

Design for Industry 4.0 (ACPA7001)

Reflective Essay - current design and development practices within construction and the built environment, - the current and future potential impact of Industry 4.0 technologies.

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1.0 Introduction

In this reflective essay we will consider the effects of Industry 4.0 technologies on the design philosophies within the civil engineering and the built environment industry. We will make additional reference to the impacts of Industry 4.0 to production engineering and operational aspects contributing to that market and to wider manufacturing if appropriate.

The built environment industry has been aiming with increasing urgency towards sustainability based goals as the global temperature rise has become clearer. In 2015 officials from all countries in the world assembled in Paris for what was to be known as the COP convention. The Paris Agreement was the result with the whole world agreeing, through progressive monitoring in further COP congresses, to limit greenhouse gas emissions “at a level that would prevent dangerous anthropogenic (human induced) interference with the climate system.”

In the built environment, these aims have meant widespread changes including real and voluntary limits on natural resource, forcing the adaptation of design to include lower grade, recycled and re-purposed materials. Alongside this, on a societal front, a growing safety culture has led a welcome reduction of factory, assembly, and site-based high-risk activities all associated with ‘manufacturing’ the product – the final structure or building. This includes exposure of operatives to working at any height and depth, to ‘hot work’, noise, harmful chemicals and fumes, and to the use of vibrating equipment which is now recognised as highly damaging to the human system. These factors have combined to drive an acceptance of lower human involvement in manufacturing facilities and at site, closely allied to the advancing goal of systemisation of buildings and structures.

The result has been a developing philosophy of ‘off-site’ production of building elements and sub-assemblies in all sectors and stages of construction. With this has come a higher regard for the circularity, sustainability, adaptability, serviceability, requirement for disassembly, and potential re-use of the building elements. This has impacts on the concept, design, production and, at the societal level, safe preparation of support structure and assembly of these assemblies on site, satisfying all of the above goals. At the same time this promotes the incorporation and development of increasingly accessible ‘Industry 4.0’ technologies in the design of these new structures, projects, sectional buildings elements and their related construction and the installed capital equipment.

2.0 Batch sizing and customisation

Within the housing industry the practice of limited customization is practised within the industry today, but only so far as a ‘pattern’ or family of house layout types of traditional build - or partially prefabricated- houses can be chosen from. Even this is within the pre-determined choices on a particular site. This is limited to where that type is noted on the Planning layout., Despite being on a much enlarged financial margin (typically 20-35%) than infrastructure engineering companies (typically 2-5%), the housebuilder offers very restricted choice suiting their own strategy, not their customers’ real wants.

Concurrently, automation technologies are emerging to support the industrialization of house production (Ref 1). Certainly the manufacturing industry has embraced automation technology and digital production far more than the built environment, restricting the ability to mass customize the house market. Limited prior use of industrialization techniques in the housing industry may explain the limited introduction of Industry 4.0 there today, despite the high potential. A mass customization strategy - aided by an more pragmatic planning system - might enable construction companies to increase automation and digitalization to promote customization, but the status quo is decidedly well below the possible take-up. Modular building and volumetric construction goes part-way towards this, and is covered later. The potential to employ Industry 4.0 methods to link design to fabrication and assembly is there, but not embraced to adequate lengths.

Some isolated examples of truly bespoke housing employing Industry 4.0 methods do exist. The Osprey Developments/Build Consultants Limited development site in March, Cambridgeshire demonstrates a concept of considerable freedom on design, backed by a family of accepted modular and systemised suppliers. This allows a bespoke solution once a plot was purchased – planning freedom was exercised here with an ‘acceptable envelope’ of solutions being adhered to within the customisation to aid speed of development. The designs were heavily biased towards modern methods of construction (MMC), the generic term applied to offsite techniques in this market, utilising advanced and connected CAD design guiding fabrication.



Osprey Developments, March, Cambridgeshire - Industry 4.0 aids customisation of housebuilding.

