Deliverable Report D4.5
Production Relevant Environment Facility Implemented for use by the DIGIMAN Consortium

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DIGITAL MANUFACTURING AND PROOF-OF-PROCESS FOR AUTOMOTIVE FUEL CELLS

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DELIVERABLE REPORT D4.5: PRODUCTION RELEVANT ENVIRONMENT FACILITY IMPLEMENTED

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Due Date	31st December 2019
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DISSEMINATION LEVEL		
PU	*Public*	***x***
PP	*Restricted to other programme participants (including the Commission Services)*	
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CO	*Confidential, only for members of the consortium (including the Commission Services)*	

NATURE OF THE DELIVERABLE		
R	*Report*	***Y***
P	*Prototype*	
D	*Demonstrator*	
O	*Other*	

SUMMARY	
Keywords	*DIGItal MANufacturing and Proof-of-Process for Automotive Fuel Cells – Proof of Process, Production Relevant Environment*
Abstract	The DigiMan project focuses on the development of an automated fuel cell assembly system. Cell assembly is uplifted from the incumbent semi-automated system to full automation and outputs to Intelligent Energy's (IE) pre-existing automated stack assembly module for its AC64 fuel cell architecture. This deliverable report under Work Package 4 describes the implementation a proof of process facility, referred to as the PoP Demonstrator, within a production relevant environment.
Public abstract for the public website (only for confidential deliverables)	Not applicable

DELIVERABLE 4.5

PRODUCTION RELEVANT ENVIRONMENT FACILITY IMPLEMENTED

CONTENTS

Nomenclature

Symbol/Acronym	Description
GDL	Gas Diffusion Layer
MEA	Membrane Electrode Assembly
AC	Air Cooled
IE	Intelligent Energy
PPE	Personal Protection Equipment
PEMFC	Proton Exchange Membrane Fuel Cell
PoP	Proof-of-Process
QC	Quality Control
WMG	Warwick Manufacturing Group
FAT	Factory Acceptance Test
SAT	Site Acceptance Test
OEE	Overall Equipment Effectiveness
MRL	Manufacturing Readiness Level
US DoE	United States Department of Energy

1. INTRODUCTION

The DIGIMAN project focuses on the development of the automation need to uplift Intelligent Energy's (IE) fuel cell assembly capability for its AC64 stack technology platform, from its incumbent semi-automated process to a fully automated solution. In doing so the uplift must be capable of interfacing with existing/future automated cell test and stack processes.

A key project objective is the demonstration and proof-of-process that the uplifted automation has attained build-to-print readiness (i.e. fully engineered and ready to be made). Delivery of this outcome is to take the form of:

i. a blueprint design for user (i.e. Intelligent Energy) configuration of fully automated and integrated cell assembly and test processes that incorporate the fully validated uplift (i.e. a soft deliverable), but, via modularisation, scale to explicit business need scenarios and production models, and,
ii. a physical entity which facilitates the blueprint design's MRL6 accreditation (via a stack build / validation programme).

This involves the extrapolation and harvesting of large volumes of data relating to the assembly of AC64 cells (50,000 data points for each cell multiplied by the number of cells per stack) which then feeds simulation engines. From this, a digital twin of a fully integrated blueprint design-based solution will be created to demonstrate the scalability of a fully integrated assembly production line. To meet FCH JU stipulations, and formal project grant agreement imposed KPIs, the outcome will be measured against a production capacity > 50,000 stacks/year with processing time < 5 seconds per cell per each stage within the process flow; and this without degrading AC64 stack performance or imparting degradation mechanisms within produced stacks.

This deliverable report, D4.5, has inputs from Intelligent Energy and the University of Warwick (WMG), and describes the implementation a proof of process facility, referred to as the PoP Demonstrator, within a production relevant environment. It documents the pre-cursory deliverable to the project's Milestone 8 (PoP Demonstrator at Volume Rate) and Milestone 9 (Stack Validation) and deliverable reports D4.6 (PoP Demo MRL6) and D6.4 (Stack Validation).

2. Background

a. Overview

Digiman aimed to develop, over a three-year project duration, a blueprint design for next generation fully automated cell assembly & testing of IE's air-cooled stacks. The programme outcomes will demonstrate operational and supply chain cost reduction via seamless integration of digital manufacturing techniques (Industry 4.0 compliant) and advanced manufacturing technology, with a fully automated uplift to existing engineered assembly processes. Once developed, the blueprint design will allow build-to-print machine configurations with ready to scale production capacity to more than 50,000 fuel cell stacks per annum by 2020. The project raises the manufacturing readiness level by introducing enhanced design for assembly, automated processes for assembly, inspection, and test, coupled with advanced supply chain digitisation.

b. Context

Within the context of the project, production relevancy relates to attainment of the EU's definition of Manufacturing Readiness Level 6, (i.e. the capability to produce a prototype system or subsystem in a production relevant environment). This is a stipulation within FCH JU's 2016 Multi Annual Work Plan, Topic 2.1 - the project's funding competition and topic. To demonstrate this a proof-of-process machine has been designed and made. This physical incarnation will be used to validate the build-to-print readiness of a digital twin as based on a blueprint design of the uplifted automation.

c. The Stage Gated Roadmap To MRL6 and Stack Validation

The innovative process technology which underpins the automation uplift needed to be demonstrated at lab-scale (i.e. capability to produce the technology in a laboratory environment) prior to progression to MRL6 validation via the following validation stage gates:

- Factory acceptance testing (FAT) of the PoP Demonstrator:
    - Transfer of the PoP Demo to IE's Loughborough facility:
      Please note: the original project plan included temporary interim transfer and installation at a WMG facility for cycle trialling, but, to allow for a 6-month schedule recovery, this stage had to be forgone,
    - Install PoP Demo
    - PoP Demo conditioning and optimisation,

- Cycling trials (see Digiman deliverable report D4.4 - PoP Demonstrator Cycling Trials Report):
    - Gasket lamination and measurement cycles
    - 1st design modification
    - Field retrofit 1st design modification
    - Repeat gasket lamination and measurement cycles
    - 2nd design modification
    - Field retrofit 2nd design modification

- Site acceptance testing (SAT):
    - Establishment of Industry 4.0 data connectivity (via OPCUA compliant communications software) between the PoP Demonstrator and IE's internal OT (Operational Technology) and IT (Information Technology) systems
    - Development of a data extrapolation tool (a mini app) to harvest data from the Pop Demo
    - Perform and complete SAT and test cells in short hybrid stack

- MRL Trials:
  - Assemble cells to generate extrapolatable data for inputting into virtual engineering simulations and discrete event simulations and enable the development of the blueprint digital twin,
  - Assemble 1st product cells and stack for MRL6 authentication,
  - 1st product stack to pass hand-over test and demonstrate MRL6 attainment

- Stack Validation:
  - Assemble product stacks including,
    - next product iteration stacks – confirm BoL performance
    - light weighted stacks
    - Digiman DfM stack

3. Production Relevant Environment

Process engineering outcomes have allowed de-risking of the blueprint design by facilitating proof-of-process demonstration. Further proofing has been provisioned via representative mock up rigs which have established component & material handling characteristics, together with their preferred packaging and presentation formats. However, for MRL6 attainment, this proof needs to be within the context of a production relevant environment.

a. Production Relevancy

To retain flatness and positional control of film-like and other non-rigid components (e.g. MEAs, gaskets & seals) web-based handling solutions are required. However, web to web lamination is notoriously difficult, especially for dissimilar materials with disparate pitch repeatability and errors which accumulate over the length of the web. For this reason, the Digiman project has developed processes which avoid the need for pitch matching between carrier web and target substrate. Via techniques, herein referred to as dynamic lamination, the target substrate is indexed and aligned independently to the web with finite (and on-the-fly) adjustment to the theoretical pitch.

