Article

Personalised Production in the Age of Circular Additive Manufacturing

Chris Turner 1,* and John Oyekan 2

1 Surrey Business School, University of Surrey, Guildford GU2 7XH, UK
2 Department of Computer Science, University of York, Heslington, York YO10 5GH, UK
* Correspondence: christopher.turner@surrey.ac.uk

Abstract: This research examines the opportunities provided by advances in digital manufacturing technologies for the provision of products designed to meet the needs of an individual consumer. The ability to co-create products with customers could enable mass personalisation to become a popular and fast-growing mode of production. Additive manufacturing, in both 3D and 4D printing forms, opens up new opportunities for circular economy-compliant production of such highly personalised products. Industry 4.0 has been seen by many as an agenda for the utilisation of interconnected digital technologies in industry, with a particular focus on manufacturing. Industry 5.0 seeks to address challenges that have grown in importance since the inception of Industry 4.0, such as the efficient inclusion of human worker skills in tandem with automation solutions, to address highly complex manufacturing scenarios while mitigating many of the environmental issues inherent with current manufacturing practices, while using circular economy principles. In examining the production of smart fabrics, this paper puts forward a framework for circular production of additively manufactured personalised products, co-designed with inputs from consumers.

Keywords: personalised production; Industry 5.0; Industry 4.0; 3D printing; 4D printing; circular economy

1. Introduction

Industry 4.0 has been seen by many as an agenda for the utilisation of interconnected digital technologies in industry, with a particular focus on manufacturing. What was once considered the domain of clerical and customer-facing businesses, internet-based technologies have enabled the servitisation of production systems and the products they produce. This has led to manufacturers offering services bundled with their products and the ability to dynamically ‘lease’ items to customers for a fee [1]. The Internet of Things has allowed a range of physical objects to become addressable active components in a connected network, linking producers with consumers and supply chain partners in real time. These changes are happening in tandem with the rise of new methods of manufacturing, thus moving from mass customisation [2] to mass personalization [3,4], with the latter allowing products to be produced for a ‘market of one’ [4–7]. The ability to co-create products with customers could also enable mass personalisation to become established as a key method production in the near future. It is also the case, though, that these changes in manufacturing must be seen in context of net-zero targets waste reduction at the production stage, reduced transport and logistics emissions and energy-efficient manufacturing. Additive manufacturing offers the possibility to proactively address such targets while producing a new generation of products capable of dynamic interactivity with their environment, user base and manufacturer.

One way in which the opportunity for co-creation of tailored products with customers could be realised is through 3D and 4D printing. This research examines barriers and new scenarios for production and matches them with enabling technologies. A case study involving a holistic consideration of smart fabric manufacture is put forward and illustrated...
within a framework for the circular production of additively manufactured personalised products. Smart fabrics, also known as 4D textiles, are fabrics that host sensors to sense the environment, process the data obtained from the external environment and actuators to control and achieve a desired response. 4D printing in combination with 3D printing will allow for the integration of electronics and sensors during the manufacturing to enable the sensing of human movements and other stimuli whilst wearing clothing made from smart fabrics. This state-of-the-art review establishes a roadmap for the exploitation of this new production route in light of human-centric and sustainability motivated goals enabled and popularised by the Industry 4.0 and Industry 5.0 paradigms.

In Section 2 of this paper, a literature review and methodology are put forward, exploring five interconnected areas required to deliver mass personalised products utilising smart fabrics. This section also puts forward pertinent research questions and highlights current gaps in knowledge. Section 3 provides a summary of smart fabrics research and sets out the framework for circular production of additively manufactured personalised products. Section 4 discusses the main points of the research and concludes the paper with a timeline for the further development of smart fabrics processes and technology for sustainable personalised products.

2. Methodology and Literature Review

In the completion of this work, a structured literature review was produced to explore the following interconnected subject areas required to deliver mass personalisation of products utilising smart textiles:

- Customer Co-Creation of Products;
- Additive manufacturing—3D printing;
- Additive manufacturing—4D printing;
- Human Centric and Personalised Production;
- Environmentally Sustainable Personalised Production.

