Lean Six Sigma in Smart Factories based on Industry 4.0

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ABSTRACT

The purpose of this article is to present the preliminary results from ongoing research on Lean Six Sigma in Industry 4.0 based on a novel and comprehensive approach. It shows that Lean Six Sigma and Industry 4.0 mutually support each other. To develop a deeper and more dynamic mutual support, updates on Lean Six Sigma based on 3 critical principles are suggested. It provides a number of sound perspectives on improvement to the Lean Six Sigma methodology to develop an intelligent, sophisticated, integrated and efficient approach for continuous improvement within smart factories. The findings assist in tackling chronic problems and new challenges in Manufacturing such as Energy Management. The suggested principles leverage Industry 4.0 capabilities for humans in the world of robots.

Keywords: Lean Six Sigma, Industry 4.0, Smart Factories, Energy Management, Quality

1. INTRODUCTION

The fast ever-increasing global competition that most manufacturing firms have been facing over recent years is associated with rapid technological changes. Industry 4.0 has been considered to be a new industrial stage in which several emerging technologies are converging to provide digital solutions (Frank *et al*., 2019). The Industry 4.0 concept has a very complex technology architecture of the manufacturing systems (Lee *et al*., 2015), which is one of the major concerns in this new industrial stage and the effective implementation of Industry 4.0 technologies is still a subject of research (Frank *et al*., 2019).

To achieve the potential advantages of Industry 4.0, appropriate managerial efforts prior to and after its adoption is needed. Quality management systems establish particular management practices that could be applied to boost these managerial efforts. Regardless of the quality methodology or name of the continuous improvement programmes, each firm needs to apply tools and techniques in their implementation process. It is crucial that the tools and techniques are appropriately selected for the team in question and applied correctly to the appropriate process (Basu, 2009).

Over the years, the worldwide approach to the use of quality systems has eventually converged on the two principles which are known today as Lean and Six Sigma. Lean, with its simple approach that concentrates on advancing the speed and efficiency of processes and providing breadth in problem solving. On the other hand, Six Sigma is more complex and offers a methodology for drilling deep into complicated problems. It also has a very structured approach to problem solving that is absent in Lean. Simply, Six Sigma is about improving the quality and accuracy of processes by reducing variation, while Lean focuses on attaining response times by eliminating waste.

According to American Society for Quality (ASQ) "DMAIC is an acronym that stands for Define, Measure, Analyse, Improve, and Control. It represents the five phases that make up the process, including the tools to use to complete those phases" (ASQ DMAIC, 2019).The Six Sigma tools and techniques with the enjoyment of a systematic data collection, analysis, and interpretation prompting optimal decisions are compiled in consecutive order in the five phase DMAIC methodology especially for analysing root causes of problem as the Analyse phase of DMAIC does. The action on DMAIC helps draw and logically filter the most important factors which involves the process outcomes (Kumar *et al.*, 2008).

Lean tools and techniques are linked to highly inter-related and wide ranging toolkits of quality management practices for removing waste. Value stream mapping (VSM), Just in time (JIT), Total productive maintenance (TPM), and other practices exemplify the Lean tools and techniques as described in the work of Bhamu and Kuldip (2014). These toolkits are aimed at eliminating waste and non-value added activities, whereas concurrently they are adding value to the customers. Accordingly, these two methods - Lean and Six Sigma - offer complementary tool kits; they address the root cause of different business challenges (Shaffie, 2012).

The integration of Lean and Six Sigma has generated an approach that is more flexible and applicable when addressing business challenges. This methodology can satisfy an essential need to develop a comprehensive tool to actually deliver top-quality service and products (Shaffie, 2012). In recent years, Lean and Six Sigma have become the most popular business strategies for adopting in manufacturing, services and public sectors. Lean Six Sigma offers a more integrated, coherent as well as holistic way of accomplishing continuous improvement and hence it leverages appropriate managerial efforts across the adoption of a very complex technology architecture of the manufacturing systems (Pepper and Spedding, 2009). Continuous improvement is the core aim for most firms in the world to assist them to achieve quality and operational excellence and to enhance performance (Assarlind *et al*., 2012).

Although the benefits of working with continuous improvement have been broadly reported in the literature, implementing it is complex and not always successful (Jurburg *et al*., 2017). Adopting effective improvement practices, capable of keeping pace with the changing technological environment particularly toward and during a new industrial stage with a very complicated manufacturing architecture, is vital to success in global markets. The work of Uriarte and her colleagues indicates that Lean with the use of simulation and in combination with Six Sigma might be one of the yet higher popular management practices in the context of Industry 4.0 (Uriarte *et al*., 2020). The necessity for incorporation of Lean Six Sigma into technologies established for Industry 4.0 institutes the new Lean Six Sigma (LSS) initiatives, namely LSS 2.0, where big data analytics as one of the elements in Industry 4.0 is integrated into Lean Six Sigma (Sordan *et al*., 2020).

What is the relationship between Industry 4.0 and Lean Six Sigma? The following sections will try to address this critical question.

2. RESEARCH METHODOLOGY

The scope of the research intends to investigate the link between Lean Six Sigma and Industry 4.0 as follows:

1-Potential support from Industry 4.0 for Lean Six Sigma

2- Potential support from Lean Six Sigma for Industry 4.0

A two-stage method for the research is applied. As the first stage, regarding the review of the literature, the systematic process of content analysis with four main steps is followed. May *et al*. (2017) and Mayring (2010) apply the systematic process of content analysis based on the following steps:

Step 1: Material gathering - definition of unit of analysis and constraining potential material

Step 2: Descriptive analysis - definition of formal features and assessment of material

Step 3: Category assortment - definition of analytical categories and application to material

Step 4: Material evaluation - analysis of material based on defined categories

The prime terms for the search in article titles, keywords and abstracts were identified as “Industry 4.0” and “Smart factories”. The publications in the last 5 years were searched on Scopus and Science online databases due to their ability for tailored and quick searches.

These steps provided a comprehensive picture of smart factories and their key elements i.e. Manufacturing Cyber-Physical Systems (MCPS) based on Industry 4.0. The stage further identified key components for each major characteristic of MCPS.

For the second stage, DMAIC was applied as the representative of the Lean Six Sigma methodology. It is a data-driven strategy used to improve processes as an integral part of Six Sigma, as a standalone quality improvement procedure or as part of other process improvement initiatives such as lean (ASQ DMAIC, 2019). DMAIC simplifies this research as it covers tools & measures for both Lean and Six Sigma.

