Designing Lean Value Streams in the Fourth Industrial Revolution Era: proposition of technology-integrated guidelines

Guilherme Luz Tortorella[*] (gtortorella@bol.com.br)

Universidade Federal de Santa Catarina, Florianópolis – Brazil

The University of Melbourne, Melbourne, Australia

Ninad Pradhan (ninad.pradhan@gmail.com)

University of Tennessee, Knoxville – United States of America

Enrique Macias de Anda (emaciasd@utk.edu)

University of Tennessee, Knoxville – United States of America

Samuel Trevino Martinez (strevin1@vols.utk.edu)

University of Tennessee, Knoxville – United States of America

Rupy Sawhney (sawhney@utk.edu)

University of Tennessee, Knoxville – United States of America

Maneesh Kumar (kumarm8@cardiff.ac.uk)

Cardiff University, Cardiff – United Kingdom

[*] ***Corresponding author***

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Abstract

Despite the envisioned interrelations, the way Industry 4.0 (I4.0) technologies can influence the design and implementation of lean value streams is still unknown and little empirical evidence is found in the literature. This article aims at proposing guidelines integrated with I4.0 technologies for designing lean value streams. We gathered experts' opinions regarding the relationship between guidelines for designing a lean value stream and I4.0 technologies. The identification of the most important relationships provided arguments for the proposition of enhanced guidelines for designing lean value streams within the Fourth Industrial Revolution context. The integration of I4.0 technologies into the guidelines for designing a lean value stream raises a distinct approach that benefits from the simplicity and efficiency of Lean Production with ease and agility of the technologies typical of the Fourth Industrial Revolution. Such technology-integrated guidelines may allow overcoming existing barriers while lead companies to superior performance results.

Keywords: Value stream mapping, Fourth industrial revolution, Industry 4.0, Lean production.

1. Introduction

Lean Production (LP) is widely acknowledged as a systematic and visual approach to reduce waste and improve flow through extensive employee involvement and continuous improvement (Womack et al., 1990; Womack, 2011). The evidenced benefits from the adoption of LP practices and principles, originally conceived based upon Toyota Production System, have resulted in widespread application of LP practices in manufacturing industry (Pakdil and

Leonard, 2017; Ciano et al., 2019) and was gradually adapted for implementation in service and public sectors organizations (Bhamu and Sangwan, 2014; Leite and Vieira, 2015; Hadid et al., 2016; Bortolotti et al., 2018). One of the key reasons for Lean popularity and implementation over other approaches such as Six Sigma is the quick wins realized from the application of its visual tools for problem solving (Dora et al., 2016). One of the most commonly applied and powerful LP practices that enables visualization and understanding of flow of information and materials across the value chain is Value Stream Mapping (VSM) (Lacerda et al., 2016; Rother and Shook, 2003). Despite its pervasiveness, generalizable implementation steps have not yet emerged (Marodin and Saurin, 2013).

A value stream is the sum of all activities (value-added or not) needed to take value from its beginning (i.e. customer order point) through to the customer receiving a product or consuming a service. In this sense, VSM is a LP practice for analyzing the current state of a value stream and designing a future (desired) state for the series of activities, hence indicating systemic improvement opportunities (Rother and Shook, 2003). Furthermore, VSM consolidates the flows of information and material, showing how they interact with each other throughout the value stream (Lacerda et al., 2016). Since VSM is usually developed by a multidisciplinary team that involves members from different departments, its application provides organizational guidance to systematize continuous improvement initiatives (Womack, 2009; Womack and Jones, 2011; Bai et al., 2019) and at the same time promote systems thinking and cross-functional collaboration required for problems that cuts across functional boundaries (Chen et al., 2010; Pavnaskar et al., 2003). Although usually associated with manufacturing processes, the practical relevance of VSM has been evidenced in several kinds of value stream, such as product development (Mascitelli, 2011), healthcare (Tortorella et al., 2017a), software development (Plenert, 2011), ergonomics (Jarebrant et al., 2016), administrative processes (Tapping and Shuker, 2003), sustainability (Faulkner and Badurdeen, 2014), wine sector

(Jiménez et al., 2012), among others. Furthermore, VSM's versatility is also represented by its extensive integration with other methodological approaches, such as discrete events simulation (Helleno et al., 2015; Goienetxea Uriarte et al., 2020), six-sigma (Salah et al., 2010), Monte Carlo simulation (Souza et al., 2018), analytic hierarchy process (Tortorella et al., 2018), fuzzy quality function deployment (Mohanraj et al., 2015) and stochastic tools (Braglia et al., 2009).

Given the focus of VSM on visualization of wastes in the value chain and promoting collaboration and teamwork across the value chain to realize less wasteful process (Abisourour et al., 2019), it has direct and synergistic relationship with fourth industrial revolution which also emphasizes on the integration of novel information and communication technologies (ICT) (e.g. Internet of Things, big data, and cloud computing) into manufacturing processes, products and services for better interconnectivity, real-time data collection/analysis that favors more assertive managerial decisions (Zezulka et al., 2016; Yang et al., 2017; Rosin et al., 2019). Such integration has also been referred to as Industry 4.0 (I4.0), and it has been claimed that these ICT may lead manufacturers to a superior performance level (Züehlke, 2010; Liao et al., 2017). However, there is limited evidence in literature to explicate how I4.0 technologies can be incorporated into existing management systems including LP. Despite the envisioned interrelations (e.g. Meudt et al., 2017), the way I4.0 technologies can influence the design and implementation of lean value streams is still unknown and little empirical evidence is found in the literature (Buer et al., 2018).