The review subject areas (listed above) were selected from a wide-ranging scan and detailed filtering of the literature available for digital manufacturing automation and product personalisation. It was then focused to include only the papers seen as most relevant by the authors, in the context of the full range of literature available. The Scopus academic database was consulted with relevant papers indexed between 2010 and 2023. In addition, the Web of Science and Scholar databases were used as comparators to identify additional works not found by Scopus. In choosing to focus on the future path of sustainable personalised production, several pertinent research questions were identified in the completion of this work:

Q1: How can customers co-create products with manufacturers? In particular, which modes of interaction with customers are most likely to be of use in the development of personalised products?

Q2: Is there a role for humans in the production of personalised products? Automation has eliminated the need for many manual activities on the production line, though the nature of personalised production may still necessitate the addition of human skills, knowhow and decision-making abilities.

Q3: Which data streams are most useful in the sustainable design, development and use of personalised products?

2.1. Mass Customisation and Mass Personalisation

Building on the achievements made in mass customisation strategies and enabling technologies [2,3], mass personalisation utilises the latest developments in manufacturing technology to produce products for a ‘market of one’ [4–7]. Also known as mass individualisation, mass personalisation requires a new approach to product design [8,9]. One approach to addressing the challenges posed by mass personalisation is to produce a product design composed of modules [8,10,11]. Berry et al. [10] demonstrates a design for personalised shoes composed of a combination of three types of modules: Common modules—shared
across related products; Customised modules—allowing for some customer ‘tailoring’ of the product; and Personalised modules—that take exact parameters relating to individual customer needs. This modularisation methodology can also be applied to the manufacturing processes used to produce the products [11]. The production of products with a high degree of personalisation presents challenges often beyond that achievable with current mass production machines and processes; often requiring reversion to manual labour intervention and in some cases artisan craft skills. Mourtzis and Doukas [7,12] note that personalisation brings challenges, such as how to integrate the customer requirements into the product design process, and the development of production on-demand manufacturing systems. Limitations to mass personalisation within industry 4.0 have been highlighted by Aheleroff et al. [13], a major factor being price, as personalised products are likely to attract a premium due to the current additional costs in their production. In addition, it is difficult to obtain customer needs and translate these into a personal design in a timely and cost-sensitive way.

2.2. Customer Co-Creation of Products

Cooperation and joint technology development ventures have been common in industry for many years and have recently included the inception of new Industry 4.0 solutions for use by members of ‘innovation ecosystems’ [14]. Hsiao and Chiu [15] explore the concept of customer co-creation in combination with mass personalisation; utilising a web front end to facilitate choices and customised options in the booking of a hotel and its services, this case study provides a demonstration of how modularisation can be used in terms of processes. Prendville and Boken [16] note the use of co-creation workshops held with customers in order to understand personalisation parameters more clearly. Existing approaches to customisation often involve modularisation; used in flexible manufacturing scenarios, including postponement of differentiation until the customer signal is received, and mixed assembly lines, among other methods [17]. However, for true personalisation, further flexibility of manufacture and accommodation of the individual customer’s needs are required. Co-creation of products with customers will involve multiple high-value contacts with the eventual owners of the manufactured outputs [6]. Zhou et al. [6] make the point that co-creation could be achieved by viewing the product as part of a ‘product-service’ bundle, involving a relationship with the customer over the lifecycle of ownership, coupled with the use of AI systems to assist in the collection and collation of the customer’s interactions with the manufacturer.

In an investigation of consumer attitudes to co-creation, Mandolfo et al. [18] found that technical product knowledge of consumers of ‘high-tech’ products may be greater than other consumer categories. These authors note that this ‘Mavenism’ can also be seen in software categories, but less in other areas, such as ‘high touch’ fashion purchases, making the point that higher knowledge may lead to an increased propensity of consumers to provide actionable product development suggestions. Rathore et al. [19] examine the use of social media platforms for the elicitation of customer views on new product development and co-creation of products; along with finding potential cost advantages of this approach, these authors propose that social media could replace the need for focus groups, as analytics for NPD may be drawn from the platform, aiding the depth of insight such mediated events may provide. Zheng et al. [20] recognise both platform-based approaches to product co-creation, involving designs for families of products and systems that are IOT (Internet of Things)-driven, and data-driven approaches—involving ‘smart connected products’ (also known as Intelligent Products) capable of sensing their environment and utilising artificial intelligence and edge computing to make context-based decisions and data-filtering actions. For platform-based approaches, digital product configurators may be employed in order to attain a degree of product co-creation. For data-driven smart product use, the onus is on the manufacturer to monitor usage (with usage data reported back to manufacturers) and design personalisation functionality into products [21]. Zhang et al. [21] propose an open architecture to formalise the co-creation opportunities provided by smart product
use, noting that opportunities exist for services to be developed around such products to enable energy-efficient usage and improved end of life/servicing/recycling, among other functionality potentially desired by customers.

