

Advanced Industry 4.0 (ACPA7000)

Assignment 2

Critically evaluate manufacturing systems at a strategic level to identify opportunities for new and emerging I4.0 technology enablers, whilst identifying the cultural and workforce factors that may contribute to delivering authentic economic and societal benefit.

Simon Shuker

December 2022

University of Wales – Trinity St David

Supervisor: Mahesh Kannath

Introduction

Klaus Schwab states in “The Fourth Industrial Revolution” (1) that all previous Industrial Revolutions have created immense societal change and opportunity. The ability of the current ongoing developments covered by the term ‘Industry 4.0’ to result in a similar social and societal change is, if anything, more pronounced. Schwab points out that “the pathway to the future is now defined by the ‘Internet of Things’, meaning the whole connected network of digital devices, machine sensors, networks, and diverse supported equipment. The extent to which this can be successfully brought about depends upon the effectiveness of the current transition period. Current manufacturing systems need to be transitioned from the partly automated, partly digital, and partly autonomous systems they currently are, into a truly connected, reliable, and flexible framework that represents a digital future for all of us.

The social and societal change this could bring about needs to be in the full recognition of the ‘why’ it is being done. There is little point progressing the whole Industry 4.0 (I4.0) concept and development if the overall human experience following the transition is poorer than before. The roll-out of I4.0 needs to be wide and deep enough to allow dissemination across all levels of society, in all areas of the developed and developing world, and in an appropriate and structured manner.

Mark Binhoff, writing in the Foreword to Schwab’s work (Ref 1) recognises this when he states that it is our responsibility to “build systems to improve the human condition.”. Binhoff adds that the totality of development and progression could, in the hackneyed echoes of the ‘Terminator’ chip, the extent of the technology’s self-sufficiency could “...conceivably escape our control”.

Schwab points out that this take-up and growth for I4.0 is likely to be exponential rather than linear, as the previous iterations were, so the danger of losing track in overall direction is very real. The hope might be that the ability and will to involve co-operation of as wide a stake holding as possible, leading to a reach across societal boundaries that has not been seen in such change periods before.

In this essay, we will briefly review at a high level the most common and current manufacturing systems to form an aerial view of the ‘status quo’ within manufacturing. We will then examine the new and emerging manufacturing technologies for their capability to improve on the current manufacturing systems. We will then attempt to define the gaps still to resolve between the status and the desirable aims and highlight the possible societal and economic benefit to be derived from I4.0 adoption.

Effectiveness of current manufacturing systems

In their simplest forms, all manufacturing systems combine plant items with human resources, at a variety of skill and supervision levels, to produce a product or process a single stage, or multiple stages, of production. The individual manufacturing system is defined by what its operations are, the total number of positions or productions in use or available, how autonomous (or otherwise) they might be.

For a definition of existing systems, Qin (2), defines most systems (using Groover's classification, 2007) as one of several general types of manufacturing systems, which are examined here:

'a manual assembly system' – is just that, a fully manual production of parts, followed by manual combination and assembly of parts into part finished or fully finished product. This is a means of manufacture at the most basic of levels and results in the most labour-intensive input. The degree of skill required can vary from unskilled assembler to highly skilled craftsman. At the niche level, the high cost of labour is in proportion to very high product costs – at whatever level of automation introduced these the craftsmen's manual roles are unlikely to be replaced, if the market demands then the craft, will remain. As an example, in fine gunsmithing many parts can be done by highly automated means, but the manual craftsman-built gun is, and always will be, the finest product available.

At the lower skill and unskilled levels manual tasks are being replaced by automation of the simplest kinds. The societal impact of replacing these tasks and roles across the developing world could potentially free many from repetitive, arduous, and hazardous manual tasks – but the employment of the workers into other operations will need both support investment and Governmental strategy for the many lower tiers of workers replaced.

'Single-station manned cells' - are generally performing a set operation across a single product or process. Skill levels here are in proportion to the complexity of the process or product - but the speed of operation and output will always be governed by worker output. As the skill, or more appropriately, the experience, of the worker increases its more likely that his place will be at that process, not rotated with other who are slower at that operation. The worker in this position has little value to the company outside that operation, and little motivation to raise his skill levels, even if that were an available option.

'Single station automated cells' There is no full manning here, the operations are fully automated, and may go through multiple cycles of production without human intervention. This showing a move towards labour cost reductions and increasing productivity can be shown over a named cell performing similar operations but will be limited to a single product line or batch.

