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Contributions of lean six sigma to sustainable manufacturing requirements: an Industry 4.0 perspective

Rohin Titmarsh*, Fadi Assad, Robert Harrison

Automation Systems, Warwick Manufacturing Group (WMG), University of Warwick, Coventry CV4 7AL, United Kingdom

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ABSTRACT

Industry 4.0 is reshaping modern manufacturing with increased data availability and accessibility. Therefore, further support of the system and product lifecycles is provided. On the other hand, sustainable manufacturing gains more attention due to the environmental concerns and resource consumption. The green impact of lean six sigma has been approached in literature. However, the changes to a manufacturing system's nature provide new insights to employ lean six sigma quality tools for further sustainability. This paper proposes a framework of using six sigma to achieve the sustainable manufacturing requirements from the perspective of Industry 4.0 and its enablers. The influence of information and communication technologies (ICTs) on the relationship between sustainable manufacturing 6R and lean six sigma DMAIC is studied. A case study of cylindrical cell battery assembly line is used to investigate the effectiveness of the proposed approach. The framework can be adjusted to suit different types of manufacturing processes and systems.

1. Introduction

After the introduction of Industry 4.0 and the increased tendency to digitalisation, more data became available in the fields of product/process design, quality control and condition monitoring (Cattaneo et al., 2018). Although Industry 4.0 as a paradigm aimed at the fast responsiveness to market competition and customer satisfaction, sustainability enhancement has a strong potential that is receiving more attention. This is mainly interpreted in the sustainable value creation (Stock and Seliger, 2016). For the product, the closed loop of the product life cycle is recognised carefully, and for the processes, the resources efficiency is discussed from a holistic perspective. On the larger scale, mature digital technologies help the conversion to circular economy through reducing overproduction, energy consumption and waste, thus, moving to more sustainable manufacturing (Nascimento et al., 2019).

From the quality engineering perspective, problems can never be solved unless discovered. Therefore, providing the historical data that cover components and processes' behaviour constitutes the basis of identifying problems and beginning the quality improvement procedure. In Figure 1, the contributions of Industry 4.0 to eight value drivers in manufacturing are illustrated. It can be noticed that the cost of quality can be reduced by 10–20% (Bauernhansl et al., 2014; Wee et al., 2015). In this vein and in relation to data, Waner et al Wagner et al. (2017) show within a well structured impact matrix the relation between Industry 4.0 technologies and many lean production systems such as just-in-time, Kaizen and 5S. The new technologies introduced in industry will replace the conventional methods of system/product life cycle data analysis (Köksal et al., 2011). In manufacturing particularly, Six Sigma is the most popular continuous improvement business strategy (Antony et al., 2019; Singh and Rathi, 2019). Consequently, it is convenient to study the implications of Six Sigma on manufacturing sustainability.

Antony et al. (2019) identified four emerging Six Sigma (in general) trends:

- The analysis of Big Data through Six Sigma.
- The neglect of environmental aspects in Six Sigma Deployment.
- The suitability of Six Sigma to SMEs.
- The integration of Six Sigma into Industry 4.0.

Sustainable manufacturing has predefined objectives but the tools used to achieve those objectives change in response to the available technologies. On the other hand, Lean Six Sigma (LSS) as a tool was not originally introduced for environmental purposes but rather productivity and cost reduction ones. Consequently, the novelty of this research paper lies in investigating the contribu-

* Corresponding author.
E-mail address: rohin.titmarsh@warwick.ac.uk (R. Titmarsh).

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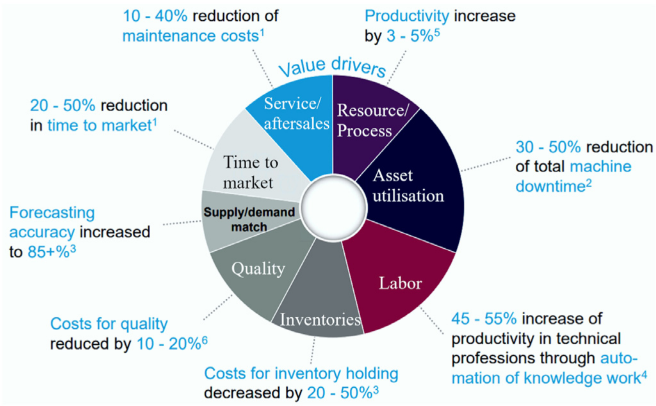

Fig. 1. Indicative quantification of Industry 4.0 influence on value drivers (Wee et al., 2015).

