Lean Six Sigma and Industry 4.0 Integration for Operational Excellence: Evidence from Italian manufacturing companies

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Abstract

This research investigates a possible integration between Lean Six Sigma (LSS) tools and principles and Industry 4.0 technologies. The aim is the development of a new pattern for Operational Excellence through the grounded theory methodology. Data collection involved interviewing Italian manufacturing managers in ten case organisations as well as a direct observation of practices linked to Industry 4.0 and LSS integration at one of the selected case organisations. Results of the study aligns with preliminary literature supporting LSS providing platform to achieve effective outcome from Industry 4.0 application. The integration needs reinvented mapping tools and implies a horizontal integration and a vertical, end-to-end integration. The latter requires the company to reengineer the ERP modules, while in the horizontal integration the real ultimate goal is to reach a complete automatic synchronisation of the processes named Autonomous Process Synchronisation. Moreover, all the data gathered from production processes and offices needs the development of new analytics at all levels. This is amongst first few studies that answers how to achieve integration between LSS and Industry 4.0 technologies and thus have several research and managerial contributions in advancing operational excellence research.

Keywords: *Lean Six Sigma, Industry 4.0, Operational Excellence, Integration, Manufacturing, Case Studies*

1. Introduction

Industry 4.0, is the new paradigm for factories of the future which induces remarkable improvements due to changing operative framework conditions. Triggers for this are general social, economic, and political changes (Lasi et al. 2014). Beyond these broad impacts, Industry 4.0, when contextualised in a specific business, has been debated as a new model for dramatically improving productivity through automation and digitalisation. This is mainly due to the connection and integration of value chains and production systems over the cyber-physical technologies and Internet of Things (IoT) (Kagermann et al. 2013; Ghobakhloo 2018; Fatorachian and Kazemi 2018; Bibi and Dehe 2018).

Since its introduction in Germany through a strategic and political agenda from the Federal German government (Kagermann et al. 2011), Industry 4.0 has been studied predominantly from a technological standpoint (Liao et al. 2017; Kolberg et al. 2017; Bibi and Dehe 2018; Schroeder et al. 2019). In the last five years, Industry 4.0 has been classified as a strategic model for competitive advantages and for achieving improvement in metrics such as cost, productivity, quality, customer satisfaction and lead time (Brettel et al. 2014; Kolberg et al. 2015, 2017; Schmidt et al. 2015; Agrifoglio et al. 2017; Lu 2017; Bibi and Dehe 2018).

Similar goals are shared by Operational Excellence methodologies such as Lean and Six Sigma that have supported organisations in the last three decades to achieve efficiency gains and enhance customer satisfaction. Majority of fortune 500 companies have implemented integrated Lean Six Sigma methodology, which can be considered as the union of the Japanese Toyota Production System (TPS), better known as Lean in Western culture (Khan et al. 2013), and the American Six Sigma (Arnheiter and Maleyeff 2005; Albliwi et al. 2015). Even if several authors tend to classify LSS more as a methodology (Albliwi et al. 2014), other authors discussed LSS as one of the best models belonging to the Operational Excellence (Chiarini

2011; Basu 2004; Salah et al. 2010; Jaeger et al. 2014) and it is implemented for reaching aims similar to Industry 4.0.

Industry 4.0 incorporates a range of new or developing technologies for supply chain integration (Kolberg et al. 2017) and similarly operational excellence methodologies have been applied at organisational and supply chain levels for better horizontal and vertical integrations (Tortorella et al. 2019). In spite of sharing similar objectives of efficiency improvement and supply chain integration, research on synergistic relationship between Industry 4.0 and Lean Six Sigma is still at its infancy.

The limited research provides an indication of greater strategic and operational benefits for organisation and its supply chain when an integrated approach is favoured over standalone approaches (Tortorella et al. 2019; Buer et al. 2018; Kolberg et al. 2017; Ma et al. 2017; Schmidt et al. 2015). The integrated approach may benefit companies by avoiding the formation of separate teams to manage and implement Industry 4.0 and Operational Excellence initiatives in isolation. In the light of this current situation, our research attempts to answer the following research question through conducting multiple case studies in Italian manufacturing organisations that are conversant to Lean Six Sigma applications and are also implementing Industry 4.0 technologies: "How organisations can effectively integrate Lean Six Sigma techniques with Industry 4.0 technologies for optimising performance?"

This implies also to understand if LLS provides a good foundation for maximising the benefits of Industry 4.0 for Operational excellence. Furthermore we want to comprehend the real benefits of LSS tools and principles regarding the deployment of Industry 4.0 technologies, and how this integration has a positive impact on Operational Excellence.

This research is inductive in nature and applied grounded theory methodology to understand synergistic relationship between Lean Six Sigma and Industry 4.0. In the first phase of the study, authors gathered data and information from semi-structured interviews with 10 managers from 10 different Italian manufacturing organisations followed by in depth investigation and observation in a selected case organisation that had a higher maturity level, compared to other 9 case companies, on Lean Six Sigma and Industry 4.0 applications.

The remainder of the paper is structured as follows, next three following sections deal with the background literature related to Lean Six Sigma tools and techniques, Industry 4.0 and a possible integration. This is followed by methodology section that introduces the grounded theory approach adopted for this study. Data and information collected through the interviews in 10 case organisations and an observation in a selected case are grouped in two specific sections and then a theoretical Operational Excellence model is presented. The conclusion section summarises the contribution of the research and the implications for practitioners. Limitations and an agenda for further research are also discussed in this last section.

2. Literature Review

2.1 Background on Lean Six Sigma tools and principles

The aim of this section is to categorise the main tools and principles of Lean Six Sigma in order to compare them with Industry 4.0 technologies.

According to some authors (Snee and Hoerl 2007; Salah et al. 2010; Snee 2010), Lean and Six Sigma projects would emerge from a first Value Stream Mapping (VSM) activity which is a specific process map for identifying all wastes including cost of poor quality (COPQ) (Abdulmalek and Rajgopal 2007). From the analysis of current state map, a future state map is drawn followed by implementation plan including Kaizen projects for waste reduction. Kaizen events are improvement projects carried out by means of operative kaizen teams

(Cheng 2018) which use consolidated tools and principles of the TPS. The implemented Lean tools contribute to reduction in the seven wastes category of the TPS, which according to Ohno (1988) are overproduction, inventory, transportation, motion, defect, waiting and over-processing. There is myriad literature dedicated to Lean tools and their applications and we focused on authors who tried to categorise the most important ones. Monden (2011) wrote one of the most important and operative books describing how to implement the TPS and what kind of tools a company can choose. Among these, we can find VSM, 5S, Just-In-Time (JIT), Heijunka, Jidoka, Kanban, Poka-Yoke and Single Minute Exchange of Die (SMED). Pavnaskar et al. (2003) claimed to have count no less than 101 different tools and principles, however in their paper there is no precise reference to all of them. For a manufacturing context where space constraints are important, they proposed 5 out 101 tools which are linked with VSM, cell and layout design, balancing processes and Six Sigma. Chiarini (2011) researched a sample of 107 Italian manufacturing companies finding what kind of Lean tools or principles the company were using and in what percentage. The companies confirmed the typical tools and principles discussed by Monden (2011), adding Lean Office, Lean Metrics and Total Productive Maintenance (TPM). Table 1 recaps the most used tools and principles along with a brief explanation of their purpose and implementation. The purpose of this review is not to discuss in details about each tools but to identify the most important tools of Lean that may have Synergistics relationship with Industry 4.0 technologies.