The academic discourse proposes integration of I4.0 technologies with LP practices but fails to go beyond 'what' to explain how the integration is feasible in reality (Tortorella et al., 2019; Buer et al., 2018). In fact, Kolberg et al. (2017) highlight that, because most of the existing initiatives are proprietary solutions tailored to specific needs, no common framework for its implementation has yet been proposed. The following quote from Buer et al (2018) summarizes the current state of research on LP and I4.0 integration: *"The immaturity of this research area* *is a natural explanation for why no implementation framework for an Industry 4.0 and lean manufacturing integration has been published in the literature"* (Buer et al., 2018, Pg.2935).

Addressing the aforementioned limitation, this research attempts to investigate how one of the most commonly cited LP practices, VSM, can be integrated with I4.0 technologies to further influence the design and implementation of lean value streams in the era of fourth industrial revolution. In a recent publication from Frank et al (2019), researchers highlighted different stages of I4.0 maturity based on application of base technologies and front-end technologies supporting transition from vertical integration (start of I4.0 journey) to automation, virtualization, and flexibilization (achieving the highest level of maturity). The base technologies such as cloud and IoT, and front-end technologies linked to smart working and smart products such as collaborative robots, augmented and virtual reality may further impact and facilitate the design of less wasteful future state value stream. Taking cue from Frank et al (2019) study, our paper also attempts to map some of the base and front-end technologies suggested by Frank et al (2019) to enhance lean value stream design.

Therefore, this article aims at proposing guidelines integrated with I4.0 technologies for designing lean value streams. For that, based upon relevant literature and experts' opinion, we verify the relationship of the main I4.0 technologies with each guideline for a lean value stream design, discussing how they may impact the existing approach. The contribution of this research is two-fold. First, from a theoretical perspective, it raises arguments on the future of value stream design and management within the Fourth Industrial Revolution era. Literature on this subject is scarce, and the few studies shallowly approach it. Second, in practical terms, it advises organizations under LP implementation about the potential changes that lean value stream design might face as I4.0 technologies are introduced. Hence, our proposal entails a shift on traditional guidelines for lean value stream design, providing an approach aligned with the ICT that are expected to revolutionize operations management. This research expands upon the preliminary study from Tortorella and Martinez (2019), which has identified the relationships between guidelines for value stream design and I4.0 but has fallen short on proposing how such relationships could actually influence the establishment of technology-integrated lean value stream guidelines. Our work adds to it since we seek to discuss how I4.0 technologies can facilitate or even change the approach for a lean value stream design in the Fourth Industrial Revolution era.

2. Background

2.1. Design of lean value streams

Regardless the context of application, VSM development usually encompasses four main steps: (*i*) identify products/services families, (*ii*) draw current state map, (*iii*) design future (lean) state value stream, and (*iv*) consolidate a plan and implement improvement opportunities. Step (*i*), identify products/services families, aims in determining families of products/services whose items present similar processing needs, and simplifying subsequent mapping activities. Generally, a product-process matrix (in which processes are presented in the columns and products are listed in the rows) is established allowing a simple visualization of similarities (Duggan, 2012; Henrique et al., 2016) or incorporating more complex mathematical models to identify them (De Lit et al., 2000; Eppinger and Browning, 2012). A minimum threshold of 80% of processes similarity is suggested to group product/services (Rother and Shook, 2003). Then, mapping activities are usually performed first on the value stream of the products/services families with greatest impact on total demand or revenue (Tortorella et al., 2018).

Step (*ii*), often performed by a multidisciplinary team, comprises drawing the current state map for the selected product/service family. Literature (Zahraee et al., 2014; Morlock and Meier, 2015; Henrique et al., 2016; Tortorella et al., 2017a) suggests that different methods can be simultaneously applied for addressing this activity, such as oriented visits (*gemba* walks), participatory observation, semi-structured interviews, system-data collection and focusgroups with the improvement team. Based on these methods, information such cycle times, inventory levels, machine downtimes, etc., is collected and inputted into the map. Moreover, current state value streams are usually recommended to be drawn from downstream to upstream processes, which is supposed to facilitate the comprehension of value from customers' (internal or external) perspective. This fact enables waste identification on both material and information flows, indicating future improvement opportunities to be addressed in the lean design (Patel et al., 2015). It is noteworthy that these opportunities may be prioritized in terms of their impact on the value stream lead time (Rohani and Zahraee, 2015).

Step (*iii*) concerns the design of the future state of the selected value stream. This future state is supposed to be an improved version (lean) of the current state map, since it aims at addressing the opportunities previously identified in a timely manner (Womack and Jones, 2011). The same team-based approach used to draw the current state map is recommended for this step. According to Hines and Rich (1997) and Rother and Shook (2003), a lean value stream is focused on increasing system's flexibility to allow rapid adaptation to changes in demand, waste elimination, minimizing inventory levels and enhancing efficiency of materials and information flows. Hence, various guidelines are found in the literature to properly design lean value streams (see Table 1). Although a few guidelines might slightly differ either in content or sequence among authors, the main concepts are kept in order to ensure a structured flow design that embraces the five main LP principles (Womack et al., 1990); i.e. specify value, identify the value stream, make value flow, let customers pull and pursue perfection.

