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Manufacturing in the cloud: A human factors perspective

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ABSTRACT

Cloud manufacturing adopts a cloud computing paradigm as the basis for delivering shared, on-demand manufacturing services. The result is customer-centric supply chains that can be configured for cost, quality, speed and customisation. While the technical capabilities required for cloud manufacturing are a current focus, there are many emerging questions relating to the impact, both positive and negative, on the people consuming or supporting cloud manufacturing services. Human factors can have a pivotal role in enabling the success and adoption of cloud manufacturing, while ensuring the safety, well-being and optimum user experience of those involved in a cloud manufacturing environment. This paper presents these issues, structured around groups of users (service providers, application providers and consumers). We also consider the issues of collaboration that are likely to arise from the manufacturing cloud. From this analysis we discuss the central role of human factors as an enabler of cloud manufacturing, and the opportunities that emerge.

1. Introduction

Cloud computing offers ubiquitous, on-demand access to shared computing resources that can be rapidly released with minimal effort or service provider interaction (Mell and Grance, 2009). It is most commonly encountered in the use of cloud-based servers where data is no longer stored locally on a dedicated machine, but 'in the cloud' on 'rented space' on remote, distributed servers. Many organisations, including those within the manufacturing domain, now use these external providers as their main mode of data storage and transfer. In addition, cloud computing supports the 'software as a service' (SAAS) model (Armbrust et al., 2010), allowing organisations to move from hosting their own software through to using a shared pool of applications that are hosted, managed and maintained remotely by third parties. This approach can hugely reduce maintenance costs and logistics associated with upgrades, and has been adopted in manufacturing through systems such as cloud-based Enterprise Resource Planning (ERP) applications (Lenart, 2011).

The notion of cloud computing applied to manufacturing is set to evolve with the emergence of cloud manufacturing (Rauschecker et al., 2011; Tao et al., 2011; Xu, 2012; Wu et al., 2013). Wu et al. (2013) define cloud manufacturing as "a customer-centric manufacturing model that exploits on-demand access to a shared collection of diversified and distributed manufacturing resources to form temporary, reconfigurable production lines which enhance efficiency, and reduce product lifecycle costs" (p. 565). Cloud manufacturing moves beyond the idea of simply using cloud computing resources within a manufacturing context, proposing the use of remote, virtualised manufacturing resources, and the sharing of a single manufacturing resource between multiple users, thus delivering 'Manufacturing as a Service' (MAAS) (Rauschecker et al., 2011). In this manner, manufacturing services, including design, simulation and other knowledge-based processes (Tao et al., 2011), can be used on a 'pay-as-you-go' basis.

This new manufacturing paradigm aims to provide heightened levels of quality and value for consumers of manufacturing services, and allows manufacturing service providers to engage in new, flexible arrangements leading to better utilisation of capabilities. It also allows consumers to use third-party manufacturing services without the upfront capital expenditure costs that might otherwise prove prohibitive.

These changes require technical innovation and process change, such as new skills and knowledge to support high flexibility production and assembly, new requirements for user interfaces and user experience of those interacting with cloud manufacturing technology, new forms of technology-mediated collaboration across the supply chain, and a shift in the role of the 'customer' of

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products as their requirements and usage patterns have a more direct influence on design. The individual and integrated effects of these changes on the distributed cloud manufacturing system are, as yet, unknown but are areas that human factors as a discipline is well placed to address.

In this paper we examine the human factors challenges presented by the adoption of cloud computing paradigms within the manufacturing context. We identify the different design and implementation challenges presented by these new forms of work and production and, where possible, suggest existing knowledge or approaches that could be used to address these challenges. This analysis identifies a set of research issues that must be addressed, and principles to be followed. These principles are necessary for the benefits of cloud concepts within manufacturing, and on resulting products, to be realised to maximum effect whilst maintaining a healthy, safe and effective work environment. By providing a structured, multi-user view of human factors issues, this paper contributes a framework for successful, human-orientated cloud manufacturing implementations, and sets out a research agenda for future human factors work within this domain.

2. Human factors and manufacturing in the cloud

Cloud manufacturing is defined as a relationship between the consumer and a flexible array of production services, managed by an intervening architecture that can match service providers to product and manufacturing processes (Tao et al., 2011; Wu et al., 2013; Xu, 2012; Macia-Perez et al., 2012). Cloud manufacturing definitions typically make explicit or imply three groups of actors: *consumers*, who request and use cloud manufacturing processes; *application providers*, who provide the software to enable the manufacturing cloud and associated ICT, and *service providers* who provide, own and operate the manufacturing services. This is represented in Fig. 1.

Through standardised descriptions of products, processes, tooling etc., used to match product requirements to service providers' capabilities (Xu, 2012), product requirements are mapped to a temporary supply chain. While consumer requirements will include product specifications, they may also include specifications of quality, cost, speed of delivery or specific organisational requirements (e.g. for security in cases of products with high commercial sensitivity or military products) (Tao et al., 2009). Likewise, service providers would express their capabilities not just in terms of their ability to physically manufacture products, but also in a number of other criteria relevant for effective supplier matching, such as availability or cost.