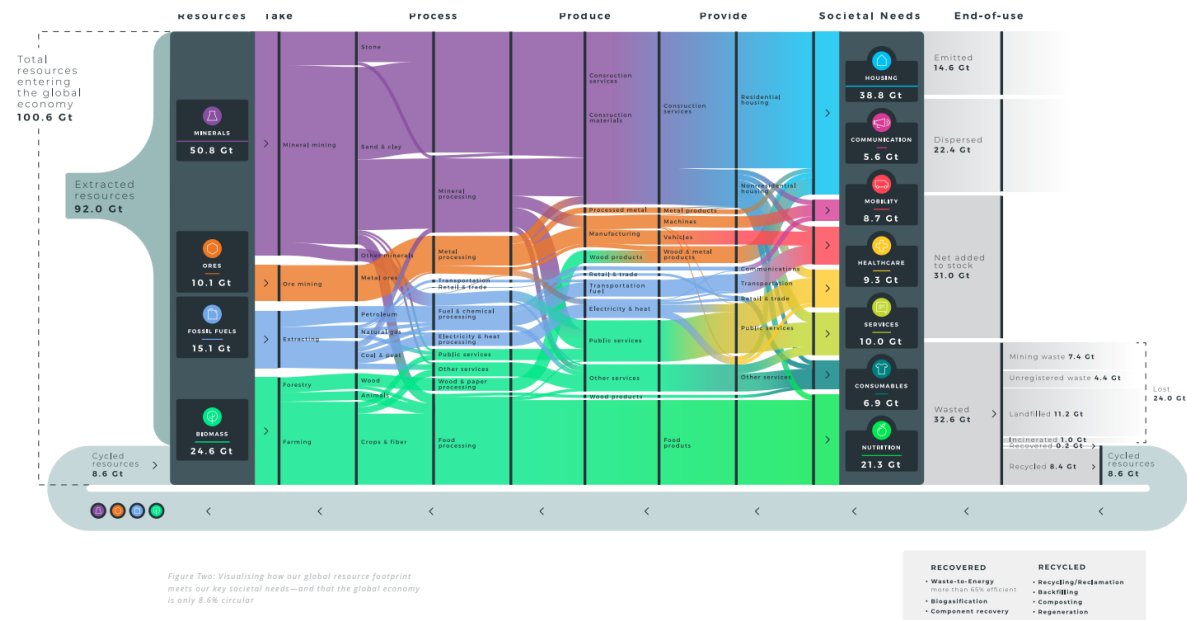
In great contrast, in manufacturing wider customisation is practised and supported by comprehensive take-up of Industry 4.0 methods. The true ‘batch size of 1’ is exemplified by the ‘Q’ Collection of Aston Martin Lagonda, where there is a high degrees of customisation of vehicles outside the core range of already high specification vehicles. The customisation includes cosmetic, power and performance upgrades, and the marketing adage that you should always sell “...1 less than the market demands...” (Ref 1) is certainly true here. However, the top of the market is not necessarily indicative of a wider desire for high degrees of individuality - firstly any widening of a ‘truly bespoke’ offering would need to be price tested and found to be commercially worthwhile. Secondly, Aston Martin Lagonda cannot maintain shareholders’ funds currently, so the move to even wider specialisations than currently might be an unwelcome commercial distraction.

3.0 Design for circularity

A desirable aim for the future from the Paris Agreement is the need for 'Circularity' or creating a closed loop between resource use, and re-use, minimising the input raw materials and maximising the degree of sustainable use of existing resources. The 'Circle Economy' organisation (<http://circle-economy.com/>) commenced from 2018 recording the global and regional 'Circularity Gap', which is the measurable gap between the desirable and actual degree of circularity demonstrated across the globe. The 'Circularity gap report' for 2018 (Ref 2) notes the world economy at only 9.1% circular, leaving a massive 'Circularity Gap' at that date. Four years later, in the 2022 Circularity Report (Ref 3) reiterates that:

