Production Planning & Control
The Management of Operations

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/tppc20

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To cite this article: Flavio Sanson Fogliatto, Guilherme Luz Tortorella, Tarcisio Abreu Saurin, Andrea Furlan & Ambra Galeazzo (06 Nov 2024): Contribution of lean production to the resilience of the Brazilian automotive supply chain, Production Planning & Control, DOI: 10.1080/09537287.2024.2421897

To link to this article: https://doi.org/10.1080/09537287.2024.2421897

Published online: 06 Nov 2024.

PRODUCTION PLANNING & CONTROL
https://doi.org/10.1080/09537287.2024.2421897

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Contribution of lean production to the resilience of the Brazilian automotive supply chain

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ABSTRACT

We propose a method to assess companies' ability to cope with different types of disruptive events by developing resilience capabilities through Lean Production (LP) implementation. We use direct and reverse mathematical operations with two expert opinion-based matrices mapping relationships between LP practices and resilience capabilities, and resilience capabilities and types of disruptive events, obtained collecting opinions from 12 experts. We apply the method in two instances. First, using results from a survey with 135 practitioners from the Brazilian automotive industry regarding their adoption levels of LP practices. Direct matrix operations using this input indicated the development levels of eight resilience capabilities and the ability degree to cope with four types of disruptive events. Second, presenting four scenarios in which a company is exposed to high- and low-impact disruptive events of temporary and permanent nature, we perform reverse matrix operations to identify resilience capabilities and LP practices best fit to cope with each type of event. From the direct analysis of practitioners' data two LP practices (*supplier feedback* and *involved customers*) and two resilience capabilities (*provide a quick response to disruption* and *adapt to disruption easily*) stand out. These practices and capabilities mainly prepare companies to cope with high impact disruptions of permanent nature.

ARTICLE HISTORY
Received 24 April 2024
Accepted 21 October 2024

KEYWORDS
Lean production; resilience capabilities; disruptive events; expert opinion; relationship matrices

1. Introduction

The occurrence of disruptive events has always been present throughout history, e.g. natural disasters (Matsuo 2015), economic crises (Revilla and Saenz 2017), and geopolitical conflicts (Bueno-Solano and Cedillo-Campos 2014). Such events produce either temporary or permanent consequences to organisations, supply chains, and business models (Davison 2020; Katsaliaki, Galetsi, and Kumar 2022), therefore demanding countermeasures fit to the impact level. Recently, implications from the COVID-19 pandemic have once again raised the attention of researchers and practitioners to the relevance of resilience development in organisations and supply chains (Ivanov 2020). Effects have been noticed in several industries, varying from material and labour shortages to sudden variations in demand and the rise of new logistics patterns (Cugno et al. 2022; Narayanamurthy and Tortorella 2021; Remko 2020; Tortorella et al. 2024).

According to Ponomarov and Holcomb (2009), resilience is the adaptive ability to anticipate threats, respond to disruptions, and restore from them by keeping continuity of operations at the desired level of control. The interpretation and application of this concept have been recently expanded. For instance, Hollnagel (2014, 2017) proposed that resilient systems may be characterised by four interrelated abilities: monitor, anticipate, respond, and learn. Hosseini, Ivanov, and Dolgui (2019), based on Biringer, Vugrin, and Warren (2013) resilience capacity concept, suggested three groups of resilience capabilities: absorptive, adaptive, and restorative. Despite the different interpretations, there is a consensus among practitioners and academics about the importance of developing resilience capabilities so that organisations can cope with unplanned disruptions (Tortorella et al. 2022a).

