on issues highlighted in the literature and informal discussions with industry stake holders, designers, colour technologist

and a range of digital colour technology suppliers, covering colour, design, assessment, and management applications.

Drivers for Change

The fashion and textiles (F&T) industry faces well-documented environmental challenges hand in hand with increasing legislative pressure to drive sustainable transformation across the sector to meet the United Nations Sustainable Development Goals (Conlon, 2024). Digital innovation is progressively recognized as a strategic enabler of systematic change, offering the potential to minimize waste through the optimization of design, production, and business operations (Akram et al., 2022; Sayem, 2022).

However, despite its positive potential and the urgency relating to 2050 climate targets, Wiegand and Martin (2023) note that elements of the fashion sector remain slow to adopt digital technologies. Achieving compliance and enabling digital transition requires investment in infrastructure and innovation but also upskilling workforces and building trust in emerging technologies. Encouragingly, digital investment is shown to deliver measurable improvements in productivity and global competitiveness (Bibi et al., 2024).

Importantly eliminating waste and pollution at the earliest stages of textile production is increasingly viewed as deliverable through digital innovations along with intelligent business strategies that prioritize material efficiency and sustainability (Lopes et al., 2024 and Orisadare et al 2025).

Authors commonly cite the F&T industries as not having changed for over a century, raise concerns at the levels of disconnect between design and wider industry roles, as well as the lack of technical skills and expertise (Postlethwaite, 2022; Sun and Zhao, 2018; Sumera et al., 2020). Whilst the majority agree that upskilling and educational paradigm shifts are a requirement to underpin successful Digital Transformation, others raise concerns that the drive for digital efficacies negatively impact on innovation and creativity (Bye and Sohn, 2010). The opportunities for commercial competitiveness, based on delivering design quality over low pricing, need a strategy that is inclusive of developing nations F&T industrial technological capabilities (Bowstead, 2022). Wang explores VR as a means of accelerating learning for textile design students but also consider design communication and collaboration with commission manufacturers in China (Wang et al, 2024).

Digital Colour and Computer Aided Design/Computer Aided Manufacturing CAD/CAM

The digitisation of the F&T industry arguably began in the 1980s with several technological innovations including the widespread adoption of colour measurement and the introduction and integration of Computer Aided Design (CAD) software and Computer Aided Manufacturing (CAM) processes. For CAD/CAM, initially graphics capabilities and

computational power limited the adoption potential to carpet, weave and jacquard i.e., fabric construction processes. The point paper-based design process more readily transferred weave skill sets to a reasonably familiar digital menu interface. Conventional weave-plans and loom-cards could be digitally printed using standard desktop hardware, yarns codes and therefore colour information could then be communicated through existing in-house systems.

A retrospective analysis of the initial digitisation of the print design process draws attention to the current needs for upskilling, particularly regarding trust in digital colour. The integration of digital technologies increases the number of processes and touch points that designers need to integrate into their creative practice. Pre-digital, the print design process typically consisted of fixed stages of concept design, hand-drafting and painting, followed by colour separation for sample screens to facilitate prototype prints or strike-offs before a design could be accepted for production. Colour knowledge was a central skill at all stages, including artisan abilities to mix and paint with consistent colour balance combining knowledge of print manufacturing and the relationship between colour usage and expensive print screens, rotary or flat. The colour separation artist, sometimes referred to as a 'copy artist,' was skilled with a paint brush but also knowledgeable of the printing techniques and processes central to accurately transferring colour design imagery onto fabric. Once screens were cut, the role of colourway development was often a separate responsibility of a 'colourist' tasked with finalising the colour options in the fabric context, matched to, or developed from, the original painted colourways.

In the next section, the development and integration of digital CAD/CAM workflow is reviewed. The purpose of this is twofold; firstly, to illustrate how this period of digital transformation was driven by manufacturing innovation (how to make more product, with greater time/cost efficiencies for measurable quantifiable return on investment); secondly, the adoption platform was based on trust in existing skills sets with software developed to resolve and speedup well understood techniques and processes central to the existing workflows. Later we question if this is still the case or if new barriers to trust in digital transformation need consideration.

Digital Transformation of Colour Workflows

Digital workflows were developed to be integrated with existing conventional design pathways, a key advantage of interfacing to CAM innovations (e.g., laser engraving). SPGPrints formally Stork Prints, introduced laser engraving system to the textiles manufacturing industries in the early 1990's (www.spgprints.com) and are still a global leader in Rotary print screen manufacture and digital print technologies.