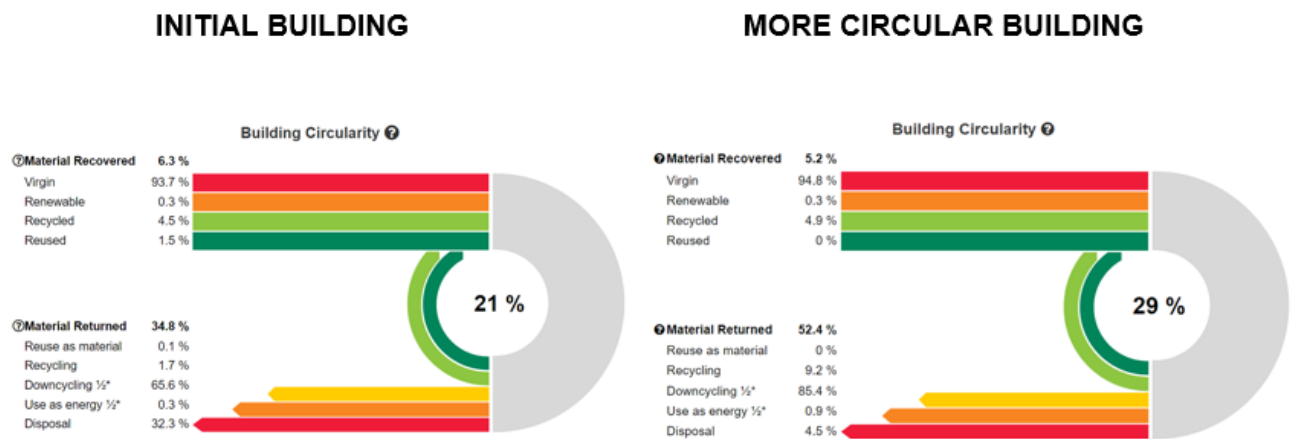
*"We know that **the world's circularity is in reverse and stands at only 8.6%**. Our 8.6% economy is wasteful, polluting and carbon-intensive. In only six years, half a trillion tonnes of virgin materials were taken from the earth to fulfil societal needs and wants: 70% more than what the earth can safely replenish".*

The demonstration of reducing world circularity – 2022 Graphic (Source- Ref 3 - see Appendix 1)



Sadly the measures enacted in that time have had insufficient effect to slow, let alone reverse the circularity gap, and the world raw resource use is on the rise still.

In civil engineering and construction there is a widely accepted move to circularity, with the learned Institutions recognising that as an essential, and commercial toolkits becoming available to measure construction circularity. (Ref 4). The Building Circularity Toolkit is available to visualise the circularity of their design. Increasing sophistication of the Industry 4.0 design tools – such as Generative Design – allows the manufactured element designer to build in his directions for resource limits, materials, fixings and manufacture to maximise the eventual circularity potential of his product – the building and element designer now has tools to guide them to the same end. The following graphic demonstrates the thrust to improve the building circularity score during responsible design, aided by the inclusion of generative design, and other Industry 4.0 driven capabilities.



Circularity resource and toolkit, LCA (Ref 4)

The learned Institutions in the built environment in the UK and elsewhere recognise the importance of circularity, and link this to the promotion of MMC, advanced design and a ‘factory-based’ offsite approach to construction. (Ref 5).

4.0 How Industry 4.0 capability is driving design.

Traditional ‘CAD’ is replaced now with ‘Building Information Modelling’, or BIM, modelling and the designer builds a collaborative ‘digital twin’ of the intended scheme. This allows full analysis of scenarios of build, fit-out, in-service operation, and decommission. This is the natural successor to the CDM requirements for full information, now made possible by the huge increase in processing power and analytical options due to I4.0 technologies.

The digital twin is utilised widely now across the built environment, with data inputs accepted in a variety of formats and sources – including video and laser LiDAR surveying, drone-mounted digital data gathering, and non-invasive electro-mechanical or radar surveying of existing concrete and steel structures. Digital twins represent a rapidly growing new field for complex infrastructure projects, such as the implementation of new digital equipment or the rollout of sitewide power resilience. For complex plant and equipment, this will become vital to ensuring complex overhauls of equipment or further digitisation can be implemented without risking unforeseen downtime.

The level of information made available within a fully connected BIM digital model has been documented as a potential threat to those who may seek to do a building, or its eventual occupiers, serious harm (Ref 6). These models contain all the building’s critical systems or weaknesses, and ‘back doors’ into the structures’ critical areas, which be made accessible by incorrect or unwitting forwarding of the model to untrusted and insecure suppliers.