The Product Service System (PSS) paradigm can facilitate co-creation activities between producers and consumers, especially when smart/intelligent products are involved [22]. The notion of green co-creation is explored by Chang [23], who examines the role of supply chain partners and consumers in achieving higher environmental performance of manufactured products. Roberts et al. [24] note that no formal performance indicators or metrics exist for co-creation activities, making it difficult for companies to gauge the value and effectiveness of such efforts, leaving the area open for further research. Sjödin et al. [25] make the point that there are barriers to co-creation, listing the following three concerns companies may have as: 'operational cultural resistance'—opposition to changes in culture from within the organisation; 'loss of operational know-how'—risk of losing competitive advantages based on sharing of proprietary company knowledge and potential outsourcing of corporate skills to third parties; 'risk of operational conflict'—confusion arising from a lack of clarity on the roles undertaken by the parties involved. When considering the form of co-creation platforms, the use of novel interaction media can further facilitate responses from customers. For example, Leclercq et al. [26] utilise a gamification metaphor to elicit responses in new product development scenarios; Augmented reality is examined by Alimamy et al. [27] as a way to interactively provide additional information on a product and options for product form manipulation to a customer; Cowan and Ketron [28] explore the use of virtual reality to provide consumers with an immersive experience for, among other uses, co-creation of products.

2.3. Additive Manufacturing—3D Printing

3D printing (or additive manufacturing) systems build components by depositing repeated layers of a substrate to form an object guided by a digital model (often in the form of a Computer Aided Design (CAD)), allowing for printing ‘on demand’ [29,30]. Cui et al. [31] provide an example case study from the aviation industry of prototype parts being printed on demand. This work also demonstrates the combined use of a cloud-based platform to allow for the remote invocation of 3D printing in a service-based mode [31]. The ability to produce exactly what is required by the customers lends this technology to the field of personalisation [32]. It is also the case that the ability to reduce or even eliminate waste can make this production route more environmentally acceptable than traditional production processes. In the medical products industry, extensive use of 3D printing can be seen, with examples such as delivery of personalised medicines [33,34]. Despeisse et al. [35] make the case for 3D printing as an active component in the achievement of the circular economy manufacturing practices. Involving the use of the distributed manufacturing model, the authors discuss the potential for the achievement of closed-loop material usage through 3D printing, and an agenda is set to help identify the barriers to further use this technology for circular production practices. In further research, Despeisse et al. [35] seek to understand the nature of supply chain linkages for materials under this production mode. One particular use for 3D printing in a circular economy context is reported by Ingemarsdotter et al. [36], involving the printing of parts to alter the appearance of a street lighting product, avoiding the need for complete replacement of the item. In the following section of this paper, the potential of 3D printing and the upcoming 4D methods (that incorporate smart materials and sensors within printed objects) will be expanded on.

2.4. Additive Manufacturing—4D Printing

As mentioned earlier in the paper, 4D printing utilises much of the 3D printing technology with the addition of smart materials and embedded sensors to provide ‘intelligent’ behaviours or functions within additively manufactured products. Biswas et al. [37] define 4D printing as the ‘evolution of 3D printing technology that allows 3D printed objects to change their shape, size, properties and function over time as desired by the consumer’. 
Biswas et al. [37] note that shape changes may include materials ‘bending, twisting, corrugating, and elongating’ in response to stimuli such as ‘temperature, moisture, light, electrical or magnetic fields’. Chen et al. [38] report the development of printed ‘smart’ and ‘stimulus-responsive’ materials via additive manufacturing, noting their particular application in the field of electronics, sensor development, wearable smart materials and robotics.