Table 1 – Lean tools and principles and their purpose

Lean tool/principle	Purpose
VSM	Mapping the current state of the processes, proposing a future state for avoiding wastes
Lean Office	Mapping transactional processes in order to reduce their lead-time and wastes (Bicheno 2008; Monden 2011)
Lean Metrics – Visual Management	Setting KPIs connected to lead time and waste at all levels and functions. Establishing a visual way of managing day-by-day shop-floor performance (Maskell and Kennedy 2007; Khadem et al. 2008)
Just-In-Time (JIT) - Pull-system	Making products only when there is demand of these ensuring a continuous flow from raw materials to finished products and synchronising all the processes (Monden 2011)
Production levelling - Heijunka	Levelling orders avoiding big lots and balancing processes according to the takt-time or rhythm of orders (Matzka et al. 2012)
5S	Cleaning up and setting in order the work place including materials, tools, gauges, etc. 5S is the foundation of the Visual Management and material flow management and all the other tools (Al-Aomar 2011)
Cellular Manufacturing	Designing a specific layout putting together workstations in a sequence that supports a levelled flow of materials with minimal transport or delay (Salum 2000). Typically, the cell is U-shaped and tries to make the so called one-piece-flow (Sekine 1992)
Single Minute Exchange of Die (SMED)	Reducing set-up time for machines avoiding in this way big lots (Shingo 1996)
Jidoka – Autonomation	Implementing automatic systems of detecting problems in machineries but letting the worker the possibility of solving the problem stopping the machine (Baudin 2007)
Kanban	Creating a visual sign for triggering the production of components from upstream workstations only when it is needed and in the right quantities according to the takt-time of received orders (Powell 2018).
Total Productive Maintenance (TPM)	Reducing machine stoppages and failures through preventive and predictive maintenance carried out by workers (autonomous maintenance) and professionals (Kunio 2017)
Poka-Yoke, mistake proofing	Implementing devices and systems in order to prevent the occurrence of mistakes or defects (Thomas 2018)

Six Sigma projects are usually more complex and structured projects that can last between three to nine months (Snee 2010) and follows a structured and disciplined methodology for problem solving- DMAIC (Define, Measure, Analyse, Improve, and Control Phases). While the

Lean toolbox involves mostly visual tools, Six Sigma toolbox incorporates range of advanced statistical tools for data analysis used in Measure, Analyse, and Improve phases of the project. Fundamentally, a team led by a Black Belt in the first Define-stage set the boundary of the problem, develop problem and goal statement, define project scheduling and get support from project sponsor to deal with resources issues and other constraints faced during the project (Harry and Schroeder 2000). In the Measure-stage, the team measures the current performance of the process in terms of COPQ, sigma quality level, defects per million opportunities (DPMO) with respect to selected critical to quality characteristics. The Analyse-stage is the most complex one where the team has to analyse data using descriptive and inferential statistical tools for identifying the root-causes of the problem. Finding the root-causes it implies to master advanced statistical tools such as chi-square test, multiple regression, ANOVA, to mention but a few statistical tools (Hoerl 2001). Once the root-causes have been identified, in the Improve-stage the team optimises those significant input process parameters by conducting design of experiment (DOE) or applying failure mode and effect analysis tool (FMEA) and improving the sigma level of the critical quality characteristics. Finally, in the Control-stage the team set up control plans in place to sustain the benefit over time and certifying the savings for the accounting and finance team (Harry and Schroeder, 2000).

2.2 Background on Industry 4.0 technologies

Industry 4.0 is a structured and complex model that encapsulates many digital technologies connected with each other to provide real time data to manufacturing and service systems for analytics purpose by use of base technologies including Internet of Things (IoT), cloud services, big data, and analytics (Frank et al. 2019; Dalenogare et al. 2018). The growing number of possible digital technologies, cyber technologies and systems connectable and integrable are uncountable and subject to a rapid and continuous evolution in an attempt to address the integration challenge through comprehensive connectivity (Fatorachian and Kazemi 2018; Bibby and Dehe 2018). We attempt to categorise them according to the current literature review, especially linked to the manufacturing context.

Hermann et al. (2016) analysed 51 papers dedicated to industry 4.0 and tried to categorise the most important elements of Industry 4.0. According to the authors, the most quoted and studied elements are cyber-physical technologies, followed by the IoT, Smart Factory, Internet of Services, Smart Products, Machine-To-Machine learning, Big Data and Cloud. The consulting firm PwC (2016) carried out a global survey on Industry 4.0 with no less than 2,000 manufacturing companies in 26 countries and reported that Industry 4.0 is based on 11 contributing technologies inclusive of those mentioned by Hermann et al. (2016) - mobile devices, location detection technologies, advanced human-machine interfaces, authentication and fraud detection, 3D printing, smart sensors, multilevel customer interaction and customer profiling, augmented reality/wearable. Similar findings were reported by Kamble et al. (2019), stating that aforementioned technologies can be integrated creating more complex cyber-physical systems and cyber-security systems.

Other authors (Jeschke et al. 2017; Dalenogare et al. 2018) classified Industry 4.0 technologies using the three main advantages introduced by Industry 4.0- vertical integration, horizontal integration and end-to-end engineering. Dalenogare et al. (2018) listed a combination of new and more consolidated technologies such as CAD/CAM, integrated engineering systems, digital automation with sensors, flexible manufacturing lines, Manufacturing Execution Systems (MES) and Supervisory Control and Data Acquisition

(SCADA), simulation and analysis of virtual models, bid data collection and analysis, digital product systems, additive manufacturing, 3D prototyping, cloud service.

There are also authors (Rüßmann et al. 2015; Romero et al. 2016; Frank et al. 2019) who, in addition to the above-mentioned technologies, highlighted how Industry 4.0 relies on new autonomous and collaborative robots, named collaborative robots (COBOTs) and autonomous mobile robots (AMR), which can help and assist workers instead of just substituting them like in the past.

Assessing the maturity of manufacturing industry with respect to Industry 4.0 applications, Bibby and Dehe (2018) concluded that majority of the UK organisations implementing Industry 4.0 are strong in the area of 3DP and big data applications and have weaknesses in the implementation and usage of cloud solutions, sensors, and e-value chain. On the contrary, Frank et al (2019) findings suggested that Brazilian manufacturing industries find it relatively easy to implement technologies such as MES, SCADA, sensors, remote monitoring and collaborative robot, cloud, and IoT; but still need more experience and learning in application of other advanced Industry 4.0 solutions including flexible lines, additive manufacturing, Augmented & virtual reality, big data and analytics as well as machine learning.

Other authors (Ahuett-Garza and Kurfess 2018; Fatorachian and Kazemi 2018) claimed that the primary objective of industry 4.0 is to improve the efficiency and responsiveness of the manufacturing system. These authors highlighted how the implementation pattern should be based on an integration of the Industry 4.0 technologies operating on the horizontal and vertical processes of manufacturing systems.

We have combined the technologies discussed by the different authors in table 2 with few regroupings of technologies under different headings. For example, we put together the integrated engineering systems and the CAD/CAM creating the Product Data Management and Product Life Management (PDM/PLM) system.

Table 2 – Industry 4.0 technologies and systems

Technology/System	Purpose and definition
IoT	Network to connect anything with the Internet through information sensing equipment to conduct information exchange and communications in order to achieve smart recognitions, positioning, tracing, analysis, etc (Patel and Patel 2016)
MES/SCADA	Software system which provides real time information about what is happening in the shop floor. It is also an information bridge between planning systems used in strategic production management (such as ERP) and manufacturing floor control supervisory control and data acquisition (SCADA) (Panetto and Molina 2008, 644)
PDM/PLM	PDM/PLM is an integrated approach including consistent sets of methods, models and IT tools for managing product information, engineering processes and applications along the different phases of the product lifecycle (Abramovici 2007, 665)
Big data collection and analytics	Big data are characterised by an immense volume, variety and velocity of data across a wide range of networks. Analytics have evolved from business intelligence and decision support systems enabling organisations to analyse big data to support evidence-based decision making and action taking (Wang et al. 2018)
Artificial Intelligence (AI) and machine learning	Artificial intelligence concerns the ability of machines to carry out tasks typically performed by a human intelligence. Machine learning is a branch of AI where machines have access to data and learn by themselves, making decisions or predictions (PwC 2016)
Cloud	Cloud computing involves delivering hosted services over the Internet. These services are typically infrastructure-as-a-service, platform-as-a-service and software-as-a-service (Jeschke et al. 2017).
3D printing, additive manufacturing	3D printing, included in the broader term of additive manufacturing, refers to the various processes used in the manufacture of products, by depositing or fusing materials layer by layer (European Commission 2017)
Smart products and customer interaction	Products with digital characteristics that enable adaptation to customers' situation during the entire product life cycle (Stock and Seliger 2016)
Digital automation with sensors and smart sensors	Machines and manufacturing processes embedded with sensors capable of collecting data, measuring, analysing and triggering other processes (European Commission 2015; Rüßmann et al. 2018)