If a high number of manufacturing service providers are encouraged to register and engage with the manufacturing cloud, and it is in the interest of the application providers to make this entry process as easy as possible, there is the potential for consumers to be offered choices from a huge and rapidly configurable array of available suppliers. It is also possible that configurations will be nested. For example, a provider of a sub-component for a customer may need underpinning capabilities such as design or simulation services (Wu et al., 2013). For complex products, it is therefore conceivable that there are many layers of manufacturing clouds.

The notion of cloud manufacturing will inevitably change how people work in a manufacturing setting, how they interact within and between organisations, how producers and production lines need to adapt to fit the demands of this new environment, and how effective product design can be maintained and even enhanced within cloud manufacturing. Manufacturing will become more distributed, providing opportunities for rapidly sourcing production facilities. This new model of sharing manufacturing resources throughout the production lifecycle represents a step-change in the nature of manufacturing operations. Many of these developments have implications for how people work, how decisions are made, and how organisations will collaborate and communicate. We would consider these to be human factors challenges. Some of these critical developments that fundamentally change work and work systems are discussed below.

2.1. Concept of decentralisation of services

Cloud concepts in principle move away from a single, all-powerful, service provider to enable a combination of distributed systems. Ironically, the way in which this is so far implemented in

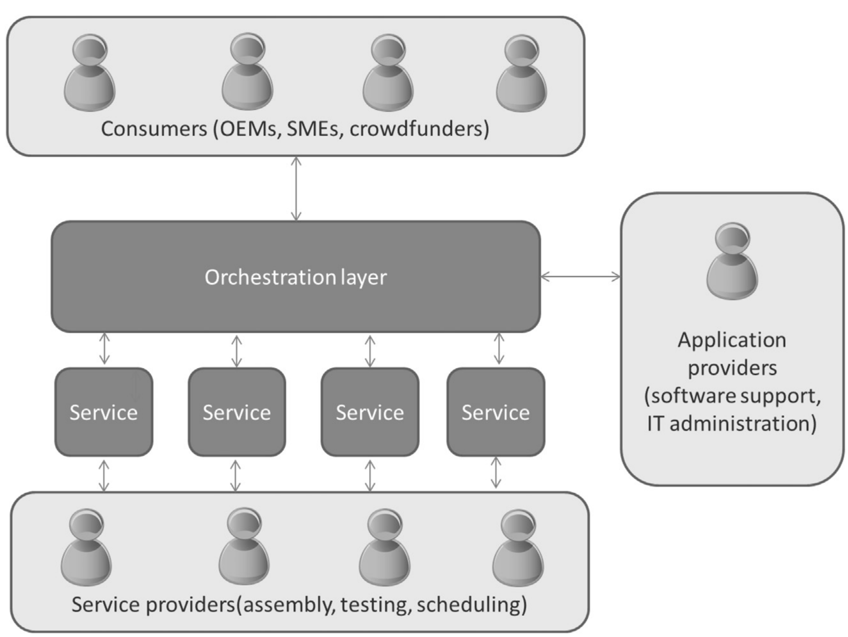

Fig. 1. Schematic of users in relation to simplified Cloud Manufacturing architecture (OEM – Original Equipment Manufacturer; SME – Small to Medium enterprise).

cloud computing is that several major organisations, such as Amazon and Google, own the majority of these servers, so whilst the data is physically distributed, its ownership is not. Also, whereas the transport of *data* from a remote point to a customer is nearly instantaneous, the transport of *products* or *components* requires an appropriate and efficient supply chain and logistics network (Christopher, 2012). The complexities of this network therefore need to be made visible to users of cloud manufacturing to inform decision-making, and immediate and straightforward transfer of resources cannot be assumed.

2.2. Concept of shared resources

Cloud computing is based on notions that function and capabilities are drawn from a pool that can be shared or 'booked' as required (Mell and Grance, 2009). This means it is the cloud application provider that is responsible for maintaining and updating sometimes specialist software, taking that cost and the need to have expertise in complex software and process away from the consumer. Applied to manufacturing, actors within the supply chain will be able to share tools and resources. This allows spare time on a specialist manufacturing machine to be 'booked', with the implication that a smaller customer could have access to specialist equipment which would be prohibitively expensive to own outright (Tao et al., 2011). This opens up opportunities, but there may also be issues associated with confidentiality – if a computer aided-design (CAD) specification is sent to a remote machine for production of a part, how is that CAD specification transmitted and stored locally on the machine? Communicating the location and permissions associated with this data is a crucial aspect of human-computer interaction of security and trust (Iachello and Hong, 2007). Also, the service provider may need to change its processes rapidly to meet different production demands, requiring new levels of knowledge about production requirements and adaptation on the part of production/assembly line operators, rather than in non-cloud scenarios where the nature of tasks may be more predictable, practised and routine. This may bring about issues of training, skills and workload.