Finally, step (*iv*) seeks to consolidate all necessary improvement initiatives and organize them into a strategic interdepartmental plan that is supposed to be followed-up on a regular basis (Edtmayr et al., 2016). Therefore, it is recommended the establishment of specific working groups that, according to members' backgrounds and roles within the organization, can address improvements with similar characteristics or inter-related to each other. However, the existence of a value stream leader or coordinator is highly suggested to ensure the convergence of all initiatives and facilitate overcoming eventual barriers for change implementation (Bicheno and Holweg, 2000; Azizi, 2015). Additionally, such leader would also facilitate the establishment of a value stream and process-oriented mindset, preventing from a narrow practice-oriented approach that usually undermines a system-wide LP implementation (Hines et al., 2004). Keyte and Locher (2016) also suggest that improvements implementation plan should be linked to organizational objectives, aligning it to strategic outcomes desired by senior management, which tends to increase their support and buy-in.

Table 1 – Proposed guidelines for designing lean value streams

It is noteworthy that previous research on VSM (e.g. Tortorella et al., 2017a; Tyagi et al., 2015) often collected data in a deterministic approach. In this sense, the effect of many uncertainty sources (e.g. machine downtime, setup, process time, labor productivity) that add variability to value stream are not captured. VSM's existing limitations can lead to marginal improvements that do not significantly affect operational performance (Standridge and Marvel, 2006; Bertolini et al., 2017). One of the reasons for this poor analysis refers to the little integration with novel ICT that could facilitate VSM development providing more trustful improvement directions (Souza et al., 2018).

2.2. Industry 4.0

Coined in the Hannover Fair in 2011, Industry 4.0 has been referred to as the new paradigm in operation management (Hermann et al., 2016). In this ICT driven industrial context, prominent technological frameworks for manufacturing processes, products and services have been developed, entailing an array of solutions to the growing customized needs of digitalization (Kagermann et al., 2013). Such novel paradigm and its potential benefits envisioned have motivated a growing demand for research particularly related to its challenges, design solutions, implementation and management systems (Xu et al., 2018). Among the mains advantages of I4.0, Fatorachian and Kazemi (2018) highlight an enhanced information sharing and decision-making process, improved integration, collaboration and resource productivity, and increased ability to meet individual customer demands.

However, managers and practitioners still struggle to grasp I4.0 concepts. One of the reasons for such difficulty may be derived from the low readiness level of ICT infrastructures, undermining the adoption and understanding of I4.0 (Liao et al. 2017). Moreover, an extensive incorporation of I4.0 technologies is also likely to influence other key aspects of an organizational structure, such as customer/supplier relationship management (Schumacher et al., 2016) and human resources development (Dworschak and Zaiser, 2014). In this sense, while the adoption of cutting-edge technologies can facilitate the achievement of a significant operational performance enhancement, at the same time it can also entail unknown structural shifts in organizations. Therefore, I4.0 inherent features and impacts still deserve further investigation in order to provide a clearer comprehension for both managers and academicians (Yin et al., 2018).

More specifically, ICT encompassed in I4.0 may slightly vary according to authors. In an attempt to consolidate the most cited I4.0 technologies in the recent literature, Table 2 lists eleven ICT mentioned and studied in ten scientific research. From these, t_{10} (big data) and t_4 (augmented reality) seem to be the most commonly mentioned technologies, since they are cited by nine different authors. Big data concept is usually related to large quantities of data for applications in predictive analytics, data mining, statistical analysis and others, increasing assertiveness of managerial decision-making processes (Lasi et al., 2014; Hermann et al., 2016). Augmented reality is referred as an interactive experience of a real-world environment in which objects are augmented through computer-generated perceptual information, facilitating the identification and anticipation to potential manufacturing issues (Jackson et al., 2011; Liao et al., 2017). In turn, t_8 (integrated engineering systems) is the least cited in the examined references, appearing in four of them. This technology is relevant for both product development and manufacturing processes perspectives, and its lower emphasis in the literature may denote its incipient understanding and application.

Table 2 – Consolidation of the main I4.0 technologies

3. Proposed method

The proposed method comprises three main steps: (*i*) experts' selection, (*ii*) interviews, (*iii*) consolidation and analysis of relationships. These steps are subsequently detailed.

For experts' selection, step (*i*), a few criteria were determined in terms of knowledge and experience level so that the gathered information was legitim and minimally reliable. First, a minimum professional experience of ten years was required, as also suggested by Baker et al. (2006) and for utilizing experts' opinion for grasping new concepts. Second, experts should have deep theoretical and practical knowledge of LP practices, as indicated by Mostafa et al. (2013), with special emphasis on VSM. Furthermore, although I4.0 was formally acknowledged in 2011, most of its technologies have been developed before that. Hence, a third criterion consisted in a minimum familiarity level with I4.0 technologies, either by means of practice or theory, as recommended by Tortorella and Fettermann (2018). Finally, to allow a diversified composition of perspectives, we looked for experts whose backgrounds were from academia, industry or both, which is a common practice in similar studies (e.g. Kumar et al., 2013; Mittal et al., 2016).

Initially, we identified twenty-two experts that met the aforementioned criteria and could be easily accessed due to their location or for already being partners in the research group's network. An email was first sent to them in order to explain the research purposes and verify their willingness to participate. Fifteen of them positively responded the email, although only ten indicated their agenda availability. In the end, after matching the profile with our selection criteria, only six experts were interviewed indicating a final response rate of 27.3%. The characteristics of these experts are presented in Table 3.

