MANUFACTURING AND PROOF-OF-PROCESS FOR AUTOMOTIVE FUEL CELLS

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DELIVERABLE REPORT

D2.1 Auto Best Practice & KPIs			
WP 2: Definition of Auto Best Practice & Baseline KPI Specification		WP leader: TME	
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SUMMARY	
Keywords	*Auto Best Practice & KPIs*
Abstract	*DIGIMAN Deliverable Report D2.1 presents a definition of Automotive Best Practice via the Toyota Production System. It then goes on to define the specification of baseline Critical Performance Indicators for the DIGIMAN Project. The aim of task 2.1 is to document these metrics and KPI targets for the emergent fully automated stack assembly concept as demonstrable and measurable (at a down-scaled rate) via the Proof of Process Demonstrator to be delivered under the project.*
Public abstract for the public website (only for confidential deliverables)	

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NOMENCLATURE

Symbol or acronym	Description
GDL	Gas Diffusion Layer
MEA	Membrane Electrode Assembly
OC	Operating Conditions
PEMFC	Proton Electrode Membrane Fuel Cell
POR	Process of record
QC	Quality control
KPI	Key Performance Indicators
VOC	Voice-of-the-Customer
QFD	Quality Function Deployment
EOL	End Of Line
PoP	Proof-of-Process
TPS	Toyota Production System
DMAIC	Define, Measure, Analyse, Improve, Control

GENERAL INFORMATION

WP2: Requirement Setting & PoP Measurement involves the setting of requirements to i) capture VOC (Voice-of-the Customer) in demonstration of the to-be-developed Blueprint Design's deployment readiness as demonstrated by operation and measurement of the Proof-of-Process uplifted automation, and ii) to demonstrate attainment of the project's pre-determined and below-stated key objectives:

- *Demonstrate that, via the uplifted automation, the blueprint design as configured as fully integrated assembly and test line, would scale to deliver production capacity >50,000 stacks/year by 2020*
- *Demonstrate for a single line a total stack power output of >5MW*
- *Demonstrate a step improvement of cell assembly cycle times from today's semi-automated >22 seconds per cell to automated processing at <5 seconds per cell (x5 times uplift)*
- *Advance stack manufacturing technology level to MRL6*
- *Develop in-process quality controls at component and sub-component level to reduce scrap rate to target <3%*
- *Model costs showing target trajectories consistent with automotive targets for 2020 at 50k stacks pa*
- *Ensure that the stack performance is not detrimentally affected by the improvements for manufacturing and assembly delivering 0.7 A/cm2 @ 0.7V world leading for air cooled fuel cell technology*

The specific scope objective from FCH-01.1-2016 work plan: *'Transpose established automotive industry best practices on production and quality to the manufacturing of PEMFC stack and stack components, such as (but not limited to) lean manufacturing, kaizen, six sigma:'* will be addressed by capture of VOC best practice performance targets as based on the Toyota Production System (TPS) and allow QFD planning for the other below work plan objectives:

- *'Development of manufacturing technologies, beyond state of the art, specific to PEM stack production processes, equipment and tools.*
- *'Identification of bottleneck processes in stack or stack component production lines:'*
- *'Identification and revision of critical sub-processes (e.g. low yield / high cost)*
- *'Improvement, modification, adaptation or even new development of at least two critical stack or stack component production steps'*
- *'Integration of in-line non-destructive quality controls'*
- *'Adaptation of stack and/or stack component design to optimise manufacturability'*
- *Development of QA strategies relevant for the transportation sector compatible with ISO/TS16949'*

1. REQUIREMENTS

This document addresses *WP2 Task 2.1 Definition of Auto Best Practice & Specification of Baseline KPIs.*

The aim of this task is to set metrics & KPI targets for the emergent fully auto stack assembly concept as demonstrable and measurable (at a down-scaled rate) via the PoP demonstrator. Value Stream Analysis and visualisations will be used to show compliance with The Toyota Production System's *House of Quality* philosophy with its *jidoka* and Just-in-Time pillars.
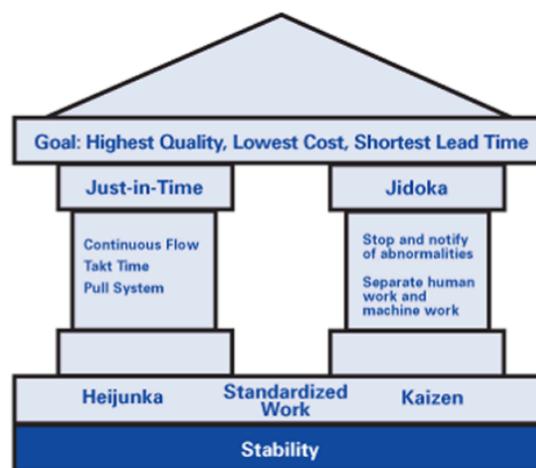
Toyota Production System "House."