We state above the journey that housebuilding is making towards systemisation in manufacture, aided by the increasing modular and kit-based house construction types. Modular buildings of timber sub-assemblies are replacing the familiar CAD designed timber roof trusses, which were evolving towards

increasingly slimmed down safety factors. Poor storage of these low-safety-factor trusses would lead to excessive deformation and render the roof impossible to build, or liable to long term deflection due to both the inherent faults introduced from handling and storage, and the minor timber shortcomings amplified by low safety factor but 'optimised' design. Chesterfield Church spire was built with green timber hundreds of years ago, its distorted corkscrew shape demonstrates to this day the result of speed over wisdom. The progress into I4.0 factory-based production allows the development of highly controlled building sections based on slab elements or assembled into 'volumetric' building systems at the factory, transported as completed slab elements or assembled and fitted-out pods.

5.0 How Industry 4.0 capability is driving production.

The principle of sectional buildings has been in use for many decades, the post WW2 housing crisis being alleviated by the 'prefab', some of which survive to this day with many faults but with the distinction of being the forerunner of today's permanent modular building. Temporary buildings have used the 'volumetric' format (delivering in completed box form) for decades – the very familiar 'Portakabin' temporary office was the forerunner of the volumetric building pod. Intense design optimisation and high systemisation using complex digital twins of the overall buildings is now developed and used by companies such as 'Offsite Construction' in Highbridge. These pod units with all utility connections in place are brought together in hundreds. They can be configured variously with high levels of customisation to form assemblies to serve as accommodation blocks for Hinkley Point C nuclear power station workers at the largest construction site in Europe, or for student accommodation tower blocks and city centre hotels.