Nomenclature

A_{pt}	Actual production time
A_{imt}	Actual unit manufacturing time
G_p	Number of good parts
P_q	Produced quality
P_d	Defected parts
Q_m	Quantity consumed during production
R_q	Rework quality
S_q	Scrap quality

tions LSS would be able to add to the sustainable manufacturing objectives especially under Industry 4.0 vision. This paper will further discuss the aforementioned trends with a focus on the sustainable manufacturing requirements under Industry 4.0. The remainder of this research paper is as follows: Section 2 reviews the literature related to Six Sigma and sustainable manufacturing. In Section 3, the research methodology is explained. Then, a case study that demonstrates the methodology implementation is described in Section 4. Section 5 concludes the paper.

2. Literature review

In this section, the Six Sigma based approaches and applications that aim to enhance manufacturing sustainability are reviewed in the context product/system life cycle or the combination of both. Then, the researches concerned with six sigma and Industry 4.0 are tracked.

2.1. Lean six sigma and life cycle

Tasdemir and Gazo (2019) developed a sustainability benchmarking tool (SBT) that could reduce the energy consumption, waste, CO_2 emissions and cost in value-added wood products industry. In the automotive industry, Ben Ruben et al. (2017) suggests a framework of LSS implementation where different tools support the implementation depending on the (DMAIC) phase, for example, Life Cycle Inventory Analysis in the "Measure" phase. Antosz and Stadnicka (2018) recommended the integration of Six Sigma, Lean philosophy and Industry 4.0 for an increased efficiency and flexibility of the Maintenance Service Process (MSP). In Fargani et al. (2017), a framework that links Life Cycle Assessment (LCA) with LSS is suggested, where the start point for both is corporation environmental strategy. Based on the belief that Lean, Green and Six Sigma are complementary to each other, Banawi and Bilec (2014) proposed a framework that aims to reduce waste in construction industry considering that the "Green" aspect expresses LCA. Cluzel et al. (2010) Cluzel et al. (2012) presented a methodology to manage the eco-design in complex industrial system based on DMAIC in order to overcome some of LCA limitations.

2.2. Six Sigma and sustainable manufacturing

After analysing the sustainable manufacturing drivers such as Supply Chain Pressure competitiveness, and market pressure, Fargani et al. (2016) recommended the use of Lean and six sigma to achieve sustainable manufacturing. Nagalingam et al. (2013) introduced a framework to estimate the performance of product recovery and returns based on design for six sigma methodology IDOV (identify, design, optimise and validate). Another framework is adopted in Zhang and Awasthi (2014) but with highlighting the leadership in the sustainable manufacturing - six sigma mixed framework. On the energy efficiency side, Chugani et al. (2017) confirm that six sigma can serve as an effective method of energy usage management and advise companies to include it in their policies. Moreover, it is shown in Cherrafi et al. (2017) that applying green and lean six sigma helps the organisations decrease their energy consumption by 7–12%.

2.3. Six sigma and Industry 4.0

Jayaram (2016) stated that Industry 4.0 and Lean Six Sigma are complement to each other, and proposed a model for managing global supply chain management. In Giannetti and Ransing (2016) and Giannetti (2017), an algorithm to predict the robustness of the manufacturing process in order to synthesise the tolerance which serves an introductory step to extending six sigma application in process improvement in the vision of Industry 4.0 predictive analytics. A framework to correct the real time deviation in manufacturing processes using Industry 4.0 techniques is introduced in Eleftheriadis and Myklebust (2016). Basios and Loucopoulos (2017) proposed an approach of organising the data collected using Industry 4.0 technologies to help organisation make strategic decisions. In Dogan and Gurcan (2018), data handling methods associated with lean six sigma phases are detailed with regard to Industry 4.0 data collection technologies. In the maintenance field, Antosz and Stadnicka (2018) proposed a six sigma-based decision making methodology for the a maintenance service process Cyber Physical System (CPS) to input the maintenance data on-site. The authors in Khan et al. (2017) derived a DMAIC sub-methodology to be used in Internet of things (IoT) project and demonstrated its application in a predictive maintenance case study.