Zolfagharian et al. [39] investigate the area of soft robots (robots that independently react to stimuli and their environment though the localised use of edge processing and artificial intelligence) and the utilisation of 4D printing techniques in their production. Zolfagharian et al. [39] point to the future of increased sensor integration as new material types are devised for use in additive electronics manufacturing, a sentiment also expressed by Huang et al. [40], who argue for increased communication cooperation between printing and materials development industries. A future use of 4D printing is in the production of wearable sensors and devices that require flexibility and production parameters defined by individual customers of the resulting products [41]. However, it is still the case that even with recent developments in the technology, 4D printing is still far from commonplace in manufacturing, and still needs to mature as an accepted production practice [42]. Another printing technique known as 5D printing is now available. This approach employs additional degrees of freedom within the printer, as opposed to 3D and 4D technologies (‘mainly rotation of print bed and rotation of extruder head’), allowing for ‘concave shapes or curved layers with extreme accuracy and precision’ [43]. At this time, new uses for this mode of printing are being developed, though with the possibility of printable sensors and processing devices, flexible integrated edge computing may be a commercial reality in the near future. Presently, the 5D printing technique is specialised to products destined mostly for medical use and will not feature in the research of this paper.

2.5. Human Centric and Personalised Production

The opinion expressed in this research is that an agenda exists whereby human skills and knowledge, augmented by intelligent systems, may provide increased productivity required of high-volume producers, while emphasising human creativity and control in the manufacture of personalised discrete components or whole products. Both the manufacturing workforce and the participating customer base can be sources of valuable insights and inputs, providing one of the essential drivers behind the recent interest in human-centric production methods; although for true personalisation in a manufacturing context, the co-creation of design by the customer requires additional levels of sophistication in the digital interfaces they may encounter, to capture their needs as actionable parameters.

Use of the digital twin concept in relation to personalised products has been investigated by a number of authors [9,44–46]. Ramesh et al. [46] examines the notion of a ‘digital thread’ associated with information capture from the initial design of the products (with input from the consumer) to manufacturing and the after-sales maintenance and servicing of the product. Ramesh et al. [46] also propose a four-stage digital twin (DT): as designed—describing the initial co-design product; as planned—the design is then evolved into a manufacturable item with the generation of additional instruction parameters for production line systems; as built—describing the physical product as manufactured; as maintained—a model that collected use data from the field. Park et al. [45] also utilise a digital twin model to control a personalised manufacturing process within smart micro factory, noting three ‘hurdles’ to the achievement of ‘market of one’ goods: access—acquiring exact customer needs through appropriate communication interfaces; cost—increases due to the need for more sophisticated shop floor machinery; and performance—increased complexity and time taken in the manufacture of individually ‘tailored products’. This service-based approach aims to address the ‘performance ’ challenge posed by personalised production by defining four information classes in which production data can be categorised: product; process; plan; resource [45]. Sakowski et al. [47] argue that data exchange in the co-creation design and manufacture stages of personalised production is an iterative and cyclical process involving bidirectionality in communication. In recognising this dynamic,
Sakowski et al. [47] in putting forward a concept for information structuring highlight the challenge of integrating the supply chain into such a production process to help evolve product designs based on, for example, customer needs changing and manufacturability challenges encountered, ensuring that only feasible designs are proposed to the customer at every stage of contact.

Zhang et al. [21] make the case for swarm intelligence techniques to be used to capture multiple customer requirement and customised design parameters, recognising the need to map and transform such information before translation into a physical entity. Such an approach, as employed by Zhang et al. [21], could hold relevance for the capture of a single customer’s personal requirements along with supply chain design inputs and those of manufacturing engineers. Efforts to both codify and quantify the tacit knowledge responses of customers involved in co-creation activities are exemplified by works such as Wang et al. [48], who propose a knowledge network model capable of semantic description capture and weighting. Knowledge networks can also demonstrate interlinkages between pieces of information and their relative importance. This is especially beneficial when taking the process a stage further and filtering the network for actionable production development paths [48]. Mladineo et al. [49] make the case for the use of artificial intelligence techniques in developing ‘cognitive’ systems and interfaces that aid customers in configuring their purchases in a cost- and time-efficient manner. Ogunsakin et al. [50] take this approach further, addressing engineering challenges presented by last-minute co-created design changes initiated by customers in terms of the manufacturing facility layout; seeking to provide a self-organisation approach for the potential automated and perhaps autonomous physical rearrangement of the factory to produce the required products at short notice. Suginouchi et al. [51] also investigate the co-creation of personalised products and digital representation of the smart factory for their realisation; this author utilises 3D printing technology, a multi-agent smart factory model and combinatorial auction mechanism to enable the scheduling of tasks. These authors provide a scheduling approach for personalised production [51]. Xia and He [52], in their work on the design of a smart factory for personalised production, develop a case study involving the production of bicycles; a framework is put forward, focusing on the role of internet-based technology to integrate customer needs into the production process.