6.0 How Industry 4.0 is driving assembly and site operations.

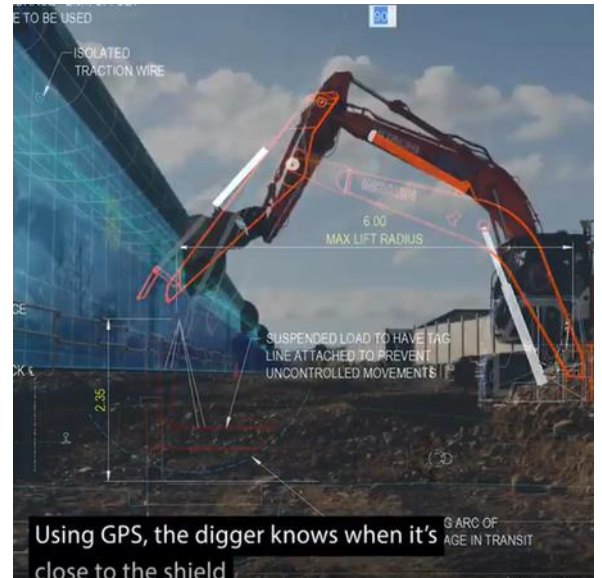
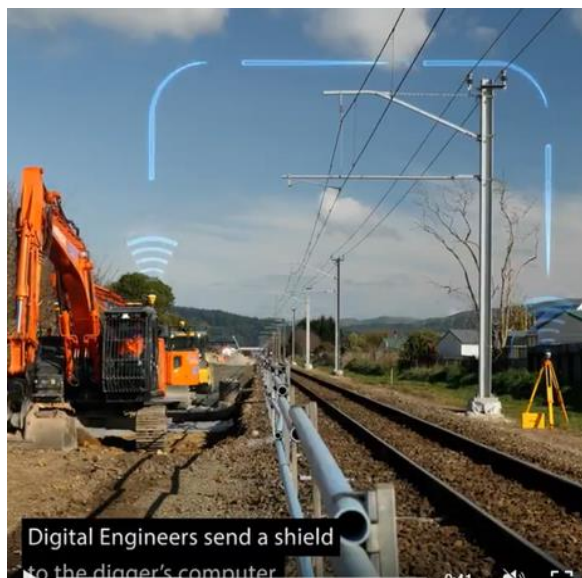
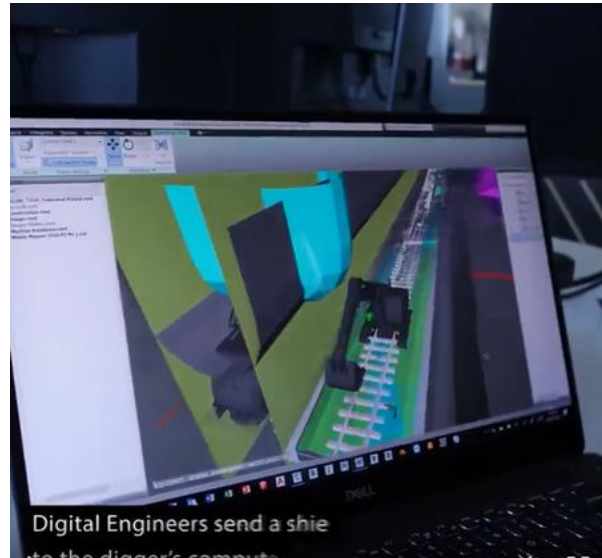
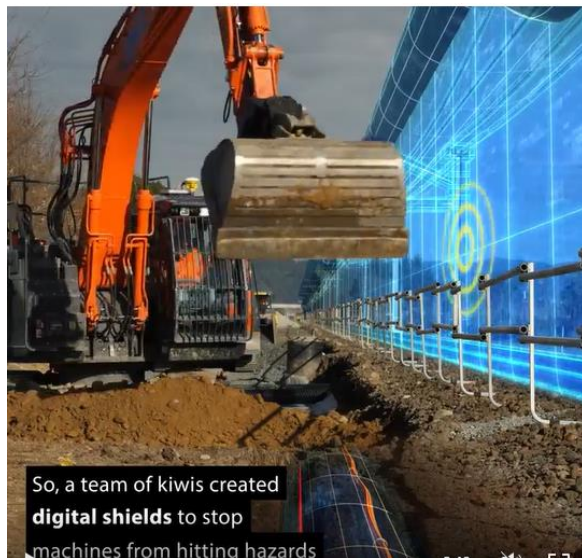
As stated above the learned Institutions are adapting to ensure that Industry 4.0 capability is built into future design, with focus on manufacture by sustainable means and assembly methods which allow circularity. The Royal Institute of British Architects (RIBA) have published their 'Design for Manufacture and Assembly' (DFMA) guidelines to guide new design projects in this. (Ref 7) The DFMA stresses how essential it is to use the nature of ways of connected designs, and the manufacture and assembly of the building elements as the principles guiding the whole building design.



<https://www.howickltd.com/applications/modular-construction/volumetric-modules>

The degree to which Industry 4.0 methods are at the heart of safe design across the construction industry is demonstrated by the following award-winning scheme. Rail operator KiwiRail, and consultants Downer and Aurecon jointly secured a New Zealand Health and Safety Award 2022 for the generation and use of digital shields built by BIM / Augmented Reality (AR) and GPS to protect rail workers and infrastructure. The GPS 3D model of the rail corridor generates the shields, which work by

locking the controls of an excavator if it strays into excluded areas - overhead lines, live rail corridor or sensitive infrastructure.



Digitally designed and sensor-controlled 'denial' areas for plant on a critical safety scheme.

Video Credit KiwiRail [#innovation]. Ref BB [Commitment to safety | KiwiRail](#)

7.0 Design for sericitzation

Design for sericitzation – the ability of staff to get to safely work on the scheme or building to service it, remove elements of it, and replace it after service - is now regarded as essential. The sophisticated digital modelling complexities emerging with Industry 4.0 allows this to be readily modelled and assessed during the early design, and accommodated at least cost.

As a real example, turbine generator kiosks and enclosures within building layouts such as energy-from-waste buildings are now able to be modelled to rule out clash of other services, and ensure that the long main rotor can be removed fully and easily through a 'soft' removeable building opening. This

would need only with small tools to achieve this, not demolition equipment which would be destructive to the closely adjacent pipe and wiring systems.