Collaborative and Autonomous Mobile Robots (COBOT and AMR)	Collaborative robot (COBOT) is a robot intended to physically interact with workers (Djuric et al. 2016). The robot could be restricted in a shared workplace or be able to move itself autonomously in the shop-floor
Augmented Reality (AR) and Smart Human Interfaces (SHI)	Communication systems which allow people to interact with a number of smart technologies such as screens, 3D glasses, exoskeletons, etc. (PwC 2016) which augment human abilities
Cyber Security	Management system allowing to resist events resulting from cyber space which may compromise the availability, the integrity or confidentiality of data stored, processed or transmitted and of the related services that ICT systems offer (Luiijf et al. 2013)

2.3 Implementation pattern for Lean Six Sigma and Industry 4.0 integration

There are very few studies dedicated to the integration, in general, of Industry 4.0 and production systems (Kolberg et al. 2017). The most significant is surely the Reference Architecture Model for Industry 4.0 (RAMI 4.0) which is in part based on International Electrotechnical Commission (IEC) standards. According to the German Plattform Industrie 4.0 (2015), the RAMI 4.0 model is based on four relevant aspects which are a horizontal, vertical, end-to-end engineering integration and humans orchestrate the value stream. From a strategic and performance point of view, the RAMI 4.0 model aims at adding value optimising the value stream at any particular time.

Similarly, Jeschke et al. (2017) and Dalenogare et al. (2018) proposed a vertical and horizontal integration between Industry 4.0 and manufacturing systems. They discussed how the horizontal integration should be expanded with end-to-end engineering processes. In this way, according to Dalenogare et al. (2018), the vertical integration is the integration between the production and the management levels, the horizontal integration the integration between production processes and suppliers, while the end-to-end engineering is the integration of product design in the whole value chain from product development until aftersales. The authors believe that Industry 4.0 could overcome some limitations of Lean production especially when products are completely different one from another in terms of cycle time. Furthermore, Dalenogare et al. (2018) suggested Industry 4.0 is better to be implemented after the introduction of Lean tools as Lean reduces the flow to essential and simple work with no waste, therefore easier to be automatized.

Moeuf et al. (2019) highlighted how, especially in the SME sector, the vertical level of integration is mainly related to ERP changes and new integrated pieces of software which control the shop-floor. However, the authors highlighted how the majority of manufacturing companies which are implementing Industry 4.0 technologies have no clearly defined performance targets to achieve.

Mapping the current literature concerning Industry 4.0 and Lean, Buer et al. (2018) classified several papers dedicated to how Lean can support Industry 4.0, how Industry 4.0 can support Lean and the performance implications of an Industry 4.0 and Lean integration. The authors discussed that the knowledge of how this integration should be done is still immature. Wagner et al. (2017), came to similar results, while Wang et al. (2016) argued how a manufacturing company that already has implemented Lean is more likely to be integrated by Industry 4.0 than the other way around. From a performance standpoint, Buer et al. (2018) reviewed several papers concluding that the integration between Lean and Industry 4.0 can lead to an increase of productivity and a reduction of waste and costs. They specifically analysed a horizontal integration on the shop-floor, including the external supply chain.

Assessing the moderating impact of Industry 4.0 on the relationship between three Lean practices (i.e. pull, flow, low set up) and operational performance improvement (e.g. productivity, delivery service level, inventory, quality, and safety) in Brazilian manufacturing sector, Tortorella et al. (2019) concluded that process related Industry 4.0 technologies negatively moderates the effects of low set up practices on performance, and product/service related technologies positively moderate the effect of flow practices on performance. Their study concluded that purely technological implementation will not lead to sustained improvement and results; lean practices may act as a precursor to Industry 4.0 implementation.

Lastly, we found one paper regarding a possible integration of Lean and Six Sigma with Industry 4.0 to improve logistics and supply chain performance (Jayaram 2016). Basically, the paper discusses the integration within the global supply chain, from suppliers to customers, which is based on four main components- connectivity, visualisation, optimisation and autonomy. In this general model, Lean Six Sigma and Industry 4.0 complement, though author suggest to first implement Lean Six Sigma followed by Industry 4.0. However, the paper had limited information on how to achieve integration between Lean Six Sigma tools and Industry 4.0 technologies.

The results of this literature review show how the implementation of Industry 4.0 in a production system, including Lean Six Sigma based systems, can be pursued from a horizontal, vertical and end-to-end engineering dimension. Lean Six Sigma as well could be implemented following the vertical integration amongst different levels of the company (O'Rourke 2005), the horizontal integration of production processes (Bicheno 2008; Monden 2011) and the integration with customer requirements (Behara 1995; Basu, 2004).

The results also tend to consider Lean Six Sigma as an antecedent to Industry 4.0, even though it is not so clear how the integration pattern should look like and what kind of performance could be enhanced and strategically followed. Moreover, there was limited evidence of link between the Six Sigma DMAIC methodology and Industry 4.0 technologies and systems.

In the following section, we used these issues connected with integration, performance and strategy, along with Table 1 and Table 2 tools as an aide memoire for understanding the integration pattern between Lean Six Sigma and Industry 4.0 through grounded theory methodology.

3. Methodology

This research is mainly an inductive qualitative inquiry based on semi-structured interviews with ten managers in ten different Italian manufacturing organisations who are applying Lean Six Sigma and Industry 4.0, followed by in depth case study and direct observation of a selected case organisation. The data and information gathered have then been analysed using grounded theory approach. Given limited research on the synergistic effect of Lean Six Sigma and Industry 4.0, Grounded theory strategy seemed appropriate choice due to its ability to evolve or 'ground' a theory in the context in which the phenomenon under study occurs (Glaser and Strauss 1967; Strauss and Corbin 1998; Parker 2001; Charmaz 2008). Eisenhardt (1989) discussed several methods for building theory from case studies, highlighting how grounded theory is particularly useful when the researcher has to deal with data and information from different sources such as interviews, direct observations, documents, etc. This research is exactly based on two different sources of data. According to Eisenhardt (1989, p. 534):

> *The method relies on continuous comparison of data and theory beginning with data collection. It emphasizes both the emergence of theoretical categories solely from evidence and an incremental approach to case selection and data gathering.*

Starks and Brown Trinidad (2007) compared three interpretative approaches, phenomenology, discourse analysis and grounded theory, demonstrating how grounded theory is particularly focused on observing phenomena where the process takes place, as in this research. Moreover, Charmaz (2006) studied how through grounded theory, theoretical elements, structures and processes are also proposed in their interactions; this is important for our kind of inquiry where we want to connect the emerging theoretical categories in a determined framework. Grounded theory methodology is well known in management studies, since its presentation by Glaser and Straus in 1967 (Strauss and Corbin 1998).

Data gathering for the study is conducted in two phases, with the first phase involving ten semi-structured interviews with production managers. The interviewer can have a variable approach to the subject; there are themes and topics which have to be covered during the interview, rather than a fixed sequence of questions (Saunders et al. 2009). The semi-structured interview in this research is organised around an aide memoire or interview protocol structured according to the relevant issues resulting from the literature review. Specifically, the issues discussed during the interview were:

- *Horizontal integration issue*: How could the Industry 4.0 technologies be integrated within the Lean tools and principles and vice versa? How could Industry 4.0 technologies and systems be integrated within the DMAIC Six Sigma pattern?
- *Vertical and end-to-end integration issue*: What kinds of integration have to be implemented among the different levels of processes and within the supply chain
- *Implementation pattern issue*: Which pattern will result in greater integration between Industry 4.0 and Lean Six Sigma.
- *Performance and strategic issue*: What are the performances (e.g. productivity, quality, cost reduction, lead time reduction, customer satisfaction, etc.) and the grand strategy pursued through this integration?

