A fuzzy maturity-based method for lean supply chain management assessment

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Abstract

Purpose – This study aims to propose a method for measuring lean supply chain management (LSCM) maturity based on the main lean practices and existing waste of a supply chain.

Design/methodology/approach – A three-stage approach was developed. First, a thorough literature review was performed to raise concepts and previous findings on maturity models (MMs) and LSCM. This review's outcomes were then validated by experts in the field using the fuzzy Delphi method (FDM). Subsequently, the proposed model was illustrated and assessed based on a multi-case study.

Findings – All companies attained high outcomes in the elimination of the waste pillar. The pillars of logistics management, continuous improvement and information technology management also stood out in the three organizations' results. The company with the lowest maturity level operates in a make-to-order production policy, which may harm the lean supply in its supply chain.

Practical implications – The proposed model can reveal external opportunities and threats and internal strengths and weaknesses in supply chains (SCs). It is also capable of providing a clear roadmap for SC improvement in companies.

Originality/value – To the best of the authors' knowledge, no study to date has proposed a MM in the LSCM context using FDM and considering the crucial relationship between lean practices and wastes.

Keywords Maturity model, Lean supply chain, Lean supply chain management, Fuzzy Delphi

Paper type Research paper

1. Introduction

Challenges created in today's global competitive landscape have led many manufacturing companies to adopt new management methods to improve their overall efficiency and competitiveness. Lean principles are a proven approach to success in manufacturing companies worldwide (Nordin and Deros, 2017). Lean principles focus on identifying customer value,

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mapping value stream, creating flow by eliminating waste, establishing a pull system and pursuing perfection (Womack and Jones, 1997; Melton, 2005).

The benefits of lean practices adoption were first documented in the automotive industry, such as reducing lead time, inventory and cost, and the increase of quality and service levels (Melton, 2005). However, these practices are not restricted to manufacturing and may be suitable for applying other business processes, such as logistics and supply chain (Almutairi *et al.*, 2019b; Kumar Singh and Modgil, 2020).

In the supply chain management (SCM) context, the adoption of lean practices emphasizes the elimination of wastes and provides efficiency in processes and information and process integration along the supply chain (Cooper *et al.*, 1997; Christopher and Towill, 2002). The application of lean in the SCM allows the creation of a streamlined, highly efficient system that produces finished products at the pace of customers' demand with little or no waste, pursuing perfection (Shah and Ward, 2003; Stavrulaki and Davis, 2010; Arif-Uz-Zaman and Ahsan, 2014). According to Nimeh *et al.* (2018), researchers are increasingly paying attention to the concept of lean supply chain management (LSCM) as an effective way to improve operations and eliminate waste along a supply chain (Jasti and Kurra, 2017). Thus, knowing the degree of readiness for LSCM implementation of a supply chain in which a company operates is essential (Correia *et al.*, 2017). The lack of preparedness or the mismatch between the supply chain maturity and encompassed management practices may lead to inefficient efforts and unnecessary wastes (Tortorella *et al.*, 2017).

Although widely discussed, integrating lean principles and practices into SCM has yet to evolve to understand better adaptation needs (Tortorella *et al.*, 2017). Moyano-Fuentes *et al.* (2019) show that LSC's current knowledge is still limited, and therefore there is no effective measure of LSCM maturity. While many researchers have proposed new LSCM frameworks, there has been a lack of participation by practitioners and, to some extent, consultants in the field of SCM (Chen *et al.*, 2017). According to Fedoskina *et al.* (2019), lean principles are highly important across various industries and their applicability needs verification within the theoretical and practical spheres. Almutairi *et al.* (2019a) argue that the lack of awareness is still one reason for LSCM implementation difficulties. Moreover, it is still unclear which LSCM practices enhance supply chain (SC) performance (Nimeh *et al.*, 2018). This study aims to fill this gap by proposing a new LSCM maturity measurement method due to increasing interest in empirical and theoretical research among professionals and academics.

This study aims at proposing a method for measuring the LSCM maturity in an area in which little research has been conducted. Very little research has been devoted to finding the missing link between LSCM practices and the waste in SCM. Furthermore, no studies have yet addressed LSCM maturity measurement regarding waste management and its relationship with best practices (BPs). Therefore, the proposed maturity model (MM) relates to lean practices and existing waste supply chains. Such relationships were identified based on the opinions of experts and practitioners. This method indicates the improvement opportunities within a company's supply chain, allowing more assertively focused efforts toward positive performance results.

The rest of the paper unfolds as follows. Section 2 provides the theoretical background and Section 3 presents the research methods, including the fuzzy Delphi method (FDM) and the MM. Section 4 exhibits the applicability of the proposed model and discusses the results. Finally, Section 5 concludes with our conclusion, practical implications, limitations and future research paths.

2. Background

2.1 Lean supply chain management

Recently, researchers have emphasized that lean principles and practices can be extended beyond an organization's boundaries to its supply chain, aiming to improve competitiveness (Anand and Kodali, 2008; Marodin *et al.*, 2017). Jasti and Kodali (2015) identified 129 unique elements/practices of LSCM, filtered with experts' help, resulting in 82. These practices have been divided into eight pillars of LSCM implementation:

(1) information technology management;

(2) supplier management;

(3) elimination of waste;

(4) just in time (JIT) production;

(5) customer relationship management;

(6) logistics management;

(7) top management commitment; and

(8) continuous improvement.

Using an extensive literature review, Tortorella *et al.* (2018) compiled 27 practices that provide a representative view of the LSCM (Table 1) with a brief description.

The implementation of LSCM is closely tied to information sharing and flow creation (Anand and Kodali, 2008). Information technology plays an essential role in waste management as much of these wastes result from inadequate information flow or the difficulty of sharing information between different tiers. Table 2 shows the main SCM wastes with coding to be used later in identification.

Tortorella *et al.* (2017), aiming to test the association between LSCM practices and performance, found results that suggest that the implementation of each of the LSCM practices bundles contributes substantially to SC performance. In agreement, Nimeh *et al.* (2018) investigated LSCM practices' effects on SC performance and the results demonstrated that all LSCM practices affected it positively. However, investigating practices alone does not guarantee lean performance improvement. The appraisal of waste is a favorable approach to enhance production system performance as it may specify possible areas of progress and sources of ineffectiveness (Bajjou and Chafi, 2019).

By performing a systematic literature review, Berger *et al.* (2018) highlighted the main difficulties in implementing LSCM practices. The authors report the lack of top management involvement in improvement projects and the need to develop specialized teams, focusing on developing training for employees and further extension of training for agents in their SC. Thus, the study suggested that it is impossible to implement LSCM practices without involving its suppliers and customers successfully. Tortorella *et al.* (2017) emphasized the need for attention to overcome LSCM implementation barriers in companies positioned at the first and second tiers of SC. Thus, to overcome these impediments, lean practices and wastes must be considered in parallel throughout the entire SC.

2.2 Maturity models and supply chain management

Maturity assessment has been applied as a discipline to obtain many concepts or phenomena' evolutionary nature. The applicability of maturity assessment to an organization refers to the state in which the institution or area is in perfect condition to achieve its objectives, expected performance and requirements (Yu and Huo, 2018). Organizational maturity is defined as the extent to which an organization has explicitly and

LSCM pillars	LSCM practices		Description
JIT production	BP1	*Kanban* or pull system	Kanban is a signaling device that provides authorization and instructions for the production or removal (transport) of items in a pull system (Marchwinski *et al.*, 2008)
	BP2	Leveled scheduling or *heijunka*	Leveling the release of production kanbans to achieve a uniform production flow across all possible product types; reducing bullwhip effect (Matzka *et al.*, 2012)
	BP3	Efficient and continuous replenishment	Allows creation of continuous material flow and JIT production without intermediate stocks
	BP4	Deliveries in small lot sizes	Smaller, more frequent batch delivery strategy to maintain production flow without intermediate stocks
Customer relationship management	BP5	Close relationship between customer, supplier and relevant parties	Collaborative supply chain with good links between links
	BP6	Long-term forecasting of customer demands	Accurate forecasts for coordinating production with demand to avoid problems like the bullwhip effect
Continuous Improvement	BP7	Two-way feedback assessment	Feedback exchange between supply chain links
	BP8	Value chain analysis or value stream mapping	A simple diagram of each step involved in the material and information flows required to bring a product from order to delivery
	BP9	Development of supply chain key performance indicator (KPIs)	Using KPIs to track and control supply chain processes, making issues more visible
Top management commitment	BP10	Value chain management team	Have a team focused on customer value analysis and the company's value chain
	BP11	Win-win problem-solving methodology	The approach is determined to maximize benefits on both sides (Carbonara *et al.*, 2014)
	BP12	Open-minded and in-depth market research conducted jointly	Joint understanding of end-user requirements so that everyone involved can work to deliver customer value (Tortorella *et al.*, 2017)
	BP13	Open-book negotiation	Supplier assumes customer risk through closer integration with customer systems and processes (Lamming *et al.*, 2005)
	BP14	*Hoshin Kanri*	Japanese term for strategy deployment when an organization initiates a lean conversion (Marchwinski *et al.*, 2008)
Supplier management	BP15	*Keiretsu*	A term used to describe Japanese business consortia that rely on cooperation, coordination and joint ownership and control to competitively position companies and industries (Ellram and Cooper, 1993)
	BP16	*Kyoryokukai*	Japanese term for "cooperative circle" or vendor association, which represents a vendor development mechanism (Hines, 1995)