Within the budgetary constraints of the Digiman project, truly dynamic lamination (i.e. the on-the-fly transfer of components between synchronously advancing transfer webs and target substrates) was deemed too costly and consequently unviable. However, to prove, with production relevancy, the concept of on-the-fly lamination of web mounted components onto a static substrate, (herein, the dynamics of static lamination), has been developed for the PoP Demo. With emphasis on constant controlled tension during, i) indexing & pin-alignment, and ii) progressive wet-out & liner release, its gasket applicator subsystems have been designed to mimic and proof the dynamic aspects of lamination (to be reported on in deliverable report D4.6 PoP Demo MRL6) but for a statically clamped substrate.

b. Web-based Components

Most none-rigid / semi-rigid components start life as web-based, raw materials. However, it is often advantageous to retain their web-based status, offering tension and therefore flatness-controlled handling advantages as they progress, via rotary conversion processes, to singulated but web-mounted components. The liners which carry the raw material can therefore morph into transfer tapes, thus carrying forward and retaining tension (and positional) control until the point of transfer to the substrate.

As gaskets are cut then exchanged between liners, their cut position is never lost. Stages within the process flow accrue cumulative tolerances, but gaskets are never singulated / bulk handled, thus their theoretical centroids and pitches are retained.

Although dissimilar in construction, but from a handling and lamination perspective, MEAs can have similar requirements and characteristics to gaskets. In high volume scenarios, both can start life as roll stock materials. Then, via rotary converting and lamination stages, they are equally suitable for outputting as web-mounted, pre-singulated components, which, when mounted onto transfer tapes offer the appropriate retention and release characteristic to preferential release and lamination onto a target substrate or web.

Note: a lack of maturity (and competition) within contemporary MEA supply chains means that their availability in web-based, reel-to-reel packaging formats is limited and infrequent. Consequently, and as mitigation, the PoP Demonstrator has been designed to offer proofing of dynamic processes via pre-

lamination, (to the cathode gasket) of pre-singulated and vacuum clamped MEA's, which can then be transfer laminated in place via the respective (i.e. cathode) gasket applicator.

c. Environmental Sensitivities

MEA fabrication often includes an 'island-placement' operation which positions and centralises the CCM (catalyst coated membrane) within an albeit still none-rigid, supporting frame a.k.a. sub-gasket. Once the rotary laminated sub-gasket sandwiches the CCM, the membrane becomes sealed and structured. At this point, if held under tension (via a transfer tape), reeled MEAs constitute a dimensionally stable cell component, which is less susceptible to stretch than a gasket.

However, with an inherently unstable construction that is based around a highly moisture sensitive membrane film – see figure 1 – MEAs can be considered neither mechanically robust nor self-supporting.

Figure 1: Schematic of a Typical Membrane Electrode Assembly (MEA)

Consequently, their handling benefits from the physical support of a sacrificial carrier or transfer tape. With web-based alignment, laminated transfer to the target assembly prior to release from the carrier is possible. From experience gleaned from its incumbent semi-automated cell assembly, in terms of cell seal integrity, IE can testify to the yield improvement potential of supported MEAs. Whereas, unsupported MEAs exhibit none-desirable physical conditions e.g. wrinkles - see figure 2(a), and waviness – see figure 2(b).

Figure 2(a): Unsupported MEA showing Ambient Condition Induced Wrinkles

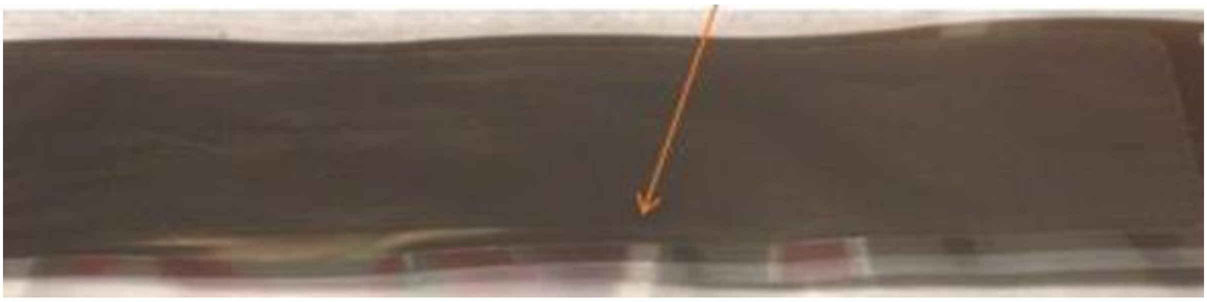


Figure 2(b): Unsupported MEA showing Ambient Condition Induced Waves

With the MEA representing the major contributor to the BoM cost of fuel cell stacks, maximum utilisation of incoming material becomes imperative. Compounding end of assembly line yield issues, wrinkles and waviness have further implications for long term stack durability. Even where these physical conditions are present but do not result in immediately detectable assembly rejects or cell leak test failures, BoL leak rates are generally high. For these reasons production relevancy requires tight temperature and humidity control.