2.3. Concept of collaborative use of data

Typically within manufacturing, as in other contexts, data can be an important component of intellectual property and is perceived to have business value (Golightly et al., 2013). The cloud computing concept can encourage data sharing. This can be through 'open data', where large sets of data, such as climate data, health services data, and geographical data are shared and distributed. This can also be 'open source' where communities of coders work to develop and enhance code collaboratively and freely distribute the code to allow others to use it. Further investigation is required as to how these concepts transfer to the manufacturing domain, given (a) the need for multiple stakeholders to adopt interoperable standards and (b) again, issues around trust, security and motivation to share potentially sensitive product data.

2.4. Concept of the lifelong contextual footprint

The increasing presence of sensors and tracking technologies enable us to maintain traceability of materials and products during and beyond manufacture. This concept is already implemented in high value manufacturing contexts such as aerospace, where sensor and tracking technologies enable detailed analysis of the behaviour of components such as aero engine blades over their lifetime. Sensored data can also have benefits in the organisation of flexible assembly environments for tracking components and assemblies (Huang et al., 2007). Cloud manufacturing offers the potential to extend this long-term tracking and analysis to more high volume products. For example, the manufacturer of a domestic appliance such as a washing machine can track the wear of materials and manage supply of replacement parts by interpreting information about frequency and types of washes. It also presents challenges in terms of presentation and distribution of performance data (particularly when different parts and components within the system have not only been produced by different machines but also when an individual part may have been produced by different, distributed machines) as well as the management of large data sets – known to be a typical 'big data' challenge.

2.5. Relevance of human factors

Some of the challenges presented above have been anticipated by early work in cloud manufacturing, with a clear acknowledgement of the importance of fostering trust within cloud networks. Other issues, such as Human-Computer Interaction (HCI) (Wu et al., 2013) and the quality of service of cloud technology (Xu, 2012), have also been highlighted, but these issues are not yet presented within a coherent user-centred framework. Such a framework would be useful when considering systemic approaches to the deployment of manufacturing clouds and associated technologies.

We also argue in this paper that the changes outlined above will have other socio-technical implications within future manufacturing. For example, a typical manufacturing supplier would normally have to go through a process of producing samples, undergoing quality checking and developing a personal customer-supplier relationship that has value for establishing trust, communication behaviours and ensuring the sustainability of the relationship (British Standards Institute, 2010). Understanding how this traditional manufacturer-supplier relationship translates to the context of cloud manufacturing, and its impact on the processes and technology for collaboration (Patel et al., 2012) is critical and as yet unknown. Also, cloud manufacturing offers not only a physical decentralisation of manufacturing, but potentially a democratisation of production, with a greater range of consumers able to request products on a customised, and even crowd-funded, basis. This has implications for common conceptions of user requirements of products, and how users may own their own design-related data, either when it is captured explicitly or monitored through their existing products. The impact and ethics of sensor-based user data, and 'big data', has pressing implications for human factors as a discipline (Sharples and Houghton, 2016).

In the following sections we present the issues and opportunities that are likely to affect people and work under a cloud manufacturing regime. While the cloud manufacturing model is radical taken in its entirety, many of the innovations that comprise cloud manufacturing are more incremental, or have equivalents elsewhere. For example, the notion of highly distributed manufacturing processes is not new, with pre-existing human factors-related work in areas such as the management of collaboration (Patel et al., 2012) or knowledge management during concurrent manufacturing (Shadbolt and Milton, 1999). Cloud computing itself is an increment on a number of technology developments (Rimal et al., 2011). However, the speed and flexibility with which services are reconfigured is likely to be fundamentally different from what has gone before. Therefore, part of the effort to understand the human factors implications of cloud manufacturing is to identify where knowledge already exists, where that knowledge needs to be adapted to meet the new capabilities of cloud manufacturing, and where new research is required.

A critical concept when considering human factors in relation to the manufacturing cloud is the notion of being 'user-centred'. This encompasses two fundamental elements – first, to put the needs and abilities of the technology users at the heart of the system and, second, to explicitly represent and involve the user within the design process (see Gulliksen et al. (2003) for a more detailed breakdown of principles and processes associated with User-Centred Design). In a system as complex as cloud manufacturing it is vital to not treat the user as a single, generic entity. There are many roles that are impacted by cloud manufacturing, and all of these need representing, whether that is in terms of the design of human-computer interfaces that users interact with to order products, new ways of working that people need to adopt for collaboration, or new tools and production techniques that they will work with to achieve product delivery. In this regard, User Experience (UX) is an important framework to bring to cloud manufacturing. The philosophy of UX highlights the importance of both context of use, and of specific users, with their needs and preconceptions (Law et al., 2009). UX covers not only the instrumental (practicality, usability) aspects of interaction with a product or service, but also the experiential, the affective and aesthetic elements of interaction (Hassenzahl and Tractinsky, 2006). Credibility, another facet of user experience (Moreville, 2004; Rosenbaum et al., 2008), would appear to be closely aligned to the issues of trust already identified.