Table 1.
LSCM practices

(*continued*)

LSCM pillars	LSCM practices		Description
	BP17	Intervention strategy	Intervention strategies affect important supplier selection and communication processes (Johnsen, 2011)
	BP18	Cascade strategy	Imposing customer performance initiatives and requirements on the vendor, and therefore on subcontractors (Johnsen and Ford, 2007)
	BP19	Mutual long-term agreement	Closer supplier relationship strategy through long-term agreements
Logistics management	BP20	Material handling systems	Movement of materials required for the production process within a facility
	BP21	Outbound transportation	Use of efficient transportation strategies such as milk run or circuit delivery (Jasti and Kodali, 2015)
	BP22	Establishment of distribution centers	Use of distribution centers for greater control of logistics processes, enabling an advanced planning structure to meet demand, raising quality and service level, and facilitating the use of strategies such as postponement
	BP23	Consignment stock	In this strategy the supplier would be the owner of the inventory kept in the customer's warehouse until consumed. The customer would pull whatever material was needed and after each production cycle the supplier would replenish to a previously agreed basic level (Corbett, 2001)
Elimination of waste	BP24	Standardized work procedures to assure quality achievement	Establishment of precise procedures for the work of each operator or machine in a production process
	BP25	Functional packaging design	Development and use of functional packaging to avoid waste and interruptions in the production flow
Information technology management	BP26	Inbound vehicle scheduling	Use of systems to ensure vehicle entry scheduling, avoiding unnecessary waiting
	BP27	Integrated information technology system	Systems compatible between supply chain links, in addition to the use of electronic data interchange

Table 1.

consistently implemented, documented, managed, measured, controlled and continually improved practices or processes (Curtis *et al.*, 2001). The more mature organizations stand out among others, enjoy a good reputation among their customers, manage their finances efficiently, pursue continuous development while seeking innovative, technical, organizational and managerial solutions (Stachowiak and Oleśków-Szłapka, 2018).

A MM aims to describe "in a few phrases, the typical behavior exhibited by a firm at several levels of maturity, for each of several aspects of the area under study" (Fraser *et al.*, 2002, p. 1). MMs can typically be characterized by their levels, dimensions, respondents and purpose. Typically, the number of levels ranges from four to six. Dimensions refer to the areas used to structure the field of interest, sometimes called key process areas, which can be one-dimensional, multidimensional and hierarchical. The advantage of multidimensional and hierarchical structures is the ability to separate maturity assessments (Batenburg *et al.*, 2014).

A MM applied in the SCM stands out is supply chain operations reference, proposed by the Supply Chain Council (Stewart, 1997). This model relates to companies' ability to manage the supply chain's full extent classifying them on four levels. Another MM is the

Waste	Code	Applied to SCM
Overproduction or early production	W1	Producing more than what is demanded by the next stage of customers in the SC
	W2	Having too many product varieties and models, which may not have the adequate demand
	W3	Transporting more than what is required by the customer (over quantity) in the SC
	W4	Having multiple suppliers to produce the same part/component
	W5	Redundant development of parts as the reuse of designs are not practiced, resulting in the development of multiple parts and, hence, the use of multiple suppliers
Transportation or movement	W6	A long, multistage SC involving many stakeholders
	W7	Taking a circuitous route from one destination to another
	W8	Making frequent delivery trips from the supplier end and to the distributor/retailer end
	W9	Having multiple subcontractors for a given part, resulting in multiple movements
	W10	Sending the wrong information to suppliers, distributors, retailers
	W11	Sending multiple information in both paper and electronic formats
Unnecessary inventory	W12	Creating multiple purchase orders, storing outdated and unnecessary documents, etc.
	W13	Storing more than what is required by the customer at various stages of the SC
	W14	Having a large batch of stock keeping units (SKU) with unnecessary and obsolete components/designs
	W15	Procuring in bulk because of distance or the uniqueness of the parts/components
	W16	The lack of use of standard parts or the lack of commonality for multiple product variants
	W17	Demand amplification due to the lack of synchronization of demand and activities
Waiting or delays	W18	Waiting for trucks to arrive
	W19	Waiting for raw materials from suppliers or waiting for the delivery of products from manufacturers, distributors or retailers
	W20	Suppliers waiting for instructions regarding shipment/production
	W21	Delay in transportation due to natural phenomena such as strikes and weather
	W22	Suppliers waiting for payment from manufacturers, while manufacturers wait for payment from distributors, retailers, customers
	W23	Waiting for approval of the purchase order, delivery receipts, custom clearance, etc.
Inappropriate processing	W24	Unnecessary serial effort due to the supply of a wrong product/part to the customer
	W25	Wrongly processed purchase order or customer order entry
	W26	Unnecessary verification/counting, inspection of shipped products at the manufacturer end and well as at the distributor/retailer end
	W27	Unnecessary dismantling of products or packing before shipment
	W28	Having both computer and manual entry regarding transactions made at various stages of the SC
	W29	Over specifications/tolerance or too much details provided for a part to the supplier
	W30	Demand information passed from one stage to another in the SC was often provided in a poor format, creating an NVA rework for recipients

(*continued*)

Table 2.
The supply chain waste taxonomy based on the seven lean manufacturing waste

Waste	Code	Applied to SCM
Unnecessary motion	W31	Too many trips or movements due to changing priorities or requirements
	W32	Improper layout in the warehouses at various stages of the SC, resulting in more movements of workers
	W33	A hierarchical structure for decision-makers in the SC who are placed at various locations, resulting in the unnecessary movement of information
Defects	W34	Making a wrong shipment to a customer, retailer or distributor
	W35	Suppliers shipping a lot with defective parts to the manufacturer and the manufacturer shipping a batch of products containing some defect
	W36	Mistakes made in the manufacturer's purchase order sent to the supplier and mistakes made by the retailers or distributors in their order entry
	W37	Wrong or exaggerated information communicated between the manufacturer and supplier, the manufacturer and distributor and vice versa
	W38	Late delivery of parts/products to the immediate customers of the SC
	W39	Over-quantity or under-quantity shipment of lots by suppliers, manufacturers, distributors
	W40	Return of goods by the customers for various reasons, like the product does not work properly, a damaged part or product due to transportation, etc.
	W41	Wrong or inaccurate demand forecasting or multiple types of forecasts used at different stages of the SC

Note: NVA - non-value added

Table 2.

Supply Chain Maturity Model proposed by Lockamy and McCormack (2004), which indicates that process performance is related to maturity and classifies the company's maturity in five levels. The one described by McCormack *et al.* (2008) brings a measurement and system performance in the form of MMs. Complementarily, Garcia Reyes and Giachetti (2010) performed a pilot test of the MM and ranked SCM practices based on a panel of experts in Mexico.

Narrowing down to LSC and MMs, very few research (Jaklic *et al.*, 2006; Arif-Uz-Zaman and Ahsan, 2014) have addressed MM in LSC contexts and no study to date has dealt with MMs in LSC considering the crucial relationship between lean practices and wastes.

3. Research method

The proposed method can be seen in Figure 1, divided into two phases, with 12 steps.

In Phase 1, the list of wastes gathered from literature went through Steps 1 to 5; a prioritization made using the FDM with nine experts in the field who ranked the wastes proposed by Anand and Kodali (2008), narrowing down to 21 elements to reduce the difficulty of implementing the maturity measurement tool (to avoid respondents' fatigue, for example). Details on this method are exposed to Section 3.1 and its application in Section 4.1.

Phase 2 concerns the proposal of the LSCM MM, which defined the levels and structure of the model in Step 6. Step 7 involves the elaboration of the matrix "Wastes versus Practices" using the list of wastes prioritized in Step 5 and the practices consolidated in the literature. The relationship between wastes and practices was obtained from three experts in Step 8 (submatrix R). Results from this step are presented in Section 4.2. Step 9 consolidates the MM. Afterward, MM was applied to three companies from different sectors in Step 10. The results of the application of the MM in the companies were analyzed and it was possible to propose improvements in it in Steps 11 and 12. Results on the application of the MM are presented in Section 4.3. The FDM is better explained in Section 3.1, while the dynamics of the proposed MM is shown in Section 3.2.