4. Implementation of a Production Relevant Facility with Environmental Controls

The installation and proof of process operation of the PoP Demo to demonstrate MRL6 attainment within a production relevant facility with appropriate and representative environmental conditions required the following implementations:

a. Legislation and Standards

Notwithstanding the mandatory requirements which cover any future Blueprint design-based machinery purchases, to comply with Intelligent Energy's Environmental, Occupational Safety & Health (EOSH) Site policy, the PoP Demonstrator must be CE marked and supplied with a copy of the supplier's EC declaration of conformity. Irrespective of the need to be subjected to approval by the WMG and IE Health & Safety Department, the equipment must also comply with the requirements of:

- The European Machinery Directive 2006/42/EC.
- The Low Voltage Directive 2006/95/EC.
- The EMC Directive 2004/108/EC.
- The European Machinery Directive 2006/42/EC.
- The Low Voltage Directive 2014/35/EC.
- The EMC Directive 2014/30/EU.
- All other relevant directives.

b. Services

The production relevant facility required the following services:

- Power: 3-phase transformer, compliant with UK / European electrical regulations.
- Electrical Connection: 415V, 3 PH, 32AMP, Neutral and Earth
- Compressed Air: 6 Bar (90 PSI) pneumatic pressure filtered & dry 5um particulate filter.

c. Operational Environmental Compliance

Environmental compliance for a production relevant facility requires the following controlled operating environment:

- Temperature: 18°C to 30°C
- Humidity: 15% to 85% RH
- Airborne particulates: to be compatible with fuel cell component related airborne dust & debris

d. Control of Substances Hazardous to Health (CoSHH)

Intelligent Energy acknowledges that no substance can be considered completely safe. All reasonable steps have been taken to ensure that all exposure of employees to substances hazardous to health is prevented or at least controlled to within statutory limits. Use of substances prohibited by law is not allowed in any circumstance.

IE undertakes to ensure that prevention and/or adequate control of exposure of employees to a substance hazardous to health shall be secured by measures other than the provision of personal protective equipment. Where exposure cannot be adequately controlled by engineering means, the company

provides appropriate personal protective equipment (PPE) as detailed in its Health and Safety work instruction (HSWI-14). Furthermore, the company ensures that all control measures meet the relevant regulatory requirements.

All employees are and will continue to be provided with comprehensive information and instruction on the nature and likelihood of their exposure to substances hazardous to health.

e. Control of Contaminants and Materials Harmful to Fuel cell Production

The use of materials which emit air born species will always need to be qualified and authorised, in terms of control of substances, hazardous not only, to health, but also to fuel cells. More often, but not in entirety, CoSHH risk assessments will also identify materials which need to be risk assessed for potential damage to electro-chemically sensitive components typical of IE's PEMFC architecture. This process is longwinded and needs to be performed via ex-situ and in-situ immediate impact (at begin of life) and longer-term degradation. It requires the availability highly skilled fuel cell scientists and test rigs which are usually in high demand and therefore, specific use cases must be approved, irrespective of chances of approval.

Of primary concern, as air-born contaminants to PEMFCs are carbon monoxide (CO) and sulphur (S); with carbon dioxide (CO2). Unreacted hydrocarbon fuels act as diluents, and are therefore of lesser concern; nevertheless, they still requiring a full regime of testing and qualification.

Concern over CO in the fuel supply is indicative of sensitivity. According to the US DOE, reformed hydrocarbon fuels typically contain at least 1 percent CO, but even small amounts of CO can block hydrogen from the catalyst sites and degrade performance (as little as 10 ppm of CO in the gas stream)., In terms of intolerance of ambient contaminants, for i) human health & safety, and ii) fuel cell stack degradation, this is an example of risk criteria coinciding. Although humans might have slightly heightened tolerances, nevertheless, thresholds must be set as low as is possible.

The US DoE also states that:

- Although of much lesser significant than the catalyst poisoning by CO, anode performance is adversely affected by the reaction of CO2 with adsorbed hydrides on platinum.
- Other contaminants of concern include ammonia (membrane deterioration), alkali metals (catalyst poisoning, membrane degradation), particles, and heavy hydrocarbons (catalyst poisoning and plugging). Both the anode and cathode flows must be carefully filtered for these contaminants, as even ppb-level concentration can lead to premature cell and stack failure.

f. Principle Hazards and Confirmation of Control Measures

The production relevant facility required the following hazard control measures to be implemented:

Principle Hazards	Control Measures Identified (add additional/delete where applicable)
General Safety • Access to prescribed area not adequately controlled • Slips trips & falls • Risk from other non-related equipment or materials • Other non-related activities in progress • Manual handling injury - stress / strain	• Access to prescribed area is restricted to HVS authorised person, HVS PIC and authorised working party • Access to and from prescribed area made safe for working party • Safety measures in place for non-related equipment and materials • Concurrent activities will not interfere/affect prescribed area/work activity
Electrical • Risk of electrical shock/burns from live conductors • Risk of burns from arching flashover • Ineffective control of hazardous voltage power supply (& isolation) • Stored energy (post isolation)	• Screen exposed conductors • Access to prescribed area restricted • Electrical status signs in place & operating • Approved PPE and safety equipment provided • Communication of full RA/SSOW • Suitable means of isolation identified • Isolation can be secured in OFF position • Allow dissipation of stored energy
Mechanical • Entrapment from moving parts • Entrapment from loose clothing/jewellery • Movement of equipment due to stored energy	• Guarding/shielding in place to prevent accidental contact • PPE provided • Loose clothing and jewellery removed • Allow dissipation of stored energy
Thermal • Burns from contact with hot gases or fluids	• Appropriate PPE provided • Monitor test activity for hazardous temperature
Chemical • Burns from corrosive chemicals via ingestion, inhalation, absorption • Contact with hazardous chemical via ingestion, inhalation, absorption, instilled	• Is COSHH assessment in place? • LEV/engineering controls in place and operating • PPE provided
Noise • Hearing damage from excessive noise	• Remove/turn off source of noise where possible. • Provide suitable hearing protection (consideration should be given to reduction in ability to communicate)

Figure 3: IE's Table of Principle Hazards and Confirmation of Control Measures

g. Personal Safety

Together with all relevant emergency procedures, IE employees (plus other contracted people with granted permits to work on its premises) will be given sufficient information and training to ensure full understanding of the hazards to health posed by the facility implementation, and the importance of the control measure(s) provided. Employees and permitted associates will be kept informed about any monitoring and their individual health surveillance results.

If the company undertakes work which may expose any of its employees and permitted associates to substances hazardous to health it will provide them with such information, instruction and training as is suitable and sufficient for them to know the risks to health created by such exposure and the precautions which should be taken.

If employees (and permitted associates) discover any defect in the control measures it provides, they should report this immediately to the Systems quality manager. Employees are trained in how to recognise defects and the implications of these.

Employees (and permitted associates) will be trained in the use of any PPE and will ensure that it is kept clean and stored appropriately. If employees (and permitted associates) are provided with respiratory equipment the company will ensure that it is examined at suitable intervals and where appropriate, that it is tested

5. PRECAUTIONS NECESSARY

• PPE for activity available as defined in SSOW and Risk Assessment
• Approved voltage test probe and proving unit available
• Emergency response procedures known and understood
• Safety rescue hook available
• Second person nominated to accompany HVS PIC
• Points of isolation for electricity known (in case of emergency)
• Please be aware of I.E. Staff working in the area.
• Isolations will be discussed prior to any being made in area
• Test area signs displayed
    ○ Green 'test area electrical system isolated' – sign removed
    ○ Red 'test area electrical system live' – sign displayed
• Correct manual handling techniques to be used at all times.
• **In emergency inform staff in the immediate area, hiring manager or in extreme cases call Fire 01509 271911 First aid 01509 271911**

Figure 4: IE's Table of Personal Safety Necessary Precautions

PPE will only be used by Intelligent Energy employees (and permitted associates) as a last resort or as a back-up measure during testing or modification of other controls. The type and use of PPE will be carefully assessed and PPE will be maintained according to the manufacturers' instructions. All changes of PPE will be properly assessed.