Table 3 – Experts' experience, background and opinion weight

For step (*ii*), each expert was individually interviewed in meetings whose duration varied from 45 to 80 minutes. Moreover, to mitigate researcher bias we verified issues of internal and external validity together with reliability and objectivity of information (Yin, 1994). Thus, two researchers (one associate professor and one Ph.D. candidate) simultaneously participated in the interviews to enhance the ability of handling data and confidence in research findings (Dubé and Paré, 2003). Although the involved experts supposedly had a significant level of knowledge on the topics, we provided a brief explanation of I4.0 technologies and lean value stream guidelines to ensure a uniform understanding. Such procedure, which prevents from misinterpretations that could lead to erroneous or biased responses (Kothari, 2004), has already been applied in previous LP research (e.g. Tortorella et al., 2017b).

Regarding questions formulation, although the literature on VSM is prolific, we adopted the eight lean value stream guidelines proposed by Rother and Shook (2003) and denoted here by g_i (i = 1,…, 8). Evidence of their utilization is vast (e.g. Abdulmalek and Rajgopal, 2007; Sa'udah et al., 2015) and they reasonably provide advice on how to design future state maps (Tortorella et al., 2018). In terms of I4.0, the eleven technologies t_j (j = 1,…,11) listed in Table 2 were applied due to their remarkable utilization and citation. Therefore, during interviews experts were asked the following: "what is the intensity of the relationship r_{ij} between the development of lean value stream guideline g_i and the I4.0 technology t_j?". Responses were given on a continuous scale of nine points, where 0 indicated 'no relationship' and 9 indicated 'maximum intensity' of relationship between g_i and t_j.

Finally, step (*iii*) consisted in consolidating and analyzing results obtained from the interviews with experts. Despite their extensive experience, due to differences in experts' backgrounds there might be some variability among their responses for r_{ij}. Hence, to consider such variability, the consolidated values for the relationship between the eight guidelines for lean value stream design and the eleven I4.0 technologies were weighted by the relative experts' experience, as shown in Equation (1). This approach of weighting experts' opinion according to their experience is quite common in the literature (e.g. Tortorella et al., 2017b; 2017c).

$$r_{ij} = \sum_{k=1}^{6} r_{ijk} \times w_k, \qquad k = 1, \ldots 6 \qquad (1)$$

where

w_k = expert's opinion weight given in Table 3.

Then, values of r_{ij} were inputted in the intersections of matrix **M**, whose rows contain the eight guidelines g_i for designing a lean value stream and columns present the eleven I4.0 technologies t_j. This matrix represents the overall scores for the relationship intensities, as illustrated in Figure 1. Furthermore, the sum of the scores of each row and column of **M** denoted the overall potential for integration of each guideline and technology, respectively. In other words, higher total values for a determined g_i represented a guideline that can be more sensitive to the introduction of I4.0 technologies. In turn, higher total values for t_j represent the overall pervasiveness that such technology may have when designing lean value streams.

Guidelines for lean value stream design	I4.0 technologies											
	t_1	t_2	t_3	t_4	t_5	t_6	t_7	t_8	t_9	t_{10}	t_{11}	Σg_i
g_1-Define *takt* time												
g_2-Select finish goods strategy												
g_3-Implement continuous flow												
g_4-Establish first-in, first-out						r_{ij}						
g_5-Determine supermarket						z_{ij}						
g_6-Create one-point scheduling												
g_7-Define interval												
g_8-Determine pitch												
Σt_j												

Figure 1 – Illustration of matrix **M**

To determine the most important relationships between the guidelines for a lean value stream design and the I4.0 technologies, a differentiation index z_{ij} was proposed. This index represents the number of standard deviations of each individual value of r_{ij} in relation to the average values of the corresponding g_i. These standardized scores for r_{ij} within each g_i are usually applied in maturity analysis (e.g. Hagg, 2003; Tortorella and Fogliatto, 2014) since they remove scale effects. Positive values of z_{ij} larger than 1.0 were used to indicate the most important relationships and, hence, prioritized for the proposed guidelines lean value stream design integrated with I4.0 technologies.

4. Results

Table 4 displays the consolidated results for **M** obtained from the six interviews. Regarding the I4.0 technologies, the one with the highest pervasiveness level across all lean value stream guidelines (total score = 55.0) appeared to be t_{10} (big data). As a value stream is composed by several steps and activities in both material and information flows, the simultaneous generation of large quantities of data is potentially huge. Traditional lean value stream guidelines may present difficulty or even neglect handling such data, impairing more assertive managerial decisions. Therefore, according to experts' opinion, the integration of big data into Rother and Shook (2003)'s guidelines can be highly beneficial for a lean value stream design. More specifically, this technology presented a distinguished relationship (differentiation index > 1.0) with five guidelines; they are: g_1 (define *takt* time), g_2 (select finish goods strategy), g_5 (determine supermarket), g_6 (create one-point scheduling) and g_7 (define interval).

These results converge in some way to indications from Meudt et al. (2017), which suggest that a main contribution of integrating I4.0 technologies into VSM would be related to recording, handling, processing, analyzing and optimizing information processes and data gathering. This contribution appears to be especially relevant when considering management of customers' demand (guidelines g_1 and g_2) and production planning and scheduling (guidelines g_6 and g_7). Furthermore, it is worth to mention that a few technologies, such as t_4 (augmented reality), t_5 (cloud computing system) and t_8 (integrated engineering systems), did not present a relatively high relationship (> 1.0) with any of the eight guidelines. Nevertheless, these technologies may also influence the design of lean value streams, although not at the same extent as the remaining ones.