The ten manufacturing companies were chosen on the strength of the following aspects:

- All selected companies have design, production and logistics departments and have strong relationship with their customers, which will allow to study horizontal, vertical, and end-to-end integration possibility.
- All companies operate in business to business environment (B2B). Generally, they manufacture in small - medium batches and there is a certain repeatability in the received orders.
- They have been implementing LSS for at least five years with a good level of implementation as evidenced from their established organisational infrastructure for LSS and performance measurement system.
- They have a precise strategic plan in the forthcoming years dedicated to Industry 4.0 implementation and integration with LSS.

Sample size in grounded theory cannot be determined a priori as it is contingent on the evolving theoretical categories (Vasileiou et al. 2018, p. 148). Charmaz (2006, p. 113) highlighted how:

> *Grounded theory saturation concerns the theoretical categories – as opposed to data – that are being developed and becomes evident when gathering fresh data no longer sparks new theoretical insights, nor reveals new properties of your core theoretical categories.*

The ten interviews in ten case companies led to data saturation due to data overlap and little new material of insight being added after eight case interviews, indicating the characteristics of data saturation (Corbin and Strauss 2008). Moreover, in the qualitative study, importance is given to data quality over quantity (Mason 2010; Costa et al., 2019) and thus ten cases are reasonable sample to attempt for theoretical generalisation instead of analytical generalisation (Barratt et al. 2011; Yin, 2014).

In the second phase of the study, data was collected from direct observation in a case study company where the first author followed the phases of the Industry 4.0 implementation and collected relevant primary and secondary data. The case study is represented by a large sized manufacturing company with 800 employees, manufacturing pumps and hydraulic components. The company has two manufacturing plants in Italy, two in South Asia and seven commercial subsidiaries around Europe and North America. This company has been implementing Lean Six Sigma for fifteen years and in the last two years has been implementing Industry 4.0 technologies. The company is motivated to launch and implement Industry 4.0 project without being forced by customers with an objective of increasing productivity, shorten lead time, increase quality and flexibility and reduce costs. The company is also trying to increase the servitization level of its products. Another reason for selecting this case study organisation is their capability and potential to implement majority of the Industry 4.0 technologies listed in Table 2, from the engineering department to the supply chain. Furthermore, the company has implemented all the Lean tools and principles in Table 1 as well as launched dozens of Six Sigma DMAIC projects. For almost two years, authors have observed the Industry 4.0 implementation stages, analysing and discussing with the managers the same four issues discussed with the ten interviewees.

3.1 Data coding and analysis method

Grounded theory methodology helped in generation of concepts and theoretical categories to emerge (Strauss and Corbin 1998). In grounded theory, there are three basic types of coding: open, axial and selective. The initial level of abstraction is open coding where data collected from interviews and observations from the case study are accurately analysed and conceptualised into appropriate categories. In the axial coding stage, data and information from the open coding categories are analysed making further connections between categories. The categories which emerged from the axial coding represent the theoretical elements of the new pattern for Operational Excellence created by integrating Lean Six Sigma and Industry 4.0. The last stage of grounded theory is selective coding, where the purpose is to find the core category of the model. A story line needs to prioritise one category over all the others and these latter are related to the core.

4. Findings

Following the four issues discussed in the previous section, we interviewed 10 production managers belonging to 10 different Italian manufacturing companies. The interviews were held between September 2018 and March 2019. The interviews were then transcribed for coding purpose. Each interview, based on six opened questions within the four main categories, lasted from 2 to 3 hours producing qualitative data that has been written down from records. Data from the interviews were then coded into meaningful description of the phenomenon. We grouped similar phenomena by assigning them a short open code and a label. Table 3 shows the open coding results from the interviews using this approach.

Table 3 – Open coding for the results from the ten interviews

Issue	Label	Description of the phenomenon	Open codes
Horizontal integration	I_1	Better identification and use of materials and equipment in the workplace and on the shop-floor through cyber-technologies	Traceability of products and equipment through cyber-technologies
	I_2	Data gathering from machine sensors analysed and processed for predictive and scheduled maintenance	Predictive and scheduled maintenance through sensors and analytics
	I_3	Smart maintenance with automatic launch of orders for spare parts	Smart maintenance
	I_4	AMR/AGV for automatizing logistics activities	AMR/AGV for logistics activities
	I_5	COBOT and augmented reality for repetitive and/or harmful manual activities	COBOT and AR for repetitive and/or harmful manual activities

	I_6	AR and smart sensors used for Poka-Yoke and mistake proofing systems	Poka-Yoke and Jidoka by means of AR and smart sensors
	I_7	Cyber technologies for improving a range of safety systems	Safety systems improved through cyber technologies
	I_8	Cyber technologies allow Visual Control in real time of process performance and product conditions	Visual control over the IoT
	I_9	Cyber technologies improve Visual Control and waste within offices	From Lean office to smart office
	I_{10}	Evolving the Kanban pull system into an Autonomous Process Synchronisation (APS) over the IoT	Introducing an APS system
	I_{11}	Using 3D printers and smart sensors for prototypes and pre-series in order to collect data for DFSS stages	3D printing and smart sensors for DFSS
Vertical & end-to-end integration	I_{12}	Redeveloping ERP modules for a better vertical and end-to-end integration	Redeveloping ERP modules
	I_{13}	Integrating the MES/SCADA with machinery, workstations and logistics equipment	MES/SCADA integrated with all manufacturing processes
	I_{14}	PDM/PLM communicates bi-directionally with machinery, workstations, logistics equipment and products	PDM/PLM integrated with all manufacturing processes and products
	I_{15}	Sharing databases and pieces of software with customers and suppliers, specifically orders and scheduling	Sharing databases and pieces of software with customers and suppliers
	I_{16}	Developing a new class of business intelligence software for analysing big data and making decisions	Business intelligence with big data
Implementation pattern	I_{17}	Removing waste before introducing automation and cyber technologies	Cyber technologies after having removed waste
	I_{18}	Deep analysis of processes before implementing Industry 4.0 technologies	Initial digital analysis of processes
Performance and grand strategy	I_{19}	Measuring in real time KPIs and other indicators	Measuring in real time KPIs and other indicators
	I_{20}	Automatic and real time calculation of cost of products	Automatic and real time cost accounting
		Grand strategies are mainly connected with achieving an increase in productivity and a lead time reduction	Grand strategy is lead time reduction and productivity growth

4.1 The horizontal integration of the tools and systems

During interview, we discussed the first issue of the horizontal integration where Industry 4.0 technologies have been integrated with Lean Six Sigma tools.

According to respondents, the first basic level of integration was based on a precise identification of the processes and activities that are specialised and repeatable. Such activities can be automated with cyber technologies to create additional capacity for employees to focus on value-added activities. In this way the company integrated the operations processes over the IoT. All participating companies were using smart sensors and RFID for identifying the states of the products and their physical locations. One manager stated: "*we had implemented 5S to set in order products and tools in the workplaces and on the shop-floor but with inadequate results. Now through smart sensors and RFID we know if everything is in the right place at the right time with a perfect traceability"*. Moreover, all companies have changed or modified their machines implementing advanced sensors for monitoring conditions and measuring parameters such as times, speed, pressures, vibrations, temperatures, etc. Few managers highlighted how, once you have all this data from sensors stored in the cloud or a server, then you need to develop analytic software and algorithms for specific analysis, including the so-called machine learning. All the respondents highlighted how, one software can be used for predictive and scheduled maintenance. This is an example where TPM can be virtually practised by integrating with IoT for predictive maintenance. In this way all respondents believe that a company could implement a new smart maintenance system able to autonomously predict failures, auto-launch of request for maintenance, and placing orders with suppliers for spare parts.

The interviewees shared example of how they have integrated range of cyber technologies with Lean Six Sigma tools for improving efficiency. 8 out of 10 companies have implemented AMR/AGV for automatizing logistics activities, as well as COBOTs and even augmented reality for repetitive and sometimes harmful manual activities. AR and smart sensors are always used as Poka-Yoke or Jidoka systems, especially during assembling and logistics activities such as picking and where workers have to control critical characteristics of the product. For instance, in one of the companies, workers who have to tighten critical-to-safety bolts wear smart 3D glasses which visualise a green light for identifying the right critical bolts. The glasses also facilitate the operator to identify the exact wrench to be used and only when the bolt is tightened at the right tightening torque, the glasses allow the operator to continue with other activities. This is a classic example of practicing mistake proofing using smart glasses which also encourages operators to follow standard operating procedures.