6. PROTECTIVE EQUIPMENT
• Safety shoes, eye protection, 12.4cal fire retardant protective clothing, insulated rubber gloves (1000v Class 0) • Other operations specific PPE as noted in RA / SSOW • Safety hook • First Aid kit & defibrillator

Figure 5: IE's Table of Personal Safety Protective Equipment

h. Access and Installation

Where a modular layout is envisaged for ensuing blueprint design-based layouts (see figure 6) budgetary constraints precluded a sectional construction, meaning that the PoP Demonstrator's layout needed to be configured around a singular, welded-frame base.

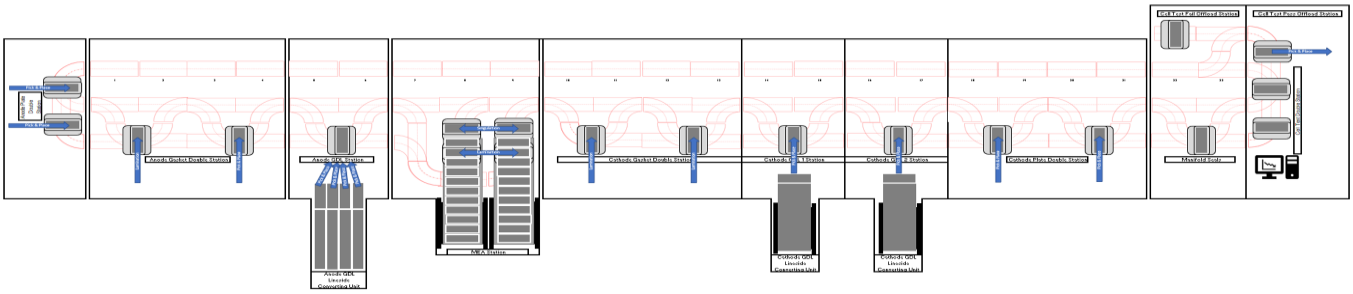


Figure 6: Envisaged Modular Layout for Blueprint Design Based Cell Assembly Line

To facilitate a workpiece indexing, the PoP Demo's linear motor-based track loops around the working envelope of a multi-axis robot, making the machine's quadrangular footprint close to equidistant in both X and Y dimension. See figure 7 for the machine footprint.

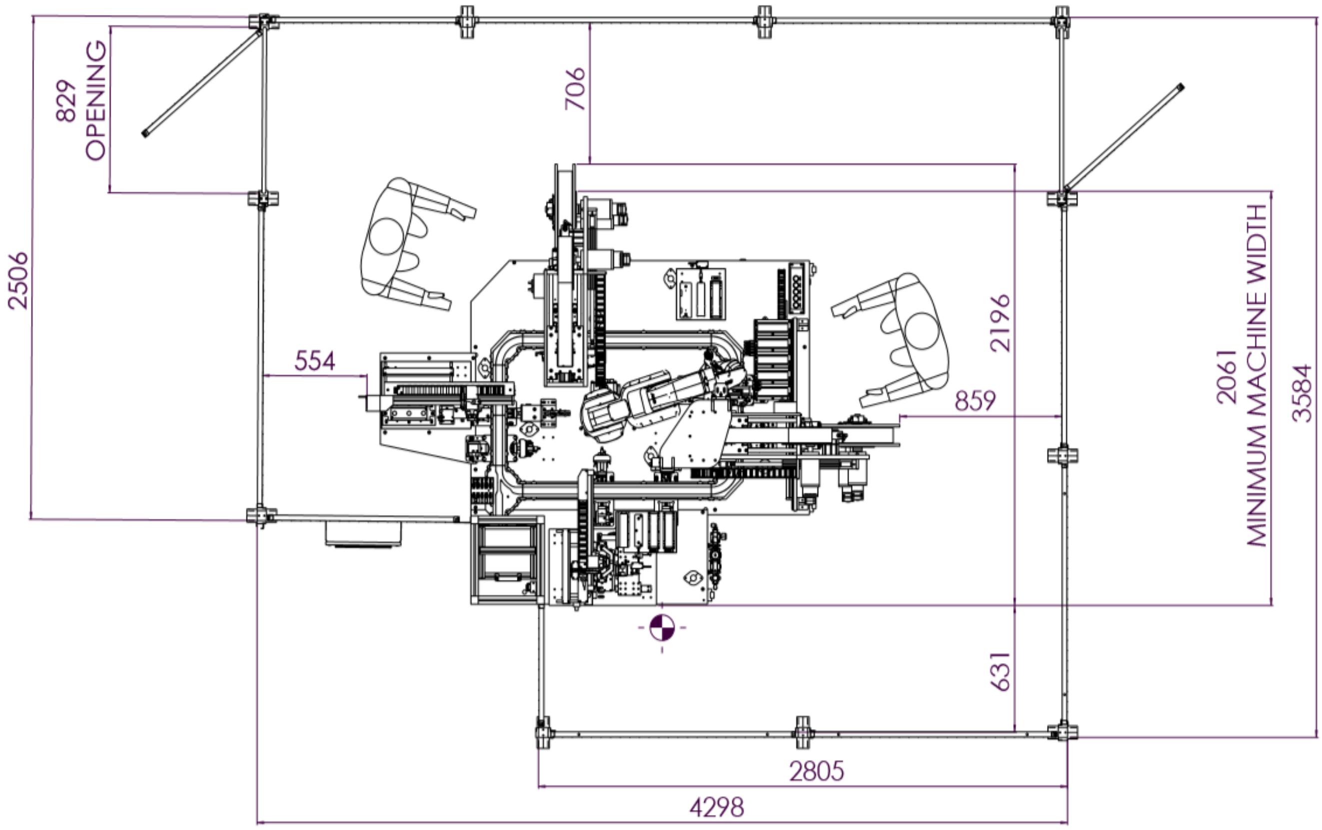


Figure 7: PoP Demo Machine Footprint (Including Safety Fence)

The layout drawing within figure 7 provides a minimum machine width. Even with the robot's reach constraining the footprint, and with the base machine stripped down to its extremities, the main box-frame plus the outrigger sections, including that of the anode gasket applicator (see figure 8), are factored within a fixed minimum machine width (MMW).