The second stage involved two steps as follows:

Step 1: the key characteristics of MCPS that can potentially facilitate the applications of Lean Six tools and the components of MCPS that can potentially support the application of the above tools are identified.

Step 2: the key characteristics of MCPS are categorised, then the Lean Six Sigma tools which potentially can support each characteristic and how these tools potentially support Industry 4.0 are outlined. The next sections will provide more details.

3. WHAT IS INDUSTRY 4.0?

This section illustrates Industry 4.0 as applied at present and the aspirational application of a range of modern techniques as well.

Emerging smart technologies such as Internet of Things (IoT) and new business environments lead manufacturing industries to move toward developing high-tech systems such as smart factories. IoT is simply the network of interconnected physical items which are embedded with sensors, RFID chips, etc. that enables them to collect and exchange data (Miragliotta *et al*., 2012). The increasingly growing application of smart components has resulted in the generation of high volume data. Smart components include self-aware and self-predict 'Sensors', and smart machines such as self-aware, self-predict and self-compare 'Controllers' and smart production systems such as self-configure, self-maintain and self-organise 'Networked systems' (Lee *et al*., 2015). Cyber-Physical Systems (CPS) is a transformative technology to manage the high volume data known as Big Data. CPS manages interconnected systems between its physical assets and computational capabilities (Baheti and Gill, 2011).

An example of CPS can be identified in Total Productive Maintenance (TPM). Process parameters (stress, productive time, etc.) of mechanical elements underlying a (physical) wear and tear are recorded digitally. Preventive Maintenance (PM) can be scheduled based on the real condition of the mechanism results from the physical object and its process parameters (Lasi *et al*., 2014).

CPS integrated with Production, Engineering, Maintenance and Logistics will transform current factories towards an Industry 4.0 factory. This future factory will totally be equipped with smart sensors, actors and autonomous systems (Lee *et al*., 2015 ; Lasi *et al*., 2014).

According to a survey by ASQ in 2014, 82 percent of companies that claim to have employed smart factories state that they have increased efficiency and 45 percent increased customer satisfaction (Shrouf *et al*., 2014).

Smart suppliers provide smart factories with smart inputs via IoT and Internet of Services (IoS). Smart manufacturing is a decentralised and self-organised process embedded with smart elements. It includes dynamic, automate and real-time communication for the management of a highly dynamic manufacturing environment including smart engineering and smart maintenance (Shrouf *et al*., 2014). Smart engineering includes product design and development and smart maintenance focuses on predictive maintenance. Smart factories are supported by smart external and internal logistics which include smart logistics tools and processes. Self-organised logistics is an example of logistics management within the organisation that react to unexpected changes in production, such as bottlenecks and material shortages (Lopez Research, 2014).

A continuous manufacturing process usually involves more compound items than a typical batch process. Figure 1 shows a general perspective of a CPS architecture for smart factories based on Industry 4.0 applied to a continuous manufacturing process such as a steel, plastics and fertiliser plant that consumes natural gas (NG) as raw material as well. A smart TPM approach can be applied to preventive maintenance in critical infrastructures and the energy (electricity and gas) transmission and distribution network. Figure 1 shows a simplified 5G structure with secure IoT and drones remote control to implement preventive maintenance for gas pipelines (Zahariadis *et al*., 2017).

The stream of smart data between all value creation elements such as smart factories, smart manufacturing, smart engineering, smart maintenance, smart logistics, smart suppliers, smart grids, etc. in Industry 4.0 is interchanged through the cloud computing (Stock and Seliger, 2016). Fog computing is the extension of the cloud and its nodes are physically much closer to CPS. They are able to provide instant connections and perform the computation of big data on their own, without sending it to distant servers. The main difference between fog computing and cloud computing is that cloud is a centralised system, while the fog is a distributed decentralised infrastructure. Some advantages of fog computing for CPS are low latency, no problems with bandwidth, high security and improved user experience (Sakovich, 2018).

Smart factories can be supplied with renewable energies from smart grids as well as supplied with NG if required. Smart grids dynamically and efficiently match generated energies from suppliers with the demand of smart factories and other consumers. Smart factories can be energy suppliers within a smart grid (Stock and Seliger, 2016).

Smart factories can dynamically compare all potential smart energy suppliers via smart grids to choose the most competitive one. They need to securely, efficiently and fairly share knowledge and make smart agreements among themselves (Al-Jaroodi and Mohamed, 2019). Blockchain is a growing list of linked records, named blocks, connected and secured applying encryption algorithms (Zyskind *et al*., 2015). The key to the effectiveness of this list is the links that are generated from one block to the next, therefore it would be difficult to change any block after it is added to the list. Blockchain can generally provide many advances for Industry 4.0 applications. This includes improved techniques for reliable information exchanges, automated and efficient negotiation processes and efficient smart agreements among enterprises (Mohamed *et al*., 2019).

As shown in Figure 1, the relationship between customers and smart factories is defined and enabled by IoT and IoS. The smart factories provide their customers with smart products and smart services which are linked to the internet. The smart factories will then collect and analyse data coming from the smart products and related applications. This real-time Voice of the Customer (VOC) enable the factories to better understand customers' experiences, needs and expectations. Customers can also contribute on product/service development and improvement via IoT and IoS capabilities (Shrouf *et al*., 2014). To sum up, the fourth industrial revolution incorporates the whole value chain process embroiled in the manufacturing industry into a very complex technology architecture of the manufacturing systems (Mohamed, 2018).