KPIs are needed to measure specific and tangible performance metrics such as cycle time, assembly related costs, yields and uptime. Without them it will not be possible to benchmark the to-be-developed full auto stacks assembly concepts against the PoP demonstrator and project them to a scaled volume production scenario. Therefore, this task requires the setting of baseline KPIs for MRL6 qualification of the Blue Print design via the PoP demonstrator in work package 4 and 6, together with a projection of volume production measures using Kaizen philosophies.

The measurable metrics will be used specifically in the validation of:

- The production readiness of a Blueprint Design based cell assembly configuration and accompanying EOL test stage in terms of direct to line shipment (at-rate) of stacks in to a Toyota volume automotive production line
- The production readiness of a Blueprint Design based cell assembly configuration for direct deployment within a TPS compliant volume automotive production line

2. LEAN MANUFACTURING & THE TOYOTA PRODUCTION SYSTEM:

2.1. Toyota Production System

The Toyota Production System is a production control system that has been established based on many years of continuous improvements, with the objective of "making the vehicles ordered by customers in the quickest and most efficient way, to deliver the vehicles as quickly as possible."

The Toyota Production System (TPS) was established based on two concepts:

- **JIDOKA (which can be loosely translated as "automation with a human touch") which means that when a problem occurs, the equipment stops immediately, preventing defective products from being produced;**
- **"Just-in-Time," in which each process produces only what is needed by the next process in a continuous flow.**

Based on the basic philosophies of *jidoka* and Just-in-Time, the TPS can efficiently and quickly produce vehicles of sound quality, one at a time, that fully satisfy customer requirements.

JIDOKA – Highlighting/visualization of problems

Quality must be built in during the manufacturing process! If a defective part or equipment malfunction is discovered, the machine concerned automatically stops, and operators stop work and correct the problem. For the Just-in-Time system to function, all the parts that are made and supplied must meet predetermined quality standards. This is achieved through *JIDOKA*.

- *JIDOKA* - machinery safely stops when the normal processing is completed. It also means that, should a quality or equipment problem arise, the machine detects the problem on its own and stop, preventing defective products from being produced. As a result, only products satisfying the quality standards will be passed on to the next processes on the production line.
- Since a machine automatically stops when processing is completed or when a problem arises and is communicated via the "ANDON (problem display board)," operators can confidently continue performing work at another machine, as well as easily identify the problem cause and prevent its recurrence. This means that each operator can oversee many machines, resulting in higher productivity, while the continuous improvements lead to greater processing capacity.

JUST IN TIME – Productivity improvement

Making only "what is needed, when it is needed, and in the amount needed!" Producing quality products efficiently through the complete elimination of waste, inconsistencies, and unreasonable requirements on the production line.

To deliver a vehicle ordered by a customer as quickly as possible, the vehicle is efficiently built within the shortest possible period by adhering to the following:

- When a vehicle order is received, a production instruction must be issued to the beginning of the vehicle production line as soon as possible.
- The assembly line must be stocked with small numbers of all types of parts so that any kind of vehicle ordered can be assembled.
- The assembly line must replace the parts used by retrieving the same number of parts from the parts-producing process (the preceding process).
- The preceding process must be stocked with small numbers of all types of parts and produce only the numbers of parts that were retrieved by an operator from the next process.