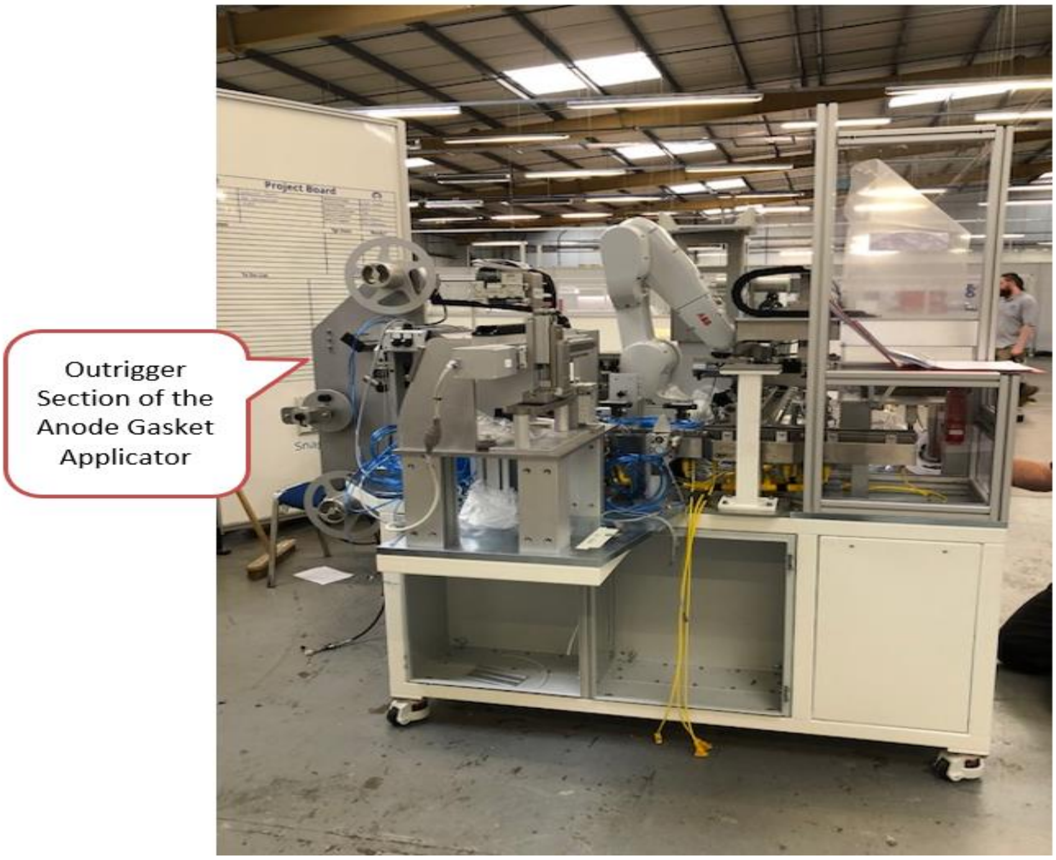


Figure 8: Side View of PoP Demo Machine Frame with Anode Gasket Applicator Outrigger

This minimum machine width exceeds standard width double doors (2*762mm – see figure 9), meaning that the double access doors and door frames had to be replaced by extra-wide, fully opening doors.

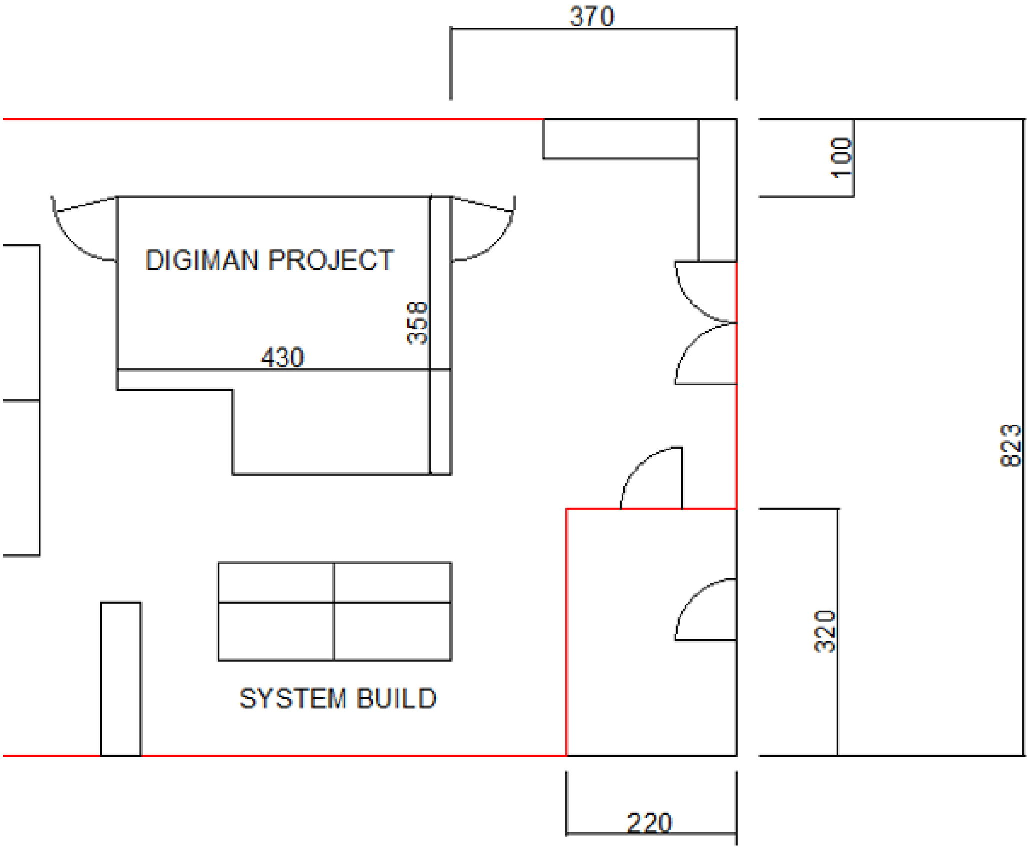


Figure 9: Facility Access and Equipment Siting Plan

i. Machine Guarding

Addressing the above described access challenges arising from the use of a singular, welded frame, machine base, and being mindful of post project completion, deconstruction and removal needs, a modular, safety fence-based machine guarding system was selected during the PoP Demo's provisional mechanical design phase.

As an add-on modular system, the self-locking/self-supporting fence sections allow the wrap-around, in-situ construction (and deconstruction) of the PoP Demo's safety enclosure. Included are e-stop circuit integrated interlocks which prohibit machine operation during human access and intervention. The integral cable routing features comply with the highest demands for cable routing systems in accordance with IEC 61537. This International Standard specifies requirements and tests for cable routing systems designed to support and accommodate cables and other electrical equipment in electrical and/or communication systems installations.

The cable routing system should be specified to withstand fire for as long as possible. The German DIN 4102-12 standard is used for testing this, a standard that is designed to test complete systems of cable trays, accessories and cables. Cable trays and cables are heated within an oven at 1000°C for 90 minutes. To be approved, the cables must still be in a usable condition. Approval comes in three classes: E30, E60 and E90 or for how many minutes the cable trays and cables are still functional. The PoP Demo's cables have been approved at the highest class, E90.