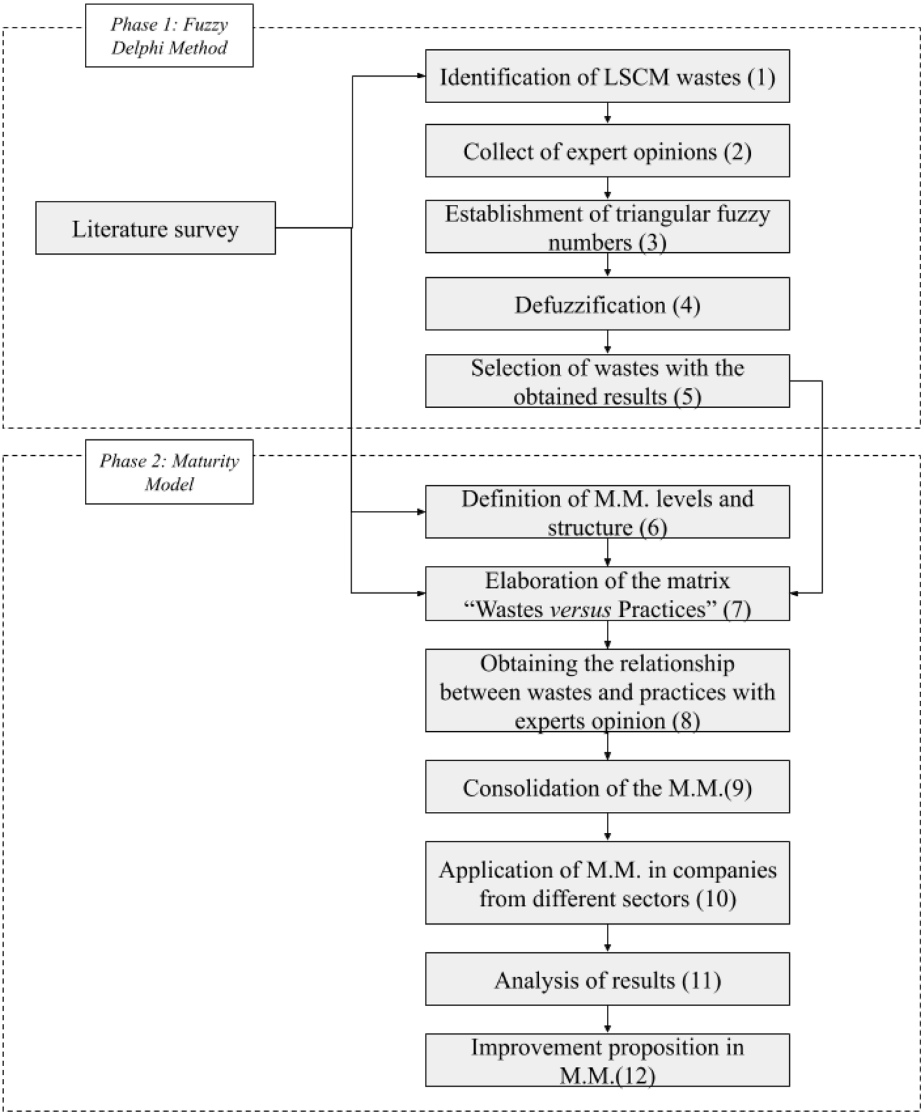

Figure 1.
Research phases and steps

3.1 Fuzzy Delphi method

One of the most commonly used decision-making techniques is the Delphi method (Cheng and Lin, 2002). It was developed in the 1960s by Rand Corporation in Santa Monica, CA, USA. This technique attempts to develop conclusions using "group consensus." Despite its advantages, the traditional Delphi method can suffer from expert opinions of low convergence, high execution cost with multiple rounds and the possibility that response organizers can filter specific expert opinions (Kuo and Chen, 2008). This happens because real-world decision-making problems are often poorly defined. Thus, the application of fuzzy set theory to real-world decision-making problems has yielded very good results. It provides a more flexible structure, where it is possible to satisfactorily correct many of the obstacles due to the lack of precision (Cheng and Lin, 2002).

The fuzzy set theory proposed by Zadeh in 1965 is a useful tool for dealing with the vagueness of human subjective judgments (Vafadarnikjoo *et al.*, 2018). Although there are many fuzzy number shapes, the triangular shape was chosen for FDM calculations. Experts answer questionnaires in two rounds. After each round, a facilitator provides an anonymous summary of expert predictions (Chen *et al.*, 2018). According to Bouzon *et al.* (2016) and Hsu *et al.* (2010), the detailed steps of FDM are described below.

Step 1: Identification of focus analysis criteria.

Step 2: Collect expert opinions using the decision group. After identifying the criteria to be evaluated, experts (decision-makers) in the field are invited to determine the importance of the criteria using a questionnaire with linguistic variables described in Table 3.

Step 3: Establish triangular fuzzy numbers. Calculate the evaluation value of the triangular fuzzy number of each criterion given by experts, find out the significant triangular fuzzy number of the criterion. Assuming that the fuzzy number that represents the evaluation value for the element j of m elements given by expert i of n experts is $w = (a_{ij}, b_{ij}, c_{ij})$, $i = 1, 2, \ldots, n$ and $j = 1, 2, \ldots, m$. So the fuzzy weight w_j of element j is $w_j = (a_j, b_j, c_j)$, $j = 1, 2, \ldots, m$, where:

$$a_j = \min_i \{a_{ij}\} \tag{1}$$

$$b_j = \frac{1}{n}\sum_{i=1}^{n} b_{ij} \tag{2}$$

$$c_j = \max_i \{c_{ij}\} \tag{3}$$

Step 4: Defuzzification. Using the simple center of gravity method to "defuzzify" the fuzzy weight w_j of each element j to the set value S_j, S_j is obtained as follows:

$$S_j = \frac{a_j + b_j + c_j}{3}, \; j = 1,2,\ldots,m \tag{4}$$

Step 5: Selection of criteria with the obtained results. Finally, the appropriate criteria can be selected by setting the limit α. The value of an α is calculated by averaging all criteria weights. The principle of screening is as follows:

Linguistic variables	Fuzzy number
Very low	(0, 0, 0.1)
Low	(0, 0.1, 0.3)
Medium low	(0.1, 0.3, 0.5)
Medium	(0.3, 0.5, 0.7)
Medium high	(0.5, 0.7, 0.9)
High	(0.7, 0.9, 1.0)
Very high	(0.9, 1.0, 1.0)

Table 3. Linguistic scale

- If $S_j \geq \alpha$ the criterion j is selected; and
- If $S_j < \alpha$ the criterion j is discarded.

As a result, it is possible to see that FDM is more flexible and robust for group decision-making (Yang and Hsieh, 2009). The results of its application are in Section 4.1.

3.2 Maturity model proposal

The LSCM MM here proposed is based on the studies of De Paula *et al.* (2012), Tortorella *et al.* (2017) and Anand and Kodali (2008). In the model, the relationship between typical LSCM problems and management BPs is made explicit by means of a relationship submatrix. The relationship submatrix (R) is the main element in the maturity matrix and one of the most significant contributions in the proposed model. The r_{ij} elements from R give an expert opinion-based assessment of how BP i can help solve the problem (LSCM waste) j, with range values from 0 (BP i is unrelated to waste j) to 9 (BP i definitely minimizes or eliminates the occurrence of waste j). Three LSCM experts reviewed *rij* relationships.

After obtaining the R submatrix, the application of the MM in companies is performed. It begins by determining how often LSCM problems occur in the company and their impact by applying a questionnaire to company experts. The proposed questionnaire is an important tool designed to analyze problems searching for their causes, which can be useful in analyzing maturity.

LSCM problems are assessed for their frequency of incidence and impact by company experts and the information is entered into the matrix. As a result, a priority list of BPs that minimizes the problems identified by respondents is produced. The frequency of occurrence of the problems (f_i) and the impact of these problems (I_i) are collected using a questionnaire, which uses the scale shown in Table 4 (De Paula *et al.*, 2012).

The impact of waste refers to the degree of damage (either financially or more generally in lean application) if this waste is present in SC. These two factors, $f_{i,}$ and I_i generate the severity parameter (g_i) of waste, calculated by multiplying these factors. The g_i values are entered into the maturity matrix (M). The matrix is composed of a series of elements, with the relation submatrix (R) being the central one. An overview of the complete matrix of the MM (M) is given in Table 5, with the elements described above.