Industry 5.0 has been proposed as a recognition that automation efforts sought and achieved through industry 4.0 projects have often neglected the value of human participation in manufacturing and the environmental sustainability of the new technology and production practices as implemented [53]. This rebalancing in favour of social and environmental goals is seen as necessary to the future viability of not just manufacturing and industrial processes, but of key contributions to the achievement of wider sustainable development and goals set by global climate agreements. Industry 5.0 should therefore be seen as a departure from previous paradigms in addressing such vital needs on an international basis [54], including an evolution of Industry 4.0 technology and the way it is used [55]. Human–machine interaction technologies are seen as core enabling interfaces in the provision of a more human-centric manufacturing process, along with the development of digital twins and use of artificial intelligence [54,56]. Xu et al. [54] leave open the question of whether the existing Industry 4.0 technology is sufficient to deliver the human centrality of Industry 5.0, or if technology needs beyond the current functionality still exist. A further question is posed by this paper in that the systems needed to support personalisation may also require both hardware and software components not currently available to automated mass manufacturing practice.

2.6. Environmentally Sustainable Personalised Production

Tiihonen and Felfernig [57] highlight a number of gaps in personalised production research, with the most pertinent being the lack of a repository or search system to capture designs for personalised products and co-created designs generated with customers. Not having to ‘reinvent the wheel’ for each product could lead to lower costs and more effi-
cient and pleasing designs for the consumer, helping them to more readily select feasible solutions. A strong argument exists that highly customised and personalised products can lead to more environmentally sustainable production, in that products meet customers’ exact needs, and production models can shift away from production in anticipation of demand, leading to the increased potential of overproduction and unwanted production of goods. Gembarski et al. [58] make the case that all stages of the product lifecycle should be considered in terms of their sustainability, this includes waste minimisation at the production stage.

The rise of personalised production also challenges the need for large scale factories, opening up the prospect of micro production facilities. Park et al. [45] make the point that the latest manufacturing robotics and machines can be housed in small scale facilities. Jackson and Zaman [59] put forward the concept of ‘Factory in a box’, where the production machinery comprising a manufacturing cell is installed within a shipping container-sized space. Originally conceived as a way to bring low to medium volume high technology manufacturing to low-wage countries (via shipping containers), this concept may gain further traction with the move towards personalised production. Prendville et al. [60] also examine small-scale factory production methodologies through a study of ‘Makespaces’, which are local ‘Community-based digital fabrication workshops’ capable of realising designs through prototyping or a low-scale production stage, as well as acting as repair facilities. While Makespaces are best known as ‘hacker’ spaces, providing the incubation resources for experimental design and development of new technology, this methodology may provide impetus to personalised production, co-creation and a new methodology for R&D in this mode of production. Prendville et al. [60] host their work in wider distributed manufacturing movements, where larger monolith factories are broken down into smaller satellite facilities located in or near local customer bases within a national territory.

Small (physical location and environmental) footprint production as discussed above is of particular relevance to small and medium sized (SME) manufacturers. Torn and Vaneker [61] examine mass personalisation strategies for use with such SME producers, particularly that of collaborative manufacturing networks. Introducing the concept of tradable production facilities, the prospect of horizontal integration between manufacturers is realisable at the SME level in the work of Torn and Vaneker [61].

The achievement of sustainable production and circular economy goals through 3D printing is an active area for research. Kreiger and Pearce [62] explored the use of LCA (Life Cycle Assessment) to establish if polymer-based 3D printing used in a distributed manufacturing setup would prove to involve a lower environmental impact than with conventional manufacturing. This was found to be the case in the research, with reductions in greenhouse gases and energy use resulting from the combined use of additive and distributed manufacturing approaches. Turner et al. [63] also make the case for the dynamic population of LCA with data streams produced by intelligent products at different stages of their lifecycle.