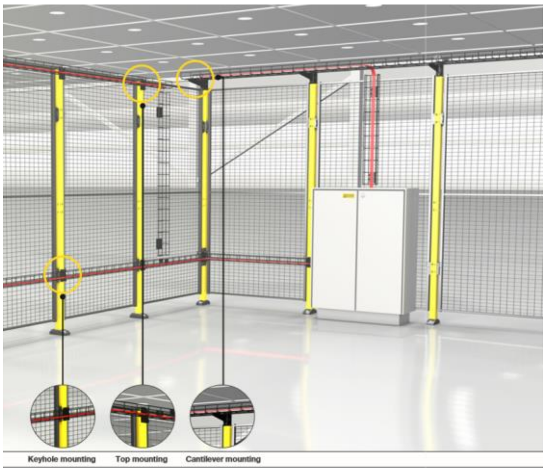


Figure 10(a): An Add-on Modular Self-locking/Self-supporting Safety Fence with Cable Routing System

Figure 10(b): PoP Demo's Modular, Safety Fence-based Machine Guarding System

The system selected for the PoP Demo's modular, safety fence-based machine guarding system complies with the Machinery Directive's demands on permanent guards from 29 December 2009.

j. Safety Distance

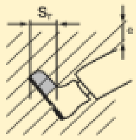
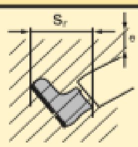
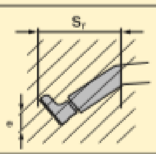
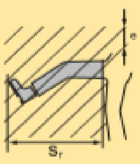
Safety distances are appropriate for protective structures. Safety distance calculation for the PoP Demo's machine guarding is based on BS EN ISO 13857:2008 (Safety of Machinery – Safety Distances to Prevent Hazard Zones Being Reached by Upper and Lower Limbs). It provides values for safety distances in both industrial and non-industrial environments to prevent machinery hazard zones being reached.

Safety distance calculations should, where possible, be based on lower limb access – note: The PoP Demo has full height fences, meaning that they extend to or beyond the height of the highest located moving part – see figure 12. BS EN ISO 13857:2008 gives information about distances to impede free access by the lower limbs. Where it is not foreseeable that the upper limbs can have access to the opening then users should refer to Clause 4.3 of the standard. As can be seen from figure 10(b), the combined fence height and safety distance make it unforeseeable for upper limbs incursions, therefore, corroborating the lower limb prevalence.

A risk assessment was to be performed to adjudicate the safety distances incorporated within the PoP Demo's overall layout. This risk assessment factored the risk between lower level (e.g. endangerment through friction) or higher levels (e.g. endangerment through entrapment). It also It covers people of 14 years and older (the 5th percentile stature of 14-year olds is approximately 1400 mm). In addition, for upper limbs only, it provides information for children older than 3 years (5th percentile stature of 3-year olds is approximately 900 mm) where reaching through openings needs to be addressed.

The PoP Demo's machine guard safety distances protect against human incursion and complies with the following:

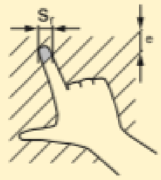
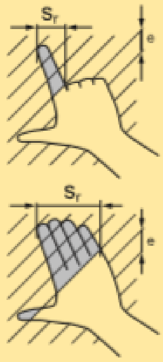
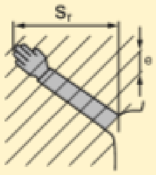
- Reaching through openings with dimensions for lower limbs - see figure 11(a)

Part of the body	Figure	Opening	Safety distance	
			Slot	Square/ circular
Tip of toe		e ≤ 5	0	0
		5 < e ≤ 15	≥ 10	0
Toe		15 < e ≤ 35	≥ 80	≥ 25
Foot		35 < e ≤ 60	≥ 180	≥ 80
		60 < e ≤ 80	≥ 650	≥ 180
Leg (as far as the knee)		80 < e ≤ 95	≥ 1100	≥ 650
Leg (as far as the crotch)		95 < e ≤ 180	≥ 1100	≥ 1100
		180 < e ≤ 240	Not allowed	≥ 1100

The coloured area shows which part of the body is restricted by the size of the opening.
If a slot is ≤ 75 mm long the safety distance can be reduced to ≥ 50 mm.
Slots > 180 mm and square or circular openings > 240 mm permit full body access. Additional protective measures must be taken.

Figure 11(a)

- Reaching through openings with dimensions for upper limbs - see figure 11(b)

Part of the body	Figure	Opening	Safety distance		
			Slot	Square	Circular
Fingertip		e ≤ 4	≥ 2	≥ 2	≥ 2
		4 < e ≤ 6	≥ 10	≥ 5	≥ 5
Finger up to knuckle where finger joins hand		6 < e ≤ 8	≥ 20	≥ 15	≥ 5
		8 < e ≤ 10	≥ 80	≥ 25	≥ 20
Hand		10 < e ≤ 12	≥ 100	≥ 80	≥ 80
		12 < e ≤ 20	≥ 120	≥ 120	≥ 120
		20 < e ≤ 30	≥ 850[1)]	≥ 120	≥ 120
Arm up to shoulder		30 < e ≤ 40	≥ 850	≥ 200	≥ 120
		40 < e ≤ 120	≥ 850	≥ 850	≥ 850

The coloured area shows which part of the body is restricted by the size of the opening.
For openings > 120 mm the safety distances for reaching over must be used and additional safety measures taken.

1) If the length of a slot is ≤ 65 mm, the thumb acts as a stop. The safety distance can then be reduced to 200 mm.

Figure 11(b)

- Reaching around safety protective features with dimensions for upper limbs - see figure 11(c)

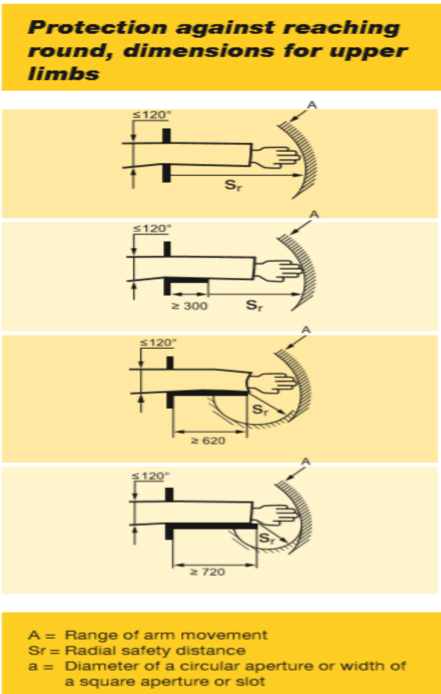


Figure 11(c)