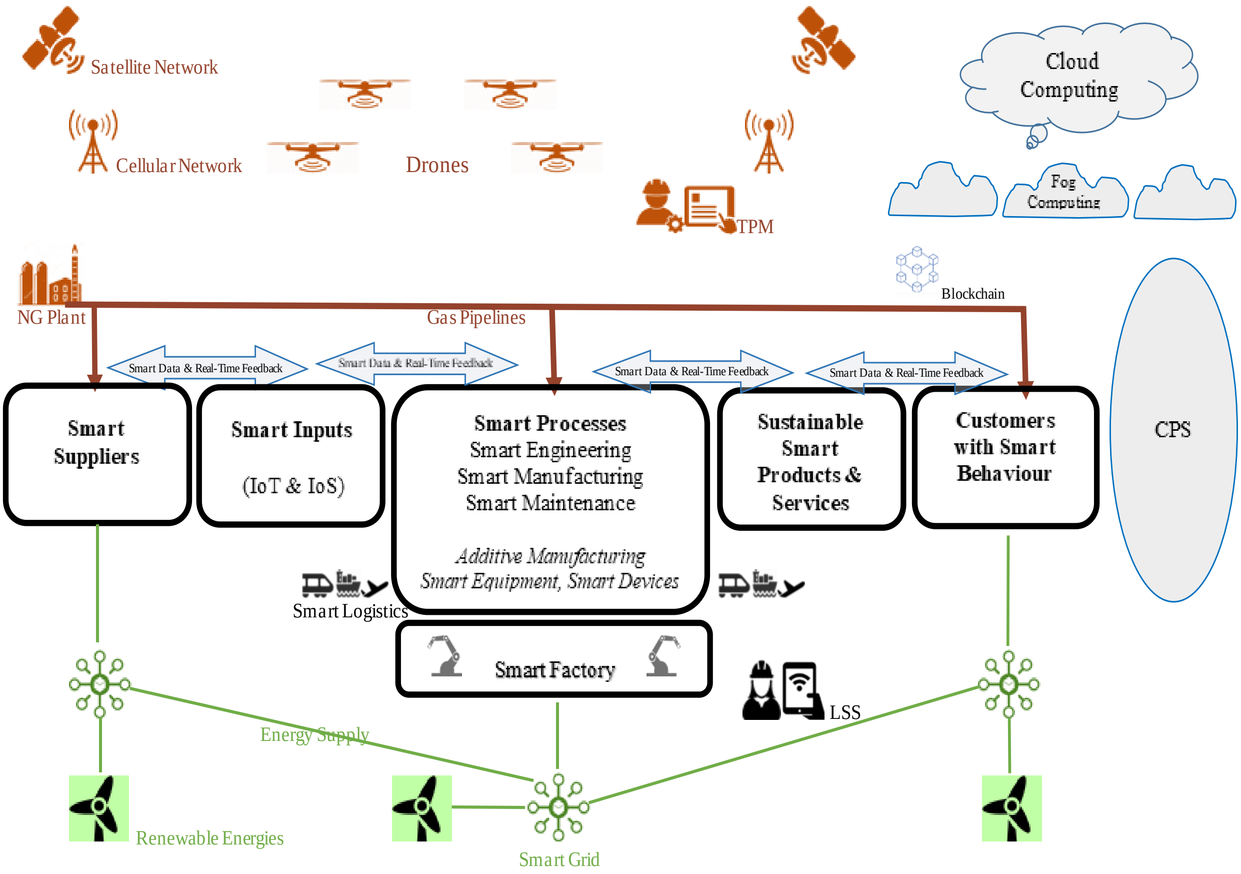

Fig. 1. A general perspective of a CPS architecture for smart factories based on Industry 4.0

4. WHAT IS LEAN SIX SIGMA?

Lean production (Womack et al., 1990) is a multi-dimensional methodology that involves a wide variety of management practices in an integrated system. The main drive of Lean production is that these practices can work synergistically to create an efficient, high quality system that produces products at the pace of customer demand with little or no waste (Shah and Ward, 2003). One feature of this system is its focus on the elimination of waste or muda (in Japanese) – anything that does not add value to a product – by means of continuous improvement activities (Ruiz-de-Arbulo-Lopez *et al*., 2013).

Under the Lean manufacturing system, seven wastes are identified: delay, overproduction, inventory, motion, defects, over-processing and transport (Dumas *et al*., 2013) and this method is a systematic approach to eliminating these wastes through continuous improvement by flowing the product at the pull of the customer in pursuit of perfection (Kubiak and Benbow, 2018).

The Six Sigma methodology is a project-driven management approach to improve the firm's products, services, and processes by continually reducing defects. It can be used as a business strategy to improve business profitability, the effectiveness and efficiency of all operations to meet or exceed customer needs and expectations (Kwak and Anbari, 2006).

According to ASQ "Six Sigma is a method that provides organizations tools to improve the capability of their business processes. This increase in performance and decrease in process variation helps lead to defect reduction and improvement in profits, employee morale, and quality of products or services" (ASQ Six Sigma, 2019). Six Sigma is known for employing challenging process improvement goals (Pande *et al*., 2000).

"Lean Six Sigma is a fact-based, data-driven philosophy of improvement that values defect prevention over defect detection. It drives customer satisfaction and bottom-line results by reducing variation, waste, and cycle time, while promoting the use of work standardisation and flow, thereby creating a competitive advantage. It applies anywhere variation and waste exist, and every employee should be involved" (Kubiak and Benbow, 2018). Lean Six Sigma as a process excellence has been widely adopted in both manufacturing and service organizations (Antony *et al.*, 2017).

Many Lean Six Sigma frameworks have been proposed by both researchers and practitioners (Timans *et al*., 2014; Yadav and Desai, 2016). These frameworks encompass various concepts, approaches, tools, and techniques. "DMAIC is a data-driven quality strategy used to improve processes. It is an integral part of a Six Sigma initiative, but in general can be implemented as a standalone quality improvement procedure or as part of other process improvement initiatives such as Lean" (ASQ DMAIC, 2019). Yet, as the work on many Lean Six Sigma frameworks have been reported, the current frameworks neglect to adapt a prerequisite for Industry 4.0 (Yadav *et al.*, 2017).

Based on the above specifications, the DMAIC methodology is applied as a representation of Lean Six Sigma to investigate its link with Industry 4.0.

5. POTENTIAL SUPPORT FROM INDUSTRY 4.0 FOR LEAN SIX SIGMA

The first and second columns of Tables 1-5 list key tools and measures for each phase of DMAIC. Then the key characteristics of Manufacturing Cyber-Physical Systems (MCPS) based on Industry 4.0 that potentially can facilitate the applications of these tools and measures are identified. The next column identifies the components of MCPS that can potentially support the application of the above Lean Six Sigma tools. Tables1-5 are adopted to investigate whether Industry 4.0 facilitates Lean Six Sigma application.