2.4. Research gap analysis

From the previous literature review, the following points can be identified:

- The environmental effect of LSS is mainly related to reducing the waste.
- LSS is mainly used for reducing variation in the processes and the products.
- Few studies introduced LSS in Industry 4.0 and LCA approaches combined together.
- The research work is more focused on the product rather than the system life cycle.
- The introduction of Industry 4.0 allows more insight into the manufacturing processes data, thus a greater opportunity and expected outcomes of Six Sigma application.

In the following we construct a methodology to address the variation by detecting it in the initial stage of the production. Addi-

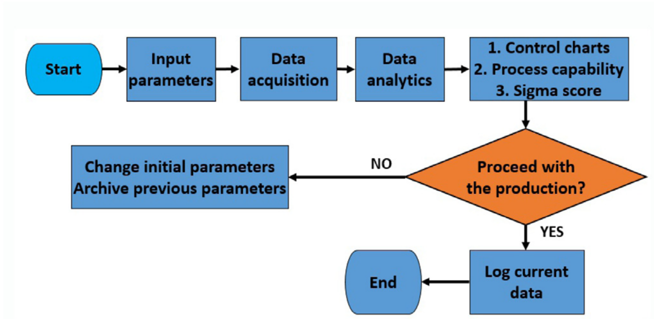

Fig. 2. Data processing to produce 6R decisions for the user.

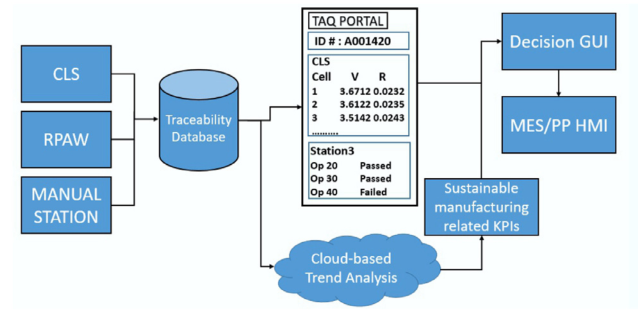

Fig. 3. Data flow in the monitoring process to analyse and present decisions to the user.

tionally the proposed approach gives the opportunity to be implemented with Industry 4.0 enablers, namely the cloud and process monitoring. Besides, the introduced approach focuses on the system lifecycle, which is novel compared to the pertinent literature.

The research questions aimed to be answered are as follows:

Q_1 How can Industry 4.0 technology enable better usage of LSS and Sustainable Manufacturing tools and approaches?

Q_2 With the accessibility to more machine and process data can undesirable outputs be eliminated?

3. Methodology

Establishing a methodology requires defining the concept of sustainable manufacturing to be considered, then the applicability of Six Sigma and its means can be decided. Using Bi's Bi (2011) applications of the 6Rs of sustainable manufacturing, a method to reduce or reuse materials and tools has been constructed. The method is illustrated in Fig. 2, which represents elements of the DMAIC cycle. The process is continuously Measured, Analysed and Improved where needed. Default parameters will be used as a baseline for the module build. These will be the same regardless of module type, size and quantity required, and will always act as the baseline before the build ramps up production. Data will be acquired from the manual and automated stations and analysed using tools from the Six Sigma toolset. This will then present a decision, based on the data collected and the results from the Six Sigma tools, to proceed with that process or build entirely, or to stop production and refer to several options. These could be generic for most organisations, such as reworking (or remanufacturing according to 6R) parts before reintroducing them to the line, or recovering the parts and contacting the supplier. The decisions would be based on certain thresholds for the process or build in the form of key performance indicators, KPIs, as well as data available in the traceability and quality (TAQ) system database. Khan and Bilal (2019) in addition to Assad et al. (2019) identified critical Key Performance Indicators (KPIs) for the manufacturing shop floor. So for example, alerts can be triggered if actual production time (A_{pt}) has exceeded planned targets for throughput milestones, or rework quality (R_q) or scrap quality S_q have not met certain thresholds. The list of KPIs selected are presented in the nomenclature table. The data retrieved from the TAQ system will provide the data to run against these KPIs.

Data from the processes on the line are stored, which can be accessed by the new monitoring service. It can also be used to analyse historical trends for review and comparison. The other comparisons can be made against the original production plan. The data flow is shown in Fig. 3. A GUI designed to show this information to a user, being a production supervisor or sustainability engineer for example, has been designed. The design is based on showing the information in a clear, simple format, so that a production decision can be made quickly, to reduce delay times.