Commonly more recent architect designed 'statement' buildings can be visual marvels, but there is commonly no way to safely access these striking Architect-designed glazed roof, or feature cladding. This makes them impossible to clean, to access high level openers to service motors, or replace broken or leaking drain or sealing elements. The addition of more sophisticated design procedures made possible by Industry 4.0 connectivity, coupled with the increased focus on operability, make these logistically difficult and unsafe practices a thing of the past.

8.0 Design for disassembly and decommissioning

Development of the Construction, Design and Management (CDM) Regulations pointed to ways of better control and recording of all aspects of the projects development, including latterly, the eventual decommissioning and dismantling of the structure or project. The requirement now for circularity reinforces the need for structures to be amenable to decommissioning of internal moveable equipment and disassembly into the buildings constituent parts, for re-use or recycling as appropriate.

A specific example of a currently intractable problem in the built environment is the lack of recyclability of decommissioned wind turbine blades. The turbine towers are commonly highly engineered steel sectional tubes which can be readily disassembled. Once the blades and nacelles – which contains the generator unit and control equipment – are removed in a simple reverse operation of the construction, the towers are readily recyclable. The blades, which are carbon or glass fibre, are laid up in large GRP factory moulds using sophisticated design, the lay-up being guided by laser-projected lines on the moulds generated by the blades digital design model.

The glass-reinforced materials are not readily recyclable, once the encasing resin is removed (with difficulty) the glass or carbon fibre can only be used as aggregate in concrete, the organic resins combusted for energy from waste by high temperature pyrolysis. Current steps to recycle the matrix by using fluidised bed thermal methods, but these are cost-prohibitive - the blades are currently going into long term store or landfill.

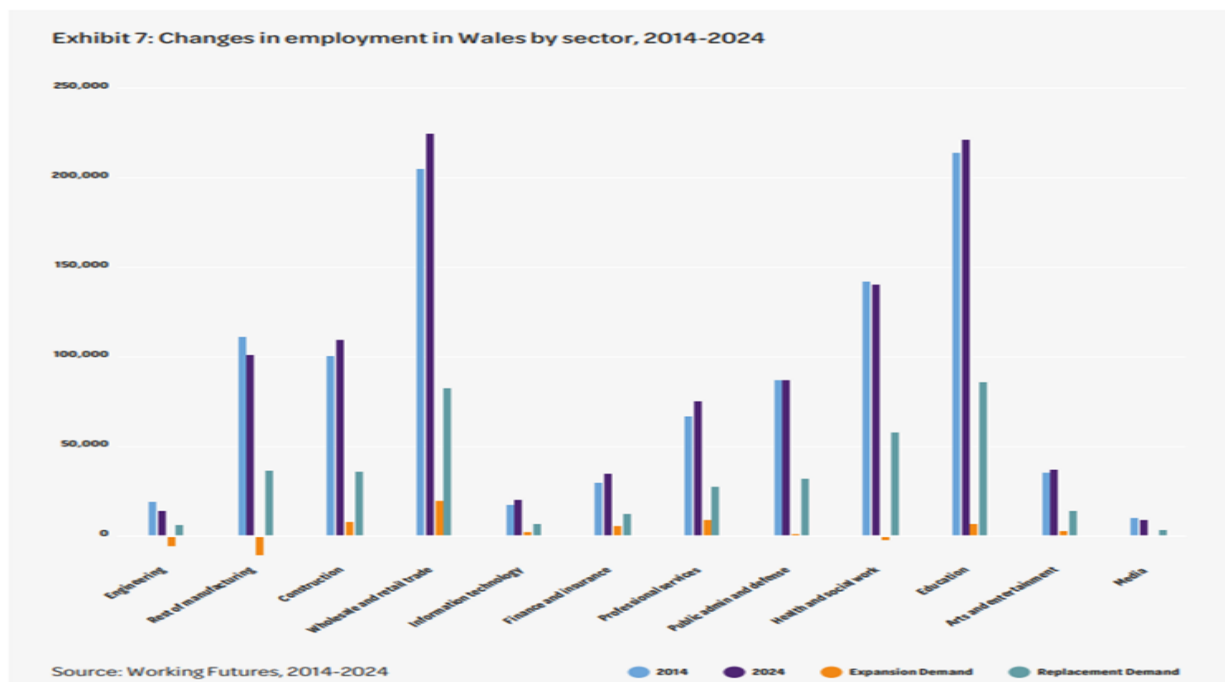
9.0 Design for Re-purposing and reuse of elements