A typical single-station automated cell is made up of one or more automated machines (a machine cluster) and an automated loading and unloading system, such as robots or conveyors, etc. The CNC machine centre system is a common example an automated cell, being able to change the tool, position the product and change the pallet automatically. The CNC machine can work with a loading robot or feeding system to load or unload the products.

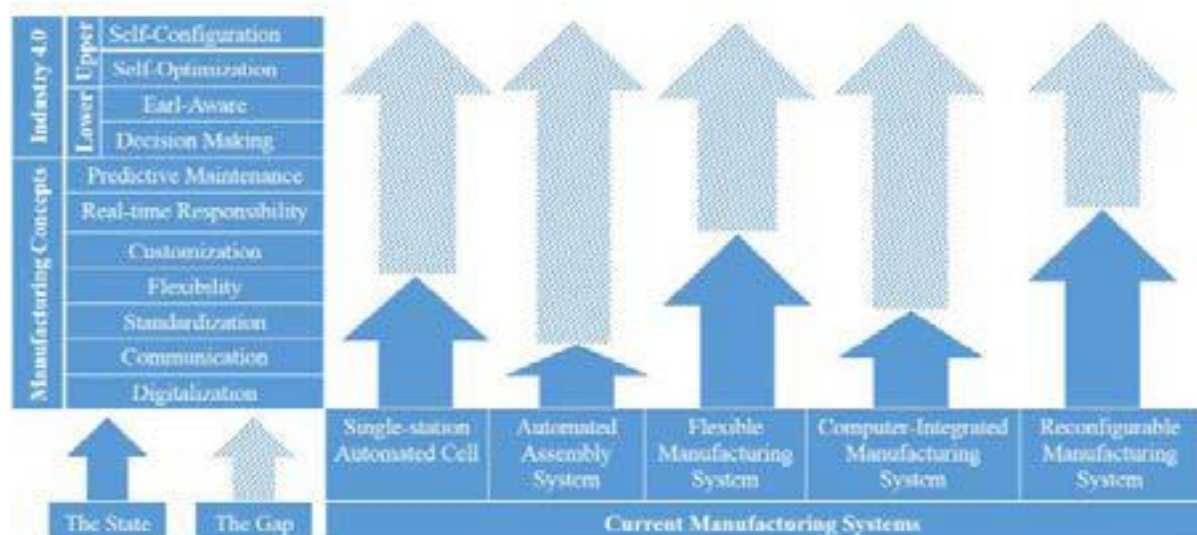
'Automated assembly system' – Similar to a manual system, the components are similar but with a handling system and feeding system replacing workers previously used. The control includes sequence control, monitoring the operating safety and quality control by automated means. At this level the system has now become capable of undertaking very high product throughput, into the millions of units. One of the most common applications of automated assembly systems is in processing sheet metal, from machining, cutting, rolling, and follow-on spot welding and plating.

'Flexible manufacturing system' – this is now moving into a highly automated mode of manufacture, which is extremely flexible in what it is capable of being adapted to do. A series of several work areas

are coupled to an automated transport feeder system, operating under computer controls. As every product can be tracked, the type of operation can be changed quickly, helping to increase raw material and machine utilization rates considerably. Again, this is operating with a smaller number of operatives, and reduces the need for stock and quick amendments can be made to changeover to another mode. This has its best advantage for milling and drilling operations.

‘Computer-integrated manufacturing system’ and ‘reconfigurable manufacturing system’. The *computer-integrated* manufacturing system is designed to be fully controlled by computing systems, and the *reconfigurable* manufacturing system has the additional ability to be very easily adaptable to adjust product or mode and address to demand changes of the market or suppliers. These systems tend to be very strongly modular, able to integrate into upstream and downstream equipment, able to be tailored to precise requirements, converted to wider use, scaled up for demand rises and able to be examined easily for errors and faults to limit impact on production.

These final examples are closest to what would be demonstrated as approaching I4.0 capability, and the only ones where there is a realistically closable gap between the optimum operating modes of these examples and the utilisation of full I4.0 scope, as shown in Qin’s gap analysis (2) – shown below.