To emphasise the importance of a user-centred, as opposed to technology-centred, approach within cloud manufacturing, and the differing needs of users and contexts, we structure human factors issues according to the three groups of actors defined by Wu et al. (2013): manufacturing service providers (Section 3) (we prefer this term to Wu's 'Physical resource providers' as knowledge and design processes are just as relevant as physical processes), application providers (Section 4), and consumers (Section 5) (we prefer this term instead of Wu et al.'s 'users' to avoid confusion with other types of users in the manufacturing cloud). As cloud manufacturing is a complex system, and changes at one point are likely to have widespread implications, attributing issues to groups of roles is not exact. Issues have been classified in terms of who is most likely to experience the consequence of the issue, or has direct responsibility for addressing the issue. Finally, a number of issues such as trust and collaboration, which, by definition, are concerned with communication between different roles, are considered from an overall systems perspective (Section 6).

3. Manufacturing service providers

We start by considering the impact of cloud manufacturing in terms of those users who will be involved in providing manufacturing services. Responsive manufacturing service provision is predicated on a number of developments on the service provider side that allow the production/assembly line to reconfigure to new demands. While these developments are not unique to cloud manufacturing, the need for manufacturers to deliver the levels of quality and flexibility required from being present on the manufacturing cloud may hasten their introduction. These developments could have a significant impact on the organisation of work, and integration of work and technology.

3.1. User-centred automation for production

Automation is a critical enabler of the cloud manufacturing paradigm (Wu et al., 2013), and can take a number of forms – robotics on the production line, automation of processes, and adaptive scheduling and resource allocation to meet the needs of multiple products and consumers generated by the manufacturing cloud (Onori et al., 2012). There is a traditional HCI perspective on this, in that all of these elements of automation will need input, monitoring and, at some stage, intervention. The presentation of production line data within the service provider needs careful design and implementation to address the usual ironies of automation (Bainbridge, 1983). For example, there is the potential that automation is being used to reconfigure processes using algorithms that are too complex for humans to execute effectively (e.g. Tao et al., 2011), yet a human is likely to be called in to assess whether the automation is performing as required. Importantly, these algorithms may be of such complexity that it is not simply a question of whether the output can be understood, but whether it is fundamentally accessible in the first place, or whether aspects of the automation can only be treated as a 'black box'. While people may develop implicit understanding of such systems, the ability to express and consciously manipulate knowledge about such systems is notoriously difficult (Berry and Broadbent, 1988) and needs to be carefully considered when presenting representations of system state and automated decision-making progress to operators.

Successful human-automation cooperation applies not only to production but also to the scheduling of assembly and manufacturing systems at a tactical level. Despite efforts to date to automate production scheduling, the human still has a critical role to play in translating constraints and requirements that lie beyond automated input (Jackson et al., 2004; Cegarra, 2008). Human-robot integration is also likely to play a greater role on the production line (Yoon et al., 2012), introducing yet another layer of automation, with Charalambous et al. (2013) noting the importance of understanding the factors around acceptance for robotics in future manufacturing environments. It is worth considering that robotics is also undergoing its own cloud revolution (Goldberg and Kehoe, 2013), where robots will share data and learned outcomes to enhance performance. Therefore, it needs careful consideration as to how networked and cloud-based performance updates are communicated through to those tasked with assessing the effectiveness of robots on production lines. Finally, from a safety perspective, the introduction of smart factory technologies that allow sensing and spatial coordination of components, workstations and operators, may also have safety benefits through proposing when operators are at risk from collision with automated equipment or are in proximity to dangerous processes (Yoon et al., 2012). If such sensors are reliable then we can move beyond the 'robot in a cage' scenario so often seen in manufacturing contexts, and begin to develop truly collaborative human-robot systems.

These kinds of developments are areas where implementation has been problematic historically because of an oversimplification of the design task as a function allocation problem (Fuld, 2000). The complexities of automation lie not in the presentation of the human-machine interface but in understanding the nature of the joint cognitive system that is to be controlled by automation (whether that be production optimisation, robot, or scheduling assistant) working *with* the human operator. Hollnagel and Woods (2005) exhort future designers in taking a cognitive systems engineering approach, and human factors can play an active role in capturing performance-shaping characteristics along with understanding the contextual factors that shape expert performance. Klein et al. (2004) present a set of challenges for automation as a team player, that can be used as principles for effective automation deployment. Alternatively, an Ecological Interface Design (EID) approach (Vicente, 2002) can be pursued. For example, Upton and Doherty (2008) present the application of EID within production scheduling. Decision-support for all aspects of manufacturing needs to respect the nature of expert problem solving, utilising external representations of problem spaces in a manner that supports forward-chaining, computational offloading (Scaife and Rogers, 1996) and the application of heuristics (Hoc et al., 2014).

3.2. Product variation and operator skills

Despite the introduction of robotics, many assembly and production lines still involve some human work to a greater or lesser extent. While product variability can be a welcome source of variation and change, it offers complexity to the production environment. Product variation may require decisions around part, fixture, tool and assembly procedure choice and as complexity increases, quality and performance tends to decrease (Zhu et al., 2008). There is general evidence that physical workload has a complex relationship with cognitive performance, with some physical demands enhancing performance, but greater demands or more complex cognitive tasks have been associated with negative effects (Perry et al., 2008). This effect may apply specifically to assembly, where mixed model assembly as a source of cognitive complexity may increase subjective cognitive demands, particularly when coupled with a physical demand such as difficult working posture (Shaikh et al., 2012).