Table 1. Potential support from Industry 4.0 for the Define phase of Lean Six Sigma

DMAIC Methodology		**MCPS based on Industry 4.0**	
Phase	**Key Tools & Measures**	**Characteristics facilitating DMAIC application**	**Components**
Define	SIPOC IPO Kano Analysis CTQ QFD CCR VOC Flow Diagram Project Charter Quality Chains Process Map Stakeholder Analysis (SA) Affinity diagrams	Integrated physical object & its digital process parameters, Digitalisation & networking (Lee *et al*., 2015; Lasi *et al*., 2014). Decentralisation, Real-time support, Modularity & Virtualisation (Mohamed *et al*., 2019; Lee *et al*., 2015). Automation & Visibility within smart factories, Creating value from big data collected within smart factories (Shrouf *et al*., 2014).	Big Data, Augmented Reality, Simulation, IoT, Cloud, Cybersecurity *(*Lee *et al*., 2015; Mohamed *et al*., 2019; Zahariadis *et al*., 2017; Al-Jaroodi and Mohamed, 2019). CPS (Lee *et al*., 2015; Lasi *et al*., 2014; Shrouf *et al*., 2014; Lopez Research, 2014). Fog computing, Blockchain (Mohamed *et al*., 2019; Al-Jaroodi and Mohamed, 2019). Smart factories using embedded CPS (Stock and Seliger,2016; Lee *et al*., 2015). 5G, Drones, Satellite Network (Zahariadis *et al*., 2017).

Table 1 is used to investigate whether Industry 4.0 facilitates the Define phase of Lean Six Sigma. The second column lists key tools and measures for the Define phase. Then the key characteristics of MCPS that potentially can facilitate the applications of these tools and measures are identified. The next column identifies the components of MCPS that can potentially support the application of the Lean Six Sigma tools for this phase.

Table 2. Potential support from Industry 4.0 for the Measurement phase of Lean Six Sigma

DMAIC Methodology		**MCPS based on Industry 4.0**	
Phase	**Key Tools & Measures**	**Characteristics facilitating DMAIC**	**Components**

		application	
Measurement	Process Capability MSA Statistics DPMO Sigma Level Check Sheets Histograms Run Charts Scatter Diagram Cause and Effect Pareto Control Charts Flow Process Charts Box Plot	Architecture based on 'self-aware component', 'Self-aware & Self-compare machine' and 'self-configure & self-organise production system' (Shrouf *et a*l., 2014; Zuehlke, 2010; Lasi *et al*., 2014). Creating value from big data collected within smart factories (Shrouf *et al*., 2014; Lee *et al*., 2015).	Big Data, Augmented Reality, Simulation, IoT, Cloud (Lee *et al*., 2015; Mohamed *et a*l., 2019; Zahariadis *et al*., 2017; Al-Jaroodi and Mohamed, 2019). Additive Manufacturing, CPS (Lee *et al*., 2015; Lasi *et al*., 2014; Shrouf *et al*., 2014; Lopez Research, 2014). Sensor, Controller, Networked system (Lee *et al*., 2015; Zahariadis *et al*., 2017). Actor- data, Sensor-data, Digital processes (Lasi *et al*., 2014).

Table 2 is used to investigate whether Industry 4.0 facilitates the Measurement phase of Lean Six Sigma. The second column lists key tools and measures for the Measurement phase. Then the key characteristics of MCPS that potentially can facilitate the applications of these tools and measures are identified. The next column identifies the components of MCPS that can potentially support the application of the Lean Six Sigma tools for this phase.

Table 3. Potential support from Industry 4.0 for the Analysis phase of Lean Six Sigma

DMAIC Methodology		**MCPS based on Industry 4.0**	
Phase	**Key Tools & Measures**	**Characteristics facilitating DMAIC application**	**Components**
Analysis	Correlation FMEA Regression RU/CS SWOT PESTLE Five Whys How How OEE	Exchange data and information between different devices and parties in real time (Shrouf *et al*., 2014; Azevedo and Almeida, 2011). Smart Connection, Conversion, Cyber, Cognition, Configuration	Analytical components, Additive Manufacturing, Smart grid, Actor-data, Sensor-data, Digital processes (Lasi *et al*., 2014).

	TRIZ Multi-Vary Analysis DOE Cp & Cpk Process Mapping Fault Tree Hypothesis Testing Interrelationship Diagram (ID) Stratification of data to get Information	(Lee *et al*., 2015; Kopetz, 2011; Shi *et al*., 2011).	Big Data, Augmented Reality, Simulation, IoT, Cloud (Lee *et al*., 2015; Mohamed *et al*., 2019; Zahariadis *et al*., 2017; Al-Jaroodi and Mohamed, 2019). CPS (Lee *et al*., 2015; Lasi *et al*., 2014, Shrouf *et al*., 2014; Lopez Research, 2014).

Table 3 is used to investigate whether Industry 4.0 facilitates the Analysis phase of Lean Six Sigma. The second column lists key tools and measures for the Analysis phase. Then the key characteristics of MCPS that potentially can facilitate the applications of these tools and measures are identified. The next column identifies the components of MCPS that can potentially support the application of the Lean Six Sigma tools for this phase.

Table 4. Potential support from Industry 4.0 for the Improvement phase of Lean Six Sigma

DMAIC Methodology		MCPS based on Industry 4.0	
Phase	**Key Tools & Measures**	**Characteristics facilitating DMAIC application**	**Components**
Improvement	Autonomation Nominal Group SMED 5S DOE Mistake Proofing Value Stream Mapping(VSM) Force Field Analysis Level Scheduling Benchmarking FMEA Affinity Diagram	Self-organised logistics (Stock and Seliger, 2016). Connected supply chain, Smart Engineering, Visibility & optimised decision-making within smart factories (Shrouf *et al*., 2014). A sustainable-oriented decentralised organisation (Stock and Seliger, 2016; Lasi *et al*., 2014).	A Cyber-Twin for each component (Lee *et al*., 2015). Advanced industrial robots (Mohamed *et al*., 2019; Qin *et al*., 2016). Mobile technology (Shrouf *et al*., 2014). Abstract planning procedures (Shrouf *et al*., 2014; Zuehlke, 2010).

		Intelligent production processes & self-configuration (Shrouf *et al*., 2014; Zuehlke, 2010; Lasi *et al*., 2014). Energy management within smart factories (Shrouf *et al*., 2014; Lopez Research, 2014). Individualisation on demand "batch size one", Automatic solutions involving operational, dispositive & analytical components, Autonomous manufacturing cells, Sustainability and resource efficiency, Self-organisation, Individualised distribution & procurement (Lasi *et al*., 2014).	Smart factories using embedded CPS (Stock and Seliger, 2016; Lee *et al*., 2015). Self-aware, Self-predict, Self-compare, Self-configure, Self-maintain & Self-organise elements (Shrouf *et al*., 2014; Zuehlke, 2010; Lasi *et al*., 2014). Information & communication technologies embedded in a cloud, CPS with embedded mechatronic components (Stock and Seliger, 2016). Smart logistics, Automated Guided Vehicles, RFID chips, QR codes (Stock and Seliger, 2016; Shrouf *et al*., 2014; Lopez Research, 2014). Smart factories, CPS, Smart Grid (Stock and Seliger, 2016; Lasi *et al*., 2014). IoT, IoS, Smart Manufacturing, Cloud (Shrouf *et al*., 2014; Azevedo and Almeida, 2011). Big data, 3D printing (Stock and Seliger, 2016).