Furthermore, all the respondents stated that cyber technologies usage have helped them to improve safety systems such as fire systems, personal protective equipment wearing as well as people's interferences with logistics vehicles and machinery. Cyber technologies allow in real time to visually control processes, products and their performances. These data and information are also displayed on screens visible to each worker. Data and information are automatically collected and managed from non-production processes such as administrative and marketing functions, helping these companies in reducing waste through the so-called Lean office (Bicheno 2008). However, in this case, the automation of data gathering is more a matter of software than cyber technologies. Indeed, 6 respondents highlighted how they had to develop new items of document-flow software in order to automatically track down transactions linked to files. Real-time visual control helps workers within office to control and manage their processes more efficiently and effectively.

The real puzzling and futuristic project for all the interviewed managers is how to synchronise all processes, from customers' orders to suppliers' production, creating a non-interrupted flow with a low level of inventory. In a traditional Lean environment this is realised by means of Kanban applications and Heijunka scheduling (Monden 2011). According to respondents, using an electronic signal over the IoT, one process could trigger the production of another one in a pure Just-In-Time way introducing a perfect one-piece-flow pull system. Naturally, before this implementation, all the processes have to be balanced meeting the takt-time pace and set-up times reduced. This is an evolution of the Kanban pull system which is referred by the respondents as *'Autonomous Process Synchronisation (APS)*'. However, interviewees acknowledge the challenges regarding risk and threats associated with sharing data and information across the supply chain which is dependent on several factors including trust amongst supply chain partners and power held by an actors in the supply chain. Three companies have also started using smart sensors and 3D printing for collecting data and managing experiments on prototypes and pre series. This is now a peculiar part of improvement projects carried out through design for Six Sigma methodology (DFSS).

4.2 Vertical and end-to-end integration

The participating companies were in consensus that integration among different levels of processes, customers and suppliers is possible through software and databases instead of making change to hardware. For examples, one of the respondents explained how they have been redeveloping relevant modules of the ERP, in particular the Manufacturing Execution System/ Supervisory Control and Data Acquisition (MES/SCADA) and the Product Data Management/Product Life Management (PDM/PLM). The MES/SCADA software was interfaced with the smart-technologies installed in the machinery, workstations and logistics equipment. The purpose of the software was to collect relevant data from machines to calculate the Overall Equipment Effectiveness (OEE) and other key indicators as well as improving scheduling of production process. The respondent highlighted how they have modified the MRP and scheduling software for automating data acquisition from the MES and the production processes. In particular data related to workstation stoppages, WIP queues, cycle times, and workers’ presence or absence. In this way, MRP can work using a real time and precise finite capacity, avoiding bottlenecks and overloads. However, it is not easy to make those modifications especially when you are using a third-party software as acknowledged by majority of interviewees. Collaboration with vendors are key to successful vertical and end-to-end integration of the supply chain.

Few of the respondents have also modified PDM/PLM software in order to directly provide information to machines, workstations and warehouse. For instance, a design change means a real-time access to new drawings and instructions for all the processes including warehouses and MRP, avoiding mistakes in terms of use of obsolete components or outdated design.

Two respondents have also been experimenting with smart sensors, embedding with finished products in order to collect data linked to product reliability from the PDM/PLM database. The other respondents believed that this particular kind of integration with customers is more for companies which sell products for end-user rather than semi-finished products which have to be further transformed or assembled. For example, one case company manufacture power take-off for agricultural tractors and is studying dedicated smart sensors for collecting data from the product such as number of revolutions, power and vibrations to assess the performance of the product and do modification in the new version.

All respondents were in consensus that a fundamental part of end-to-end integration is sharing databases and software with customers and suppliers, specifically orders and scheduling. Similarly, for internal synchronisation between processes, seven respondents stated that they are implementing electronic pull system with a supplier.

Lastly, all respondents are uncertain about how to manage the big data collected through the implementation of these new cyber-technologies. According to respondents, such a huge storage of data needs a new class of business intelligence software based on new algorithms in order to analyse and make decisions.

4.3 Implementation pattern issue

When to implement new cyber-technologies and software has surely been one of the most difficult choices for these companies. According to one respondent, "*Industry 4.0 is something so discussed and recommended by customers, consultants, academics and institutions that you are tempted to implement it everywhere with no plans".* Furthermore, in Italy in the last few years, manufacturing companies have received several government funds for implementing Industry 4.0. This scenario creates a push system whereby organisations are pushed by this sort of automation and digitalisation rush. Majority of the respondents concur that they have also made mistakes in the implementation pattern. The first and most common mistake is to use automation such as robotics, automated vehicles and others before having analysed and removed wastes. Agreeing to this viewpoint, three respondents stated that they bought expensive logistics AGV instead of rethinking their shop-floor layouts; another bought 3D printing for making complex and non-reproducible prototypes, as well as smart sensors which measure anything but what is really necessary.

According to a respondent, "*you soon realise that before implementing whatever new technology, you must analyse deeply processes for figuring out what you really need".* There was a common viewpoint among respondents that cyber technologies should only be implemented after streamlining and reengineering processes. Lean Six Sigma can provide a good base to remove waste and minimize variation before embarking on automation and use of cyber technologies. This implies, Lean Six Sigma can be a foundation for successfully integration of Industry 4.0 technologies with internal and external processes.

4.4 Performance and strategic issue

All interviewees concurred that when cyber technologies and software are well integrated through IoT, horizontally and vertically, a manufacturing company should be able to measure and control in real-time all the performance indicators.

Three interviewees discussed how they are analysing what kinds of KPIs they really need, implementing new analytics software for managing the collected big data; however, according to them, this is far off to be something simple. First of all, one respondent stated that there was a certain resistance inside the company to change KPIs within ERP modules "*We tried hard to implement new KPIs connected with the acquired data from new technologies, however these KPIs were considered not official, therefore, after a while we bounced back to the previous ones.* "

Connected with the issue of ERP modules, four respondents with similar viewpoint emphasised how through cyber technologies and smart sensors they might be able to measure in real time all costs connected with the products creating what they call an automatic accounting system. For instance, one respondent stated, "*we could be able to calculate for each product the quantity of raw materials, all the production times, all the logistics times dedicated and even the time the accounting department devotes to invoicing such product. This could lead to the end of the calculation of overhead costs."* However, all the respondents asserted that their ERP finance modules are still based on specific standard costs and times to calculate the cost of the product.

Finally, all the respondents highlighted how the integration of Lean Six Sigma and Industry 4.0 in their manufacturing companies is following a grand strategy pursued for years based on lead time reduction, because this means waste and cost reduction, and productivity growth.

5. Findings from direct observation in the case company

Following the same four issues used during the interviews in the first phase of the study, we started analysing in the second phase of the study how the selected case company has integrated the Industry 4.0 technologies within Lean Six Sigma tools and techniques. Like many other companies, this company first implemented Lean Six Sigma for several years before embarking on implementation of Industry 4.0 technologies.

Observation is important in order to get data and information that cannot be directly explained by the interviewees. Furthermore, it might be helpful for understanding phenomena avoiding a possible bias introduced by the interviewees. In this particular case, the first author observed and collected some interesting operative document to understand how this selected case company developed its own new Operational Excellence model over time. The notes taken from the observation were collected and analysed for qualitative analysis. We tried to group similar phenomena assigning them a short open code and a label. Table 4 shows the open coding results from the observation using this approach.