2.7. Research Gaps Identified

Several gaps in the literature have emerged from the aforementioned survey. Both products and manufacturing production line machines are capable of providing data, though case studies and examples are still difficult to find in literature. New digital technology-supported interaction platforms are being developed along with more effective methods to identify and capture relevant customer parameters concerning product design. It is still the case, though, that holistic frameworks for the development of personalised products are rare in published papers and often do not cover the need for whole lifecycle consideration of manufactured goods and the minimisation of their impact on the environment.
3. Framework for Circular Production of Additively Manufactured Personalised Products

When considering the development of a framework for the additive production of personalised products, it is essential that the key information flows are mapped. In producing sensorised and intelligent products via a 4D printing process, the opportunity exists to leverage the information collection, processing and communication functionality that such goods inherently possess (though perhaps not always make full use of at present). In addition, it is the aim of this research to consider the circularity potential of this production method in terms of information described and communicated by the manufacturing process and the products themselves whilst in use with a customer. In Figure 1, the proposed framework for circular production of additively manufactured personalised products is shown. The framework uses as an example product, smart fabrics, with built in sensors to detect the following physiological and morphological changes in their human wearers:

- Core temperature;
- Pulse rate;
- Sweat;
- Walking pace and physical activity levels;
- Changes in morphology and strength due to age.

![Figure 1. Framework for circular production of additively manufactured personalised products.](image)

Smart fabrics, also known as 4D textiles, are fabrics that host sensors to sense the environment, processing elements to process the data obtained from the external environment and actuators to control and achieve a desired response. As a result, smart fabrics require an interdisciplinary approach that integrates electronics, microcontrollers and the use of advanced materials with novel mechanical, chemical and electrical properties. This requires that these elements are closely designed while taking each other’s inherent properties into consideration. In the future, such materials would be more integrated with senses and augment our natural abilities. Unlike current techniques that add sensors, electronics, microcontrollers and actuators onto existing fabrics after their manufacture, 4D printing will be integrated at the manufacture stage into order to achieve more integral designs,
and to be able to make use of this integral designs to achieve advanced and enhance functionalities [64]. For example, the morphology structure and property of the fabrics could enhance signal propagation between distributed sensors on the smart fabric. As can be seen in Figure 1, at point 1 already manufactured intelligent garments are providing real-time data streams describing physiological changes in their human wearers. This data can be filtered and captured in a knowledge base, as one factor to be used to inform the overall performance of materials in the printed garment. At point 2 the roundel (adapted from Biswas et al. [37]) describes the five core factors required to assess and further develop 4D printed materials for use in intelligent garment ranges. The factors are as follows:

- **Smart materials**—3D printed material that are able to change over time [37] and contain sensors and miniaturised (Edge) processing functionality;
- **Interactive response**—smart materials that are capable of measuring physiological changes such as the temperature of a human wearer of a garment, for example;
- **Mathematical modelling**—the degree and nature of the shape change of 4D printed smart materials may be predicted using such techniques [37], along with sensor outputs from the materials (when integrated in the materials);
- **Printing platform**—the type of printer used to produce the materials and its control by software based systems, whether it is 3D or 4D capable [37];
- **External stimuli**—exemplified by advances such as soft robotics, where smart materials aid the robot in working safely alongside a human worker [37].

The aforementioned factors produce data within the knowledge base, stored within the database component (shown at point 3 in Figure 1). The database component also contains processed information relating to the data collected from customers whilst existing products are in use. The AI algorithms are used to analyse such incoming data and make generalisations for use in the global development of existing and new product designs (shown at point 4 in Figure 1). Point 5 in Figure 1 introduces an interface module that allows for human input; this may take the form of decision support visualisations presented to manufacturing and supply chain component production staff, though interfaces may be provided to customers for product personalisation and co-creation at the purchasing stage of new products. As shown in Figure 1, Point 6 is the 4D printing facilities; again, these are software controlled and driven by the findings of the AI module with data inputs and human inputs (via the human in the loop interface). At the bottom right side of the framework, new personalised products are delivered to consumers (point 7 in Figure 1), with ‘in field usage’ data streamed back to the manufacturer and supply chain. The ability to recycle the personalised wearables used by the workers in such manufacturing systems becomes important due to worker mobility. Furthermore, the module 4 in Figure 1 enables in field usage data collected in module 1 to be reused in the worker’s new workplace.

### 3.1. Potential Information Flows Possible in the Framework—With Uses

As outlined in Figure 1, the framework accepts and processes a wide variety of data sources. When examining the complex functionality enabled by the framework, the following individual information flows are of particular interest:

- **Sensor data:**
  - Produced by Wearable sensors.
- **Human in the loop:**
  - Customer interactions—personalisation and product co-creation.
  - Worker interactions—decision support, decision verification (where automated), ergonomics and factory worker safety.
- **Reuse, remanufacture, recycling:**
  - Inclusion of new processes for reuse, remanufacture, and recycling;
  - Product ‘in use’ health data (product maintenance purposes);
  - Inclusion of new materials and their relationship with Reuse, remanufacture and
recycling decisions.