Table 4 is used to investigate whether Industry 4.0 facilitates the Improvement phase of Lean Six Sigma. The second column lists key tools and measures for the Improvement phase. Then the key characteristics of MCPS that potentially can facilitate the applications of these tools and measures are identified. The next column identifies the components of MCPS that can potentially support the application of the Lean Six Sigma tools for this phase.

Table 5. Potential support from Industry 4.0 for the Control phase of Lean Six Sigma

DMAIC Methodology		MCPS based on Industry 4.0	
Phase	**Key Tools & Measures**	**Characteristics facilitating DMAIC application**	**Components**
Control	SPC SOP Gantt Chart PDCA Activity Network Diagram Radar Chart Milestone Tracker Diagram Earned Value Management(EVM)	The intelligent cross-linking and digitalisation throughout all phases (Stock and Seliger, 2016). A sustainable-oriented decentralised organisation (Stock and Seliger, 2016; Lasi *et al*., 2014). Intelligent production processes & self-configuration (Shrouf *et al*., 2014; Zuehlke, 2010; Lasi *et al*., 2014). Predictive Maintenance within smart factories, Remote monitoring within smart factories (Shrouf *et al*., 2014), Architecture based on 'self-aware component', 'Self-aware & Self-compare machine' and 'self-configure & self-organise production system' (Shrouf *et al*., 2014; Zuehlke, 2010; Lasi *et al*., 2014). Integrated physical object & its digital process parameters (Lasi *et al*., 2014).	Self-maintain & Self-organise elements (Shrouf *et al*., 2014; Zuehlke, 2010; Lasi *et al*., 2014). 5G, Drones, Satellite Network (Zahariadis *et al*., 2017). IoT, IoS, Smart Manufacturing, Smart Engineering, Smart Logistics (Shrouf *et al*., 2014; Azevedo and Almeida, 2011). A Cyber-Twin for each component (Lee *et al*., 2015). Sensors, Controllers, Networked systems, intelligent & adaptive algorithms (Mohamed *et al*., 2019; Shrouf *et al*., 2014). Machin-Cyber Interface, Big data (Shrouf *et al*., 2014; Lopez Research, 2014). Cloud, Fog computing, Blockchain (Mohamed *et al*., 2019; Al-Jaroodi and Mohamed, 2019; Zyskind *et al*., 2015).

			CPS (Lee *et al*., 2015; Lasi *et al*., 2014; Shrouf *et al*., 2014; Lopez Research, 2014).

Table 5 is used to investigate whether Industry 4.0 facilitates the Control phase of Lean Six Sigma. The second column lists key tools and measures for the Control phase. Then the key characteristics of MCPS that potentially can facilitate the applications of these tools and measures are identified. The next column identifies the components of MCPS that can potentially support the application of the Lean Six Sigma tools for this phase.

Carefully scrutinising Tables 1-5 suggest that Industry 4.0 generally supports Lean Six Sigma and brings potential opportunities to facilitate and strengthen its application. These tables provide a schematic but very useful guideline to facilitate the application of Lean Six tools and measures in smart factories based on Industry 4.0.

6. POTENTIAL SUPPORT FROM LEAN SIX SIGMA FOR INDUSTRY 4.0

Tables 6.a and 6.b are adopted to investigate whether Lean Six Sigma supports Industry 4.0. First, the key characteristics of MCPS are categorised in Tables 6.a and 6.b Then, the Lean Six Sigma tools and measures which potentially can support this characteristic are identified. The next column outlines how these tools and measures potentially support Industry 4.0.

Table 6.a. Potential support from Lean Six Sigma for Industry 4.0

MCPS based on Industry 4.0	**Lean Six Sigma Methodology**	
Characteristics	**Key Tools & Measures**	**How this supports Industry 4.0**
The intelligent cross-linking and digitalisation throughout all phases of a product life cycle from the raw material acquisition to manufacturing system, product use and the product end of life (Stock and Seliger, 2016).	TPM, OEE, VOC, DOE, FMEA, QFD, Affinity Diagrams, CCR, Quality Chains, Process Map, Scatter, Cause and Effect, Flow Process Charts, Statistics	End-to-end engineering across the entire product life cycle Through-life engineering services
The cross-company and company-internal intelligent cross-linking & digitalisation of value creation modules throughout the value chain of product life cycle and between value chains of adjoining product life cycles (Stock and Seliger, 2016).	VSM, IPO, SIPOC, Flow Diagram, CTQ, VOC, Kano Analysis, QFD, Quality Chains, CCR, Process Map, Stakeholder analysis, DOE, Affinity diagrams	Horizontal integration across the entire value creation network

The intelligent cross-linking and digitalisation within the different aggregation & hieratical levels of a value creation module from manufacturing stations via manufacturing cells, lines and factories, also integrating the associated value chain activities such as marketing and sales or technology development (Stock & Seliger, 2016).	OEE, Flow Diagram, CTQ, QFD, Quality Chains, CCR, Process Map, Stakeholder Analysis, Process Mapping, Stratification of data to get Information, Affinity diagrams, Interrelationship Diagram	Vertical integration and networked manufacturing systems
Smart logistics with Automated Guided Vehicles (Stock and Seliger, 2016; Shrouf *et al*., 2014; Lopez Research, 2014). Self-organised logistics *(*Stock and Seliger, 2016). Connected supply chain (Shrouf *et al*., 2014).	SCM, TQM, Pull System, Kanban, JIT, Reduce Batch Sizes, Quick Changeover, Integrated Logistics, Cellular Manufacturing, One Piece Flow	Sustainable Supply chain with agile reaction to unforeseen events
A sustainable-oriented decentralised organisation (Stock and Seliger, 2016; Lasi *et al*., 2014). Automatic solutions involving operational, dispositive & analytical components, Autonomous manufacturing cells, Sustainability and resource efficiency (Lasi *et al*., 2014).	Elimination of 7 wastes, Theory of Constrains, TPM, JIT, Kaizen, Control Charts, OEE, SMED, Mistake Proofing, Value Stream Mapping, Force Field Analysis, Level Scheduling, Benchmarking	Resource efficiency
Smart Engineering (Shrouf *et al*., 2014).	DOE, DMADV, QFD, FMEA	Product design & development
Mass customisation (Shrouf *et al*., 2014; Kagermann *et al*., 2013; Fogliatto *et al*., 2012).	TQM, VOC, TPS, Reduce Batch Sizes, Eliminate Queues, Kaizen	Product/Service customisation