Table 4 – Open coding for the results from the observation

Issue	Label	Description of the phenomenon	Open codes
Horizontal integration	O_1	5S might be improved by means of RFID and bar codes	5S tool improved with RFID and barcodes
	O_2	TPM might be improved through smart sensors especially in the predictive maintenance system	Predictive maintenance improved with smart sensors
	O_3	Collecting data from processes and products using smart sensors, analysing them through Six Sigma	Collecting data for Six Sigma through smart sensors
	O_4	Embedding new statistical analytic tools for big data within the DMAIC pattern	Analysing big data for Six Sigma with analytics
	O_5	Helping workers with SHI in order to avoid mistakes and increase their productivity	Improving productivity and quality by means of SHI

	O_6	Synchronising all the shop-floor processes through E-Kanban and exchanged automated signals	Synchronisation amongst production processes
	O_7	Completely redesigning the logistics flow automating material transports with AGV and smart AMR. Synchronisation with production processes	Improving logistics by means of AGV and AMR
	O_8	Repetitive and difficult activities within cells and in the lines might be performed by COBOTs	Redesigning cells and lines using COBOTs
	O_9	Cyber security affects all the implemented cyber technologies over the IoT	Cyber security over the IoT
	O_{10}	Smart sensors and SPC software can give autonomous feedback to the machine	Autonomous SPC
Vertical & end-to-end integration	O_{11}	All the data collected from the IoT and the ERP modules should be stored and managed in the cloud	Data storing and management in the cloud
	O_{12}	ERP modules should be integrated with analytics	ERP integration with analytics
	O_{13}	PDM/PLM modules should be interfaced with all the end to end processes exchanging data with all the other ERP modules	Improving PDM/PLM integration
	O_{14}	MES and SCAD modules should be interfaced with all machines and production processes exchanging data with all the other ERP modules	Improving MES/SCADA integration
	O_{15}	CRM modules should automatically collect data and information from products in the market and customer interfaces	CRM integrated with data and information from customers
	O_{16}	Some ERP modules such as production scheduling should be shared with the suppliers	Sharing ERP modules with suppliers
	O_{17}	All the ERP modules have to be re-engineered creating a stronger integration amongst databases	Stronger integration of the ERP databases
	O_{18}	Industry 4.0 should introduce a vertical integration as well an end-to-end integration by means of the ERP modules	Vertical and end-to-end integration through ERP modules
Implementation pattern	O_{19}	Industry 4.0 technologies have to be implemented only after having tried	Firstly, removing waste through Lean Six sigma

		to remove waste by using traditional Lean Six Sigma tools	
	O_{20}	Using an adapted smart form of VSM for identifying waste and proposing improvements through smart technologies	New smart VSM
Performance and grand strategy	O_{21}	Data should automatically come up from cyber entities and processes for calculating the cost of the product. Any cost is classified as direct	Automatic accounting for calculating product cost
	O_{22}	All the performances of the shop-floor should be measured in an automatic way. Data should automatically come up from cyber entities for the KPIs	Measuring KPIs automatically
	O_{23}	Industry 4.0 is strategically implemented mainly for reducing the lead time from product incoming to shipping	Grand strategy is lead time reduction

A number of LSS tools have benefitted from integration with Industry 4.0 technologies according to Table 2. Firstly, the company has used specific sensors for understanding whether all tools and gages are in their due positions in the workplace or not. This is connected with the second step of the 5S tool, set in order (Agrahari et al. 2015). Figure 1 shows an example of Wi-Fi smart sensors behind the established tool location in the workplace. The sensors are connected in the IoT and the use and positioning of the tool can be monitored.

Figure 1 – Tools in a workplace monitored through smart sensors

Moreover, sensors and RFID can now track down in real time products and material on the shop-floor during their path, similar to findings reported by Buer et al (2018) who concluded that RFID is a useful tool to achieve Lean automation. This affects and improves the outcomes from application of Lean tools such as 5S and one-piece-flow. The company has also modified critical machines and assembly lines in order to collect data and information concerning the conditions of the process; in particular, cycle times, stoppage caused due to failures and set-up times, productivity, non-conformities and reworking times. These data and information are automatically collected by means of a MES software which is integrated in the ERP software used by the company concurring with the Industry 4.0 framework proposed by Fatorachian and Kazemi (2018). Smart sensors embedded in the machinery have led to implementation of a predictive maintenance system reducing stoppages for failures (Tao et al. 2018; Koenig et al. 2019).

Smart sensors for collecting data linked to critical characteristics of the process permit SPC with autonomous feedback to the machine in case of deviation from the limits and unlikely patterns in the data appear, which led the company to completely change the SPC software and the machine sensors. This also helps the company during the DMAIC project phase, especially in measure phase to check the stability of the process before calculating process capability index and in control phase to monitor the stability of the process and raise alarm if an out-of-control condition occurs or about to occur. Assembly lines and cells have also been redesigned implementing COBOTs for helping workers in repetitive and non-ergonomic activities. The company has employed the chart shown in Figure 2 for analysing all the activities within cells and lines deciding whether the activities can be automated. Other manual activities, especially in logistics, where mistakes can be easily introduced, have been improved by the means of SHI such as 3D glasses and tablet with augmented reality. The company plan to re-train the Six Sigma Green and Black Belts on big data and analytics, implementing a dedicated software in the cloud. Related to the cloud and the internal servers, the company has also launched a risk assessment for identifying all the critical issues in terms of cyber security.

Figure 2 – Example of the chart for analysing activities within cells and lines

Cell: 13T	**Products:** T and S	**# operators:** 5 (min 2-max 6)	**Average Takt-Time:** 68 secs/piece
Activity	**Cycle time**	**Operator**	**Improvement**
Withdraw from box ⇨	10 secs	A	Put the tilted boxes nearer the operator
Fixing product in the template ▽	15 secs	A	
Assembling 6 screws with the pneumatic screwdriver ○	30 secs	A	
Transfer to another operator ⇨	5 secs		
Fixing product in the template ▽	20 secs	B	We can use a COBOT to reduce the cycle time improving also activities from an ergonomic point of view
Assembling product holding it in the template ○ + ▽	50 secs	B and C together	
Visual inspection of the alignment □	20 secs	B and C together	The COBOT could also check the alignment of the components

⇨ Transport ▽ Holding ○ Assembling □ Inspection

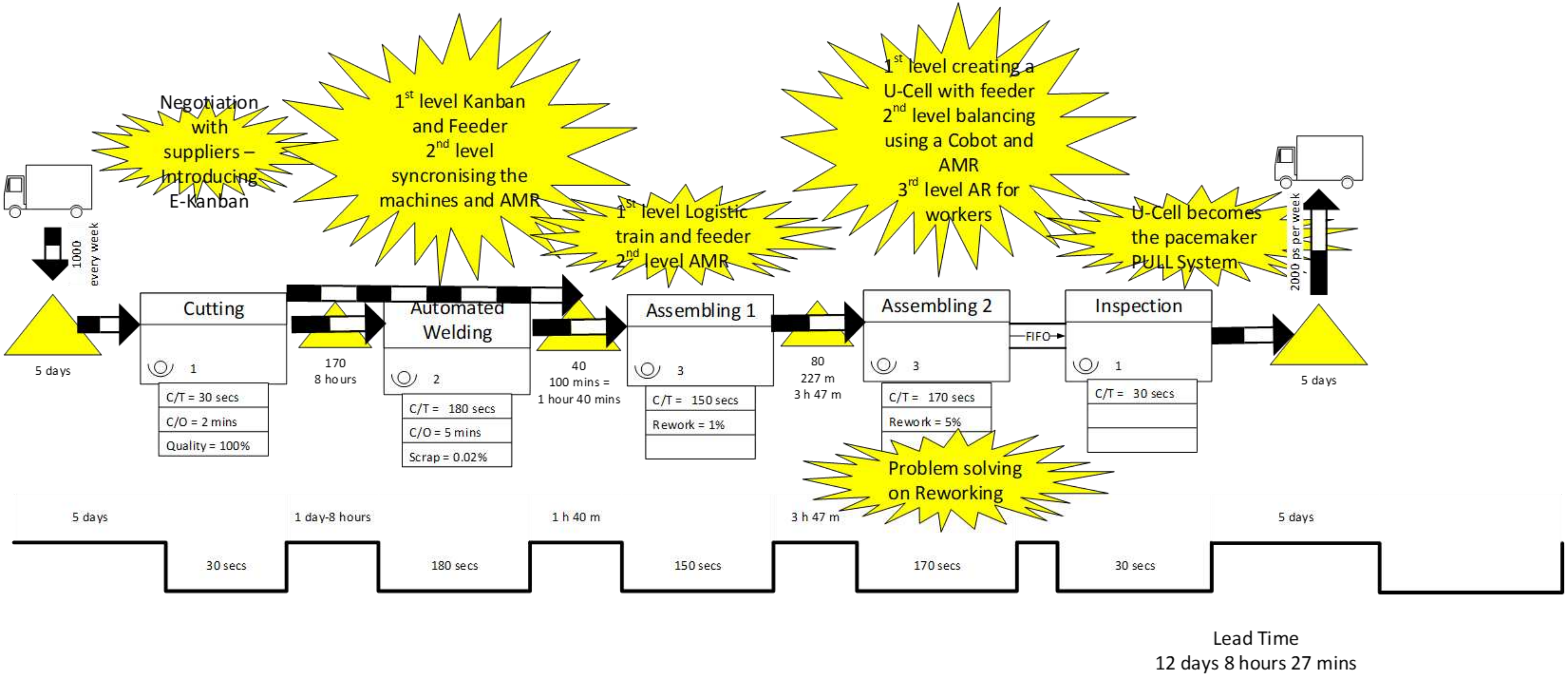
For achieving vertical and end-to-end integration, the company has reengineered all the software modules and databases to collect data and information from the machines, sensors and cyber technologies and storing them in the cloud and internal servers. The MES software has been modified for a complete integration with machines and workplaces as well as a perfect integration with other modules such as MRP, accounting and finance and PDM/PLM. The latter is now more integrated with the ERP and allows to collect data from customers and supply chain partners in terms of reliability, quality and inspections of the several components for the finished product. However, we observed many interoperability issues encountered by the company during value chain integration when collating data from customers and suppliers, mainly due to different software and databases used across the value chain.