Analogue textile printing requires a separate printing screen for each design colour, typically a rotary printing machines has between 4 and 12 colour stations with up to 24 for more

elaborate designs. Depending on complexity an engraved screen can cost between £100 for a simple design and £300 - £500 for more intricate compositions that require significantly more time and skilled input.

Pre-production a separation is created either by hand, where each colour component is traced using paint brushes and an opaque paint to copy the original design style onto a transparent sheet of acetate film. Or digitally where the original artist's hand craft is captured during scanning, but the CAD operator is still required to make technical judgments using bespoke software tools in conjunction with their own creative skill set.

The outcome for both processes is a colour-negative for each design colour, in analogue processes the acetate film is repeated with multiple photocopies to cover the full screen length and the screens are pre-coated in a light sensitive lacquer emulsion. The painted areas of the separation block intense light which bakes hard the exposed lacquer leaving a clear silhouette of the design area to be colour printed. During laser engraving the digital separation files direct the laser to cut away the hardened lacquer emulsion to again leave a clear silhouette of the design on each of the necessary screens. Colour separations are still a requirement for digital printing where colourways are expected. The colour separation processes and colour composition can be considered as integral to the aesthetic and authentic appearance of printed textiles designs.

Ultimately the laser engraving innovation offered significant business returns in the speed of production compared to intensive manual methods, and also direct and indirect cost savings (e.g., rotary screens can be 'stripped' by the laser and re-utilised) in terms of material usage and reduced waste. The engraving machine is used to laser away existing lacquer holding the colour separation information and the screen allocated to a new print job. The digital design file eliminates the need for costly storage of physical screens for reruns and a need for a ready supply of expensive screens for each new print job in production. The responsiveness to design developments and changes previously restricted by the physical time inherent in the painting and drawing techniques is a further advantage of digitisation. A focus on colour, inherent design skills and intuitive knowledge of physical colorants is still the driving force for colour decision-making and the core knowledge of the system users.

These observations aside, once a design is committed to print screen production the associated time and cost commitments mean there is little to no opportunity for change, bar the colour combinations. The introduction of digital printing direct to fabric was heralded as the catalyst to change the F&T industry for the better through the adoption of digital technology. ITMA 1991 saw the launch of the TruColour TCP (Gooby, 2024) with the capability to print reactive dyes direct to fabric though with the print area limited to the size of the print-drum. The innovation triggered the ambition for the F&T industries to adopt digital workflows but also instigated an extension to traditional design roles where skilled staff became referred to as 'CAD designers. Previously three or more design professions, these were now merged, with significant implications for understanding digital colour.

Physical to Digital Colour and back to Physical Colour

Colour workflows are where we see the most impactful transformation and the introduction of fundamental digital colour issues that are not necessarily integrated or highlighted in contemporary design education. Image capture, the scanning of original artwork or archive documents, was the primary starting point. Whilst a main focus of the CAD designer might be the alignment of A3 scanned sections to digitally piece together the full design repeat, the colour workflow involves the translation of physical colour into digital colour and vice versa as design developments are printed out for assessment. It is important that practitioners with a creative investment in colour understand the key colour communication issues relating to digital colour, and it turns out that this is extremely challenging.

Colour appearance can vary significantly due to a range of factors, including the context of the viewing environment, lighting conditions, as well as the physical properties of the substrate. Different colour spaces (RGB, sRGB and Adobe 1998) offer varying colour gamut or reproducible colour ranges, which can complicate accurate colour matching across digital and physical media. As a result, achieving consistent colour representation during the design development stage is often time-consuming and technically challenging. It can also be wasteful in terms of material resource and so impact negatively on the environment.

At the production stage, this challenge continues with the use of laboratory dips—small fabric samples dyed to match the brand's colour standard. These are exchanged between the design team and the mill or dye house until an acceptable match is achieved. Colour standards, such as Pantone, are commonly used as reference points, and pass/fail protocols are applied based on visual and instrumental assessments. Additive colour theory, or additive colour-mixing, is where colour lights (usually red, green and blue or RGB) can be combined to create a wide range of colours. Emissive displays based on RGB primaries are ubiquitous in the modern world. An understanding of RGB technology requires an appreciation of several different disciplines – the biology of the human eye, the physics of light, and the psychology of perception to name but three – and is therefore challenging even for STEM graduates. The multidisciplinary nature of colour is one reason for the observation that it is poorly understood by many people (Vazirian et al., 2023). There is more than one RGB colour space and it is important to appreciate that each stage of the workflow may have its own RGB representation. For example, an image captured by a camera may be represented by the RGB of the camera system. When the image is transferred to a computer and displayed it needs to be converted to the RGB space of the display. There are also numerous standard RGB spaces including sRGB and Adobe (1998) RGB (Westland and Cheung, 2012). Generally, we can say that an RGB representation is device dependent; that is, it has meaning only in terms of the relevant device (and its settings). However, in addition to this complication, is the problem of how to relate the device-dependent RGB data that is present in CAD systems with the CIE XYZ data that is recorded for actual physical textiles or garments using colour measurement devices. The CIE XYZ colour space is a mathematical model generated by the International Commission on Illumination (CIE) in 1931 to represent all colours numerically based on how humans perceive them. It is the foundation for many other colour spaces including RGB-based