Table 6.b. Potential support from Lean Six Sigma for Industry 4.0

MCPS based on Industry 4.0	**Lean Six Sigma Methodology**	
Characteristics	**Key Tools & Measures**	**How this supports Industry 4.0**
Flexibility: Intelligent production processes, and self-configuration to consider different aspects, such as time, quality, price and ecological aspects (Shrouf *et al*., 2014; Zuehlke, 2010; Lasi *et al*., 2014).	TQM, TPM, One Piece Flow, Pull System, Kanban, JIT, Reduce Batch Sizes, Quick Changeover, Integrated Logistics, Cellular Manufacturing	Flexibility (Product/service, Mix, Volume, Delivery)
Visibility & optimised decision-making within smart factories (Shrouf *et al*., 2014). Decentralisation (Lasi *et al*., 2014).	Hypothesis Testing, Control Charts, Process Capability, MSA, SPC, DPMO, Sigma Level, OEE, Correlation & Regression, SWOT, PESTLE, FMEA, Multi-Vary Analysis, DOE, Cp & Cpk, Force Field Analysis, Benchmarking, Scatter, Cause and Effect, Pareto	Optimised decision-making
Predictive Maintenance involving intelligent & adaptive algorithms (Shrouf *et al*., 2014; Mourtzis *et al*., 2016; Lee *et al*., 2015). Self-aware, Self-predict, Self-compare, Self-configure, Self-maintain & Self-organise elements (Shrouf *et al*., 2014; Zuehlke, 2010; Lasi *et al*., 2014).	TPM, OEE, Condition Based Monitoring	Proactive Maintenance
Individualisation on demand "batch size one" based on additive manufacturing, Individualised distribution & procurement (Lasi *et al*., 2014).	Pull System, Kanban, JIT, Reduce Batch Sizes, Quick Changeover, Integrated Logistics, Cellular Manufacturing, One Piece Flow, Eliminate Queues, Kaizen	Improve Flow, Reduce Inventory, Decentralised production units
Automatic solutions involving operational, dispositive & analytical components (Lasi *et al*., 2014).	DMADV/DFSS, DOE, QFD	Product/Process Development or Existing

		Product/Process Optimisation
Modularity to enable greater interconnectivity, interoperability, data-sharing and information transparency, allowing high level of technical support and decentralised decision-making (Stock and Seliger, 2016; Lasi *et al*., 2014).	Concurrent/Parallel Processing, Modularity, Decoupling	Minimise Lead time
Self-configurability & self-maintainability at the production system based on machine twins in CPS (Stock and Seliger, 2016; Lee *et al*., 2015).	TPM, OEE, Condition Based Monitoring, Preventive Maintenance	Equipment & Plant Overall Effectiveness

Carefully scrutinising Tables 6.a and 6.b suggest that Lean Six Sigma generally supports Industry 4.0 and facilitates its continuous improvement. Also, this table provides a provisional but very useful guideline to facilitate the application of Lean Six tools and measures in smart factories based on Industry 4.0.

7. MUTUAL SUPPORT BETWEEN LEAN SIX SIGMA AND INDUSTRY 4.0

The primary interpretation from tables 1-5, 6.a and 6.b suggests that Lean Six Sigma and Industry 4.0 mutually support each other. This section illustrates the findings with two critical examples i.e. a chronic Lean Six problem and a new challenge for energy management in Manufacturing.

First a chronic and rather well known Lean Six problem will be presented to show that Industry 4.0 can assist to tackle it. Then a new challenge for energy management will be discussed to show that Industry 4.0 can facilitate its solution. For both cases the benefit of Lean Six Sigma for smart factories will be identified as well. These examples are intended to illustrate the potential mutual support between Lean Six Sigma and Industry 4.0.

Voice of the Customer (VOC) in Industry 4.0

Customers' input is extremely valuable and obtaining valid customer feedback is a science. Scientific techniques such as critical incident analysis, focus groups, content analysis and surveys are applied to identify the "voice of the customer." Kano developed the following model of the relationship between customer satisfaction and quality (Figure 2). The model shows that there is a basic level of quality that customers assume the product will have. If this quality level isn't met the customer will be dissatisfied; note that the entire "Basic quality" curve lies in the lower half of the graph, indicating dissatisfaction.

However, delivering basic quality is not enough to satisfy a customer. The “Expected quality” line indicates those expectations that customers explicitly consider. The model shows that customers will be dissatisfied if their quality expectations are not met and satisfaction increases as more expectations are met.

The “Exciting quality” curve lies totally in the satisfaction region. This is the effect of innovation. Exciting quality represents unexpected quality items. The customer receives more than they expected. Competitive pressure will constantly raise customer expectations. Today’s exciting quality is tomorrow’s basic quality. Companies that try to lead the market must innovate constantly. On the other hand, companies that try to deliver standard quality must continually research customer expectations to define the presently accepted quality levels. It is not enough to track rivals as expectations are prompted by outside elements too (Pyzdek and Keller, 2009).

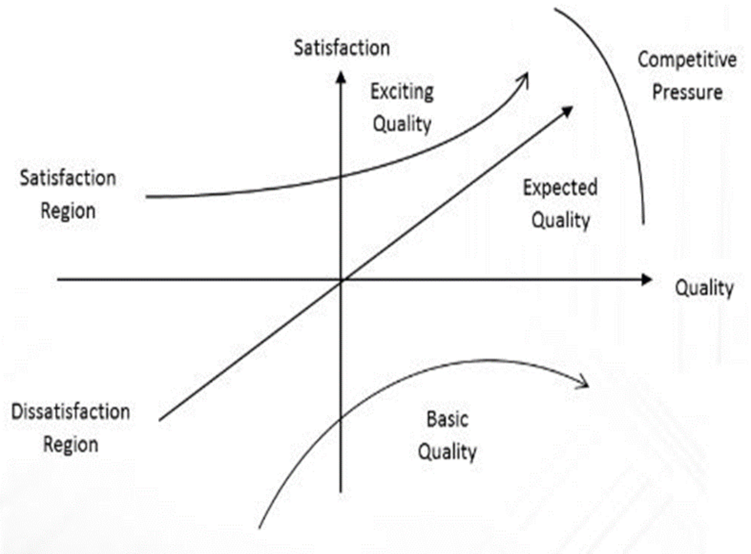

Fig. 2. Kano model (Pyzdek and Keller, 2009)

Some people believe that Six Sigma does not go far enough. Defining quality as only the lack of nonconforming product reflects a narrow view of quality. Motorola never intended to define quality as simply the absence of defects. However, some have misunderstood Six Sigma in this way. One problem with common Six Sigma is that it deals with only half of the Kano model. By addressing customer expectations and prevention of non-conformances and defects, Six Sigma focusses on the portion of the Kano model on and below the “Expected Quality” line. This improvement is required but it will not guarantee that the firm remains viable in the long term. Long-term success needs that the firm innovate. Innovation is the result of creative activity (Pyzdek and Keller, 2009).