Illustration of the Toyota Production System:
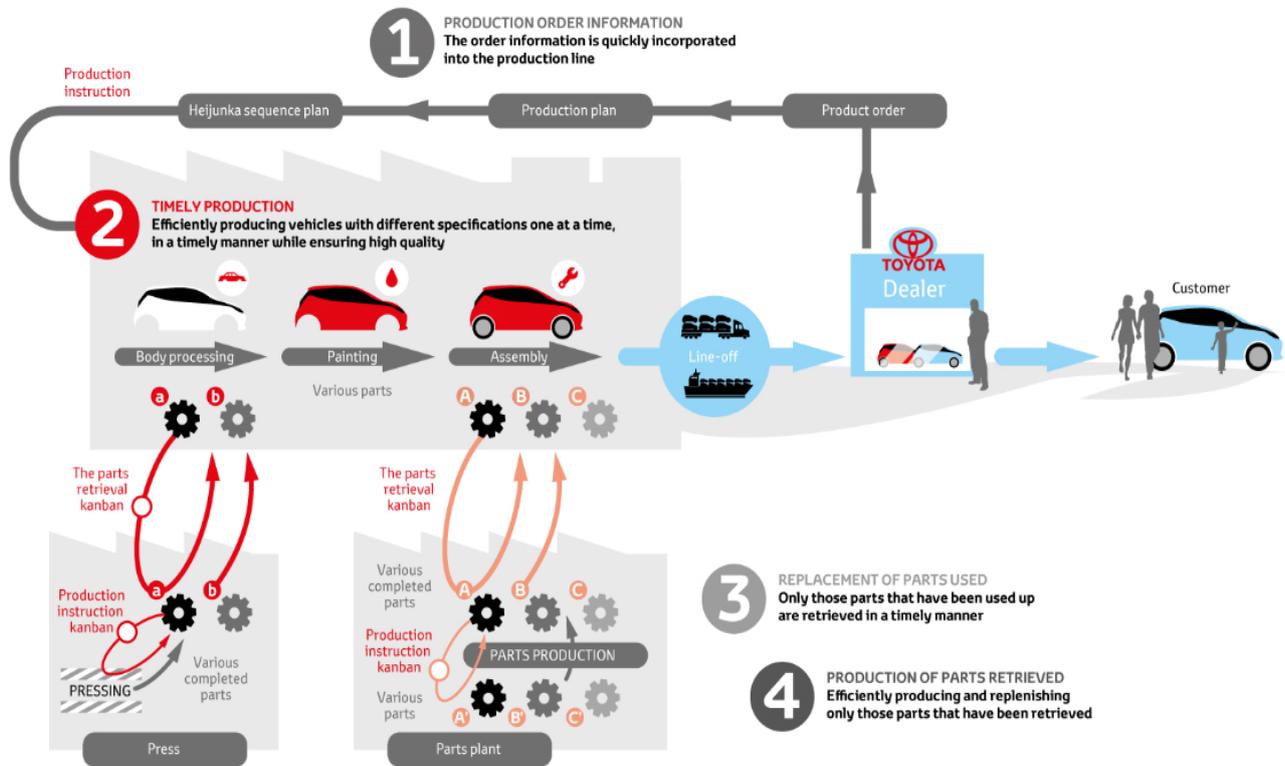
Producing and delivering ordered vehicles in a timely manner

2.2. Requirement Setting & Proof-of-Process Approach

Definition of automotive best practice & specifications of baseline KPIs as provided by TME will be used to validate DIGIMAN's delivery of the following:

- Lean manufacturing - methodologies will be developed in the form of line-side converting of components from roll-stock raw material demonstrating automotive best practises with pull-demand (i.e. Kanban) for minimised, line-side inventory of raw material. This arrangement would also aid flexible, fast response job change-over (SMED – Single-Minute Exchange of Die) thereby benefiting production flow (addressing the TPS's Muri type waste).

- Continuous improvement - digital cause & effects relationships will be developed and exploited. Causation data will be mined from the to-be-developed digital characterisations of material physical attributes and codified by i) localised spot defects / blemishes and ii) homogeneity / structural none-conformities. Data rich sensing capability (of cause metrics) will be embedded within fully automated work piece handling assembly systems i.e. IIoT enable smart carriers. This will be complemented by big data sources derived, in part, from in-service functionality self-monitors as harvested via IE's pre-existing asset management capabilities. This will enable digital cause / effects modelling and offer knowledge based guidance for on-going opportunities for continuous improvement i.e. kaizen

- Six Sigma - DMAIC methodologies will be served and an industry wide gap in supply chain processes for the converting of imperfect roll-stock into pre-screened (known-good) and

ready to assemble GDL components. These best practises will be codified and embedded within the to-be-developed Digital QC system. The Digital QC functionality will be enhanced, and progressively refined through linked digital cause / effects modelling, thus offering closed loop six-sigma implementation and control.