To determine the degree of development of the company's LSCM, the proposed model includes the following variables:

- f_i – frequency of occurrence of the problem/waste (according to the scale of Table 4);
- I_i – the impact of the problem (according to the scale of Table 4);

Table 4. Frequency of occurrence and impact of problem scale for questionnaire response

Value	Frequency	Impact
1	Never Occur (0%–10% of situations)	Extremely low
2	Rarely Occur (10%–20% of situations)	Low
3		
4	Seldomly Occur (20%–50% of situations)	Moderate
5		
6	Frequently Occur (50%– 90% of situations)	High
7		
8		
9	Always Occur (90%–100% of situations)	Extremely high

Source: De Paula *et al.*, (2012, p. 10290)

			Waste/ Problems W1	W2	. . .Wx	Lower lever il_i	Criticality level cr_i	Upper level sl_i	Development score Ds_i	Development score k pillar Ds_k	Maturity score k pillar ML_k	Overall maturity level general maturity
			f_1 I_1 g_1	f_2 I_2 g_2	. . . f_x . . . I_x . . . g_3							
LSCM pillars	Practices BPs	BP1	R submatrix r_{ij}			il_1	cr_1	sl_1	DS_1	DSk_1	ML_1	GM
		BP2				il_2	cr_2	sl_2	DS_2	DSk_2	ML_2	
		. . .				. . .	. . .	. . .	. . .	. . .	. . .	
		BPy				il_y	cr_y	sl_y	DS_y	DSk_y	ML_y	
Problem Score				pi_1	pi_2				pi_x			

Note: GM = general maturity

Table 5.
Maturity matrix

- g_i – problem severity parameter, calculated as follows:

$$g_i = f_i{*}\mathrm{I}_i \tag{5}$$

- r_{ij} – the relationship between BP i and problem j, obtained from the relation submatrix R;
- p_{ij} – gives the relevance of the problems/waste as a function of their relation to the BPs, calculated as follows:

$$p_{ij} = \sum\nolimits_{i=1}^{y} r_{ij}, \; j = 1, \; \ldots, \; x \tag{6}$$

- sl_i – gives the worst possible score for not correctly implementing BPi using three terms (note that g_i = 81 denotes the highest severity parameter attributable to a problem), calculated as follows:

$$sl_i = \sum_{j=1}^{x} r_{ij}{*}\; p_{ij}{*}81, \; i = 1, \; \ldots, \; y \tag{7}$$

- il_i – gives the best possible score for not correctly implementing BPi using three terms (note that g_i = 1 denotes *the* lowest severity parameter attributable to a problem), calculated as follows:

$$il_i = \sum_{j=1}^{x} r_{ij}{*}\; p_{ij}{*}1, \; i = 1, \; \ldots, \; y \tag{8}$$

- cr_i – gives *the* calculated critical score for BPi calculated as follows:

$$cr_i = \sum_{j=1}^{x} r_{ij}{*}\; p_{ij}{*}g_i, \; i = 1, \; \ldots, \; y \tag{9}$$

- DS_i – gives the development score for BPi, which shows how developed this practice is in the SC, on a scale from 0 to 10, where 10 indicates the best development outcome, calculated as follows:

$$DS_i = \left(\frac{sl_i - cr_i}{sl_i - il_i}{*}10\right), \; i = 1, \; \ldots, \; y \tag{10}$$

- DS_k – gives *the* LSCM$_k$ pillar development score (categories of practice), calculated as the geometric mean of the DS_i scores within the pillar;
- ML_k – gives the LSCM$_k$ pillar maturity score as a function of its DS_k score using the ranges in Table 6.
- GML – gives the total LSCM maturity level, which is limited by the lowest ML_k score, as follows:

$$GML = \min_{all\ k} ML_k \quad (11)$$

By performing these calculations, it is possible to identify, in addition to the degree of maturity of the company's LSCM, opportunities for improvement.

4. Model application and discussion

4.1 Lean supply chain management waste selection

Nine experts were chosen to participate in the selection process, five of them from industry and four from academia, with an average of 11 years of experience in LSCM. The nine-person panel size is efficient and effective. Similar studies have used a comparable number of participants for FDM. For example, Hsu *et al.* (2010) used 9 specialists, Bueno and Salmeron (2008) and Bouzon *et al.* (2016) used 10 specialists and Ma *et al.* (2011) used 13 specialists. Information on the years of experience and industry for each expert is provided in Table 7.

These experts were asked to rate the importance and relevance of waste according to the scale in Table 3. After that, some discrepancies in responses were observed and the second round of the method was performed. Then, the answers on the linguistic scale in Table 3 were converted into fuzzy numbers and the weight $w_j = (a_j, b_j, c_j)$ for each waste j was calculated. The weights w_j were converted into crisp numbers S_j and selected with the screening of Step 5 described in Section 3.1, where $\alpha = 0.629$. Thus, a list of the 21 most relevant wastes was obtained for the MM, as shown in Table 8.

4.2 Development of submatrix R

Three experts in the field of LSCM, with, respectively, 12, 8 and 2 years of experience in the area, were invited to fill in the relationships present in submatrix R, answering how each practice could solve or mitigate each waste, as explained in Section 3.2.

Maturity level score for pillar k	DS_k range
Maturity level 1	0–2.50
Maturity level 2	2.51–5.00
Maturity level 3	5.01–7.25
Maturity level 4	7.26–9.50
Maturity level 5	9.51–10.00

Table 6. DS_k Maturity levels

Expert	Industry/Academia	Years of experience in LSCM
Expert 1	Industry	17
Expert 2	Industry	15
Expert 3	Industry	5
Expert 4	Industry	8
Expert 5	Industry	10
Expert 6	Academia	4
Expert 7	Academia	17
Expert 8	Academia	14
Expert 9	Academia	6

Table 7. Information on experts

Seven wastes in Lean manufacturing	Applied to SC processes	Weight of waste (S_j)	Selection result
Overproduction or early production	Producing more than what is demanded by the next stage of customers in the SC	0.796	Selected
	Having too many product varieties and models, which may not have the adequate demand	0.663	Selected
	Transporting more than what is required by the customer (over quantity) in the SC	0.541	Not selected
	Having multiple suppliers to produce the same part/component	0.493	Not selected
	Redundant development of parts as the reuse of designs are not practiced, resulting in the development of multiple parts and, hence, the use of multiple suppliers	0.663	Selected
Transportation or movement	A long, multistage SC involving many stakeholders	0.544	Not selected
	Taking a circuitous route from one destination to another	0.570	Not selected
	Making frequent delivery trips from the supplier end and to the distributor/retailer end	0.426	Not selected
	Having multiple subcontractors for a given part, resulting in multiple movements	0.563	Not selected
	Sending the wrong information to suppliers, distributors, retailers	0.696	Selected
	Sending multiple information in both paper and electronic formats	0.507	Not selected
Unnecessary inventory	Creating multiple purchase orders, storing outdated and unnecessary documents, etc.	0.493	Not selected
	Storing more than what is required by the customer at various stages of the SC	0.785	Selected
	Having a large batch of SKU with unnecessary and obsolete components/designs	0.693	Selected
	Procuring in bulk due to distance or the uniqueness of the parts/components	0.659	Selected
	The lack of use of standard parts or the lack of commonality for multiple product variants	0.681	Selected
	Demand amplification due to the lack of synchronization of demand and activities	0.878	Selected
Waiting or delays	Waiting for trucks to arrive	0.611	Not selected
	Waiting for raw materials from suppliers or waiting for the delivery of products from manufacturers, distributors or retailers	0.704	Selected
	Suppliers waiting for instructions regarding shipment/production	0.581	Not selected
	Delay in transportation due to natural phenomena such as strikes and weather	0.452	Not selected
	Suppliers waiting for payment from manufacturers, while manufacturers wait for payment from distributors, retailers, customers	0.578	Not selected
	Waiting for approval of the purchase order, delivery receipts, custom clearance, etc.	0.556	Not selected

(continued)

Table 8.
Result of the selection of the most relevant LSCM wastes for the MM

Seven wastes in Lean manufacturing	Applied to SC processes	Weight of waste (S_j)	Selection result
Inappropriate processing	Unnecessary serial effort due to the supply of a wrong product/ part to the customer	0.715	Selected
	Wrongly processed purchase order or customer order entry	0.774	Selected
	Unnecessary verification/counting, inspection of shipped products at the manufacturer end and at the distributor/retailer end	0.674	Selected
	Unnecessary dismantling of products or packing before shipment	0.552	Not selected
	Having both computer and manual entry regarding transactions made at various stages of the SC	0.378	Not selected
	Over specifications/tolerance or too much details provided for a part to the supplier	0.444	Not selected
	Demand information passed from one stage to another in the SC was often provided in a poor format, creating an NVA rework for recipients	0.574	Not selected
Unnecessary motion	Too many trips or movements due to changing priorities or requirements	0.607	Not selected
	Improper layout in the warehouses at various stages of the SC, resulting in more movements of workers	0.781	Selected
	A hierarchical structure for decision-makers in the SC who are placed at various locations, resulting in the unnecessary movement of information	0.596	Not selected
Defects	Making a wrong shipment to a customer, retailer or distributor	0.733	Selected
	Suppliers shipping a lot with defective parts to the manufacturer and the manufacturer shipping a batch of products containing some defect	0.730	Selected
	Mistakes made in the manufacturer's purchase order sent to the supplier and mistakes made by the retailers or distributors in their order entry	0.707	Selected
	Wrong or exaggerated information communicated between the manufacturer and supplier, the manufacturer and distributor and vice versa	0.581	Not selected
	Late delivery of parts/products to the immediate customers of the SC	0.685	Selected
	Over-quantity or under-quantity shipment of lots by suppliers, manufacturers, distributors	0.670	Selected
	Return of goods by the customers for various reasons, like the product does not work properly, a damaged part or product due to transportation, etc.	0.819	Selected
	Wrong or inaccurate demand forecasting or multiple types of forecasts used at different stages of the SC	0.630	Selected

Note: NVA - non-value added

Table 8.