The re-use of elements from wind turbine towers is noted above – the re-use of these elements is likely to be restricted more by the insurability of 'second-hand' tower elements than any lack of strength suitability of these recycled units. Much stress has also been placed on the re-use of foundation elements – piles and slabs – as the ground carries more unknowns and the most significant risks in the built environment and construction. Foundation reuse is however a growing trend in sustainable engineering construction. The reuse of existing piles and their contribution to newly constructed piles are difficult to establish, and new computational analysis methods made possible by Industry 4.0 capabilities will make this a more readily verifiable - and cost-saving - option for new buildings. (Ref 8).

It is common for previously used building elements to be re-used in newer constructions – in an ad-hoc manner where the new loading expected is trivial compared to the large load capabilities clearly still shown by the salvaged material. The re-use of elements and the substitution of low carbon materials into building refurbishments will continue using the new analysis tools made possible by Industry 4.0 sophisticated analysis. The restrictions of the planning and building control systems, sadly, look set to place restrictions on some sectors of decarbonisation in historic building restorations. (Ref 9).

10.0 Societal issues arising from Industry 4.0 developments in this industry

The adaptation of skillsets needed to re-skill into Industry 4.0 will be a challenge for the built environment industry. The higher legislative demands on health and safety and the rise in skillsets needed will naturally suit only proportion of the current workforce. Workers able to make the transition to using Industry 4.0 – such as on-site tablets containing all relevant technical, safety and risk assessment information - may find greater autonomy and more interesting work. However, the competence required for continuous adaptation of the production system is critical to the success of manufacturing, and the built environment will be no different (Ref 10). Employers will need personnel with creativity and decision-making skills as well as highly digitally aware staff if they are to incorporate the changing demands that MMC and Industry 4.0- driven digital construction will require at the site level.



Changes in employment in Wales by sector, 2014-2024 Source: Working Futures, 2014-2024. (Ref 11)

From the above graph (Ref 11), the significant classification of work sectors relevant to design and construction in our sectors show conjectured changes in engineering dropping 2014-24, possibly due to the adoption of higher efficiencies. However, construction shows a rise, IT shows a small rise, and professional services a healthy rise over that period. Past evidence shows when significant job losses

are predicted, after a painful period of adjustment - at least for some workers – the process leads to more jobs being created than destroyed.

11.0 Conclusions

From the points demonstrated above, we can draw the following conclusions:

- The world has failed since 2015 to become more circular in its responsible use of resources – more work is therefore needed to progress circularity in our actions, construction especially included.
- That Industry 4.0 is making a mixed incursion into the built environment and construction industry –the promoters and originators of Industry 4.0 design and tools should promote and engage more heavily with this sector.
- The ready availability of powerful Industry 4.0 design and analysis capabilities will not automatically drive the construction industry and the built environment out of its established design and manufacture - more funded education of business is needed, backed by investment and training, may be necessary to progress Industry 4.0 development until it achieves its own momentum.
- There is considerable opportunity for further establishment of Industry 4.0 within this sector-market opportunity for industry suppliers to educate at all levels.
- There are questions of security of BIM data– high security of model integrity, release only at appropriate and protected access levels and monitor.
- The Industry 4.0 developments may well result in a workforce that is effective and well-educated in Industry 4.0 techniques and progression – without active supervision of the workplace trends and emerging gaps, inequality in readiness and acceptability of Industry 4.0 will embed and remain – Government opportunity – to fully embrace Industry 4.0 development and roll-out, supporting re-training to upskill where necessary to displaced employed groups and incomers from other industries.

12.0 References

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13.0 Appendices

Appendix 1- The demonstration of reducing world circularity – 2022 Graphic (Source- Ref 3)