4. Case study

4.1. Description

The case study in this paper is AMPLiFII. This is an Innovate UK project split across four years, AMPLiFII 1 taking the first two years, and AMPLiFII 2 closing in early 2020. The objective of this project was to implement a pilot line for battery module production, specifically looking at battery modules using cylindrical cells. The batteries are configurable in size and energy by changing the cells in use, or changing the series and parallel connection in the module. Automation on the line includes the use of a cell testing plus pick and place robot, known as the cell loading system or CLS, as well as the use of a robot pulse-arc welding robot, RPAW.

The case study takes the CLS as the example using cell voltage. The CLS tests cells for their internal resistance and voltage. Acceptance upper and lower limits are manually set to the specification of the cell supplier or the specification of the design of the module being assembled. Cells are tested in nests, each nest containing 30 cells. In the past, rejected cells have been quarantined, which could lead to them being scrapped. Applying the new monitoring process to a sample set of CLS data yields an insightful view into the part performance, and data has been manipulated to avoid confusion between measuring the performance of the process, and measuring the performance of the part batch.

4.2. Results and discussion

Taking a sample set of 21 cell nests, Six Sigma tools from the PMI Data Analysis Package v2 have been used to calculate the average for this batch, as well as the upper control limit. The lower control limit, LCL, was manually set to 0, as it is impossible to have a negative number of failed cells. The charts can be seen in Fig. 4. On the individual chart, the x axis shows each cell nest. On the y axis is the number for cells that failed the voltage test. The moving range chart shares the same x axis, and the y axis is the difference between that nest and the previous nest. The dashed line is the average $\bar{X}$ for the Individual chart and $\bar{R}$ for the moving range chart. The upper control limit, UCL, is in light blue.

Using the calculated average and limits, the process capability can be determined. A process capability indicates that the process is not capable of performing. Combined with this, specification limits can be used to visually show whether the process is capable of performing to those specifications. In this case, the limits represent the part performance. The process capability can be seen in Fig. 5. The control limits are shown in red, and the specification limits are shown in green. This is an extreme case, as the user would immediately be able to spot a problem, with the upper

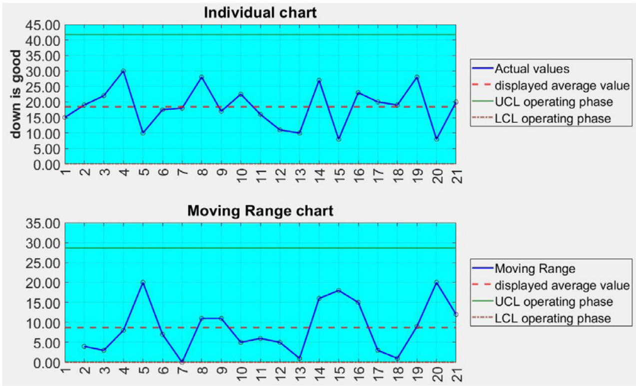

Fig. 4. Control charts for the batch (PMI, 2018).

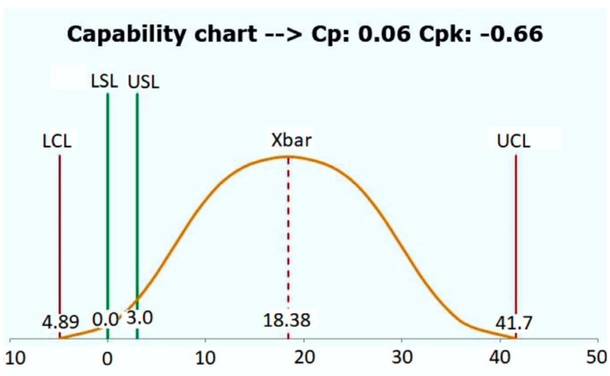

Fig. 5. Process capability chart for the batch (PMI, 2018).

DPMO and Process Sigma Calculator

N = No of units	630
D = No of observed defects	386
O = Defect opportunities per unit	1

DPO = Defects per Opportunity	0.6126984
Yield (%)	38.73016%
DPMO	612,698
Process Sigma*	1.2 *with +1.5s shift

500,000	50%	1.5
540,000	46%	1.4
579,000	42%	1.3
618,000	38%	1.2
655,000	34%	1.1
691,000	31%	1
726,000	27%	0.9

Fig. 6. DPMO and Process Sigma Score (PMI, 2018).

control limit, UCL, being at 41, higher than the actual number of cells in one nest. If the UCL were below 30, but the LCL and UCL did not fit within the upper and lower specification limits, USL and LSL respectively, this would also indicate to the user that a problem with the batch could be present.