Research gap between current manufacturing and the attainment of I4.0 capability. (2)

Emerging technologies and their impact in closing the gaps

How can the manufacturing industry embrace the emerging technologies to approach the opportunity that I4.0 affords? One classification of these emerging technologies is noted in the table below (Ref BB):

Table 1.1: Twelve Key Emerging Technologies

Technology	Description
Artificial intelligence and robotics	Development of machines that can substitute for humans, increasingly in tasks associated with thinking, multitasking and fine motor skills.
Ubiquitous linked sensors	Also known as the "Internet of Things." The use of networked sensors to remotely connect, track and manage products, systems and grids.
Virtual and augmented realities	Next-step interfaces between humans and computers involving immersive environments, holographic readouts and digitally produced overlays for mixed-reality experiences.
Additive manufacturing	Advances in additive manufacturing, using a widening range of materials and methods. Innovations include 3D bioprinting of organic tissues.
Blockchain and distributed ledger technology	Distributed ledger technology based on cryptographic systems that manage, verify and publicly record transaction data; the basis of "cryptocurrencies" such as bitcoin.
Advanced materials and nanomaterials	Creation of new materials and nanostructures for the development of beneficial material properties, such as thermoelectric efficiency, shape retention and new functionality.
Energy capture, storage and transmission	Breakthroughs in battery and fuel cell efficiency; renewable energy through solar, wind, and tidal technologies; energy distribution through smart grid systems; wireless energy transfer; and more.
New computing technologies	New architectures for computing hardware, such as quantum computing, biological computing or neural network processing, as well as innovative expansion of current computing technologies.
Biotechnologies	Innovations in genetic engineering, sequencing and therapeutics, as well as biological computational interfaces and synthetic biology.
Geoengineering	Technological intervention in planetary systems, typically to mitigate effects of climate change by removing carbon dioxide or managing solar radiation.
Neurotechnology	Innovations such as smart drugs, neuroimaging and bioelectronic interfaces that allow for reading, communicating and influencing human brain activity.
Space technologies	Developments allowing for greater access to and exploration of space, including microsatellites, advanced telescopes, reusable rockets and integrated rocket-jet engines.

Source: World Economic Forum Handbook on the Fourth Industrial Revolution and World Economic Forum Global Risks Report 2017.

Readiness for the Future of Production Report 2018 1

Emerging Technologies from 'Readiness for the future of Production', World Economic Forum (3).

From the list of 12 key emerging technologies listed in the table 1 above, half are either an enabler to manufacturing, or others are facilitating advances within manufacturing systems. From the overarching promise set out in the opportunity presented by I4.0, can these new Industry systems be developed equitably across economies and industries, and across continental regions and countries to allow a balanced growth across the whole range of human activity? Strong precedents from the previous industrial revolutions would suggest that this might be a distant hope. We will outline these emerging technologies, as follows.

Industrial Internet of Things

The 'Internet of Things' – or IoT – is a founding technology within I4.0, and readily seen across domestic life as well as commercial business and manufacturing. In domestic life IoT is seen as intelligent appliances, connected to each other and the internet, to exchange data and trends of operation between themselves, their users, or their monitoring management organisations. In commercial business, the Industrial IoT exists as sensors sited across the business to collect data in the same way, collecting and reporting on the modes of operation and health – or otherwise – of the assets and equipment. This technology can be deployed across all building fabric and operational assets, and the installed operational plant, all the time gathering complex insight into the plant, systems and building performance.

As the sensors are in real time, IoT can gather trends and the contained machine learning interprets those into raw data for predictive maintenance and production issues. The ML algorithms examine the data gathered and then plan for the best operational activity and schedule. The power of the Industrial IoT does already allow transmission of the full designs and the data needed to manufacture the products remotely, where the required adequate equipment to produce the product – for example in

AM - exists locally or can be sourced. As a result, the complete information to generate the product is available and can therefore be transferred to third parties. Whilst this demonstrates the enormous utility of being able to locally produce critical elements and products conceived and designed continents away, such as vital prosthetics for operative repair, this capability could emerge as a limitation. Should the security of this data be open to compromise, particularly if the product is a high-volume element capable of being mass-produced with no recognition of the originator's intellectual property, then the design is at large and open to exact and unauthorised production.

Horizontal and Vertical integration

A significant factor leading to the whole utility of I4.0 techniques is possibility of vertical and horizontal integration of systems, whether within an organisation, or between that organisation and industry partners and stakeholders. The possibility of connection and open visibility of systems and data between machines and companies allows for refinement of collaboration, communication on issues and inconsistencies, and allowing deeper analysis of what will drive better efficiencies between the parties.