Table 4 – Relationships between guidelines for lean value stream design and I4.0 technologies

In terms of lean value stream design, the guideline with the highest potential for integration with I4.0 technologies was g_3 (implement continuous flow), with a total score of 68.2 and important relationships with t_1 (collaborative robots) and t_9 (additive manufacturing, rapid prototyping or 3D printing). ‘Continuous flow’ is also known as one-piece flow, single-piece flow, or make-one, move-one (Womack and Jones, 2011). It refers to producing and moving one item at a time (or a small and consistent batch of items) through a series of processing steps as continuously as possible, with each step making just what is requested by the next step (Rother and Shook, 2003). It can be achieved through many ways, ranging from moving assembly lines to manual cells. As it entails a minimum inventory level between workstations, material and information flows become much more sensitive to any variation or disruption in their processes (Braglia et al., 2009). Since the adoption of ‘collaborative robots’ and ‘additive manufacturing’ might provide a more flexible and agile productive flow (Brettel et al., 2014; Karre et al., 2017), it is quite reasonable to expect that these I4.0 technologies can positively favor the implementation of continuous flow.

It is noteworthy that although guidelines g_4, g_5 and g_7 had lower total scores than g_3, each one presented three important relationships with I4.0 technologies, instead of the only two ones for g_3. These findings indicate the overall potential of incorporating certain I4.0 technologies into a lean value stream design, which has been somewhat envisioned by Tamás et al. (2016) and Mrugalska and Wyrwicka (2017). In fact, our results show that all lean value stream guidelines proposed by Rother and Shook (2003) can be influenced by at least one I4.0 technology. However, the practical changes implied by such relationships are not yet clear and deserve further attention from researchers and practitioners. To better discuss how these relationships may change the design of lean value streams, we propose in the next section a revised set of technology-integrated lean value stream guidelines.

5. Technology-integrated lean value stream guidelines

Following the analysis of results and aligning with original but isolated indications previously presented in the literature (e.g. Tamás et al., 2016; Meudt et al., 2017; Wollschlaeger et al., 2017), we propose a revised version of Rother and Shook (2003)'s lean value stream guidelines. This proposition seeks to discuss how I4.0 technologies can facilitate or even change the approach for a lean value stream design in the Fourth Revolution era. Analogously to Rother and Shook (2003), we propose eight technology-integrated lean value stream guidelines (denoted by tg_i) as displayed in Table 5. Some of these technology-integrated guidelines were renamed to consider the most important I4.0 technologies (differentiation index > 1.0) found from experts' opinion.

The first guideline, named as *tg_1-Real-time takt definition*, mainly integrates two I4.0 technologies (t_9 and t_{10}). Takt time is a parameter that represents customers demand pace and is usually established for a fixed slot of time (horizon of demand). This parameter allows the basic verification of productive bottlenecks and capacity issues linked to material flow (Childerhouse and Towill, 2002). However, customers' demand actually changes in a much higher frequency than traditional planning methods can manage. In this sense, Big Data adoption may enable shorter loops of analysis (Xu et al., 2018), identifying demand shifts that deserve significant changes in capacity planning. When capacity changes are required to meet *takt*, technologies such as 'Additive manufacturing or 3D printing' could rapidly provide additional increments of capacity without significant losses in production mix flexibility (Lasi et al., 2014). However, the cost and quality implications of adopting such technologies for demand management needs further verification.

The guideline *tg_2-Constant adaptation of finish goods strategy* refers to continuously shifting finished goods strategy for each product family based upon the constant monitoring of changes in customers' demand profile. Different finished goods strategies, such as 'make-to-order' and ‘make-to-replenish’, can be chosen according to specific characteristics on customers’ demand (Duggan, 2012). Following the concept of the previous guideline, if ‘Big Data’ is integrated into existing customer relationship management techniques and production control, significant variations in both customers’ demand and processes lead time are more easily identified (Liao et al., 2017). Hence, managers may proactively change their finished goods strategies or apply the concept of ‘decoupling point’ to delay the packaging of finished goods closed to the customer delivery point (Olhager, 2010). Rapid adjustment in inventory levels with capacity increments based upon flexible ‘Additive Manufacturing’ technologies may also be feasible option.

For *tg*$_3$*-Implement highly flexible continuous flow*, I4.0 technologies such as ‘Collaborative Robots’ and ‘Additive Manufacturing’ could be useful in ensuring a proper workload balance among workstations. These technologies could not only provide a more stable production pace, but also help to recover production pace whenever one workstation misses its rhythm. As mentioned before, one of the main difficulties in establishing continuous flow is the high stability required to maintain it (Womack, 2011; Jiménez et al., 2012) and the eventual re-balances needed to meet variations in demand (Braglia et al., 2009). In this sense, the integration of these technologies might favor the achievement of more flexible and stable productive flows, corroborating to smaller and continuous batch sizes.

Besides the benefits of incorporating ‘Collaborative robots’ and ‘Additive Manufacturing’ already discussed in the *tg*$_3$, the guideline *tg*$_4$*-Establish monitorable and flexible first-in, first-out* assumes the adoption of ‘RFID-tag at working units’. RFID-tags utilization on shop floor mainly facilitate identifying and tracking of materials/products (Thoben et al., 2017). This fact benefits inventory accuracy and management, which is a common issue in a value stream management (Moeuf et al., 2018). First-in, first-out (FIFO) lanes aim at organizing material flow establishing a visual and logical sequence of materials that also underpins a simpler information flow between workstations (Womack, 2009). Thus, technological devices that add a more robust material and inventory control might converge to the objectives of establishing FIFO lanes, while allow more flexible adjustments in FIFO lanes' dimension.