The pattern for integrating Industry 4.0 technologies and cyber technologies with LSS started with an analysis carried out with the VSM tool. The company, periodically, assesses processes in terms of waste, lead time calculation and develop implementation plan for improvements through this map. The VSM is drawn in a so-called as-is version and then a future-state VSM is designed by a team (Rother and Shook 1999). The future state has to be reached through action plans sometimes called as Kaizen (Rother and Shook 1999). The company readapted the traditional VSM and named it as *'smart VSM'* in order to identify potential improvements through the Industry 4.0 technologies. Figure 3 shows an example of such an adapted map where the Kaizen events with the explosion boxes refer to the usage of Industry 4.0 technologies for improvement.

According to the observation results, the company has implemented Industry 4.0 technologies for achieving automation only after having minimising waste and stabilising the processes using LSS tools and techniques. The following quote from the company's managers explain their aforementioned justification – *"if you act the other way around you could end up wasting money and make the waste even less identifiable for elimination or minimisation."*

Lastly, in terms of performance and grand strategy, the company is trying to automatize the data collecting process in order to continually measure all the KPIs and in particular the cost of the product. The company aims to implement an automatic accounting system as an evolution of the current Activity Based Costing (ABC) system (Özbayrak et al. 2004). The grand strategy for this company is to reduce the lead time, transforming the production system into a completely make-to-order system.

Figure 3 – The readapted smart VSM for identifying improvements based on Industry 4.0



Grounded theory, at this point, tries to group the open codes which emerged from the interviews and from the observation into axial codes. Axial coding consists of identifying relationships among the open codes. According to Strauss and Corbin (1998), for each open code the conditions that give rise to it have to been identified in order to understand what the common casual conditions with other codes are. For instance, in the I_1, and O_1 open codes, smart sensors and RFID are the common conditions identified and the causes are the implementation of 5S and material flow. Axial codes can be considered as the theoretical elements which demonstrate the integration between LSS and Industry 4.0. Table 5 shows how the open codes from Table 3 and Table 4 have been grouped accordingly, once more, with the four issues used during the interviews and the observation.

Table 5 – Axial coding from the interviews and the observation

Issue	Codes	Axial codes (Theoretical elements of the model)
Horizontal integration	I_1,O_1, I_8	5S, material flow, and visual control with smart sensors and RFID
	I_2,I_3,O_2	From TPM to smart maintenance
	I_5,O_8,O_1	Redesign cells and lines with COBOTs and AR
	O_5	Improving productivity and quality with SHI
	I_{10},O_6	From Kanban to Autonomous Process Synchronisation
	I_4,O_7	Improving logistics activities with SHI and AMR/AGV
	I_7, O_9	Improving safety management and cyber security through cyber technologies
	I_9	From Lean office to smart office
	O_3, O_4, O_{10}	Collecting data for Six Sigma DMAIC projects over IoT for data analytics and process control including autonomous SPC
	I_{11},O_3	Collecting data for DFSS with 3D printing and smart sensors
	I_6	Poka-Yoke and Jidoka by means of AR and smart sensors
Vertical & end-to-end integration	I_{12},O_{18},O_{17}	Redeveloping ERP modules for a better integration
	I_{13},O_{14},O_{18}	Improving MES/SCADA integration in the ERP
	I_{14},O_{13},O_{18}	Improving PDM/PLM integration in the ERP
	I_{15},O_{16}	Sharing ERP with suppliers (scheduling and orders)
	I_{15},O_{15}	Sharing ERP with customers (CRM and scheduling)
	I_{16},O_{11},O_{12}	Analytics for Business Intelligence in the cloud
Implementation pattern issue	I_{17},O_{19}	Integrating Industry 4.0 after having removed waste
	I_{18},O_{20}	Initial digital analysis and smart VSM
Performance and grand strategy	I_{19},I_{20},O_{21},O_{22}	Automatic real time performance measurement and cost accounting
	I_{20},O_{23}	Grand strategy is lead time reduction and productivity growth

At this stage, the identification of a core category is vital for connecting other theoretical elements with the core one which delimits the theoretical model (Hallberg, 2006). A so-called story line connects categories and groups of codes with each other. The authors revisited emerged theoretical elements in Table 5 and interviewed a manager and two senior managers of the company where observation was conducted. The core category was immediately identified by all the managers as 'Grand strategy for lead time reduction and productivity growth'; in fact, according to the managers this is the ultimate goal of an integrated approach.

The managers also identified 'Automatic real time performance measurement and cost accounting' as the second most important category strictly bound to the core one, since it gives them the right direction towards achieving the grand strategy of lead time reduction and productivity growth. Connected with the second category they believe that 'Vertical & end-to-end integration' as well as 'Horizontal integration' are connected with it. In fact, according to the managers and the interviewees, a manufacturing company could automatically start measuring performance and costs once they have integrated LSS and Industry 4.0 and improved the ERP. Once more, connected with the two groups of categories we have 'The initial digital analysis and smart VSM' which in turn is triggered by 'Integrating Industry 4.0 after having removed waste'.

As a last result, we tried to classify the main Industry 4.0 technologies above discussed according to the DMAIC stages. Table 6 shows which stages are the most affected by the technology in the first column.

Table 6 – Industry 4.0 technologies and DMAIC stages

Technology/System	Stage
MES/SCADA	Define-Measure-Control
PDM/PLM	Define-Measure-Control
Big data collection and analytics	Measure-Analyse-Improve
Artificial Intelligence (AI) and machine learning	Define-Measure-Analyse-Improve-Control
3D printing, additive manufacturing	Improve
Smart products and customer interaction	Measure-Analyse-Improve-Control
RFID	Measure-Control
Smart sensors	Measure-Control
Collaborative and Autonomous Mobile Robots	Improve
(COBOT and AMR)	Improve
Augmented Reality (AR) and Smart Human Interfaces (SHI)	Measure-Analyse-Improve-Control

6. Discussion and Conclusion

This research investigated and demonstrated how Industry 4.0 technologies and Lean Six Sigma tools and techniques can be integrated to provide competitive advantages to organisations. This is a novel finding that contributes to the limited literature in the field of integrated Lean Six Sigma and Industry 4.0 research (Tortorella et al. 2019; Rossini et al. 2019; Buer et al. 2018; Kolberg et al. 2017; Wang et al., 2016; Jayram, 2016). Majority of the existing literature on integrated approach is either conceptual or uses survey to explain relationship between Lean and Industry 4.0 (e.g. Tortorella et al. 2019; Buer et al. 2018). Using grounded theory, we interviewed ten managers and we observed how a manufacturing company has managed to take an integrated approach for achieving operational excellence. The pattern of integration from the two stages of research demonstrate several issues and some novelties, also highlighting challenges and pitfalls which can be encountered during the integration process.