colour spaces and CIELAB. It is also the basis of the ICC system that allows colour to be transmitted between different devices (such as camera and displays) without loss of colour fidelity (see Figure 1).

Understanding colour through a digital workflow is therefore more challenging than it may at first appear and there is evidence that colour education is not equipping students with the skills that they need (Csillag *et al.*, 2018). The Colour Literacy Project, endorsed by the Inter-Society Color Council and the International Colour Association aims to change the way that colour is taught in schools, colleges and universities in order to address the limitations in contemporary curricula (Kingsburgh, 2023).

The need to be able to convert between different colour spaces requires digital colour management. Historically, different colour devices would be managed using a ‘closed-loop’ system which is applicable to vertically organised and self-contained manufacturing facilities (Green, 2023). Today, open-source colour management systems exist such as the International Color Consortium (ICC) which was introduced in 1993 (ICC, 2025; Sharma 2018). However, although open-source systems such as ICC enable colour communication between cameras, displays and printers they do not extend to colour measurement devices notably spectrophotometers. This limitation poses significant challenges to companies that wish to digitise their colour workflows, especially when the variation in models and manufacturers for these devices is taken into account. A further limitation to digital colour workflows is the gamut, or typical visible range, issue (Henry and Westland, 2020). Commercially available image-reproduction devices such as displays and printers are not capable of reproducing all colours; each device has a limited gamut (Vazirian et al., 2023). This means that some of the colours that a display can reproduce are outside the gamut of the printer and vice versa.