The determination of supermarkets to connect processes is justified when variability is a main concern in the value stream (Rother and Shook, 2003). Such variability may be originated due to several reasons (e.g. machine downtime, changeover, absenteeism, etc.) that interchangeably occur with different intensities. Therefore, the inherent stochastic nature of a value stream undermines the establishment of optimal inventory policies for supermarkets (Souza et al., 2018). This transient characteristic can be better addressed if technologies such as 'RFID-tags', 'Machines with digital interfaces and sensors' and 'Big Data' are incorporated into the value stream, allowing the re-dimensioning of supermarket policies and catalyzing inventory replenishment through digital interface with workstations. This integration is represented by the fifth guideline *tg_5-Determine transient supermarket*.

Conversely to what is proposed by Rother and Shook (2003), the guideline *tg_6-Create multiple-point scheduling* suggests the establishment of multiple scheduling points. Based upon the benefits of 'Big Data', all workstations in a productive flow can be considered a scheduling point to which production orders can be easily sent and updated. Furthermore, one of the reasons for creating a one-point scheduling is to avoid mistakes and misinterpretations from leaders whenever a production rescheduling is needed (Klibi et al., 2010). Therefore, the introduction of Big Data into this guideline facilitates information gathering and sharing (Veza et al., 2015) allowing a more reliable scheduling of multiple workstations, which may be specifically beneficial for material flows comprised by job shop arrangements (Bertolini et al., 2017).

The guideline *tg_7-Constantly define interval* integrates technologies such as 'Artificial intelligence (AI) and machine learning algorithms', 'Remote production process management' and ‘Big Data’ into the traditional production levelling, also known as *heijunka* (Womack and Jones, 2011). Levelling production reduces unevenness and, hence, wastes in the value stream, since it enables to produce intermediate products at a constant rate so that further processing may also be carried out at a constant and predictable rate. In contexts with high variability (either originated from demand or internal processes) are present, the interval definition must be flexible and easily followed. Thus, while AI could support fast adaptations in interval calculations (Mičieta et al., 2016), the combination between Big Data and Remote production process management would provide instant updates regarding fluctuations and variations that could jeopardize interval achievement (Duggan, 2012). This integration would enhance interval feasibility since it considers real-time variations for its determination.

Finally, the last technology-integrated lean value stream guideline refers to *tg_8-Determine and remotely manage pitch*. Pitch is management timeframe that helps to verify whether the value stream is flowing according to demand rhythm (Zahraee et al., 2014). Furthermore, it is usually recommended that pitch verification should be visually available, binary (either on customers’ demand pace or not) and preferably physical, i.e. could be easily checked based upon the delivery of a product unit or packaging (Tortorella et al., 2017a). However, monitoring pitch requires discipline from leaders and supervisors (Childerhouse and Towill, 2002), who are usually embedded in several daily routine tasks (Jiménez et al., 2012). In this sense, adopting 'Remote production process management' technologies could facilitate pitch control, enabling the reduction of eventual time-consuming activities from leadership and allowing others (besides frontline leaders) to verify the current status of the value stream.

Table 5 – Proposition of technology-integrated lean value stream guidelines (tg_i)

6. Conclusions

This study proposed guidelines for designing lean value streams that are integrated with I4.0 technologies. For that, we used two main sources for proposing such integration: literature evidence and experts' opinion. The contribution of this research is relevant from both practical and theoretical perspectives.

First, in theoretical terms, our study raises arguments on the future of lean value stream design since it envisions the incorporation of novel I4.0 technologies into each of the traditional guidelines from Rother and Shook (2003). Literature evidence on this subject is still scarce (Buer et al., 2018; Tortorella et al., 2019), and the existing studies lack further conceptual details. Thus, this research not only specifies how I4.0 technologies could enhance and benefit a lean value stream design, but is also suggests how these existing and widely accepted guidelines may change so they become more robust and aligned with the Fourth Industrial Revolution era. It was interesting to observe how some of the front-end technologies for smart working and smart products, suggested by Frank et al (2019), such as collaborative robots and virtual reality will influence and benefit the lean value stream design. Majority of the steps of lean value stream design can be achieved through automation and virtualization as a result of I4.0 technologies implementation.

From a practical perspective, the proposed guidelines advise organizations under LP implementation about the potential changes that lean value stream design might face as I4.0 technologies are introduced. Hence, our proposal entails a shift on traditional guidelines for lean value stream design, emphasizing how novel ICT could support a distinguished and technology-integrated lean value stream management that benefits from the simplicity and efficiency of LP with the ease and agility of the technologies typical of the Fourth Industrial Revolution. Such technology-integrated guidelines may allow overcoming existing barriers while lead companies to superior performance results.

Certain limitations of this study are worth to be mentioned. Although the proposed guidelines have emerged from experts' opinion, more extensive empirical validation is still required. In fact, the development of case studies and field applications based upon the proposed guidelines for a technology-integrated lean value stream design would add evidence that could potentially entail further changes and propositions. However, as the adoption of I4.0 technologies is still incipient in most industries, such practical verifications would deserve especial attention to mitigate biased outcomes. In this sense, empirical studies could be carried out to validate these guidelines, while applied studies should be performed to verify the actual challenges and benefits from their adoption. For example, how I4.0 technologies can help to address the limitations of lean application in high variety and high variation environment. With access to real-time data through IoT and cloud, and addressing variety issues through additive manufacturing / 3DP, it will be interesting to test lean application in high variety and variation environment.