Production must therefore manage complexity in a manner that optimises human skills and knowledge, without negatively impacting workload and performance. In part, this requires designing workstations to accommodate product flexibility in an ergonomic manner (Bautista and Cano, 2008), but it also requires the development of accurate models that link physical and cognitive demands (Marras and Hancock, 2014). In addition, organisational policy can mitigate the effects of reduced quality that might arise from assembly variability by resisting the urge to use temporary staff, particularly in upstream build activities, as opposed to downstream testing activities where the quality impact may be minimal (Stratman et al., 2004).

4. Application providers

While cloud manufacturing is more than just cloud computing applied to manufacturing, advances in ICT are still major enablers of cloud manufacturing. Underpinning the cloud manufacturing vision are developments in enhanced ICT-based communication such as standards or ontologies for specifying products or service capabilities, and automated orchestration of supply chains. These are most likely to be the responsibility of the application providers delivering the ICT capability and management services for the manufacturing cloud (Tao et al., 2011; Wu et al., 2013). Therefore, application providers will have primary responsibility for ensuring the usability and utility of enabling services.

4.1. Quality of service and user experience

One critical issue for software and services provided through the cloud will be Quality of Service (QoS) (Tao et al., 2009). With cloud technology (or Software as a Service) the aspiration is that technology can be developed centrally, but then distributed to all users on a thin-client basis, in the expectation of rapid exchange of data between client and server (Wu et al., 2013). In practice, this places certain constraints on the user interface that can be developed in terms of both the functions that can be supported via a cloud/thin-client architecture, and in terms of network quality of service (e.g. system response, continuity of connectivity) (Duan et al., 2012). In human-machine interfaces where action and feedback must be tightly coupled, the cognitive cost of system response can fundamentally alter strategies and resultant performance (Golightly et al., 1999). This is likely to be most apparent in applications that require complex interactions or displays at the user-end, such as CAD systems or visualisations for product configurators. Also, the QoS on the cloud could vary depending on the requirements of the consumer, who may accept a lower QoS for a lower cost (Yi et al., 2012).

Going beyond this, the providers of the technology that empower the manufacturing cloud will be responsible for User Experience arising from any software tools. It will be critical for providers of software to consider the different types of user, particularly consumers, that will interact with the manufacturing cloud. Consumers are likely to be varied in their needs, expectations and experience with using technology ranging from specialist procurement teams within large organisations to individuals working in SMEs, or even private consumers of products. It is incumbent on the application providers to actively involve potential users in the design of technology to make sure it is not only fit for purpose but also, particularly for public consumers, offers a service that is findable, engaging and trustworthy. To that end, frameworks such as the widely adopted User Experience Honeycomb (Moreville, 2004) may point to the characteristics that application providers need to embed within their services. For evaluation, Tolia et al. (2006) propose a series of metrics for evaluating user experience with thin-client applications. This could be taken forward as a set of metrics that are specific to cloud manufacturing technologies, complimenting more general evaluation approaches such as the Technology Acceptance Model (Venkatesh et al., 2003).

4.2. Visibility and mental models

A further consideration for the application layer is one of mental models (Wilson and Rutherford, 1989), and the perception of cloud services as made visible through the application layer. Consumers of cloud computing services are often unaware of who is hosting what service, and where – all they perceive is the end functionality. For other users, perceiving the mechanisms of the cloud is critical, again when considering issues of trust and tracking IP (Gillam et al., 2013). Such issues are likely to be mirrored in the manufacturing cloud. For example, a consumer requesting a low-risk, low-value product may take a more laissez-faire attitude to selecting a supply chain, being orientated purely around cost, as opposed to the producer of a high-value, high-risk product (e.g. aerospace). This will differ again for cloud systems administrators who need a high degree of situation awareness of both the configuration of services, and of the performance of the technical architecture (e.g. servers etc.) that are providing the cloud manufacturing system (Barrett et al., 2004). Human factors can contribute both methods for eliciting those models (e.g. Langan-Fox et al., 2000), and to ensure those models are appropriately represented to the user.

Data security is also an issue that faces cloud computing generally (Armbrust et al., 2010; Ryan, 2011) and has proved the primary barrier to widespread adoption of cloud services. While there are many technical aspects to cloud security to be considered (see Subashini and Kavitha, 2011 for a review), concerns around security are heightened in the area of cloud manufacturing (Xu, 2012) because of the value of proprietary data and intellectual property relating to product design or value-adding manufacturing techniques. For some domains, such as defence manufacture, this might have a national security aspect. Organisations operating within a collaborative approach such as cloud manufacturing must convincingly demonstrate the security of data exchange and storage using appropriate and understandable terminology in order for individuals and teams to have trust in this security (Patel et al., 2012). This selection of terminology is not a straightforward task, as has been demonstrated in recent cases regarding attitudes towards personal data, such as the care.data implementation in the UK (Hoeksma, 2014). By making sure the HCI design of cloud systems is salient, and role-appropriate, the application layer will demonstrate effective security management (Iachello and Hong, 2007) and, therefore, theUX characteristic of credibility (Rosenbaum et al., 2008).