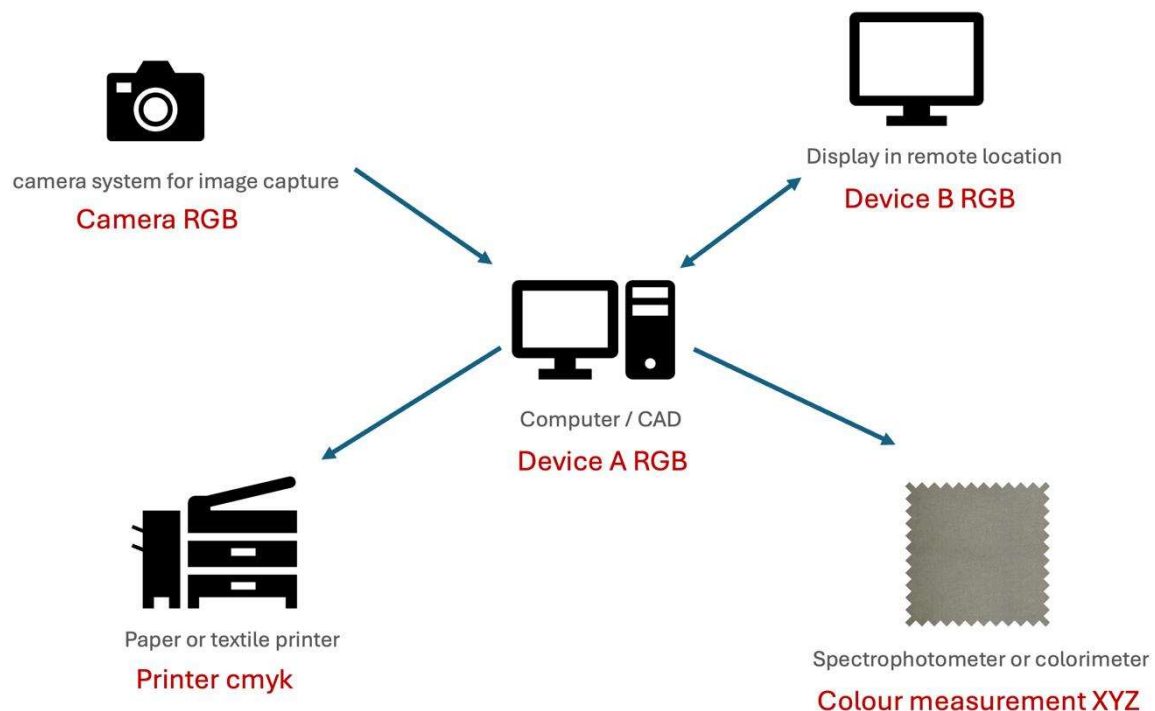


Figure 1: Simplified digital colour workflow

Figure 1 shows a very simplified digital colour workflow. Colour measurement devices are used to measure the spectral reflectance factors of physical garments or textile swatches and the colour can be represented using the CIE XYZ representation. Images can be captured using camera-based systems that are recorded in a camera-dependent RGB colour space. Images can then be viewed and edited on a computer system working in its own device dependent RGB colour space. Printers may be part of the workflow and these often use a CMYK representation, though multi-primary systems may be used with textile printers. Other users in the workflow may wish to view images in remote locations using computers that will represent colour in a colour space native to the particular display being used.

Different software platforms offer the functionality to select different working colour spaces and levels of integrated colour management tools from the International Colour Consortium (ICC <https://www.color.org>) to support a user in navigating device dependency issues (Sharma, 2018). The conversion of colour between different colour spaces is built into all colour print, automatic colour management is applied as standard in that a built-in lookup table will convert the colour intentions, from physical media to a digital RGB working colour space, digital print colours are converted via mathematical transforms to the nearest best colour match. In more colour sensitive workflow, the working colour spaces can be defined via ICC colour profiles within design focused software such as Adobe Photoshop. Although these profiles are underpinned by a generic averaging of a given devices typical colour performance (the colour gamut), the colour transforms are more effectively aligned.

The gold standard of colour management can be considered to be a bespoke approach. Rather than relying on the performance of generic profiles, custom colour information is applied to the input and output profiles. Colour monitors are required to be calibrated on a regular basis and characterisation information is generated to create precise information capturing a digital printer's colour performance under given conditions. This profile includes the software settings as well as the unique relationship between a selected substrate, paper or fabric ink-sets and printer settings. Given the necessary levels of user expertise with care and attention to technical maintenance routines, cross media accurate colour can be reliably and consistently delivered. Additional software functionality can be utilised to provide users with colour print preview information. In Photoshop a gamut warning function can be configured, any colour selected from outside of printer capabilities are simply greyed out in the print preview. In more industry specific colouration software, from specialist F&T solution providers, gamut information is embedded in the colour-picker tools providing users clear information regarding colour judgments and the potential for accurate colour reproduction on the printer and substrate.

In summary digital colour workflows can be trusted when the colour challenges and solution protocols are applied. Arguably this is more achievable in a vertical company structure where the colour technologies are vendor specific and technical skill sets are reliably intergraded into the workforce. Based on a range of industry perspective, designers to technology suppliers, in the next section we explore the colour workflow related complexities that can arise in today's complex global supply chain and the need for commercial responsiveness.

Digital Colour Integration in Contemporary Design Practice

The following highlights the way digital design and coloration technologies have been steadily adopted and intergraded beyond the manufacturing bases transforming the design and colour devolvement phases. Initially the high cost of bespoke software made a financial justification challenging for what where essential craft processes using basic materials. As the value of digital connectivity emerged in an increasingly extended global supply chain the need for greater creative control warranted the investment in Digital Transformation. Much in the same way as current drivers for faster response to market trends has highlighted the need for a remix of skills to deliver on the potential for leaner business models (Noris et al., 2021, and Casciani et al., 2022).

The issues and challenges relating to accurate colour commination is seldom raised or discussed amongst the perceived advantages of digital technologies. Digital fashion *per-se* is discussed as a means to advance industry hand-in-hand with sustainable societal goals, (Nobile et al., 2021), issuers relating to the current fragmented supply chain and the complexities that this brings to achieving environmental transparency are established and well understood (Joy et al., 2012). The potential advantages of big data and advances in AI computer learning technologies are credible platforms for enhancing reliable decision-making and co-creation (Acharya et al., 2018).

The view that digital manufacturing, sampling and prototyping are drivers for innovation and transformation (Bertola and Teunissen, 2018) is equally well established, however statics show digital fabric production as only accounting for 2-3% of the global printed fabric markets. Workflows from concept design, to fabric production and garment manufacture are often complex hybrid models with colour objectives osculating between digital and analogue print workflows. To fully benefit from the predicted environmentally improved landscape of right first-time data, digital design and dematerialisation (Marquesone et al., 2022, and Luo et al., 2022), financial inhibitors as well as the often-discussed lack of expertise are seen as barriers to exploiting and adopting digital innovations (Casciani et al., 2022). Others' focus on the opportunities that digital transformation offers as an enabler for the move towards more circularity (Hyunh, 2022) with the caveat that current business approaches need to change to more effectively deliver on sustainable transition. There is also recognition that the design process requires a systematic re-think to fully realise the benefits of digital transition (Ng et al., 2022). For the expected paradigm shift to take place the absence of technical skills is again reinforced as a barrier (Chan et al., 2023). Others see the benefit of digital tools as a means of bringing simplification to the design processes (Yezhova, 2024), perhaps in comparison to the current protracted and hybrid nature of many supply chains.