First of all, from grounded theory we found a story line which can be interpreted as the pattern for succeeding in implementing the integrated operational excellence. Our research moves beyond 'what' to explain 'how' and 'why' the actual integration between Lean Six Sigma and Industry 4.0 is possible and the rationale for LSS as a precursor to effective Industry

4.0 implementation (Tortorella et al. 2019; Buer et al. 2018). Manufacturing companies may start implementing Industry 4.0 technologies after streamlining and reducing variation in business processes through LSS. Only at that point Industry 4.0 can really boost performance, otherwise companies could end up automating the waste, even introducing more costs. This leads to the following proposition that could be tested in future research

Proposition 1: Lean Six Sigma can provide foundation for maximising the impact of Industry 4.0 technologies on operational performance

The above proposition is in no way a prescriptive guideline for organisations to follow. Organisations can directly implement Industry 4.0 solutions without first implementing LSS. But this may lead to sub-optimal solutions, even though Industry 4.0 technologies have capabilities to minimise Lean wastes through automation. Our proposition aligns with the famous statement from Bill Gates:

> *"The first rule of any technology used in a business is that automation applied to an efficient operation will magnify the efficiency. The second is that automation applied to an inefficient operation will magnify the inefficiency."*

In order to integrate Industry 4.0 and LSS, manufacturing companies should then analyse processes by means of reinvented mapping tools such as a smart VSM and other customised digital maps. The most operative part of the integration is based on the results of this mapping activity that may facilitate in achieving horizontal integration as evidenced from other studies as well (Buer et al. 2018; Kamble et al. 2019; Frank et al. 2019). In the horizontal integration, apart from a technological development of all processes using the cyber technologies, the real ultimate goal of the integration is to reach a complete Autonomous Process Synchronisation (APS) through the use of e-Kanban pull system to achieve uninterrupted flow with a low level of inventory (MacKerron et al. 2014). This conclusion leads to proposition 2 that provides avenues for future research.

Proposition 2: Horizontal integration can be augmented by integrated application of Industry 4.0 and Lean Six Sigma approach

The vertical and end-to-end integration brings many challenges and pitfalls for the company connected to the reengineering of the ERP modules like other authors showed (Moeuf et al. 2019). MES/SCADA, MRP, PDM/PLM and CRM software requires more customisation; for instance, MES/SCADA module has to be integrated with sensors installed within machineries as well as production and logistics processes. Even office activities could be integrated with these ERP modules. The MRP can schedule production processes using data and information gathered by the MES/SCADA for achieving precise and real time finite capacity. For an end-to-end integration process, manufacturing companies must strive to share and integrate their databases and modules with customers and suppliers. The sharing of information across the supply chain is not new for manufacturing organisations and is build on the foundation of trust and long-term relationships with buyers and suppliers. This leads to the last proposition of our study.

Proposition 3: Vertical and end-to-end integration can be augmented by integrated application of Industry 4.0 and Lean Six Sigma approach

Contrary to findings from Bibby and Dehe (2018) who reported majority of the companies were strong only in the application of certain Industry 4.0 technologies such as 3DP and Big data, our findings from ten cases demonstrate usage of range of technologies including ‘base technologies’ such as cloud, IoT, Big data, and analytics and ‘front end technologies’ including smart products, smart working, smart manufacturing, and smart supply chain (Frank et al.

2019). In addition, our paper goes beyond Industry 4.0 technology application to explain how Lean Six Sigma tools can be integrated with Industry 4.0 technologies.

Other minor challenges for these manufacturing companies regarding an integration of DFSS with 3D printing and smart sensors embedded in the final product as well as the possibility of having a new class of SPC with autonomous feedback to the machine. All the data gathered from production processes and offices needs the developments of new analytics at all levels, from predictive maintenance and business intelligence systems. The findings also have implications for Green Belts and Black Belts, who need to train themselves on using big data analytics and machine learning for effective integration of Industry 4.0 and LSS tools and techniques.

Furthermore, the proposed integration challenges the manufacturing companies in reaching an ideal real time performance measurement system where all the KPIs and the cost of products are automatically measured. However, some interviewed managers believe that there are many difficulties in doing this, mostly linked with an accounting structure based on cost and time standard and other organisational ERP issues. It also requires significant inputs and support from third-party software providers to make changes in their offerings and customising it to the needs of the clients. The issue of inter-operability needs to be resolved for seamless end-to-end integration.

Lastly, from the story line of the grounded theory emerges what the grand strategy of this new LSS and Industry 4.0 Operational Excellence model really is. Basically, the manufacturing companies in this sample are aiming at a lead time reduction and productivity growth.

6.1 Practical implications

The results of this research have many implications for practitioners. First, the pattern for achieving integration could be used by consultants and managers as a guideline for the implementation. In this paper, we explicitly give examples of why streamlining the processes and reducing variation can aid and facilitate effective implementation of Industry 4.0 technologies for achieving horizontal, vertical, and end to end integration of the manufacturing operations and its supply chain. This finding is of direct relevance to Lean Six Sigma and Industry 4.0 managers in organisations on how to maximise the benefits from an integrated approach. In our qualitative study, we provide several examples of integration including automatic cost and accounting system (replacing activity based costing), use of smart sensors and IoT to embed some of the Lean tools application such as 5S, Hejunka, Poka Yoke, and TPM, use of COBOTS, AMR/AGV, VR, to achieve standardisation, error minimisation, and automatizing logistics and other operation activities. Practitioners may adopt or adapt the proposed smart VSM and digital charts, as well as ponder how to embed each LSS tool with specific industry 4.0 technologies, from the simple 5S to the more sophisticated SPC and TPM systems.

The issues of vertical and end-to-end integration also lead towards an IT reengineering process. The results of this study encourage practitioners for a better integration between MES/SCADA, MRP and other MRP modules. Managers need to analyse and design how to interface their ERP modules with customers and suppliers software. Lastly, practitioners have to be aware that the integrated model cannot exclude the development of analytics for business intelligence and the mapping of the KPIs data needed. Industry 4.0 technologies can collect big data from processes and it is important to design new methods for identifying what really matters in terms of data collection.

6.2 Agenda for further research

Limitations of this research open avenues for further research on the topic. The suggested integration pattern is based on limited sample of Italian manufacturing companies, not directly connected with end users. Researchers should test this model with other manufacturing companies in B2B and B2C environment through case studies and quantitative analysis. We want to test three propositions, at least in the manufacturing sector, and compare differences in findings in other sectors or in other geographical areas.

The issue of when to implement Industry 4.0 in an LSS context it is also worthwhile of further investigation. Companies do not want to automatize the waste like it has happened in the past, but now we have a new generation of smart and collaborative automation, including machine learning, and the approach is surely different. Connected with the new technology, the skills which have to be acquired by Lean practitioners and Six Sigma Green – Black Belt may also require further research and adaptation.

From a practical and theoretical point of view, it could be interesting to understand how to reach the ground-breaking 'Autonomous Process Synchronisation' as an evolution of the Kanban pull system. Also, more investigation is required on achieving autonomous SPC for quality control and, in general, how these smart technologies can reduce waste within cells, lines and machines. The possibility of introducing an autonomous accounting and performance measurement system is another innovative challenge for companies. There are still many difficulties to overcome, e.g. starting first with technological solutions without first addressing process and people issue, can result in more chaos. Lean automation can now be realised by effective integration with Industry 4.0 technologies. Lastly, the grand strategy of lead time reduction and productivity improvement in the proposed operational excellence may only be relevant to the selected cases, especially those operating in the B2B environment. Similar to early days of LSS implementation, where the focus was efficiency improvement and cost reduction, the proposed operational excellence model may see a shift in their grand strategy focus from lead time reduction to achieving highest level of customer service and satisfaction, especially in the B2C environment.

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