Where an organisation is sited across many different locations, the sharing of data horizontally across those locations ensures the whole organisation is aware of stock issues, and the likely causes, and possible mitigations, of any upcoming delays. For effective vertical integration in manufacturing, I4.0 ensure effective sharing of data through the common divisional silo barriers is possible – all stages from research and development, manufacture, marketing, sales, and after-market are connected to shared data and intelligence. The benefits are there for all parties and the opportunity is there to operate as a more proactive company.

The use and growth of Big Data

The ability of companies to generate, store, share, analyse and utilise data is fundamentally changed by the onset of I4.0 and the 'Big Data' that it makes possible. The gathering of data, useful and otherwise, has been possible for as long as manufacturing has been in place – the aspiration being to use this potentially valuable intelligence to progress to the 'better mouse trap'.

With the onset of I4.0 driven data sensing, collection, and analysis; the concept of Big Data emerges to encompass the accumulation of large amounts of performance data. Up to now the useful interpretation this volume of data would have been beyond the capability of humans, even with normal computing, to make sense of. The vastly more powerful computing and analytical systems can now examine this data, sort, and seek trends and biases that have not been reachable until now.

Coupled with machine learning applied to the sorted data this Big Data can now inform on decisions for all aspects of industry manufacturing. This reaches from machine arrangements and layout to the performance of raw materials in the pre-production storage, and extension into commercial aspects of incoming enquiries, customer behaviour and trends, and material or resource prices.

As we can imagine, Big Data, when derived from thoughtful measuring and sensing, and collated with purpose, can assist in every current aspect of industry improvement, and lead to the initiation of many concepts of study that are only possible because of its creation. The sensing of performance levels in remote equipment, and prediction of a coming issue will lead to an effective predictive maintenance schedule.

Cloud Computing, connectivity and new computing technologies, generative design, biological computing, neural network processing.

The possibility of higher computing power leads us to easier and faster optimisation of design options, which allows the customer to indicate his preferences to an extreme level of detail – considerably different from the original production line of Henry Ford’s Model T, which he proudly sold as available in any colour, “.as long as it’s black”.

Generative design has emerged as an extraordinary tool of computational iterative analysis, using high levels of computing power, in house or in the cloud, in combination with the decision making of machine learning to fully optimise an element’s design. Within the limits of the required shape, imposed loads, material properties and restraint cases set by the user, the generative design process can arrive at a fully converged design arrangement that is way beyond the imaginative capability of a very capable human engineer, producing a finished design that is the most economical in terms of materials. Where the design input includes the intended mode of advanced manufacture – such as additive manufacturing – the generative process can include the limitations of the materials, the process, and the known limitations of that material when produced by that process. As noted elsewhere for Additive Manufacturing, the limitations of anisotropy of the formed materials, surface irregularity and the degree to which final processing by subtractive manufacturing will be needed pose some important questions which need to be judged carefully for effective production. These potential issues sensibly limit the criticality of the formed elements which will need both design and material process development to overcome.

However, the power of generative design as a tool of sustainable manufacturing is clear- Airbus have noted that upwards of 5.0M tonnes of CO2 emissions per year might be saved with the use of generative design in their operations (4).



From one of the oldest manufacturing systems in existence, metal casting, an example can aptly demonstrate the progression that can be achieved by advanced computational design and simulation. The Cast Metals Federation is based in Tipton, report that even the centuries-honed technique of sand

casting can be optimised to higher levels of performance by I4.0 simulation and design. Their member Peel Jones Copper Products produce a critical copper alloy casting used in steel blast furnaces. The casting had complex internal cooling channels to withstand the aggressive blast furnace conditions. The casting was re-designed using advanced CAD and simulation of the casting process, using analysis of fluid flow and heat transfer modelling. The optimisation allowed tighter tolerance on the casting wall thickness, and a doubling in productivity from more reliable mould and cast outcomes. Scrap weight was reduced by 16%, the final casting weight by 15kg. This reinforces the further progress that even the most primary of manufacturing industries can make using the advanced methods of design and analysis the new I4.0 techniques can bring. Further developments employing another of the I4.0 technologies to seek beneficial progress in the product, where realistic outturn costs are vital to the longevity of this form of industry. (5)

Additive manufacturing (AM)

AM (refers to the creation of a designed product by creating a solid version formed by layers of deposited material, layered from a raw material substrate in according to a transmitted electronic stream of data formed from the CAD design on the designer's computer. This has its own material limitations – the nature of the deposited material needs consideration due to possibilities of anisotropy within the material created, a naturally layered structure and a tendency to exhibit possible failure points at the layer joins, often needing further machine working to arrive at a safe structural result and the desirable final shape to the product.