A greater focus on a design driven approach to a more 'systemic' transformation is a valid strategy. The development of innovative technologies that support data management and transparency together with the development of digital methods that can deliver an authentic digitalisation of creative process and aesthete values (Casciani and D'Itria, 2024).

Methodology

This study adopts a Design-Based Implementation Research (DBIR) framework to investigate the use of colour technologies across concept design to manufacturing workflows in the fashion and textile industry. DBIR is appropriated for this research, as it supports the investigation of real-world problems through sustained collaboration between industry practitioners, technology developers, and academic researchers. The methodology integrates literature evaluation, qualitative inquiry, and technical assessment to generate a comprehensive understanding of stakeholder experiences, technological capabilities, and implications for future curriculum design.

The combined purposes are the longer term aim of reducing CO₂ emissions and material waste by enabling accurate, first-time-right colour decisions through improved digital colour workflows. The more immediate objective is to better understand the complexities of digital colour workflows, identify existing skill gaps, and explore opportunities for upskilling through targeted education and professional training development initiatives.

The interviews focus on understanding the current landscape of digital colour workflows and identifying barriers to effective implementation. Design practitioners' discussion to explore workflow challenges, decision-making processes, and skill development needs. Insight from Colour technology suppliers help to understand technical constraints, innovations, and training requirements.

By integrating literature evaluation into the DBIR framework, helps ensure the investigation is also informed by current academic perspectives for a deeper development of knowledge that has a stronger potential to foster long-term, systemic change in both educational and industrial approaches to support the UK's fashion and textile industry to remain competitive.

Stakeholder Interviews

A qualitative research approach was used to explore the role of colour in the fashion design process using a semi-structured group interview methodology with a team of colour specialists. The discussion was guided by broad thematic questions, allowing for open-ended responses, encouraging participants to share insights regarding their familiar colour design workflow.

Each participant described their individual responsibilities and contributions to the colour design process explaining how colours are chosen and developed, with insights of how colour decisions are managed across different stages of the design process. Other topics introduced when appropriate related to common challenges and problems with the colour communication methods and the impact of current and future sustainability goals.

Participants also offered suggestions for improving current workflows including reflections on how colour focused training could be of benefit.

The session took place in a collaborative setting that encouraged open dialogue and peer-to-peer exchange adhering to standard ethical research practices. Participants were provided with a clear explanation of the study's purpose and intended use of the data. Consent was obtained prior to the interview, with participants agreeing voluntarily to take part.

Tracing the digital colour approval between processes within Burberry design teams brought to focus the complexity of the communication challenges inherent in contemporary colour design workflows. Colour concepts move from inspirational sources (often with physical samples) and are digitally matched by the eye of a skilled CAD designer. Creative colour judgements are further progressed and reviewed via paper prints produced with a bespoke colour managed monitor screen to printer system. Final colour outcomes are ultimately matched to in-house digital colour standards before being progressed into the manufacturing workflow. Here standard colour approval protocols are progressed through established technical protocols where lab dips are created and evaluated through standard spectrophotometric devices. Burberry (<https://www.burberryplc.com>) has its own in-house colour assessment laboratory located alongside the design studios at the brand headquarters that supports vertical manufacturing facilities as well as an extensive global supply chain. Even with extremely high levels of colour expertise and the necessary investments in colour assessment technologies the complexity of digital colour communication is recognised as a costly and materially wasteful process. The impact of colour gamut issues makes attaining cross-media colour fidelity complex. Even with bespoke colour management, evaluating colour in a real-world context requires other factors to be accounted for. Consistent lighting conditions are paramount in consistent visual assessment of colour, comparing real world objects to digital simulations brings the issue of observer variation and colour perception. Whilst individuals can be skilled in colour assessment the fact is that colour perception varies between individuals and therefore varies from the standard-observer equations that underpin colour management principles. The addition of fabric texture and variable in surface qualities add another level of challenge presenting further barriers to effective colour communication. The issue of fabric appearance was highlighted as a significant problem by the design team responsible for fabric trims the challenge of colour matching different materials that make up a garment. Much of the discussion between the Burberry design teams and colour specialists was insightful but affirming of problems and challenges, cross-media colour fidelity with the added tensions relating commercial realities, the delivery of colour as essential added-value. The recognition of common colour related challenges and a desire to share knowledge, suggest enhanced colour literacy as a professional development route.