Linked to the above point, organisations vary in their levels of knowledge and competence when adopting cloud computing, and it is likely that similar problems will be encountered when adopting a cloud manufacturing approach, as this involves both new approaches to manufacturing *and* the adoption of new technology. These issues are most acute with SMEs and micro organisations who may have very limited competence and capacity outside of their speciality (Golightly et al., 2015). One issue for them may simply be being aware of cloud manufacturing services and the opportunities they present (the UX characteristics of 'findability'). Werfs et al. (2013) provide a model, based on a socio-technical systems approach, to understand strategies to effective cloud computing adoption with SMEs. A strategic aim for the cloud manufacturing community would be to use this kind of framework to ensure the engagement process and tools are in place to lower the barrier of entry for potential suppliers and consumers. Human factors can contribute by understanding levels of knowledge and competence for users, and designing user interfaces for application services that appropriately reflect this knowledge.

4.3. Expressing human capabilities

Primarily, cloud manufacturing software is tasked with taking descriptions of manufacturing services and matching these to product descriptions from consumers. While standards exist for the mapping of product characteristics, it is as yet unclear how non-technical aspects such as trust or organisational skills can be represented in ontologies and decision-making processes. For example, Zhang et al. (cited in Xu, 2012) visualise manufacturing capability as comprised of four dimensions - task data, resource data, participator data and data regarding operator knowledge. While this provides a high-level categorisation, the framework for specifying operator knowledge in particular, is not yet defined.

Techniques from the knowledge engineering community may play a role here. In the late 1990s and early 2000s, there were efforts to formalise many aspects of knowledge and skills (Milton et al., 1999) which included techniques, both as processes of elicitation (e.g. critical decision method; Klein et al., 1989) and models (e.g. hierarchical task analysis (Shepherd, 2015)) that are common practice for the human factors community, and could be brought to bear on specifying and populating models of operator knowledge and skills.

5. Consumers

The principle motivation for the cloud manufacturing approach is to provide greater responsiveness to customers – faster, more cost-effective production of goods based on specific requirements generated by the customer. While the consumer in this setting has been typically viewed as an Original Equipment Manufacturer (OEM), the opportunities offered by decentralised and shared services means a far greater range of people could take the role of manufacturing consumers.

5.1. Expressing requirements

One of the core concerns of human factors is to support and promote a full user-centred design process that includes incorporating user needs and active user participation (Gulliksen et al., 2003). Therefore cloud manufacturing is of potential interest to human factors because the flexibility with which manufacturing services and products can be procured offers new opportunities for closer coupling between a user's requirements and the final product. Specifically, the power of cloud manufacturing may lie in addressing the needs of customised production (Rauschecker et al., 2011). The flexibility of cloud manufacturing allows these requirements to be much more varied, reflecting any number of variants on a central product theme, in line with the principles of mass customisation (Simpson, 2004), allowing the supply chain to keep pace with ever-changing customer information and requirements.

Such a process assumes that customer information is readily available. The evidence, however, is that there is an overemphasis within product planning on customer data quantity and technological development over data quality and insight (Kohn, 2005). This overemphasis may become even more pronounced when products have footprints of data about their use and performance. The weak link in the chain to achieving mass customisation may not be the responsiveness of the supply chain, but the quality of consumer data that is being used to drive customisation in the first place. This is exacerbated in the case where there is a desire to meet aesthetic and/or affective requirements. Human factors has a role to play here, in that much effort has gone into attempting to characterise and capture affective and emotional requirements through approaches such as Kansei (Jindo and Hirasago, 1997) and Citerasa (Khalid and Helander, 2004). Ontologies that cover the relationship between affective requirements and product design parameters are required to achieve this, and Golightly et al. (2012) present some initial work in this area.

5.2. End-user participation

Cloud manufacturing may offer new means for participation and involvement for users within the design process. For example, rapid prototyping coupled with early user evaluation is a very successful way of ensuring the usability and appeal of products at an early stage (Lopez and Wright, 2002). The speed at which products can be produced, potentially using lower cost service providers than one might use for final production, means that rapid prototyping may be facilitated by cloud manufacturing. Also, services such as simulation, which are prohibitively expensive for smaller companies to own in-house, can be outsourced via the cloud (Tao et al., 2011). For example, Taylor et al. (2014) give an example of a platform to provide a range of simulation services to SMEs, via the cloud, on a pay-as-you-go basis. Such services can be used both to preview aspects of product design and, in some cases, provide the specification for personalised goods such as orthopaedic products.

In the most radical conceptualisations of cloud manufacturing, the low threshold to entry of the manufacturing cloud opens up production to a whole new range of users (Tao et al., 2011), and aspects of this are becoming a reality with the introduction of advanced 3D printing facilities, or crowdfunding where a group of individuals or organisations work together to fund and specify a product (Greenberg et al., 2013). As such, cloud manufacturing offers new opportunities for users not just to act as participants in a design process, but to actually own the design process – the very embodiment of user-centred design.