- Reaching over safety protective features with dimensions for upper limbs - see figure 11(c)

Height of hazard zone a	***Height of protective structure b***									
	1000	1200	1400	1600	1800	2000	2200	2400	2500	2700
	Horizontal safety distance from hazard zone c									
2700	0	0	0	0	0	0	0	0	0	0
2600	900	800	700	600	600	500	400	300	100	0
2400	1100	1000	900	800	700	600	400	300	100	0
2200	1300	1200	1000	900	800	600	400	300	0	0
2000	1400	1300	1100	900	800	600	400	0	0	0
1800	1500	1400	1100	900	800	600	0	0	0	0
1600	1500	1400	1100	900	800	500	0	0	0	0
1400	1500	1400	1100	900	800	0	0	0	0	0
1200	1500	1400	1100	900	700	0	0	0	0	0
1000	1500	1400	1000	800	0	0	0	0	0	0
800	1500	1300	900	600	0	0	0	0	0	0
600	1400	1300	800	0	0	0	0	0	0	0
400	1400	1200	400	0	0	0	0	0	0	0
200	1200	900	0	0	0	0	0	0	0	0
Protective structures measuring less than 1400 mm should not be used without additional safety measures.										

Figure 11(d)

As can be seen from figure 12 the PoP Demo's safety fence to (machinery) hazard dimensions far exceed the minimum safety distance calculations as mandated by BS EN ISO 13857:2008 and have been purposely designed to allow safe working under interlocked and fully authorised working via competent and certified personnel during the machine's commissioning phases.

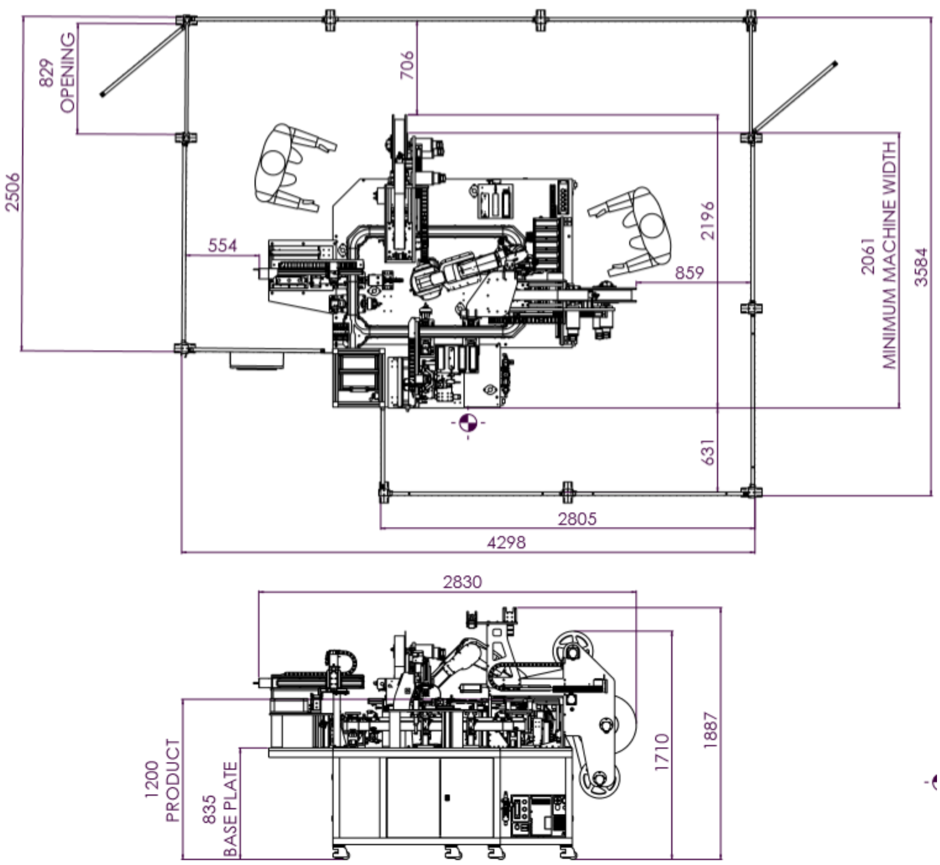


Figure 12 – Machine and Safety Fence Dimensions

k. Traceability

For production relevancy the PoP Demo has been designed with the capability to comply with Intelligent Energy's traceability & data collection standardised process. It can therefore trace components (batch), to assembled and tested cells via unique ID's and the supporting MIS (Management Information System).

The MIS data requirements are as follows:

A. Operator ID login/logout at start-up, during and at end of production runs via manually actuated scanning and data capture of unique IDs to facilitate:

   i. Operator / unique ID cell assembly traceability,
   ii. Date and time records data acquisition,
   iii. Line ID records data acquisition (for multiple line scenarios),

B. In process (does not incur cycle interrupts or additional cycle time) scanning and data capture of unique cell ID, component batch and cell end-of-line test data, via manually actuated and automatic on-the-fly (where applicable) readers to facilitate cell assembly work-in-progress tracking.

C. In process (does not incur cycle interrupts or additional cycle time) scanning and data capture of cell and unique carrier IDs to facilitate:

   i. Process control and retrospective traceability of carrier related (digital) cause/effects,
   ii. Cycle interrupts and error message outputs in the event of failures,
   iii. Line ID records data acquisition (for multiple line scenarios),

D. In process (does not incur cycle interrupts) manual scanning and data capture of cell ID and codified defect modes to facilitate:

   i. In-coming component defect recording,
   ii. Defects during cell assembly,
   iii. Stock control of on-line component inventory,
   iv. Cycle interrupts and error message outputs in the event of failures,
   v. Error trapping cycle interrupts and error message outputs in the event of incorrect / incomplete scans,
   vi. Remote access connectivity for IE remote process monitoring,
   vii. To output requisite data in SQL record and or CSV (Comma Separated Variable) file containing the data generated from cell assembly for a maximum of one shift's duration,

For information, unique cell identification is via the marking of an external component with a 2D data matrix containing the following. This marking is in the form of a square, maximum size 5mm x 5mm and minimum size 3mm x 3mm conforming to ISO/IEC 16022 applied centrally to the underside of the component.

I. DATA HARVESTING

Traceability and data collection steps have been integrated into the POP demo machine design. All component materials/parts are barcode scanned. Within the POP demo in operational mode, the barcode details scanned will be assigned to a unique QR code located on the external component that is scanned prior to placement onto the carrier. Data collected throughout the PoP Demo cycle is stored in a dedicated database as developed by WMG and IE and allows identified quality critical data to be analysed and correlated via a digital cause and effect dashboard (Work package 6). Figure 13 below shows the data harvesting architecture and digital cause and effects relationships.