To complement insights from internal colour specialists, one-to-one interviews were conducted with industry vendors specializing in digital colour and digital design technologies. The interviews took place remotely via Microsoft Teams, allowing for flexible scheduling and direct engagement with individual participants. A semi-structured format was used to encourage open dialogue while maintaining consistency across sessions. Each interview lasted approximately 45–60 minutes and was again guided by a set of thematic questions designed

to explore how technologies are integrated into client workflows, the challenges faced during implementation and regulatory compliance addressing sustainability. Participants were briefed on the study's purpose and gave verbal consent to participate individual identities were anonymized in the report to protect proprietary information and privacy

In summary, the perspectives of technology suppliers echoed the colour-related challenges and workflow improvement opportunities identified by design teams and discussed in current literature. VeriVidi (<https://www.verivide.com>), a UK-based designer of industry-standard lighting booths and digital imaging systems, and TUKATECH Inc. (<https://tukatech.com>), a US-based developer of fashion design CAD/CAM solutions, both agreed that users' technical understanding of colour could benefit from further development. They highlighted, for example, the importance of grasping concepts such as colour-space variability and the underlying causes of primary colour challenges. Enhancing this knowledge could foster greater trust in technical solutions and support the adoption of more effective practices.

The often-necessary complexity of some technical solutions can act as a barrier to user independence from high levels of vendor support, a challenge also noted in the literature, where such support resources can become overstretched. In organisations with in-house technical expertise, tensions may arise between teams whose professional credibility is tied to the commercial success of colour outcomes and those whose evaluations are grounded in objective, technical assessments of colour reproducibility. Both vendors observed that as a brand's workflow becomes more digitised, the more critical accurate colour becomes. Within highly digitised environments, colour outcomes are subject to greater internal scrutiny, in contrast to other parts of the supply chain where colour quality is often assessed through pass/fail routines and delivery timelines may take precedence over colour accuracy.

Colour Measurement Study

This colour measurement study forms part of a larger project designed to better understanding the realities of colour critical working relationship among the diverse F&T stakeholders whose business effectiveness depends on accurate colour communication protocols.

The underlying research aim is to build trust between creative and technical colour workflows by providing a deeper and more informed understanding of digital colour assessment. Our human perception of colour adapts depending on context, in reality a single colour cannot readily be perceived in isolation as its appearance is always influenced by its surroundings.

Scientific colour measurement devices are designed to provide objective colour assessment to help navigate subjective colour. However, whether it's an engineered colour standard such as a Pantone swatch or a finished garment displayed in a retail environment, colour is inherently a contextual experience. Lighting conditions, pattern effect, materials, textures, and even viewer expectations all impact how colour is seen and interpreted.

Further work is needed to independently assess and resolve how measurement technologies colour navigate consistency and accuracy, the following pilot study pioneers a better understanding of measurement variability

In order to understand the variability between different colour measurement instruments a total of 189 Coloro swatches were measured using various spectrophotometer devices. Coloro is a colour forecasting company that developed a standardised colour system called the Coloro Index, which consists of 3,500 unique colour samples. The Coloro Index is designed to provide a universal and objective language for colour communication across various industries, including fashion, design, and manufacturing. Each colour in the Coloro Index is identified by a unique seven-digit code, representing the colour's hue, lightness, and chroma. Structured systematically using the Munsell System, it ensures perceptual uniformity across the colour space, offering a more reliable foundation for generating evenly spaced colour sets compared to incrementally developed libraries.

The 189 colour swatches for this study were systematically selected from the full colour system using an algorithm known as 'maxminc' to maximise the colour variability across the full swatch range (Cheung and Westland, 2006). Figure 2 shows the measured spectral data for one of the samples (the Coloro 150-77-21 swatch) using each of the instruments (Table 1). Each of the colour measurement instruments were selected to provide a data set representative of industry standard makes and models and different calibration routines. The Datacolor 800 and X-rite 7800i are bench top spectrophotometers for high precision measurement. The X-Rite Ci64 is a high-end handheld sphere spectrophotometer and the Caddon camera-based multispectral imaging system combines the capabilities of spectrophotometry with high-resolution imaging. It's designed to overcome the limitations of traditional spectrophotometers, when dealing with complex, patterned, or textured surfaces. X-Rite NetProfiler is a cloud-based system used for calibration to ensure that spectrophotometer measurements are consistent.