Industry 4.0 brings potential opportunities to improve Lean Six Sigma practice. As already explained, there is a dynamic and sound relation between smart factories and customers in Industry 4.0 that is enabled by IoT and IoS technologies. Smart elements embedded in MCPS can strengthen the Lean Six Sigma techniques. MCPS via smart data and real-time feedback facilitate the application of "Voice of the Customer" and support innovation to address the portion of the Kano model above the "Expected Quality". Innovation and creative activity will be supported by digitalisation, automation, simulation, virtualisation, augmented reality and networking. Creating value from big data and integration of physical objects with their digital process parameters can lead smart factories towards the long term success.

Energy management in Industry 4.0

Globally the industry sector accounts for more than a third of energy consumption (Kesicki and Yanagisawa, 2015) and about 35 percent of energy and process related greenhouse gas (GHG) emissions (Allwood *et al*., 2012). Almost 80% of these emissions is from energy use and energy efficiency is potentially the most significant and economical means for mitigating GHG emissions from industry (Worrell *et al*., 2009). The UK industrial sector accounts for about 21% of total delivered energy and 29% of CO2 emissions. Although major improvements have been in the energy intensity of manufacturing (defined as energy use per unit of economic output), significant reductions in GHG emissions are still needed (Griffin *et al*., 2016).

The 2015 edition of Energy Technology Perspectives (ETP 2015) shows the vital role of identifying regulatory strategies and co-operative frameworks to advance innovation in areas like variable renewables and carbon capture. It indicates that efforts to decarbonise the global energy sector are lagging further behind for that year. ETP 2015 focuses on setting out pathways to a sustainable energy future and incorporating detailed and transparent quantitative modelling analysis. Energy decarbonisation is under way, but needs to be boosted and recent trends reaffirm the need to accelerate energy technology innovation, including through policy support and new market frameworks (IEA OECD, 2015).

There is a high number of variables that affect energy consumption of equipment. These variables may originate from equipment conditions or manufacturing surroundings. A methodology based on the equipment aspect can be developed from energy losses within loading time. This approach identifies energy losses during breakdown, setup & adjustment, speed and so on. However, there are other hidden energy losses before loading time which are crucial to measure to determine equipment energy effectiveness. This aspect should also cover energy losses before loading during preventive maintenance, engineering, improvement and non-scheduled times. This aspect monitors the actual energy performance of a machine relative to its performance capabilities under optimal equipment conditions.

A model based on the manufacturing processes aspect can be developed from energy losses during operation time. This approach considers energy losses due to lack of skills, materials, tools and so on. However, there are other hidden energy losses pre-operation which are vital to measure to determine equipment energy effectiveness. The manufacturing processes aspect should also identify pre-operation energy losses during time losses due to management, organisation, personnel, and inputs and so on. This aspect monitors the actual energy performance of a machine relative to its equipment settings under optimal manufacturing processes.

Over recent years the share of electricity generation from the renewables in grid electricity has increased. For example this amount in Scotland has increased from 11.7% in 2004 to 42.3% in 2015 (Gov.Scot, 2017). Both energy efficiency and renewable energy can contribute to much lower CO2 emissions and significant employment opportunities. A clean energy industry can improve energy security, environmental protection and economic benefits. Renewables and energy efficiency create more jobs per unit energy than fossil fuel technologies and can be applied as an engine for economic growth (Wei *et al*., 2010).

There is an essential need to develop the new broad model to cover the energy aspect of equipment energy effectiveness. This approach considers thermodynamic efficiency of the process to minimise energy losses due to thermodynamic inefficiencies. If there are technical constrains to identify or address these inefficiencies, Best Practice Energy Per Unit (BEPU) can alternatively be applied. The energy aspect considers all energy data such as type of energies from all potential suppliers. This aspect monitors the actual energy performance of a machine under optimal energy usage.

Total Equipment Energy Effectiveness (TEEE) is suggested as a new methodology to address the current challenge of a distinct lack of a comprehensive model for energy management in manufacturing. The model embraces all potential aspects of equipment, manufacturing processes and energy features for measuring equipment energy efficiency. TEEE is a measure of how efficiently equipment consumes energy compared to its full potential and can be applied as a tool to improve energy efficiency. An article will be published shortly to outline this methodology with all details.

As shown in Figure 3, the TEEE model is a comprehensive framework that covers all equipment, manufacturing processes and energy aspects. Two British and two large international manufacturers have been selected for TEEE application. The international firms are PT Kerry Ingredients Indonesia, which is a global food company, and PT Astra Daihatsu Motor, which is the largest car manufacturer and second best-selling car brand behind Toyota, in Indonesia. The results show a good practice for both international companies. They also present key opportunities for improvement to meet the new sustainability requirements. The case study still continues and the outcome will be presented when the process is completed.