It has been established that the additive manufacture of solar panels can reduce the product cost by 20%. Commercial companies have recognised utility of AM in the medical sector – the cosmetic giant L'Oréal source artificial skin grown by AM for testing skin suitability and product safety (4). Continuing with medical systems the production of bespoke implants, valves and other resilient tissue replacements is very straightforward with AM and related depositional technologies, as ably demonstrated by the MADE laboratories and production facilities in UWTSD Swansea.

Cyber Security

We are all sadly aware of the degree to which external agents, organised or not, are constantly striving to bypass the security measures on our computing systems and seek to do harm, steal data and IP, deny service of web or in-house platforms, or simply disrupt personal or business systems because of the challenge it presents or for financial reward. With all businesses inevitably now becoming 'data companies', their very existence of will hinge on greater security of their assets, communications, and business systems. If I4.0 is to progress for business good in any way, then it must come with commensurate security needed to maintain the integrity of business systems and functions.

Many of the threats common across business arrive in emails, but the threat can be from any angle, internal and external, and the challenge must be flexible and adaptable as the threat, hopefully at least a step ahead. Earlier computing systems have been breached by attempts to steal intellectual property, remotely change control codes so that machines either come to a halt or create faults within products or install denial of service threats into web or in-house systems.

This increasing security needed is progressed by the application of artificial intelligence, the use of blockchain in creation of unique identification, and machine learning to analyse what is normal and what is not and revise that assessment continually. As these systems are applied, they will remove the ability for compromise of the digitized and connected systems that businesses are converting to and are increasingly relying on to drive their effectiveness – surely the whole point of I4.0.

Many cyber security approaches utilise AI and ML to effectively study what is presented to them in terms of incoming data, messages, and files, effectively learning at a rapid rate to adapt to a rapidly changing threat level. The costs of cyber security coverage are considerable and a daunting choice for small business to take, whether to protect fully and pay, or relax the level of protection and risk an attack not screened out by normal protection methods. Increasingly, a lower cost suite of cyber solutions is gathering pace to cover this important sector of manufacturing and business users.

Automation through autonomous robots and cobots

Autonomous robots are completely self-sufficient plant items that can manage their own tasks without supervision and make decision themselves within their limits of programming. Increasingly, the manufacturing production line has been populated by increasing numbers of robots able to operate and work autonomously on complex tasks, and cobots, which are designed and used to interact and cooperate with a human. Robots may be used to move or position heavy parts and assemblies, acting to reduce manual risk, overloading manual handlers and raise safety levels by removing human tasks from the traditionally dangerous shop floor or constantly moving production line. Their operation can be continuous if product and materials are available and presented to them. Selecting products from warehousing can be achieved easily, as robots are able to operate faster, more efficiently and outside the environmental limits needed for human workers in large and open buildings that are difficult and expensive to heat for human occupation.