These instruments measure spectral reflectance factors; the proportion of light reflected by a sample at different wavelengths in the visual spectrum. The CIE system emulates some properties of the human visual system to convert spectral reflectance factors for a sample into CIE XYZ and CIELAB values. CIELAB is approximately perceptually uniform so that differences between two points in the space that represent two colours can be used to indicate the visual colour difference between the colours. Colour differences are presented as Delta E (ΔE) values where a ΔE of less than one unit is often considered to be small enough to represent a commercial colour match. For textiles, colour matching is normally done under a light source that approximates D65 (a white light source with a correlated colour temperature of 6500 Kelvin) since CIE standard illuminant D65 is representative of average northern daylight.

Sometimes colour differences calculated using the CIEDE2000 formula are preferred to simple CIELAB colour differences because they have been shown to better correlate with visual differences.

It is evident from the spectral reflectance factors illustrated in Figure 2 that there are some substantial differences between the data produced by the different instruments, particularly in the orange/red long-wavelength range.

Table 1: The sources of data used

Device	Type of Instrument
Digital Standard	Provided by Coloro
Datacolor 800	spectrophotometer
Datacolor 800	spectrophotometer using NetProfiler
X-rite 7800i	spectrophotometer using NetProfiler
X-rite Ci64	spectrophotometer using NetProfiler
Caddon	Camera-based multispectral imaging system

The spectral data were converted to CIELAB values for the D65 illuminant and the CIEDE2000 colour differences (ΔE_{00}) between measurements from different instruments were calculated. Colour differences for this swatch varied from 21 to 0.73 ΔE_{00} units. The largest difference (0.73 ΔE_{00} units) was observed between the X-rite 7800i and the Coloro digital standard. Conversely, the greatest agreement (0.21 ΔE_{00} units) was achieved between the two Datacolor 800 devices (with and without Netprofiler).