- 4D printer:
  - Optimisation potential of design and printing process used to form product based on real time manufacturing status feedback from the printer;
  - Monitoring of materials and energy use in real-time.

### 3.2. Data from Wearable Sensors for Use in the Redesign of Manufacturing Activities

Currently, wearables such as smart watches are used to collect vital data in normal daily activities, such as: heartbeat, ECG, carotid pulse, respiration, breathing pattern, skin temperature, skin impedance and physical activity. This enables users to plan their activities and ensure that they stay active in daily life. The added advantage of this is the reduction and potentially prevention of the onset of chronic diseases. Research exists that also looks at how they can be used to inform ergonomics, data collection and help in prevention of injuries in manufacturing systems that involve extensive manual activities. For example, in Oyekan et al. [65], the authors introduced a cognitive framework together with wearable sensors that support engineers and workers in an aerospace manufacturing system. Shown in Figure 2, the CAWES (Cognitive Architecture for Wearable Sensors) is based on the application of the ACT-R framework [66] to develop a data fusion pipeline for data streams from multiple wearable sensors.

![Figure 2. CAWES architecture—A Cognitive Architecture for Wearable Sensors (CAWES).](image-url)
3.3. Human in the Loop

In an age of AI and highly automated production, the question is posed whether human inputs are no longer required for much decision making on the factory floor. However, it is the case that there are limits to automation, and human skills and knowledge are not just useful to manufacturing enterprises, but in fact essential [67]. The range and depth of knowledge provided through the analysis of sensor data derived from wearable sensors whilst in use requires the need for the integration of human decision making and assessment skills. This is particularly pertinent for decision making regarding manufacturing activities and the development of new products. The ability to streamline and explain automated actions implemented by AI-enhanced systems is paramount if human workers are to integrate their own knowledge and skills as a joint enterprise with automation solutions. In delivering meaningful human machine interactivity, the correct interface needs to be selected and developed. Müller [68] highlight the following software enabled interfaces for human machine interaction:

- Brain—machine interface;
- Speech and gesture recognition;
- Artificial intelligence that enhances human creativity, analytical and decision making skills;
- Digital twin and simulation;
- Causality based AI.

The last interface mentioned by Müller [68] utilises causality-based AI; such an interface may be realised through the use of Explainable Artificial Intelligence (XAI), a technology that allows black box operation AI approaches to provide human legible explanations on how automated decisions or reasonings have been arrived at [69]. It is this technology that holds the most promise in enabling human workers to remain in, or enter, the increasingly automated decision-making loop. The digital twin and simulation systems, now in common use as components in factory floor operation and planning systems, provide a visualisation metaphor to be used with XAI. It is also possible to envisage XAI as a stage gate process flow, composed of annotated steps taken by AI systems with the possibility even of capturing and integrating the tacit knowledge of workers, perhaps further helping to enable the systematic support of Nonaka’s tacit knowledge creation and conversion cycle [70]. Such integration of the human in automated systems is necessary as decisions regarding environmental factors, inherent in the implementation of circular economy approaches in manufacturing, are often complex and involve consultation with multiple stakeholders and the knowledge and parameter sets in their ownership.

3.4. Product and Materials Reuse, Remanufacture and Recycling

Fine grain control over materials use is now possible with the production of intelligent products through production line reporting, in use tracking of products and their maintenance needs and improved matching of products and their constituent parts to appropriate end of life strategies. The change in ownership models to a service based ‘rental’ structure [35] may also improve the ability of manufacturers to select appropriate treatments at end of consumer use of a given product, potentially allowing increased reuse and repurposing of returned goods and a decrease in the need to remanufacture and recycle (both options requiring resources and/or energy over the reuse option). Products are able to report on their maintenance needs allowing for prognostic treatments to be made before the product breaks, with the possibility to reuse or remanufacture worn parts, avoiding the need to dispose of the entire product due to failure and so lengthening its lifespan [71]. The identification of new manufacturing processes and availability of new materials is a time-consuming task. In codifying both manufacturing processes and materials composition within a knowledge base and dynamically combining this data with live streamed evidence of how both perform in real life, the possibility exists for improved support in making the decision of when to develop and launch new products supported by AI enabled data and semantic text mining approaches.
4. Discussion