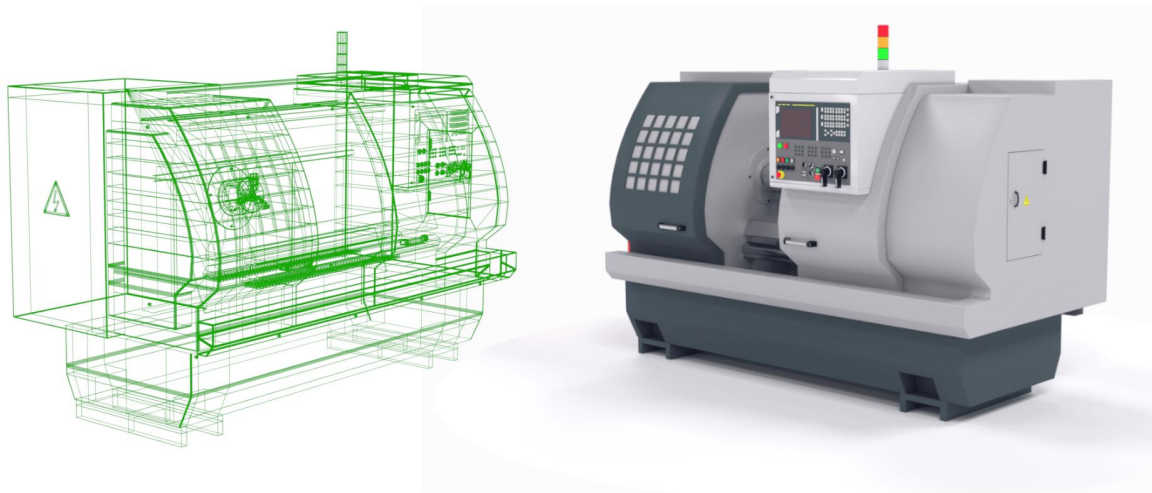
From the days of the Fiat advert in 1979 (“Designed by humans, ‘handmade’ by robots”), showing the entire production of the Strada model to be done by robots, production lines for automotive products have been characterised by this rapid and ongoing trend into robotic use. The product vehicle showed legendarily poor product quality in use and low service life – so the celebrated case of the Fiat Strada shows starkly that just because the operation is possible to be automated, doesn’t necessarily mean that automating an operation will automatically produce a better product. Two years later, British Leyland built the Mini Metro in Longbridge using robots – evidence of the long-term quality and corrosion issues faced by those models also gives little encouragement that the lessons from previous iterations of robot build quality had been learned.

Digital twins

In manufacturing, the concept of a ‘digital twin’ of any product assembly or scheme is made possible by the power of advanced simulations, sensor flexibility, data collection, computing and design brought about under I4.0. The manufacturer can view what their facility is doing, the states of activity of all equipment, and the any needs for maintenance, current or shortly to arise. The remote inspection and monitoring are made possible with zero risk to staff and operatives.

This ‘digital twin’ can combine with machine learning to strategize the production equipment, optimise raw material feed, or process rates and reduce possibility for critical blockage, possibly avoiding outage

of the whole production process. Employee training can be safer and at higher rate by running scenarios of issues, operational change, and activity multiple times to guide the optimum path to efficiency. The risks to staff, costs and lost time are all reduced by this, encouraging buy-in from all levels from operations to the Boardroom.



A digital twin of a CNC machine.

Virtual reality, augmented reality

With the introduction of digital models in increasing complexity the area of augmented or virtual reality has emerged – in this a visual representation of a model or situation can be combined and overlaid onto the real world. The fact we are familiar with this in gaming terms indicates that business has been using this tool in its processes for longer than we may have been aware of it. The concept of VR can be effectively used in training and familiarising staff with any new situation, worksite, or location – particularly in situations where the location is either inaccessible, dangerous to life or too high-risk to train in live terms, this training can be well advanced using the VR concept. In addition, the facility being studied may well be in design form only and to study access and ease of working properly needs to have experienced input on the ground from operators or experienced staff adding the valuable insight only they can.

We already have ability to present a live 3D model of a working scheme – on the recent Wales Road scheme A465 Gilwern the public were able to view a live aerial view of working scheme with traffic flowing, presented on tablets held up to a physical terrain scale model of the existing landscape. There were no headsets needed, the viewer is seeing the ‘view from above’ as if flying over the area of their choice. For health and safety training, British Water, BIM4Water and Bentley Systems showed in August 2022 (ref AA) on digitalisation of the water industry that VR of H&S messages, reviewing safe systems of working using the whole suite of digital tools can be vastly more effective and retained for far longer than paper or audio-visual systems. The more engaging format was novel and allowed far greater immersion in the real situation and brought out more comment from those who had seen and experienced risks at first hand that were recalled by the experience. The importance of this in industry and manufacturing cannot be underestimated with complacency and unfamiliarity with situations still being leading causes of workplace injury, and worse.

Conclusions

A common thread with the changes brought about by I4.0 is that companies need to understand they are changing into data companies. The value of the data they hold for legacy manufacturing, as well as the accumulation of current operations as 'Big Data', will become one of the businesses most valuable assets.

It's quite clear that the 'customisation' of product and offering will be crucial under I4.0. Customers. Ordering is connected and faster, and single personalised product runs such as the Moonpig Christmas card, will become even more prevalent – trivial example but a powerful one. Alterations to single or multiple orders and changes to the client's needs are more easily accommodated.