Further, future research could be conducted to identify other potential relationships between I4.0 technologies and guidelines for lean value stream design, leading to complementary steps towards effective value streams within the fourth industrial revolution context. Finally, it is important to acknowledge that our findings were raised from the perceptions of a small number of experts with different backgrounds (academia, industry or both). Hence, a confirmatory analysis with some more experts would also be recommended as future working opportunities. Authors are also interested to further develop and refine the I4.0 framework of Frank et al (2019) linked to application of base and front-end technologies and how different LP practices including VSM fits within the integrated lean-I4.0 framework. Another opportunity is related to the use of weights based on experts' experience to consolidate opinions. As experts present a very long experience (i.e. 15 to 25 years), results would not be very different if those weights were not used. In this sense, future works could consider using some simulations of other weights to consolidate scores and compare them.

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Guidelines for lean value stream design	I4.0 technologies											
	t_1	t_2	t_3	t_4	t_5	t_6	t_7	t_8	t_9	t_{10}	t_{11}	Σg_i
g_1-Define *takt* time												
g_2-Select finish goods strategy												
g_3-Implement continuous flow												
g_4-Establish first-in, first-out						r_{ij}						
g_5-Determine supermarket						z_{ij}						
g_6-Create one-point scheduling												
g_7-Define interval												
g_8-Determine pitch												
Σt_j												

Figure 1 – Illustration of matrix **M**

Table 1 – Proposed guidelines for designing lean value streams

Rother and Shook (2003)	Tapping and Shuker (2003)	Duggan (2012)	Keyte and Locher (2016)	Lee and Snyder (2017)
1-Define *takt* time	1-Define *takt* time	1-Define *takt* time	1-Define *takt* time	1-Define the mental model
2-Select finish goods strategy	2-Implement continuous flow	2-Balance capacity to meet *takt* time	2-Identify which steps add value to customers	2-Establish the workflow
3-Implement continuous flow	3-Define interval and level production	3-Define interval and level production	3-Search for reducing flow disruptions	3-Select the initial lean elements
4-Establish first-in, first-out	4-Balance the workload	4-Identify pacemaker and determine pitch	4-Determine countermeasures to stabilize flow	4-Identify precedents and priorities
5-Determine supermarket		5-Create scheduling system for pacemaker	5-Level production	5-Balance the workload
6-Create one-point scheduling		6-Management of customer demand changes	6-Balance workload	6-Design scheduling logic
7-Define interval			7-Determine pitch	
8-Determine pitch				

Table 2 – Consolidation of the main I4.0 technologies

I4.0 technologies	Definition	Authors										Citation frequency
		1	2	3	4	5	6	7	8	9	10	
t_1-Collaborative robots	Robots intended to physically interact with humans in a shared workspace.	X			X				X	X	X	5
t_2-RFID-tag at working units	Identification system that uses small radio frequency identification (RFID) devices for identification and tracking purposes.	X		X		X	X			X		5
t_3-Machines with digital interfaces and sensors	Automation systems with embedded sensor technology for real-time monitoring through data gathering.	X	X	X		X			X		X	6
t_4-Augmented reality	Interactive experience of a real-world environment in which objects are augmented through computer-generated perceptual information.	X	X	X	X	X	X		X	X	X	9
t_5-Cloud computing system	Shared pools of configurable computer system resources and higher-level services that can be rapidly provisioned with minimal management effort, often over the Internet.	X	X	X	X	X	X	X				7
t_6-Artificial intelligent and machine learning algorithms	Machine mimics cognitive functions that humans associate with other human minds, such as learning and problem solving.	X	X			X			X	X		5
t_7-Remote production processes management	Monitoring of shop floor with real-time data collection and remote control of production through Manufacturing Execution System and Supervisory Control and Data Acquisition.	X	X	X		X	X					5
t_8-Integrated engineering systems	ICT integrated to facilitate information exchange in both product development and manufacturing processes.			X			X			X	X	4
t_9-Additive manufacturing, rapid prototyping or 3D printing	Technologies that build 3D objects by adding layer-upon-layer of material, regardless the kind of material.	X	X				X	X		X		5
t_{10}-Big data	Utilization of large quantities of data for applications in predictive analytics, data mining, statistical analysis and others.		X	X	X	X	X	X	X	X	X	9
t_{11}-Internet of Things (IoT)	Network of devices, vehicles, and home appliances that contain electronics, software, actuators, and connectivity which allows these things to connect, interact and exchange data.	X	X	X	X	X	X		X		X	8

Notes: 1- Kolberg and Zühlke (2015); 2- Kolberg et al. (2017); 3- Jackson et al. (2011); 4- Dworschak and Zaiser (2014); 5- Kagermann et al. (2013); 6- Tortorella and Fettermann (2018); 7- Xu et al. (2018); 8- Liao et al. (2017); 9- Hermann et al. (2016); 10- Lasi et al. (2014).