In Figure 3 the anticipated future developments in 3D and 4D printed smart fabrics are shown in terms of the research agendas relating to Personalisation, Circularity and Human Centric manufacturing. From the current era, with wearable sensors as add on modules to textiles, to the introduction of 4D printed active smart textiles [64] it can be seen in Figure 3 that the focus will shift to the extension of the usable lifespan of products and prediction of the longevity of the constituent materials and feedback of in-use data to inform the development of the next generation of products. The sensors themselves will eventually be integrated into the materials and will be either separable at end of life or recyclable/re-manufacturable. Similarly electronics and processing capability will become printable by 3D technology in the form of ‘soft’ electronics. With current developments in wearable sensors there exists a potential wealth of data for use by manufacturers. The integrated electronics in intelligent textiles will be able to provide a range of sensing capabilities and with on-board Edge processing may be able to provide XAI annotated data streams to both users and manufacturers. It may also be possible for a part manufactured intelligent textile to partake in it’s own construction and configuration (from an information exchange standpoint), enabling the printer to take configuration and positioning data from integrated sensors within the products as they are being printed or later on in manufacturing and supply chain logistics. Active 4D printed fabrics with shape changing abilities, when coupled with soft-electronics could provide a new level of intelligent fabrics and clothing that is capable of dynamic shape change abilities depending on real time sensing of the wearer and their usage patterns. Such a combination of functionality could also have potential application within medical textile uses such as active bandages and muscle/joint supports worn by patients and health/fitness users.

![Figure 3. 3D/4D printed smart fabrics Development with implications for Personalisation, Circularity and Human Centric Manufacturing (adapted from Lancos et al. [64]).](image-url)
product personalisation interface to capture users’ needs. Along with the ability of smart textiles to convey their usage pattern to the manufacturer, this would enable a customers need to be better understood, and with the use of AI, the generation of new product design suggestions to present to a consumer when they either purchase a new product from the manufacturer or ask for their existing purchase to be repaired or updated. In terms of question 2, it is put by this research that the skills and knowledge of the human worker should be augmented with technology in many cases rather than replaced. This is the case in that the framework for circular production of additively manufactured personalised products (Figure 1) ingests data streams collected and processed by the CAWES architecture (Figure 2) in order to provide AI recommendations to both workers and users (supported by XAI-derived justifications and explanations of the decision proposed by a software implementation of the framework).

In answering question 3, this research has found that in the case of smart data streams, such as those relating to the dimensions of the customer and usage patterns, can be collected. The recent availability of appropriate sensors capable of detecting parameters such as garment shape change, environmental conditions and tension with-in field usage of the product can be utilised to influence the maintenance of existing items and the development of new designs. In collecting data globally from customers, the database could even provide, through AI, the ability to suggest new product design choices and scenarios to both manufacturers and consumers alike.

5. Conclusions

In harnessing the latest Industry 4.0 digital manufacturing and sensing technologies along with 3D and 4D printing technology, a new level of personalisation in the production of products is now within reach. With such developments, it is also now possible to evaluate and track the environmental impact of products whilst in use. In realising circular economy ambitions the ability to provide wearable sensors and intelligent textiles provide a new level of information for manufacturers and functionality for consumers, though industry must be cognisant of the need for environmental solutions for electronics waste and the need for greater reusability, recyclability and re-manufacturability in this sector. Industry 5.0 set out a challenge of how to reintegrate human workers into the production process and harness both the knowledge and skills to provide the next generation of intelligent circular economy-compliant products; the data streams possible now and in the future provide a new range of opportunities to realise human centric manufacturing ambitions.

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References


22. Liu, Z.; Ming, X.; Song, W.; Qiu, S.; Qu, Y. A perspective on value co-creation-oriented framework for smart product-service system. Procedia CIRP 2018, 73, 155–160. [CrossRef]


24. Roberts, D.L.; Palmer, R.; Hughes, M. Innovating the product innovation process to enable co-creation. RD Manag. 2022, 52, 484–497. [CrossRef]


63. Turner, C.; Oyekan, J.; Garn, W.; Duggan, C.; Abdou, K. Human Centric Manufacturing in the Circular Economy: A new Agenda for Intelligent Products in Industry 5.0. *Sustainability* 2022, 14, 14847. [CrossRef]


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