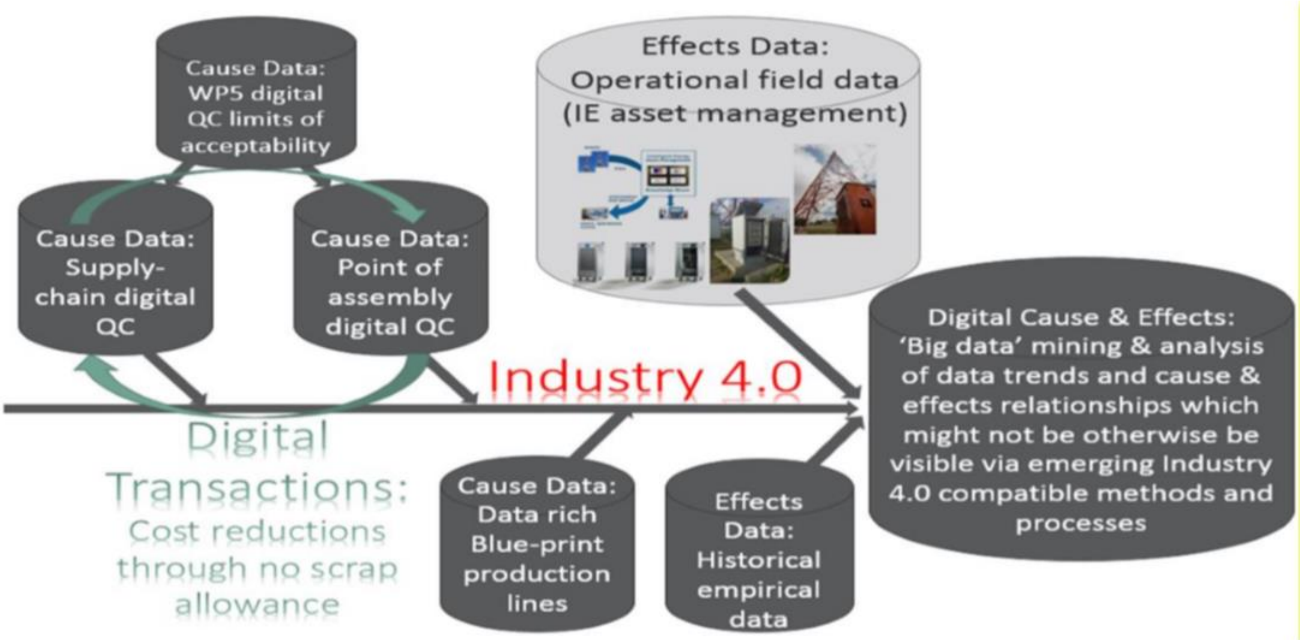


Figure 13: PoP Demo's Data Collection Architecture

5. Completion and Next Steps

The Digiman project's charter (from FCH JU Multi-annual Work Plan 2016) is to advance the assembly solution's manufacturing readiness from MRL4 to MRL6. Within Digiman's context, for MRL6 attainment, this means uplifting the cell assembly automation and proving it (build-to-print ready), within a production relevant, temperature and humidity-controlled environment. The proof, via a stack assembly and test validation programme, therefore requires a fully production representative facility. Via the FAT / Cycling Trials / SAT stage gates this implementation has now been completed.

The stack validation programme has commenced and the 1st product stack has passed its hand-over test stage therefore demonstrating MRL6 attainment.

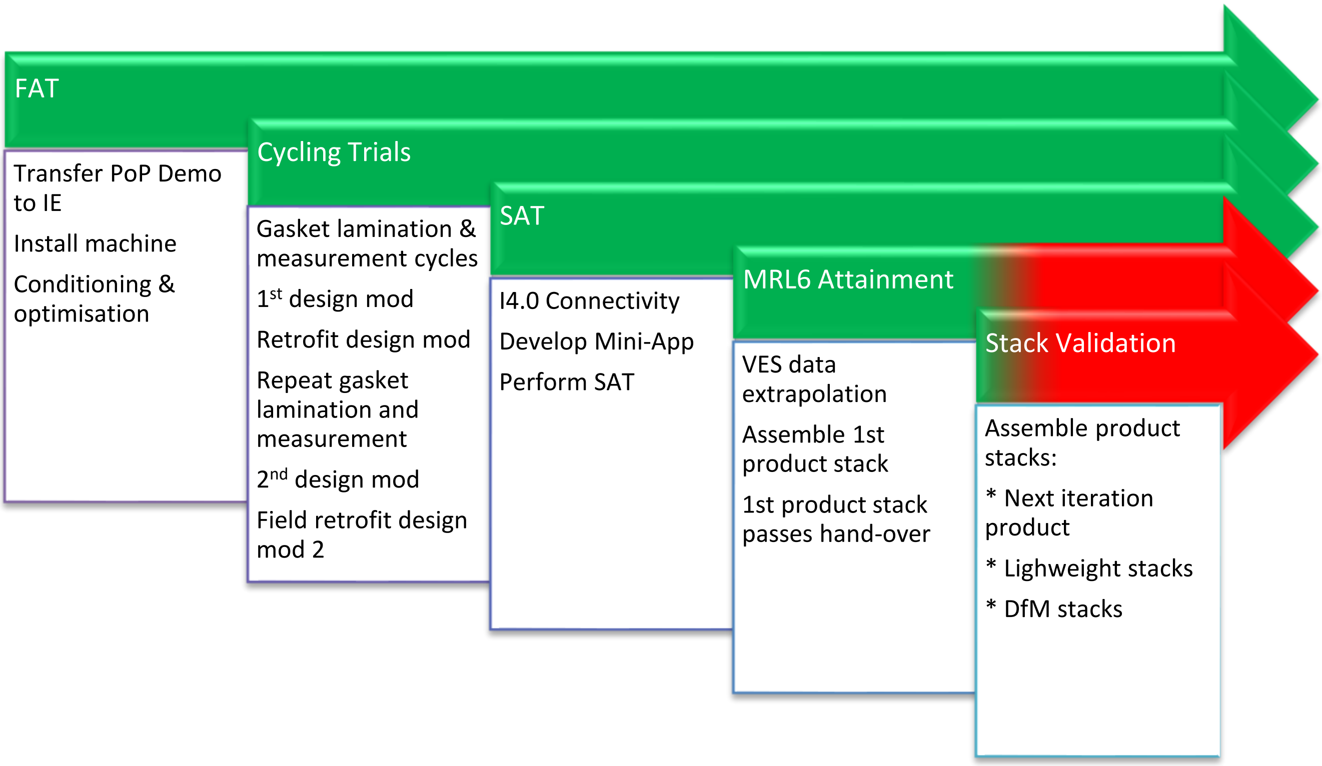


Figure 14: MRL6 & Stack Validation Roadmap

The next steps are to i) complete the stack validation programme (Task 6.4), and ii) perform and report the findings from digital cause and effects analysis of the harvested data (Task 6.5).

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