The weighted average of the experts' answers was calculated according to their time experience to obtain the submatrix R. Thus, the submatrix of relations R is shown in Figure 2. Wastes inserted in submatrix R are numbered according to Table 2 and practices as already shown in Table 1 of Section 2.1.

By observing the result of filling out the R-relations submatrix, it is possible to verify some practices that have a more substantial impact on solving various wastes, which indicates that they deserve greater attention from companies. In this matter, BP3 – efficient

	W1	W2	W5	W10	W13	W14	W15	W16	W17	W19	W24	W25	W26	W32	W34	W35	W36	W38	W39	W40	W41
BP1	8.4	1.2	1.2	4.2	8.4	4.2	4.8	1.2	6.6	5.2	3.6	4.0	3.0	2.0	2.6	2.4	1.8	6.6	4.4	1.6	6.0
BP2	5.0	3.0	2.4	1.8	7.6	5.2	3.0	1.2	3.0	6.6	3.2	1.8	1.2	0.6	2.6	1.2	1.8	5.2	5.0	1.8	3.8
BP3	5.0	3.6	1.8	2.2	7.0	6.0	9.0	1.2	6.6	7.8	3.2	2.6	2.4	1.2	1.2	1.2	1.2	6.4	7.2	2.4	5.2
BP4	5.8	4.2	2.4	2.4	7.2	4.6	6.0	1.8	6.0	6.0	1.2	2.4	1.8	2.4	1.2	1.2	1.2	6.0	6.0	2.4	3.6
BP5	6.6	4.6	3.0	5.2	5.4	4.6	4.4	3.0	7.2	7.6	6.0	2.4	4.2	1.8	4.0	4.0	2.8	5.6	6.0	3.6	6.6
BP6	7.8	6.4	2.4	4.2	6.6	4.8	2.4	1.2	7.2	3.6	1.8	1.2	0.6	1.2	1.2	0.6	1.2	3.8	3.8	2.4	6.8
BP7	2.4	2.4	3.0	6.2	3.2	5.0	1.8	3.6	5.0	3.6	3.6	3.8	3.0	1.8	4.4	3.6	3.8	2.4	1.8	3.0	3.6
BP8	5.2	3.0	2.6	4.4	4.4	4.4	3.8	2.4	3.2	2.6	1.8	1.2	3.6	6.2	2.6	2.6	2.0	1.8	5.2	2.0	1.8
BP9	3.2	3.0	1.8	4.6	3.6	5.6	2.4	1.8	5.4	4.6	3.2	2.4	1.2	1.2	4.2	3.2	4.0	4.0	2.4	5.6	3.6
BP10	3.6	5.0	4.4	4.2	4.4	4.4	3.2	3.0	5.0	3.8	2.4	2.4	3.8	5.8	3.0	3.2	2.4	4.4	5.0	4.6	3.0
BP11	4.0	5.0	5.0	6.0	4.0	5.0	5.0	5.0	4.0	3.0	4.0	5.0	6.0	4.0	6.0	7.0	5.0	4.0	4.0	5.0	4.0
BP12	5.4	6.0	2.4	3.0	3.6	6.2	1.8	1.2	3.0	1.2	1.2	0.6	0.6	1.2	1.2	1.2	1.2	1.2	1.2	1.8	6.2
BP13	6.0	2.6	3.0	4.6	3.8	3.0	2.4	3.0	5.4	1.2	1.2	1.2	1.2	1.2	1.8	1.8	1.2	0.6	3.2	1.2	6.0
BP14	3.2	5.4	4.8	1.2	4.0	4.8	3.6	3.8	3.8	1.8	1.2	1.2	1.2	3.2	1.2	1.2	1.2	2.4	1.2	1.2	6.0
BP15	6.0	5.0	3.8	6.6	5.2	3.8	4.4	3.6	7.2	4.6	4.0	5.0	3.6	2.4	3.4	2.4	3.2	5.6	4.8	2.0	6.8
BP16	5.2	3.6	5.0	3.0	5.0	4.8	4.2	4.8	6.2	3.6	1.8	1.8	2.0	0.6	1.2	3.6	3.2	3.2	5.6	1.8	6.2
BP17	3.8	1.8	2.4	2.0	2.4	1.2	2.6	3.0	3.8	3.8	1.8	1.8	3.6	2.4	2.4	4.8	3.0	2.6	2.4	2.4	4.0
BP18	4.4	4.4	4.4	2.4	4.0	4.4	1.2	4.2	5.6	3.2	1.8	1.2	0.6	1.4	0.6	1.4	1.2	1.8	2.6	2.4	6.6
BP19	6.0	3.6	3.6	2.4	4.8	6.0	2.4	3.0	6.6	3.8	2.4	2.4	1.2	1.2	0.6	1.2	1.2	4.0	6.0	1.8	7.2
BP20	4.4	1.2	0.6	4.0	3.8	2.4	1.2	1.8	3.2	2.6	5.4	5.0	2.4	3.0	5.0	1.8	2.6	4.4	3.8	2.4	5.0
BP21	2.4	1.2	2.4	3.6	3.2	0.6	5.0	1.2	1.8	7.2	3.2	1.8	0.6	1.8	4.4	2.4	2.4	7.8	2.4	6.6	2.4
BP22	2.4	2.4	2.4	3.6	3.6	3.0	3.6	1.2	1.2	5.6	2.4	3.6	2.4	6.0	4.8	1.8	3.0	7.8	2.4	2.4	1.8
BP23	4.6	5.6	3.6	2.4	6.6	7.2	3.6	1.8	3.8	3.8	2.4	2.4	2.4	2.4	2.4	3.0	3.0	3.6	5.6	3.0	2.4
BP24	2.4	3.0	3.6	7.2	1.8	3.8	1.8	5.0	1.8	3.0	6.6	7.2	7.0	1.2	4.8	7.0	7.8	1.0	1.2	6.2	1.2
BP25	2.4	3.0	3.0	1.8	1.8	2.4	4.2	3.6	1.8	1.2	1.2	1.2	2.4	6.0	2.4	2.4	3.0	2.4	2.4	7.0	1.2
BP26	1.2	1.2	1.2	1.8	2.4	1.8	2.4	1.8	3.2	6.6	2.4	3.6	2.4	3.0	5.6	3.0	3.0	7.2	3.0	1.2	1.2
BP27	4.8	4.8	3.0	7.2	4.0	4.6	1.2	2.0	5.2	4.6	4.6	7.8	5.8	1.2	6.6	1.8	7.8	5.0	4.4	1.8	7.2

Note: Different shades of gray represent different intensities of relations between practices and wastes. The darker, the stronger the relation

Figure 2.
Submatrix of relations R

and continuous replenishment, BP24 – standardized work procedures to assure quality achievement and BP27 – integrated information technology system stand out.

Among the wastes, some show strong relationships with a greater number of practices and, consequently, with more SC areas. These include problem W41 – wrong or inaccurate demand forecasting or multiple types of forecasts used at different stages of the SC, problem W17 – demand amplification due to lack of synchronization of demand and activities, which can lead to the bullwhip effect and problem W13 – storing more than what is required by the customer at various stages of the SC. The submatrix filled with the weighted average of expert responses was inserted into the MM's final matrix in the Appendix. The model was then ready to be applied in companies, as shown in the next section.

4.3 Application of maturity model

We show the versatility of the proposed MM by considering three polar cases (companies from different sectors, sizes and countries).Polar cases provide for a more realistic perspective as they account for the assortment of case types within the industry (Eisenhardt and Graebner, 2007), which throws up rich and diverse learning longitudinally (Zairi and Al-Qurtas, 2003; Bhattacharya *et al.*, 2013). To protect the three companies' anonymity, they are referred to as Company A, Company B and Company C.

Company A is a large British-Dutch multinational company founded in the 1920s in the consumer goods business and owns over 400 brands. In its sector of activity, the company stands out and has a global performance in about 190 countries, which makes its supply chain more complex and makes it difficult to control, providing the occurrence of problems. The surveyed branch is in New Jersey, USA.

Company B has been a prominent mid-size optical company operating in Southern Brazil for over 40 years. Due to its sector, the company needs great agility and flexibility in its SC, as problems greatly impact the level of service delivered to its customers.