However, while cloud manufacturing offers huge potential for rapid production, the risk is that standardisation, and ergonomics knowledge, is ignored in the process. For example, the design of products for children (toys) needs careful consideration of safety, materials design, and issues such as anthropometry (Norris and Wilson, 1999). The cloud manufacturing architecture should embody a means for maintaining strong design standards and safety principles, even if it does support more rapid configuration of products, with regulation at all levels being a noted challenge of cloud manufacturing (Tao et al., 2011). The case for ensuring ergonomic and product design standards are part of this regulation is important.

6. Collaboration

While groups of users may have their own specific human factors considerations, there is a set of concerns associated with the interactions between groups, particularly between the resource providers and consumers (Rauschecker et al., 2011). These relate to the nature and mechanisms of collaboration in the manufacturing cloud. Participating organisations must have an understanding of the human and organisational issues associated with collaborative work to ensure that their respective infrastructures and processes optimise the benefits of moving towards a more distributed way of working.

6.1. Collaboration mechanisms

Collaborative work in cloud manufacturing environments will be across organisational and professional boundaries, in distributed, mobile and co-located workspaces. Companies are often aware from experience that neglecting a consideration of human factors is a barrier to collaboration and the use of collaborative technologies (Patel et al., 2012). However they are not able to assess the importance of these factors, or how supporting them will optimise work in terms of quantitative and qualitative gains. It is important therefore to assess the nature and goals of the collaboration environment, that is, is it high-pressured or high risk? Other considerations might include whether there is a focus on minimising delays, the quick resolution of problems, reducing costs, and/or in improving the quality of the product, or whether a high level of commercial security is required.

Strong team relationships underpin successful collaborative behaviour. In a study of product design, Zhang et al. (2013) found communication took up 17% of project time, and was rated amongst the most critical activities of product design. Relationships are best fostered through initial and periodic face-to-face meetings, particularly during early stages of design during the product development lifecycle. This facilitates the development of personal relationships and the subsequent emergence of trust between team members. Strong face-to-face skills and interpersonal relations have been predicted to be of even greater value where products are in part monetised through ongoing service relationships with customers (Baines et al., 2013) and purely contractual arrangements can restrict opportunities for effective, sustainable collaboration (Quayle et al., 2013).

Establishing and maintaining common ground can facilitate collaboration by reducing communication demands and increasing trust. However, common ground can be challenging to develop when individuals, teams and organisations are faced with cultural differences, in terms of working with others of a different nationality and professional discipline. Individuals and teams must share a common technical understanding of tasks and processes, including those related to safety (Nenonen et al., 2015), as well as maintain shared awareness and shared mental models of the tasks and processes being conducted by each other internally and externally (Salas et al., 2005). Historically, knowledge management processes can help intra-organisational teams exchange knowledge and understand each other's competencies and constraints (Carneiro, 2000; Détienne, 2006).

In addition, relevant parties in the value chain must always be aware of the current task status as well as information about outstanding tasks (Carroll et al., 2003). Task dependencies must be clear during the early stages of a project and subsequently appropriate coordination is required to ensure that the manufacturing process is as efficient as possible. Responsibility for coordination of these activities must be clearly defined. Methods from human factors, such as visualisation methods that have worked to align interdisciplinary teams in areas such as rail engineering (Schock et al., 2010), may also have value here in communicating roles, constraints, and task progress.

6.2. Trust

Related to general issues of collaboration are specific issues of trust. This is distinct from 'security' and 'privacy', as it extends not just to data, but also to confidence in partners to deliver to the appropriate standards (Ilgen et al., 2005). Trust is fundamental to efficient and effective collaboration, which will subsequently translate into the creation and production of more superior products (Salas et al., 2005). Relationships between organisations are likely to be different to traditional relationships between OEMs, tier one and tier two suppliers, in terms of whether they are short- or long-term relationships and the level of trust between them. In particular, consumers must also trust that the application providers provide the best solutions to process and production planning ('credibility') and trust in the manufacturing resource provider's ability to deliver their product.

Even when confidentiality agreements and technical safeguards are in place, there may still be psychological barriers which prevent sharing information using collaborative technologies. For example, Patel et al. (2012) found that employees working at an aerospace company refused to use a collaborative functionality allowing remote colleagues to control their computer in order to change viewpoints of a 3D model to facilitate decision-making. This was due to an underlying trust issue in handing over control to external parties. Therefore management must foster a supportive organisational culture to ensure open communication channels and intra- and trans-organisational trust, which can reduce the cumulative effect of allowing small inefficiencies to be a part of their working environments. There will thus be a shift in the emphasis on inter-organisational trust (based on historical working relationships) to trust in data security, confidentiality and delivery. Tools to assess the readiness for collaboration and concurrent working can be useful here, such as CoScope (Patel et al., 2010).

There is a potentially huge benefit to collaboration through cloud manufacturing. As discussed earlier, the manufacturing cloud is dependent on a move towards open standards, ubiquitous product data flow and more flexible exchange of data. For example, Suh et al. (2008) propose a ubiquitous manufacturing model where data about products are available to all stakeholders throughout the product lifecycle. In such an example, the OEM as a customer may support SMEs in their supply chain to adopt cloud-based Manufacturing Execution Systems (MES). While this gives the SME access to software they may not have had the capital to afford on their own, the OEM can use the open MES platform to understand the performance and quality of their suppliers, providing a mutual benefit.