2.3. Lean Validated Blueprint Models: Value Stream Analysis & Discrete Event Simulation Approach

The to-be-developed PoP Demonstrator facility will enable accurate blueprint modelling and simulation of at rate vehicle assembly line targets (i.e. 50,000 stack/pa) with pull demand scenarios via the following techniques:

- Adoption of Muda philosophy with specific focus on
    - Over production,
    - Waiting time
    - Unnecessary transport or conveyance
    - Over or incorrect processing
    - Excess inventory
    - Motion
    - Defect generation.

- VSA (Value Stream Analysis) will be used to demonstrate single piece flow of an AC64 cell through,
    - The to-be-designed full auto cell assembly and in-line QC / leak test blueprint, and
    - A pull-demand from a to-be-specified end-of-line stack test process and handover procedure
- De-coupled stages of a single piece flow that can be subjected to DMAIC investigation and optimisation, with bottlenecks defined / measured / analysed and smoothed by discrete event simulations, which accommodate, both,
    - On-the-fly dynamic lamination of layered cell components and
    - Ganged stationary pick-&-place assembly of singulated components.
- From automotive value stream maps and discrete event simulations of the operation of a cycle time optimised and volume scalable (at rate) version of the fully auto uplifted AC64 production system,
    - Hard bottleneck outcomes will be demonstrated via value stream analysis and visualisations.
    - Soft bottleneck scenarios will be modelled by the to-be-developed Digital Cause / Effects tool.

3. STACK PERFORMANCE RELATED METRICS & KPIs

3.1. Stack Performance[1]

Metric	Unit	KPI
Stack nominal gross power	kW	2.1
Rated Voltage	Vdc	51.84
Electrical efficiency rated	%	54.5
Mass	Kg	2.9
Specific Power	W / kg	714
Power Density	W / L	726
Stack Environment[2]	Deg C	+5 °C to +50 °C ambient
System Environment[3]	Deg C	-40 °C to +50 °C ambient
Altitude	m	0 to 4000m
Start-up Time	Secs	<5
Fuel composition	-	99.95% gaseous hydrogen or better
Fuel Supply Pressure	bar.g	0.4 to 0.7

1. Example Stack Configuration – 72 cell

4. MANUFACTURING METRICS (PROJECT REPORTING REQUIREMENTS)

4.1. Stack Assembly

Metric	Unit	KPI
Production rate in units/h	Stacks / h	10
Production rate in units/yr	Stacks / yr	60,000
Production rate in power/yr	MW / yr	120
Scrap rate	%	<3
Quality acceptance criterion	NA	Power, voltage, current, leak rate
Number of direct staff per number of units produced	Person / unit	1
Number of staff per MW power produced	Person / MW	0.025
Production line footprint (based on blue print-based design plus automated stack assembly based on IE existing design @ 5 secs Takt time)	M^2	28
Operational Efficiency (OEE - Overall Equipment Efficiency)	%	85%
Manufacturing Readiness Level	MRL	From 4 to 6

5. BLUEPRINT DESIGN PERFORMANCE METRICS & KPIS (COMMON LANGUAGE AND TARGETS)

To be used in:

- Task 2.4 - Technical Cost Modelling
- Task 2.5 - DIGIMAN Interim & Final Report
- Task 4.7 - Proof of Process and Production Relevant Facility
- Task 6.4 - Stack Manufacturing Validation Testing

From the TPS and / or as derived from commonly used, generic automotive industry terms this section provides a project taxonomy from the following Metrics and with accompanying KPIs:

5.1. OPR – Operation Production Ratio (TPS)

An important KPI of plant productivity is the Operation Production Ratio (OPR) defined as:

- OPR = (Total working time – Line Stop time) / Total working time
  - Ideal target is 100%.

Few Toyota car manufacturing plants in Europe target 97% OPR.
   Where:

- Total working time = Regular working time + Production Overtime

- Regular working time = standard declared production time
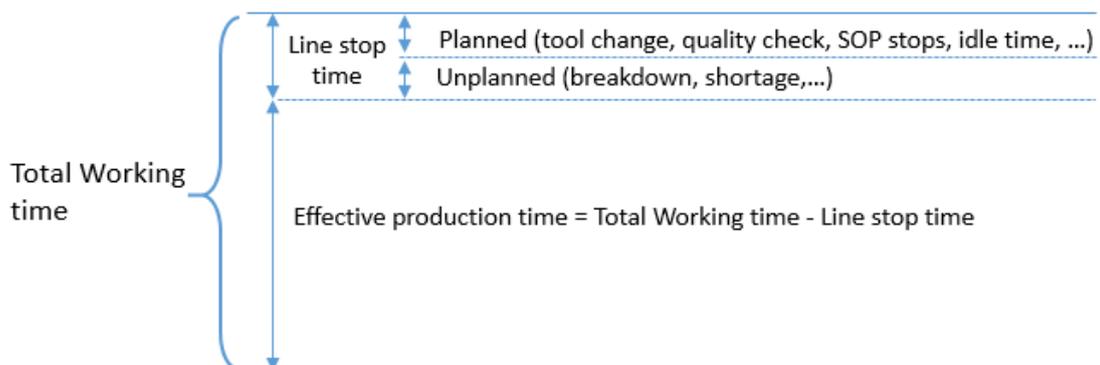
5.2. Non-Production Overtime (TPS)

All activities performed during non-production overtime such as 4S, Quality Circles, Kaizen activities, inventory count, etc. are excluded from "Total working time" and measured separately.

5.3. Unpaid time (TPS)

Activities / delays / stops for any reason during which wages are not paid, are excluded from the "Total working time". However, any activity that affects the working pattern hours, amount of working time and/or delays production must be reported.

5.4. OEE – Overall Equipment Effectiveness

Definitions:
- If OEE = 100%, then:

    – Manufacturing of only good parts (Quality – Q)
    – Within Takt time (Performance – P)
    – With no downtime (Availability – A)

- World class OEE = 85% / engine assembly line OEE = 73%

- Increased through TPM (Total Productive Maintenance):

$$OEE = Q \times P \times A \quad \text{Eq.1}$$

$$Q = {}^{Good\ Count} / {}_{Total\ Count} \quad \text{Eq.2}$$

$$P = {}^{(Ideal\ Cycle\ Time\ x\ Total\ Count)} / {}_{Run\ Time} \quad \text{Eq.3}$$

$$A = {}^{Run\ Time} / {}_{Planned\ Production\ Time} \quad \text{Eq.4}$$

    – Ideal cycle time = theoretical time required to produce one part
    – Run time = planned production time – down time
    – Planned production time = all time – scheduled time

5.5. FFT – First Time Through

Definitions:
- Percentage of units complete a process at quality without:

    – Scrap (S)
    – Rerun (RR)
    – Retest (RT)
    – Rework (RW)
    – Return (RN)

- Similar to Q in OEE but focussed at operational / process level

- Also referred to as FPY (First Time Pass). TPY (Through-Put Yield), FTY (First Time Yield), FTQ (First Time Quality. In terms of data processing some subtle differences, but inherently terms are interchangeable

- Engine assembly line FFT = 95% (Typing / Piston assembly, Ford China)

$$FTT_{OP} = {}^{Units\ Entering\ Process\ -\ (S\ +\ RR\ +\ RT\ +\ RW\ +\ RN)} / {}_{Units\ Entering\ process} \quad \text{Eq.5}$$

5.6. SLM&V - Service Life Modelling & Validation

Definitions:

- SL = service life, modelled (MSL) and validated (VSL) KPIs for a metric which establishes test-to-failure rates for the Blue Print's bespoke design elements which,

  - Involve movement under load with frictional interfaces e.g. plain bearings, flat bearing surfaces & pressure plates, linear guides

  - Utilise novel polymer bearing technology

  - Do not carry an original manufacturer's service life prediction / guarantee

- LLR = life-limited replaceables (or wear-out part) e.g. any of the above which can be considered life limited wear out items but used within a design context which accommodates automated wear monitoring / alerts and economical in-service replacement

- LT = life testing of the Blue Print design subsystems via continuous, powered dry-cycling (simulated actuation rather than actual production) of the PoP demonstrator's actuators and associated moving parts

- ALT = above life test but at accelerated actuation speeds

- MTTF = mean time to failure, can be used in technical cost modelling in the context of life-limited replaceables i.e. $MTTF_{LLR}$

$$MTTF_{LLR} = {}^{\Sigma\ (start\ of\ down\ time\ -\ start\ of\ uptime)} / {}_{Number\ of\ Failures} \qquad Eq.6$$

- MTTR = mean time to replace, can be used in technical cost modelling in the context of life-limited replaceables i.e. $MTTR_{LLR}$

$$MTTR_{LLR} = {}^{\Sigma\ (start\ of\ uptime\ -\ start\ of\ downtime)} / {}_{Number\ of\ Failures} \qquad Eq.7$$