Company C, a large company in Santa Catarina State, Brazil, is one of Brazil's largest shipyards, focused on the production of luxury yachts for over 25 years. As it operates in a very specific and demanding market, in addition to delivering its yachts to customers around the world, the company has a differentiated SC, which needs a search for perfection and reduction of problem incidence.

To define each company's maturity level, the questionnaire to uncover the frequency and impact of the occurrence of LSCM wastes was fulfilled by an expert in each company. According to the same table, these answers were given on the scale of Table 4 of Section 3.2 and later converted into numerical values. The responses are shown in Table 9.

The answers converted into numerical values composed the maturity matrix. Each company could obtain the maturity level within each LSCM practice pillar and the company's overall maturity level in the LSCM area. Company A achieved a maturity level of 4, according to the scale of Table 6. This company reached the same score in all LSCM pillars.Companies B and C achieved a score of 3 for maturity level for LSCM. However, Company B reached maturity 4 in some of the pillars of practices, differing from Company C, which reached maturity 3 in all pillars. Their maturity matrix can be seen in Table 10.

4.4 Combined analysis of results

The three companies studied here are of different sizes, located in different locations and represent different industries. Therefore, we do not compare the maturity results among them but analyze the model's outcomes in different scenarios. While observing each company's maturity score within the LSCM pillars, all companies' attained good outcomes in the elimination of the waste pillar (highest score). The pillars of logistics management, continuous improvement, and information technology management also stood out in the three companies' results. The maturity score of companies across all pillars can be seen in Figure 3.

From these maturity scores, it is possible to identify the company's maturity level in each pillar's practices, as shown in Table 10 of the previous section. Company A, which has maturity level 4 for LSCM, has also matched this level across all practice pillars. Company C has maturity level 3 for LSCM and this same level for all pillars of practices.

Despite presenting maturity level 3 for the LSCM, Company B presented level 4 in the logistics management, elimination of waste and information technology management pillars, presenting level 3 in the remaining five pillars. It is important to note that these were the three highest-rated pillars for this company, with the continuous improvement pillar ranking fourth. The two highest scores were on the same pillars for the three companies, with the elimination of waste being the highest scoring pillar and logistics management the second-highest scoring pillar.

Table 9.
Responses of the three companies to the questionnaire

Waste	Company A		Company B		Company C	
	Frequency	Impact	Frequency	Impact	Frequency	Impact
W1	Seldomly occur	Medium	Always occur	Medium	Seldomly occur	Extremely high
W2	Rarely occur	High	Frequently occur	Low	Frequently occur	Very high
W5	Never occur	High	Rarely occur	Very Low	Rarely occur	High
W10	Rarely occur	Very high	Seldomly occur	High	Frequently occur	Medium
W13	Seldomly occur	High	Frequently occur	Low	Seldomly occur	Very high
W14	Never occur	Low	Frequently occur	Medium	Frequently occur	High
W15	Rarely occur	Medium	Frequently occur	Medium	Seldomly occur	High
W16	Never occur	Very high	Seldomly occur	Very Low	Always occur	Very high
W17	Seldomly occur	Medium	Frequently occur	Low	Frequently occur	High
W19	Never occur	Extremely high	Frequently occur	Medium	Frequently occur	Very high
W24	Never occur	Low	Rarely occur	Medium	Frequently occur	High
W25	Never occur	Low	Seldomly occur	High	Frequently occur	High
W26	Never occur	Low	Frequently occur	Low	Always occur	High
W32	Never occur	High	Seldomly occur	Medium	Rarely occur	Medium
W34	Never occur	Medium	Rarely occur	High	Never occur	Extremely high
W35	Never occur	Very high	Always occur	High	Rarely occur	Extremely high
W36	Never occur	Medium	Rarely occur	High	Frequently occur	High
W38	Rarely occur	Medium	Rarely occur	High	Frequently occur	High
W39	Rarely occur	High	Rarely occur	Very high	Seldomly occur	Very high
W40	Never occur	Very low	Rarely occur	Medium	Rarely occur	Extremely high
W41	Seldomly occur	Very high	Seldomly occur	Very high	Always occur	Very high

Table 10. Companies A, B and C maturity matrix

	Lower lever il_i	Criticality level cr_i Company A	B	C	Upper level sl_i	Development score Ds_i Company A	B	C	Development score k pilla Ds_k Company A	B	C	Maturity score k pillar ML_k Company A	B	C	Overall maturity level GM Company A	B	C
JIT production																	
BP1	8,555.76	129,441.72	214,270.96	338,758.32	693,016.56	8.234	6.994	5.176	8.320	7.126	5.199	4	3	3	4	3	3
BP2	6,887.04	97,505.32	161,790.48	270,179.56	557,850.24	8.355	7.188	5.221									
BP3	8,682.28	122,266.72	206,772.96	346,484.40	703,264.68	8.365	7.148	5.137									
BP4	7,770.68	111,821.60	183,478.56	302,105.16	629,425.08	8.326	7.174	5.265									
Customer relationship management																	
BP5	9,743.56	132,740.56	232,289.28	388,674.04	789,228.36	8.422	7.145	5.139	8.252	7.103	5.079	4	3	3			
BP6	7,525.32	122,837.08	184,388.28	307,389.16	609,550.92	8.085	7.062	5.019									
Continuous improvement																	
BP7	6,710.16	81,014.84	155,316.80	258,984.60	543,522.96	8.616	7.232	5.301	8.575	7.193	5.44	4	3	3			
BP8	6,366.40	81,452.40	152,624.36	228,751.64	515,678.40	8.526	7.128	5.634									
BP9	6,924.40	85,326.80	160,915.28	262,240.44	560,876.40	8.585	7.22	5.391									
Top management commitment																	
BP10	7,678.84	94,866.12	170,734.08	283,877.52	621,986.04	8.581	7.346	5.504	8.367	7.137	5.181	4	3	3			
BP11	9,144.00	104,419.40	212,855.00	339,835.60	740,664.00	8.698	7.215	5.479									
BP12	5,300.96	82,503.48	136,160.64	220,416.60	429,377.76	8.18	6.914	4.927									
BP13	5,642.00	91,588.16	142,345.48	228,457.72	457,002.00	8.096	6.971	5.063									
BP14	5,666.80	82,963.08	130,305.36	234,095.36	459,010.80	8.295	7.251	4.961									
Supplier management																	
BP15	9,189.04	128,970.16	215,214.40	369,240.76	744,312.24	8.371	7.197	5.102	8.318	7.139	5.015	4	3	3			
BP16	7,590.92	110,135.48	181,003.28	308,749.60	614,864.52	8.311	7.144	5.041									
BP17	5,456.48	71,644.08	135,321.20	215,160.16	441,974.88	8.484	7.025	5.196									
BP18	6,044.04	92,888.40	141,569.40	255,386.16	489,567.24	8.204	7.197	4.843									
BP19	7,364.56	111,890.08	176,228.24	307,796.28	596,529.36	8.226	7.134	4.901									
Logistics management																	
BP20	6,332.84	83,752.36	147,020.76	246,690.04	512,960.04	8.472	7.223	5.256	8.603	7.29	5.496	4	4	3			
BP21	6,174.64	71,229.56	136,203.44	220,292.20	500,145.84	8.683	7.368	5.665									

(*continued*)

Table 10.

	Lower lever il_i	Criticality level cr_i Company A	B	C	Upper level sl_i	Development score Ds_i Company A	B	C	Development score k pilla Ds_k Company A	B	C	Maturity score k pillar ML_k Company A	B	C	Overall maturity level *GM* Company A	B	C
BP22	6,341.64	70,307.64	140,681.40	227,777.76	513,672.84	8.739	7.352	5.635									
BP23	7,434.36	95,344.92	172,942.52	278,884.24	602,183.16	8.522	7.217	5.436									
Elimination of waste																	
BP24	7,310.36	65,498.36	167,944.92	272,451.96	592,139.16	9.005	7.253	5.466	8.919	7.361	5.655	4	4	3			
BP25	5,044.72	52,078.88	107,113.36	172,549.20	408,622.32	8.835	7.471	5.85									
Information technology management																	
BP26	5,588.20	60,154.88	123,718.36	207,828.24	452,644.20	8.779	7.358	5.476	8.649	7.312	5.255	4	4	3			
BP27	9,140.88	117,400.84	209,042.92	371,639.92	740,411.28	8.52	7.266	5.043									