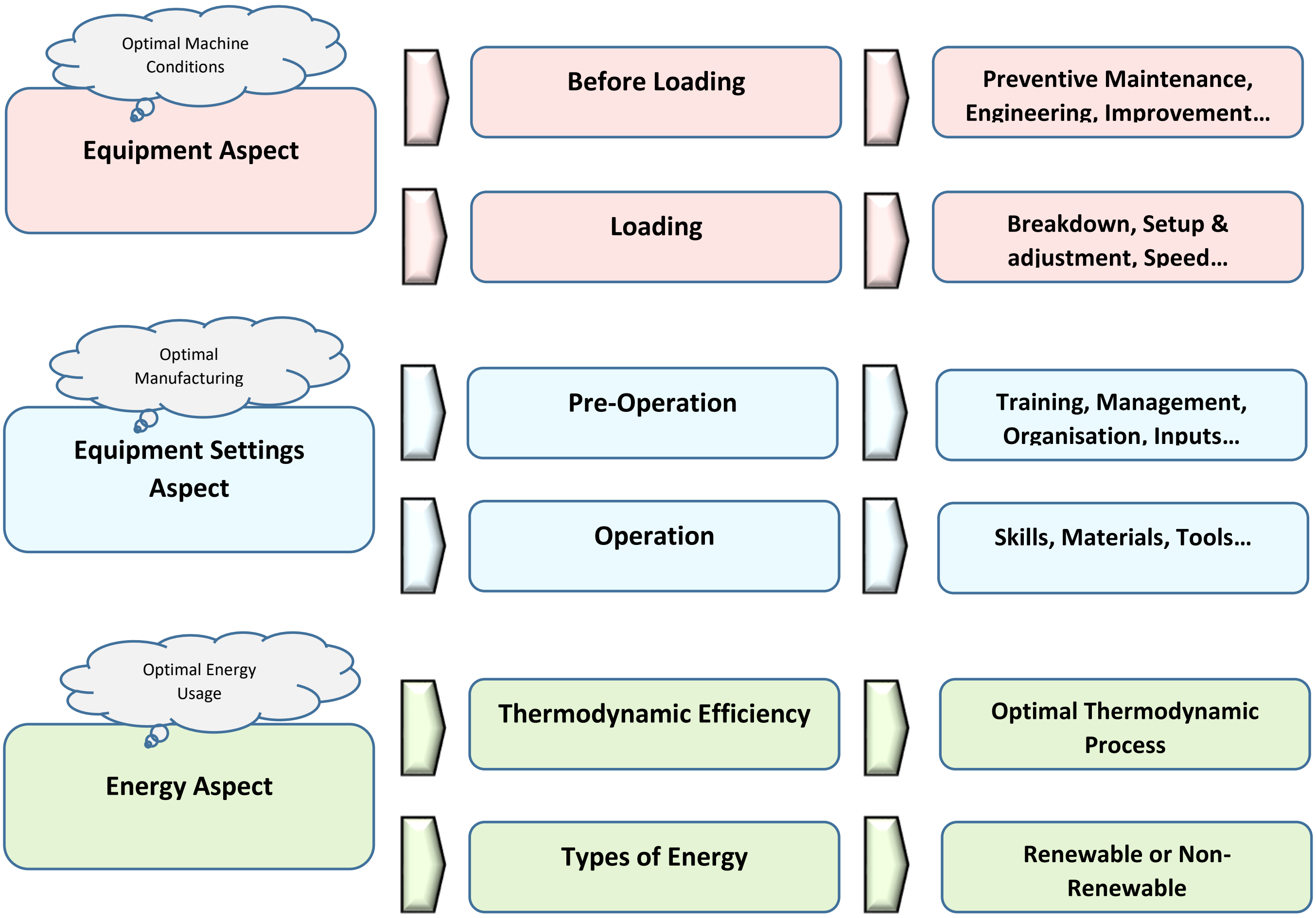

Fig. 3. The three aspects of TEEE

The level of comprehensiveness can be a possible serious impediment to apply a total energy effectiveness methodology in many firms. MCPS based on Industry 4.0 can facilitate this application. First, a seamless method to manage data acquisition and transferring is needed. Then proper sensors should be selected. Data to information conversion brings self-awareness to equipment. Information from every connected machine is pushed to the central information hub and the analytics bring self-comparison to equipment.

TEEE can be applied as a comprehensive Lean Six Sigma tool to analyse equipment or plant energy effectiveness. The fourth row (Analysis) in Table 1, indicates what components of MCPS can potentially support the application of TEEE. IoT and IoS generate smart data for Equipment (before and after loading), Equipment Settings (pre-operation and operation) and Energy Aspect (thermodynamic efficiency and types of energy). Also, smart factories can dynamically compare all potential smart energy suppliers via smart grids to choose the best one. Smart grids provide smart data for Energy aspect. Applying analytical components for big data coming from IoT and IoS can provide TEEE in real-time. The smart elements of CPS, based on TEEE results, improve the energy effectiveness automated and dynamically. This would be a major improvement towards sustainability.

8. DISCUSSIONS AND CONCLUSIONS

Lean Six Sigma is a fact-based and data-driven methodology (Kubiak and Benbow, 2018). IoT and IoS generate the high volume data (Lee *et al*., 2015). CPS manages big data (Baheti and Gill, 2011) and therefore it is able to provide Lean Six Sigma with any required real-time data. Lean Six Sigma can gain from integrated physical objects, their digital process parameters and analytical components in intelligent processes to continuously improve smart factories.

All tables 1-5, 6.a and 6.b show no key Lean Six Sigma 'people-oriented' tools and measures. If there are comprehensive methodologies such as TPM in the tables, their positive contributions to Industry 4.0 mainly originate from the 'technology-oriented' aspect of the tool not 'people-oriented'.

Lean Six Sigma suggests continuous improvement to all sectors of manufacturing and services to match emerging technologies and dynamically meet all new economic, environmental, social, political and legal requirements. This approach can be applied to it as well. Lean Six Sigma needs to leverage Industry 4.0 capabilities and opportunities and review and update itself. Then it will be able to better support Industry 4.0, its development and improvement.

Updating Lean Six Sigma based on the following three principles will result in developing stronger and more dynamic 'mutual support' between Industry 4.0 and Lean Six Sigma:

1) Shift from 'people-oriented' to 'technology-oriented'. It would be particularly important for Lean.

2) Transform 'people-oriented' elements (to behaviour elements and then) to services elements and then to smart data via IoS

3) Transform 'technology-oriented' of Lean Six Sigma to smart data via IoT and IoS

The outcome of the above changes would be an intelligent, sophisticated, integrated and efficient methodology for continuous improvement in Industry 4.0.

To outline the type and level of shift from 'people-oriented' to 'technology-oriented' further research is required. Lasi *et al*. (2014) consider adaptation to human needs and they suggest that new manufacturing systems in Industry 4.0 should be designed to follow human needs instead of the reverse. Perhaps the above principles and particularly the first and second, leverage Industry 4.0 capabilities for humans in the world of robots.

Due to the COVID-19 pandemic, the mapping of linkage between DMAIC measures and MCPS characteristics is based on the definition of measures and characteristics, and authors' experience. A future comprehensive survey containing 'Levels of Linkage' questions with the involvement of multiple companies from different sectors should be carried out. It is quite important to distinctly study large companies and small and medium enterprises (SMEs), and, desirably, factories with batch processes such as car manufactures and continuous manufacturing plants such as oil refineries and steel makers. It would enable us to compare the results and have a deeper understanding of Lean Six Sigma in different smart factories.

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