Providing the issues of trust, mentioned above, can be satisfactorily addressed, there is the opportunity that collaboration can be massively enhanced by the flexible exchange and presentation of product data. The role for human factors will be to understand the changes in different partners' information needs from a traditional manufacturing environment to cloud manufacturing; to understand and support the communication and coordination required for new task structures; and help in the definition of shared decision-making, new forms of collaborative HCI and the successful embedding of co-operational processes, for example by striving to deliver requirements for shared and visible information to support collaborative decision-making. In addition, human factors experts can highlight training needs based on the different skills and behaviours required in this new collaboration environment.

Table 1
Tactical contribution of human factors to cloud manufacturing user groups.

	Characteristics	Human factors contribution
Service providers	Automation	• Joint cognitive systems approach; principles for automation as a team-player • User-centred representations including ecological interface design
	Product variability and operator skill	• Flexible workstations • Models of cognitive complexity • Organisational policy
Application providers	Quality of Service	• Application of User Experience frameworks • Metrics for Quality of Service and user experience
	Visualisation and mental models	• Elicitation of mental models for design • Engagement processes
	Orchestration and exchange	• Knowledge elicitation approaches (e.g. Critical Decision Method, Hierarchical Task Analysis)
Consumers	Expressing requirements	• Methods for eliciting affective requirements (e.g. Kansei) • Ontologies for user-centred requirements
	End user participation	• Utilisation and evaluation of rapid prototypes • Safety standards for product design
Collaboration	Collaboration mechanisms	• Visualisation tools for common ground • Collaboration readiness tools
	Trust	• User-centred design for coordinating technologies • Training needs analysis

7. Discussion and future directions

This paper has outlined the relevance of human factors within the emerging production paradigm of cloud manufacturing. Importantly, cloud manufacturing not only presents a number of challenges for human factors practitioners; just as apparent are a set of opportunities that human factors would wish to inform and promote. Consumers can have more say in product design, either explicitly through the expression of customisation requirements, or more implicitly through the data footprint of their use of products. The potential availability of modelling software and cheaper prototyping allows a more iterative, user-centred approach to product design and development. On the operating side, if well-managed, the introduction of new forms of technology and customer-responsiveness gives manufacturing service providers the opportunity to upskill their workforce, while realising more effective (and cost-effective) robotics and automation. Human factors should be open and responsive to these opportunities.

While some tactical suggestions have been offered as to how human factors can contribute to specific topics within cloud manufacturing (summarised in Table 1), it is crucial to reflect on the systemic nature of this new production environment. The interconnected nature of organisations, and of data and control within organisations, will require a holistic approach to understanding how people and manufacturing technology co-exist. In addition, the high degree of multi-layered automation moves into the arena of joint cognitive systems (Hollnagel and Woods, 2005). Some users, at least, will be interacting not directly with physical systems, but overseeing control systems, for example by controlling parameters that determine the performance of whole production lines, rather than controlling specific machines. The joint cognitive systems approach means considering humans and automation as combined units, while considering representations of control in terms of how constraints and interdependencies can be represented. Also, it is unlikely that cloud manufacturing systems will all be implemented on 'green-field' sites, especially where organisations have already sunk substantial capital into existing manufacturing infrastructures. Cloud manufacturing technology needs to be considered at a whole-systems level in order to predict potentially undesirable disruption to associated processes and performance. Also, the ongoing management and development of cloud manufacturing means that changes and adaptations are inevitable, and such changes will be prone to the same widespread impact as any other large scale complex control system (Hollnagel, 2007). Therefore, human factors apply not just to the development of cloud manufacturing now, but on an ongoing basis.

Efforts to support the implementation of cloud manufacturing should not start with, say, HCI or job re-design work, but at an earlier stage, identifying new roles and responsibilities, and changes that will occur across the production lifecycle. We also note that changes to the lifecycle are likely to be influenced by other initiatives, such as the introduction of sustainable and 'circular' manufacturing, which come with their own ergonomics considerations (Sinclair and Siemieniuch, 2014). From here, it will be possible to determine forms of work and new forms of decision-making, the latter being critical given the importance of planning and coordination in a supply chain that is operated and configured with a high degree of automation and collaboration. It is only after this systems-level analysis has been completed that it will be possible to determine user interface design, change management and integration processes that will bring about effective cloud manufacturing. Critically, across all of these phases, it is imperative to actively involve users in design and evaluation, whether that be the user interfaces for interacting with cloud services, or change in practices and processes that emerge from adopting a cloud manufacturing paradigm.

Finally, the cloud manufacturing model raises an important question for where human factors places itself as a discipline so that it can provide knowledge and expertise. The advantages of good ergonomics design for assembly and effective production, not to mention product quality and usability, are clear (Falck et al., 2010). As the product lifecycle becomes more decentralised and more agile through the cloud (Tao et al., 2011), so the ergonomics discipline has to be better placed (maybe EaaS, or 'Ergonomics as a Service') to ensure the right competencies are embedded within product design and production planning at the right time. There is therefore a challenge for how human factors must orientate itself to remain relevant within this future manufacturing landscape.

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