Note: GM = general maturity

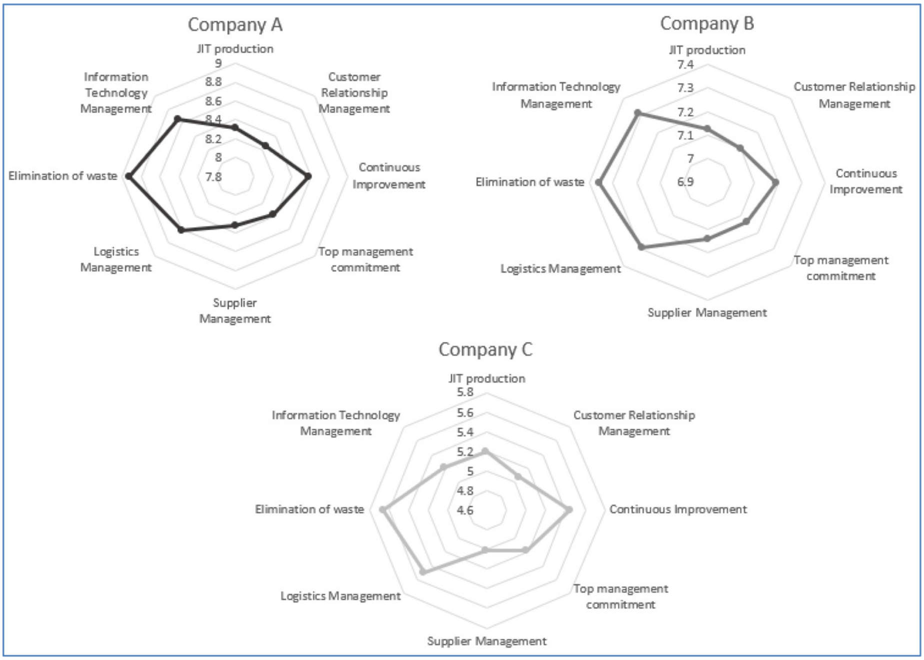

Figure 3.
Maturity score in the LSCM pillars of each company, with scales adapted to the values obtained by each one

Company A is a large company with a global presence and the consumer goods sector, with a make-to-stock production policy, which facilitates the scheduling of its products and supplies. Thus, it was expected that the company would present SC operations with better-structured practices and fewer problems. It is also the oldest company among the three analyzed, which makes it more experienced in its market.

Company C is the most recently established organization. One factor that hinders the control and predictability of its SC is the make-to-order production policy. Waiting for customer orders and specifications to be part of their purchasing and production makes the entire SC more complex, in addition to the fact that they act in a luxury market.

Company B, with an intermediate score, works with a strategy between make-to-stock and make-to-order: the postponement. Their products are stocked semi-finished and are finished only with the customer's order. In this way, the inbound part of their SC is simplified, as in a make-to-stock strategy. The outbound part, i.e. the distribution part, becomes more complex as in the make-to-order strategy.

4.5 Discussion

According to the extensive literature review by Tortorella *et al.* (2017), some LSCM practices stand out in citation numbers. Among the most cited practices are pulled system and leveled scheduling, both from the JIT production pillar. These practices are traditionally associated with lean, but the companies analyzed in this research did not have a high level of maturity in this pillar. This is possible because the companies had already consolidated and structured their production systems before the concern with the adoption of lean practices. In addition, according to Fedoskina *et al.* (2019), pulled systems require significant development from industrial participants and the capabilities of suppliers.

On the other hand, practices such as establishing distribution centers and consignment stock linked to the logistics management pillar are more recently being associated with LSCM (Tortorella *et al.*, 2017). Furthermore, according to Kumar Singh and Modgil (2020), lean becomes more strategic for companies as the competition is focused on a competitive supply chain, extending strategy beyond production. This explains the fact that these were the pillars with the highest maturity score for the companies and their recent rise in the literature.

The elimination of waste pillar had the highest maturity score in the three companies. This pillar represents one of the principles of lean philosophy, the elimination of the seven wastes of Ohno (1988), so it tends to be the first to be developed in trying to implement this philosophy in SC. Anand and Kodali (2008) stated that using IT elements can resolve or eliminate most of the seven wastes. This is following the results found, as the information technology management pillar stood out in the score, especially in the two companies with better maturity scores, which points to a lower incidence of waste.

For Jasti and Kodali (2015), the top management commitment is mandatory to implement any type of operational strategy in the organization. The practices associated with this pillar did not obtain a high maturity score, which could explain the lack of development of companies in the other pillars. According to these authors, this pillar supports all others in their quest for a high degree of development in LSCM. Thus, it is possible to observe that the results of the model were consistent with the existing literature in the area.

Moreover, implications for manufacturing strategy should be clarified, as it is one of the most relevant topics in the SC domain lately. Implementing lean principles may provide greater manufacturing efficiency, reduced cost and better flexibility and profitability (Vonderembse *et al.*, 2006). However, lean implementation has turned supply chains more vulnerable (by lowering buffers availability) to deal with unexpected disruptive events. Although lean practices may lead to higher performance results than resilient SC practices (Ruiz-Benitez *et al.*, 2018), it is relevant to mention the possible synergistic relationship between lean and resilient paradigms.

With the purpose of enhancing the firm's ability to cope with disturbances in the supply chain, some lean practices can help to increase resilience to unanticipated events (Birkie, 2016; Ruiz-Benitez *et al.*, 2019), such as the ones related to information sharing. In this matter, LSC practices encourage resilient SC practices when the purpose is to enhance the economic and operational performance. Additionally, some industry sectors, such as the automotive industry, have experienced significant reshoring lately (Qamar and Hall, 2018). Companies are rethinking the manufacturing strategy with a focus on better risk management, especially after the COVID-19 outbreak. LSC practices, such as efficient and continuous replenishment, deliveries in small lot sizes and close relationships between customer, supplier and relevant parties, appear to be linked to this trend toward the regionalization of manufacturing. However, reshoring must be considered as an alternate for manufacturers of some specific product categories rather than a general tendency that affects all manufacturing activities (Butollo, 2020).

5. Conclusion

This research aimed to develop a MM for LSCM assessment. This objective was achieved by means of a literature review, the use of FDM for selecting wastes and MM application in three companies. Next, we discuss the practical implications and limitations and future research.

5.1 Practical implications

The model proposed in this study can highlight external opportunities and threats and internal strengths and weaknesses in SCs. This information can help practicing managers to be more assertively focused on performance results across SC. In addition, a critical analysis of the factors used in generating the maturity score can provide managers with useful information. Experts' perspectives are useful in reducing uncertainties and enhancing the efficiency and effectiveness of the LSCM practices. Understanding and compiling data and observations on SC's most effective practices can help shape corporate strategies for implementing lean in SC. Thus, the knowledge of the most influential practices allows companies to draw up a list of priorities and formulate LSCM implementation actions. Moreover, this study's results can help academic researchers study the relationship between LSCM practices and waste management.

5.2 Limitations and future research

Despite sharing deep insights into LSCM and maturity with practical application, some limitations emerged from this research, which leaves room for future work in the field. First, future work may focus on creating a portfolio of improvements for companies based on their level of maturity and the lowest maturity scoring practices. In addition to the improvement portfolio, a joint action plan could be developed to increase its maturity level in the main points raised. Although the proposed model allows this type of analysis, the present research did not present the results in this way. One of the limitations for this was the impossibility of presenting the results to companies, mainly due to this research's time limitation.

Another suggestion for future endeavors is an analysis of the structure of the MM after its application. This analysis can be done with experts in the field, aiming to refine the proposed MM to make its results more accurate. The model was applied to three companies, and the results were analyzed for coherence and agreement with the existing literature. Still, no deeper analysis was made to improve the model structure. In addition, future research may target the MM's application in a larger sample of companies of various sizes and sectors, seeking to create reliable relationships between the contexts in which the companies are inserted and their maturity levels achieved with the application of the model.

Another limitation that could lead to future research is the level of SC digitalization. Future research can improve MM by considering the transformation of the physical products to "smart" artifacts, which are often problematic to firms involved in value-adding activities. Digitalization technologies such as cyber-physical systems and the internet of things are the latest trends in SC that could be instrumental in expanding this stream of research through efficient and effective data collection and analysis.