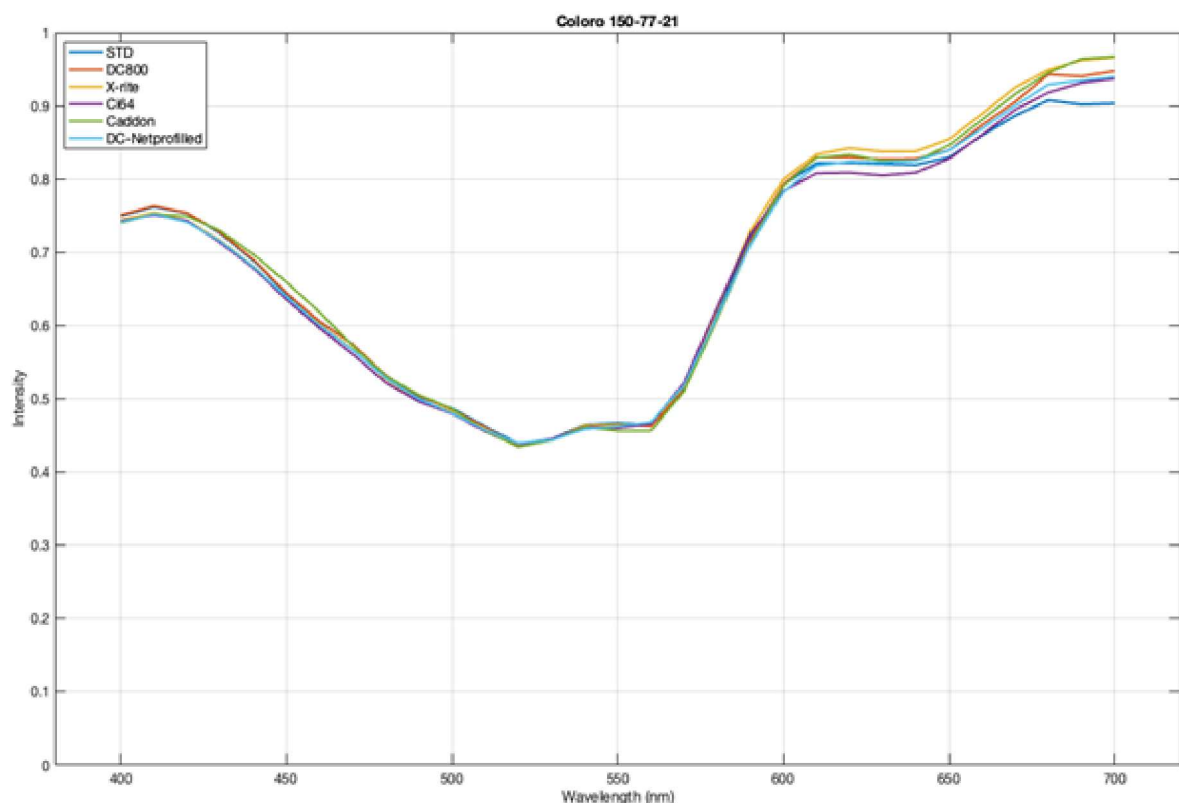


Figure 2: Spectral data measured for one sample using six different instruments

Although it is interesting to compare the colour measurements for a single sample, to derive more robust insights we should look at the measurements of all 189 samples used in the study. Table 2 shows the average colour differences between the instruments. Note that the imaging system (the Caddon) was most different to the other devices. The largest single-sample colour difference (not evident in Table 2) was 3.88 and this was between the X-rite Ci64 and the Caddon. These two instruments also were most dissimilar when all samples were considered as can be seen in Table 2 with a mean colour difference of 1.20 ΔE_{00} units.

Table 2: Mean CIEDE2000 colour differences for the same samples measured by different instruments (Net = NetProfiler)

	Standard	DataColor 800	DataColor 800 Net	X-rite 7800i Net	X-rite Ci64 Net	Caddon
Standard						
Datacolor 800	0.27					
Datacolor 800 Net	0.42	0.38				
X-rite 7800i Net	0.41	0.38	0.29			
X-rite Ci64 Net	0.68	0.73	0.52	0.61		
Caddon	1.16	1.03	1.02	1.11	1.2	

Some further work – not reported in this paper – showed that machine learning could be used to reduce the errors shown in Table 2.

Conclusion

As digital workflows become increasingly efficient and streamlined contemporary CAD design teams are increasingly engaged in colour-critical decision-making. Colour objectives and standards now move fluidly between digital design and development stages, product and fabric simulations, and physical sampling often across a range of substrates depending on the garment makeup. Lack of trust in colour measurement is a major hurdle towards colour digitisation across supply chains. This study had revealed three reasons that inhibit greater trust.

The first reason is lack of understanding. Colour is a complex multi-disciplinary phenomenon and there is urgent need for upskilling of the workforce in colour literacy. The second reason is limitations of the technology. The colour measurement study in this project revealed large colour differences between different colour measurement devices and even between the same devices used differently (for example, with and without netprofiling). In a closed-loop or vertical manufacturing model it can be possible to mitigate this limitation through standardisation of the colour-measurement hardware and software. However, in modern

globally dispersed supply chains the lack of agreement between different colour measurement devices can be debilitating. The increasing use of various imaging devices for colour measurement (such as the Caddon that was considered in this study) offer some new technical abilities but actually might make the agreement between different devices worse. The third reason is that there are open-source, vendor-neutral colour management solutions in the digital imaging world (for example, the internet) but these solutions (such as ICC) do not extend to traditional colour measurement devices such as spectrophotometers and colorimeters. Some optimism can be found in the use of machine learning to correlate colour measurements between different devices; however, future commercial solutions are likely to require vendor collaboration and trust that exceeds that found in the competitive practices of the last 50 years.

These problems – one due to lack of trust and two due to technological limitations in colour measurement – are hindering the incorporation of colour information in digital workflows in design and manufacturing companies. The impact of this is fewer right-first-time colour decisions and an inability to optimally eliminate waste within the industry.

In order to address the first problem of colour education it is proposed that new curricula at universities and colleges are needed to equip students with multi-disciplinary knowledge and practical skills in colour. The Colour Literacy Project, supported by the International Colour Association, is currently working on this problem and in collaboration with schools and universities to develop a new curriculum that is suitable for the 21st Century. However, the impact of this sort of initiative will not be felt for several years. A more serious problem is the proliferation of different colour measurement devices and the lack of correlation in the measurements that these devices make. More research in this area is needed; it is not easy to convert the measurements taken by one device to those of another. Based on the results from this study, it may be that machine-learning approaches will be able to solve this problem and form the basis of an open-source vendor neutral approach to colour measurement that has been so successful (through the ICC system) in the colour imaging field.

Disclosure Statement

No potential conflict of interest was reported by the author(s).

Additional information

Funding

The Future Fashion Factory programme was supported by the Arts and Humanities Research Council under grant no. AH/S002812/1

Acknowledgements

We are grateful for the support of industrial project partners: Burberry Ltd, Chromashare Ltd, Vervide Ltd and Tukatech Inc. Collaborative agreements included Intellectual Property and Confidentiality clauses which prevent in-depth description of some project results.

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