Support from Government and regulatory bodies, and of private sector companies, is vital in the progression of I4.0 – the table below (Ref BB) indicates the importance of the Institutional Framework accounts for 20% of the contribution towards readiness for I4.0. We have examined emerging technology and innovation above, and these are noted as having approximately the same importance at 20%.

Table 2.1: Readiness Assessment Weighting Scheme

Drivers of Production	Weights
Technology & Innovation	20%
Human Capital	20%
Global Trade & Investment	20%
Institutional Framework	20%
Demand Environment	15%
Sustainable Resources	5%
Structure of Production	Weights
Complexity	60%
Scale	40%

I4.0 - Readiness Weighting assessment (3)

The contribution of human capital has a similar contribution towards this readiness, again around 20%. The range of roles for fully skilled, semi-skilled and unskilled workers unlikely to be converged by these new industries, if anything the disparity is likely to be increased. To the extent to which the role and perception of engineers is also open to change – to what extent the trained engineers being currently prepared for early iterations of I4.0 will still be required when – for instance - the AI-driven generative design can fulfil many of the steps they are trained to originate and oversee.

The demand environment - indicated at 15% - clearly dictates the size and scale of enthusiasm and backing for I4.0 progression – with no market there would be no progression. However, the demand for higher levels of business and personal connection to the IoT indicates that the demand is there and will continue to do so.

Lastly, the access to sustainable resources is listed as 5% of the readiness weighting. The sustainable economy is supported by the key aspects of I4.0 which is the ability to be more efficient in design, lowering wastage of materials, processing time and costs, and in materials in the finished product. There are also negative factors brought in by the growth predicted.

The advances in AI-assisted geological surveying and mineral extraction will allow lower costs to produce refined production metals, indicating that the impacts can be reduced, and likelihood of site restoration increased. As an example, it remains to be seen whether the sustainable path created would be seen as a more desirable path for extractive mineral companies than recognising a higher profit level from the reduced costs of production. This argument can be proposed for every stage the finished product goes through.

Additionally, increased computing power at high processing rates, generates terabytes of 'Big Data' which must reside largely in the 'Cloud'. This data resides within many 'Data Centres' – each one with high power consumption, with additional back-up generator power, and further additional batteries performing the UPS between normal and emergency power use. The addition of personal and domestic cloud storage to these industrial computing requirements does mean a growing power need which will have to be generated on top of the growth in needs from other sectors of human activity – a serious negative to the sustainable story of I4.0.

To round off our study, at present the new range of emerging I4.0 technologies can provide, on their own or in combination with others, a new age of customisation and service - the ability for industry to provide any customer with the unique bespoke product at the scale of just one. Similarly, products can be provided to a scale of many thousands or above, and the product or assembly can be changed by largely automatic means with little lost time. There are already vast reductions in development time, costly design iterations, prototyping, and product testing – all these functions can be performed virtually, with lower cost, material use, and time expended using I4.0 techniques. This can be of benefit to all, from bespoke model for a prosthesis sent to a manufacturer for production in another continent to a long-established production line that can now allow easy alterations to design or material, quickly adapting with little interruption to production.

The emergence of the new I4.0 truly linked manufacturing systems could well open an age of change that sees huge improvement across the human experience of work and consuming. Indeed, the raft of opportunity presented by the ongoing I4.0 technologies presents the greatest potential for manufacturing to influence both economic and societal change in history.

References

1. **'The Fourth Industrial Revolution'**, published by *FT.com*. Klaus Schwab. 2018.
2. **A Categorical Framework of Manufacturing for I4.0 and beyond.**
Qin, et al, Mechanical & Manufacturing Engineering, Cardiff University, Procedia CIRP 2016
3. **Readiness for the Future of Production Report.** Martin et al, World Economic Forum, 2018
4. **Examining the benefits of AI powered generative design.** AI Spectrum Podcast: Acain, AI Spectrum & Parella, NX Design. Nov 2022.
5. **Fluid flow, heat transfer modelling & casting simulation.** Cast Metals Federation Case Study: Peel Jones Copper Products: <https://www.castmetalsfederation.com/case-study/blast-furnace-tuyere> Nov 2022.
6. **British Water, BIM4Water & Bentley Systems webinar.** Digitalisation of the water industry, utilising the whole suite of digital tools. Robson et al. Aug 2022.
7. **Emerging I 4.0 Technologies.** Immerman, G. MachineMetrics, I4.0 <https://www.machinemetrics.com/blog/industry-4-0-technologies> Sept 2020