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Appendix

Table A1.
Maturity model

	Waste/problems														
	W1	W2	W5	W10	W13	W14	W15	W16	W17	W19	W24	W25	W26	W32	W34
	f_1	f_2	f_5	f_{10}	f_{13}	f_{14}	f_{15}	f_{16}	f_{17}	f_{19}	f_{24}	f_{25}	f_{26}	f_{32}	f_{34}
	i_1	i_2	i_5	i_{10}	i_{13}	i_{14}	i_{15}	i_{16}	i_{17}	i_{19}	i_{24}	i_{25}	i_{26}	i_{32}	i_{34}
	g_1	g_2	g_5	g_{10}	g_{13}	g_{14}	g_{15}	g_{16}	g_{17}	g_{19}	g_{24}	g_{25}	g_{26}	g_{32}	g_{34}
JIT production															
BP1	8.4	1.2	1.2	4.2	8.4	4.2	4.8	1.2	6.6	5.2	3.6	4.0	3.0	2.0	2.6
BP2	5.0	3.0	2.4	1.8	7.6	5.2	3.0	1.2	3.0	6.6	3.2	1.8	1.2	0.6	2.6
BP3	5.0	3.6	1.8	2.2	7.0	6.0	9.0	1.2	6.6	7.8	3.2	2.6	2.4	1.2	1.2
BP4	5.8	4.2	2.4	2.4	7.2	4.6	6.0	1.8	6.0	6.0	1.2	2.4	1.8	2.4	1.2
Customer relationship management															
BP5	6.6	4.6	3.0	5.2	5.4	4.6	4.4	3.0	7.2	7.6	6.0	2.4	4.2	1.8	4.0
BP6	7.8	6.4	2.4	4.2	6.6	4.8	2.4	1.2	7.2	3.6	1.8	1.2	0.6	1.2	1.2
Continuous improvement															
BP7	2.4	2.4	3.0	6.2	3.2	5.0	1.8	3.6	5.0	3.6	3.6	3.8	3.0	1.8	4.4
BP8	5.2	3.0	2.6	4.4	4.4	4.4	3.8	2.4	3.2	2.6	1.8	1.2	3.6	6.2	2.6
BP9	3.2	3.0	1.8	4.6	3.6	5.6	2.4	1.8	5.4	4.6	3.2	2.4	1.2	1.2	4.2
Top management commitment															
BP10	3.6	5.0	4.4	4.2	4.4	4.4	3.2	3.0	5.0	3.8	2.4	2.4	3.8	5.8	3.0
BP11	4.0	5.0	5.0	6.0	4.0	5.0	5.0	5.0	4.0	3.0	4.0	5.0	6.0	4.0	6.0
BP12	5.4	6.0	2.4	3.0	3.6	6.2	1.8	1.2	3.0	1.2	1.2	0.6	0.6	1.2	1.2
BP13	6.0	2.6	3.0	4.6	3.8	3.0	2.4	3.0	5.4	1.2	1.2	1.2	1.2	1.2	1.8
BP14	3.2	5.4	4.8	1.2	4.0	4.8	3.6	3.8	3.8	1.8	1.2	1.2	1.2	3.2	1.2
Supplier management															
BP15	6.0	5.0	3.8	6.6	5.2	3.8	4.4	3.6	7.2	4.6	4.0	5.0	3.6	2.4	3.4
BP16	5.2	3.6	5.0	3.0	5.0	4.8	4.2	4.8	6.2	3.6	1.8	1.8	2.0	0.6	1.2
BP17	3.8	1.8	2.4	2.0	2.4	1.2	2.6	3.0	3.8	3.8	1.8	1.8	3.6	2.4	2.4
BP18	4.4	4.4	4.4	2.4	4.0	4.4	1.2	4.2	5.6	3.2	1.8	1.2	0.6	1.4	0.6
BP19	6.0	3.6	3.6	2.4	4.8	6.0	2.4	3.0	6.6	3.8	2.4	2.4	1.2	1.2	0.6
Logistics management															
BP20	4.4	1.2	0.6	4.0	3.8	2.4	1.2	1.8	3.2	2.6	5.4	5.0	2.4	3.0	5.0
BP21	2.4	1.2	2.4	3.6	3.2	0.6	5.0	1.2	1.8	7.2	3.2	1.8	0.6	1.8	4.4
BP22	2.4	2.4	2.4	3.6	3.6	3.0	3.6	1.2	1.2	5.6	2.4	3.6	2.4	6.0	4.8
BP23	4.6	5.6	3.6	2.4	6.6	7.2	3.6	1.8	3.8	3.8	2.4	2.4	2.4	2.4	2.4
Elimination of waste															
BP24	2.4	3.0	3.6	7.2	1.8	3.8	1.8	5.0	1.8	3.0	6.6	7.2	7.0	1.2	4.8
BP25	2.4	3.0	3.0	1.8	1.8	2.4	4.2	3.6	1.8	1.2	1.2	1.2	2.4	6.0	2.4
Information technology management															
BP26	1.2	1.2	1.2	1.8	2.4	1.8	2.4	1.8	3.2	6.6	2.4	3.6	2.4	3.0	5.6
BP27	4.8	4.8	3.0	7.2	4.0	4.6	1.2	2.0	5.2	4.6	4.6	7.8	5.8	1.2	6.6
	p_i	121.6	96.2	79.2	102.2	121.8	113.8	91.4	70.4	122.8	112.2	77.6	77.0	70.2	66.4

(*continued*)

	Waste/problems W35 f_{35} i_{35} g_{35}	W36 f_{36} i_{36} g_{36}	W38 f_{38} i_{38} g_{38}	W39 f_{39} i_{39} g_{39}	W40 f_{40} i_{40} g_{40}	W41 f_{41} i_{41} g_{41}	Lower lever il_i	Criticality level cr_i	Upper level sl_i	Development score Ds_i	Development score k pillar Ds_k	Maturity score k pillar ML_k	Overall maturity level GM
JIT production													
BP1	2.4	1.8	6.6	4.4	1.6	6.0	8,555.76	cr1	693,016.56	DS_1	DS_{k1}	ML_1	GM
BP2	1.2	1.8	5.2	5.0	1.8	3.8	6,887.04	cr2	557,850.24	DS_2			
BP3	1.2	1.2	6.4	7.2	2.4	5.2	8,682.28	cr3	703,264.68	DS_3			
BP4	1.2	1.2	6.0	6.0	2.4	3.6	7,770.68	cr4	629,425.08	DS_4			
Customer relationship management													
BP5	4.0	2.8	5.6	6.0	3.6	6.6	9,743.56	cr5	789,228.36	DS_5	DS_{k2}	ML_2	
BP6	0.6	1.2	3.8	3.8	2.4	6.8	7,525.32	cr6	609,550.92	DS_6			
Continuous improvement													
BP7	3.6	3.8	2.4	1.8	3.0	3.6	6,710.16	cr7	543,522.96	DS_7	DS_{k3}	ML_3	
BP8	2.6	2.0	1.8	5.2	2.0	1.8	6,366.40	cr8	515,678.40	DS_8			
BP9	3.2	4.0	4.0	2.4	5.6	3.6	6,924.40	cr9	560,876.40	DS_9			
Top management commitment													
BP10	3.2	2.4	4.4	5.0	4.6	3.0	7,678.84	cr10	621,986.04	DS_{10}	DS_{k4}	ML_4	
BP11	7.0	5.0	4.0	4.0	5.0	4.0	9,144.00	cr11	740,664.00	DS_{11}			
BP12	1.2	1.2	1.2	1.2	1.8	6.2	5,300.96	cr12	429,377.76	DS_{12}			
BP13	1.8	1.2	0.6	3.2	1.2	6.0	5,642.00	cr13	457,002.00	DS_{13}			
BP14	1.2	1.2	2.4	1.2	1.2	6.0	5,666.80	cr14	459,010.80	DS_{14}			
Supplier management													
BP15	2.4	3.2	5.6	4.8	2.0	6.8	9,189.04	cr15	744,312.24	DS_{15}	DS_{k5}	ML_5	
BP16	3.6	3.2	3.2	5.6	1.8	6.2	7,590.92	cr16	614,864.52	DS_{16}			
BP17	4.8	3.0	2.6	2.4	2.4	4.0	5,456.48	cr17	441,974.88	DS_{17}			
BP18	1.4	1.2	1.8	2.6	2.4	6.6	6,044.04	cr18	489,567.24	DS_{18}			
BP19	1.2	1.2	4.0	6.0	1.8	7.2	7,364.56	cr19	596,529.36	DS_{19}			
Logistics management													
BP20	1.8	2.6	4.4	3.8	2.4	5.0	6,332.84	cr20	512,960.04	DS_{20}	DS_{k6}	ML_6	
BP21	2.4	2.4	7.8	2.4	6.6	2.4	6,174.64	cr21	500,145.84	DS_{21}			
BP22	1.8	3.0	7.8	2.4	2.4	1.8	6,341.64	cr22	513,672.84	DS_{22}			
BP23	3.0	3.0	3.6	5.6	3.0	2.4	7,434.36	cr23	602,183.16	DS_{23}			
Elimination of waste													
BP24	7.0	7.8	1.0	1.2	6.2	1.2	7,310.36	cr24	592,139.16	DS_{24}	DS_{k7}	ML_7	
BP25	2.4	3.0	2.4	2.4	7.0	1.2	5,044.72	cr25	408,622.32	DS_{25}			
Information technology management													
BP26	3.0	3.0	7.2	3.0	1.2	1.2	5,588.20	cr26	452,644.20	DS_{26}	DS_{k8}	ML_8	
BP27	1.8	7.8	5.0	4.4	1.8	7.2	9,140.88	cr27	740,411.28	DS_{27}			
	81.4	71.0	75.2	110.8	103.0	79.6	119.4						

Table A1.