Table 3 – Experts' experience, background and opinion weight

Expert	Experience time (years)	Opinion weight (%)	Background
E_1	18	16%	Academia
E_2	19	17%	Academia
E_3	16	14%	Automotive industry and Academia
E_4	15	13%	Eletronics industry and Academia
E_5	25	22%	Automotive industry
E_6	22	19%	Metal-mechanics industry
	115	100%	

Table 4 – Relationships between guidelines for lean value stream design and I4.0 technologies

Guidelines for lean values stream design	I4.0 technologies											Total score
	t_1	t_2	t_3	t_4	t_5	t_6	t_7	t_8	t_9	t_{10}	t_{11}	
g_1	1.5	3.4	2.1	4.2	5.1	3.8	2.1	2.8	8.2	7.5	2.8	43.5
	-1.1	-0.3	-0.8	0.1	0.5	-0.1	-0.8	-0.5	**1.9**	**1.6**	-0.5	
g_2	1.4	4.8	1.7	3.7	4.6	4.1	1.9	2.4	8.5	6.4	3.3	42.8
	-1.2	0.4	-1.0	-0.1	0.3	0.1	-0.9	-0.7	**2.1**	**1.2**	-0.3	
g_3	7.8	6.8	6.5	5.5	5.8	3.8	6.4	5.1	7.9	6.9	5.7	68.2
	1.3	0.5	0.3	-0.6	-0.3	-2.0	0.2	-0.9	**1.4**	0.6	-0.4	
g_4	6.9	7.2	6.4	4.7	4.7	4.3	5.7	4.4	7.0	6.8	5.6	63.7
	1.0	**1.3**	0.5	-1.0	-1.0	-1.3	-0.1	-1.2	**1.1**	0.9	-0.2	
g_5	4.1	7.5	6.9	4.1	5.3	3.4	5.9	4.3	6.7	7.1	5.8	61.1
	-1.0	**1.4**	**1.0**	-1.0	-0.2	-1.5	0.2	-0.9	0.8	**1.1**	0.2	
g_6	5.2	7.4	7.5	3.8	6.8	7.4	6.4	3.7	4.7	7.9	6.2	67.0
	-0.6	0.9	0.9	-1.5	0.5	0.9	0.2	-1.6	-0.9	**1.2**	0.1	
g_7	2.2	3.4	5.7	2.7	7.1	8.1	7.8	5.2	5.9	8.1	4.2	60.4
	-1.5	-1.0	0.1	-1.3	0.7	**1.2**	**1.1**	-0.1	0.2	**1.2**	-0.6	
g_8	2.5	4.8	3.2	5.9	4.4	4.9	8.3	3.3	3.8	4.5	4.7	50.3
	-1.3	0.1	-0.9	0.9	-0.1	0.2	**2.4**	-0.8	-0.5	0.0	0.1	
Total score	31.6	45.3	40.0	34.6	43.8	39.8	44.5	31.2	52.7	55.0	38.3	

$Note_1$: Numbers in white cells represent the average weighted values r_{ij} of relationships for each guideline

$Note_2$: Numbers in gray cells represent the standardized values z_{ij} of relationships for each guideline (differentiation index)

$Note_3$: Bold numbers refer to the most important relationships (>1.0) between I4.0 technologies and guidelines for lean value stream design

Table 5 – Proposition of technology-integrated lean value stream guidelines (tg_i)

Original lean value stream guidelines	Most importantly related I4.0 technologies	Technology-integrated lean value stream guidelines	Characteristics
g_1-Define *takt* time	t_9-Additive manufacturing, rapid prototyping or 3D printing t_{10}-Big data	tg_1-Real-time *takt* definition	To constantly monitor and update *takt* time considering variations at customers demand, internal processes and material supply through big data analysis and processes cycle times adjustments with additive manufacturing.
g_2-Select finish goods strategy	t_9-Additive manufacturing, rapid prototyping or 3D printing t_{10}-Big data	tg_2-Constant adaptation of finish goods strategy	Agility in adapting finish goods strategy according to variations in customers demand profile analyzed through big data and rapid increments in capacity by additive manufacturing.
g_3-Implement continuous flow	t_1-Collaborative robots t_9-Additive manufacturing, rapid prototyping or 3D printing	tg_3-Implement highly flexible continuous flow	Balancing workstations through utilization of collaborative robots and adjust processes cycle times with additive manufacturing to bear an adaptive continuous flow.
g_4-Establish first-in, first-out	t_1-Collaborative robots t_2-RFID-tag at working units t_9-Additive manufacturing, rapid prototyping or 3D printing	tg_4-Establish monitorable and flexible first-in, first-out	Constantly monitoring and re-dimensioning first-in, first-out lanes through RFID, allowing rapid replenishment by increments in capacity with additive manufacturing.
g_5-Determine supermarket	t_2-RFID-tag at working units t_3-Machines with digital interfaces and sensors t_{10}-Big data	tg_5-Determine transient supermarket	To determine supermarket policies (minimum, maximum and replenishment points) for transient productive conditions, enabling optimal quantities of inventory.
g_6-Create one-point scheduling	t_{10}-Big data	tg_6-Create multiple-point scheduling	Gathering and sending data to various workstations in the value stream, allowing real-time scheduling adjustments that may mitigate delivery service issues.
g_7-Define interval	t_6-Artificial intelligent and machine learning algorithms t_7-Remote production processes management t_{10}-Big data	tg_7-Constantly define interval	To allow real-time and remote production levelling taking into account instant variations in material flow (e.g. process cycle time, changeover, machine downtime, etc.), customers' demand and suppliers' delivery.
g_8-Determine pitch	t_7-Remote production processes management	tg_8-Determine and remotely manage pitch	To enable shorter management timeframes through remote management in order to facilitate faster decision-making processes that can address issues on the value stream and keep up with the required rhythm of the flow of value.