Finally the defects per million opportunities, DPMO, and the process sigma score can be calculated. The number of units being 21 lots of 30 cells totalling 630. The number of bad cells in this batch totalled 386. The opportunities per unit is 1, because the cell can either pass or fail the voltage test. The DPMO therefore is 612,698. This yield results in a sigma score of 1.2. The process sigma score chart is presented in Fig. 6.

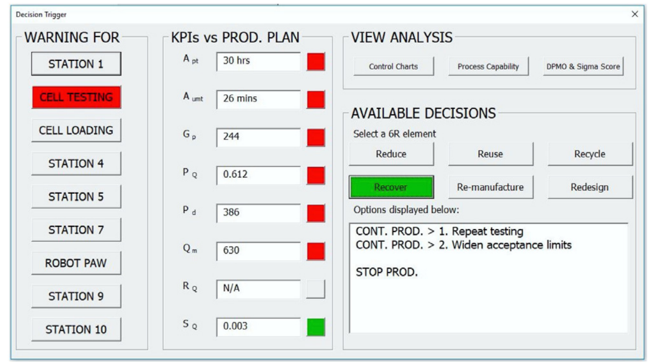

Fig. 7. Decision GUI giving 6R element options to the user.

These form part of the GUI presented to the user, shown in Fig. 7.

The process that has a potential problem is highlighted in red on the left hand side to the user. The user can select this process, view KPI values and the analytics such as the control charts shown in Fig. 4, the process capability shown in Fig. 5 and the DPMO score shown in Fig. 6. Finally the user will be able to view and act on the 6R related decisions.

Now with this new level of production monitoring the user can determine the best course of action. For example, the user can see that the difference between the failed cells and the voltage test limits is only 0.003 V. Therefore, in alignment to the Recover element of 6R, the failed cells can be recovered from quarantine and retested, with the limits for the test widened by that margin. This will reduce scrap. There are also Reuse and Recycle options, where some may not be suitable for this application, they may be perfectly acceptable for other battery applications.

The method and solution shown in this paper take core tools and approaches from LSS and traditional green belt projects and applies them in a continuous improvement style, part of the last stage of the DMAIC cycle, but further than that, it combines the elements of the 6Rs of Sustainable Manufacturing, to truly mitigate the chances of wastes. LSS on its own aims to reduce waste from a pure manufacturing point-of-view by reducing the variability in a process, ensuring that the maximum amount of produced product falls within the acceptable limits. However, it does not advise on what to do with produced product that is unacceptable, or how to change inputs to achieve produced products falling within acceptable limits. Therefore, combining the two approaches produces a powerful technique in reducing environmental impacts of manufacturing.

Take the project led at an Indian automotive manufacturer by Ben Ruben et al. (2017), in their case, they have carried out a project that follows the LSS project framework but with the addition of environmental considerations (Ben Ruben et al., 2017). This allowed their team to make better informed decisions regarding how to reduce their raw material consumption and other process inputs to achieve a reduction in defects of 10,000 ppm (Ben Ruben et al., 2017). In comparison, in the research carried out by the authors the LSS tools have been combined with the 6Rs of Sustainable Manufacturing to go further than investigating environmental considerations like raw material and energy consumption as contributors to sources of variation.

5. Conclusion and future work

In conclusion, using a combination of Six Sigma tools, KPIs and the elements of 6R gives the user an added dimension to view the production status and make more informed decisions. The combination of Lean Six Sigma and 6R provides better potential of sustainable production in the future in accordance to modern manufacturing technologies of Industry 4.0 and an industry-wide goal to reduce waste. The solution is also scalable to provide access to IoT sensors, collected data or interfacing with a digital twin. This would allow the integration of more data sources to enable technologies like machine learning and predictive maintenance.

Depending on the amount of historical data available, what processes are involved in the manufacturing sequence and which KPIs are more relevant to that organisation than others, the GUI could also be adapted. Another path aspect is the integration to the organisations supply chain, to inform suppliers of higher defect rates and manage goods shipments depending on reuse or recycling.

CRediT authorship contribution statement

Rohin Titmarsh: Conceptualization, Methodology, Software, Formal analysis, Resources, Writing - original draft. **Fadi Assad:** Software, Validation, Formal analysis, Investigation, Writing - original draft, Visualization. **Robert Harrison:** Supervision, Funding acquisition, Writing - review & editing.

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