At the same time, most manufacturing and services companies have embarked on Lean Production (LP) initiatives for the past three decades. LP promotes improvements in the flow of value through systematic waste reduction and people involvement (Furlan, Vinelli, and Dal Pont 2011; Womack, Jones, and Roos 2007). LP fosters socio-technical changes aligned with customers' (internal or external) expectations (Galeazzo and Furlan 2018; Soliman and Saurin 2017; Tortorella et al. 2015). Nevertheless, owing to the COVID-19 pandemic, a renewed debate has emerged regarding the impact of LP implementation on companies' resilience (Browning et al. 2023), particularly given the limited slack

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resources that characterise a lean operation and that may be fundamental to promoting resilience in the face of disruptive events. The trade-offs between leanness and resilience have been a topic of investigation. On the one hand, some studies (e.g. Birkie 2016; Tortorella et al. 2021, 2024) indicated that organisations must not quit their LP initiatives in order to cope with unplanned disruptive events, suggesting that most LP practices can be used to leverage resilience to mitigate disruptions' implications. On the other hand, there has been indications that when slack resources (e.g. extra staff, alternative suppliers, safety inventories, and generous time margins) are eliminated, organisations tend to become more vulnerable to disruptions (Chopra and Sodhi 2014; Taleb, Goldstein, and Spitznagel 2009), stretching the system and losing resilience. Such conflicting indications reflect the complexity of the relationships between LP and resilience regarding companies' ability to cope with disruptive events (Ruiz-Benítez, López, and Real 2018, 2019). In fact, LP, resilience, and disruptive events have different facets, and a number of combinations between these three constructs is possible – e.g. LP is composed of several principles and practices which are usually adopted to different extents, while resilience has both a proactive and a reactive dimension, and unexpected disruptive events can vary widely in terms of duration of their impacts. This complexity has not been addressed by prior studies which can explain their contradictory findings. Therefore, there is a need for an assessment method that accounts for such complexity, offering a more nuanced perspective of the relationships between lean and resilience to unexpected disruptions.

In this study, we propose a method to assess companies' ability to cope with different types of disruptions based on the development of resilience through LP implementation. The method builds on previous studies (i.e. Fogliatto, Silveira, and Royer 2003; Tortorella and Fogliatto 2014; Tortorella et al. 2022b) that proposed algebraic operations with relationship matrices. Two sequential relationship matrices are developed: one that associates lean practices with resilience capabilities and another that associates resilience capabilities with types of disruptive events. The existence of associations (or relationships) between pairs of elements in each matrix and their magnitude is assessed by a panel of 12 experts on LP and resilience. We illustrate the relationship matrices' direct analysis using responses from a survey carried out with Brazilian companies in the automotive sector. 135 respondents indicated the adoption level of 10 lean practices and this information was used as input in the first relationship matrix. Two results were obtained from the direct analysis: the development levels of eight resilience capabilities in the companies (from the first relationship matrix) and their ability to cope with four classes of disruptive events (from the second relationship matrix). The reverse analysis of the relationship matrices was illustrated simulating scenarios in which companies are faced with one of four classes of disruptive events obtained by combining high or low impact and temporary or permanent nature. The analysis pointed out which resilience capabilities and lean practices should be developed to increase the companies' ability to cope with each class of disruptive event. Our study contributes to the literature on LP and its impacts on resilient performance. We propose a method that can be used to diagnose companies regarding their resilience capabilities to cope with disruptive events. The central piece of our proposed analysis, an expert-based assessment of relationships between lean practices, resilience capabilities, and disruptive events, was validated for consistency using concepts from the Statis method (Lavit et al. 1994), which was designed to analyse subjective pairwise comparison data and has few applications reported in the OM field (e.g. Tortorella et al. 2022b). The method allows analysing simulated scenarios in which disruptive events take place, identifying lean practices best suited to support them. We are not aware of any other existing method that is similar with respect to its objectives.

Our research is empirical, grounded in the collection and analysis of real-world data to enhance operational processes. We employed two surveys—one targeting experts and the other practitioners—and conducted a simulated experiment to gather and analyse this data. Such approach allowed us to validate existing theories and derive practical insights, aiming to offer actionable recommendations that improve operational efficiency and effectiveness. Additionally, our research contributes to theoretical advancements in the field through the proposed method, thereby bridging the gap between practical applications and theoretical development.

The remainder of this paper is structured as follows. Section 2 brings a brief theoretical background on the main concepts related to our study. Section 3 describes the proposed method, with results presented in section 4 and discussed in section 5. Section 6 concludes the article and indicates future research opportunities.

2. Background

2.1. Lean production

Although initially observed in the manufacturing environment (Womack, Jones, and Roos 2007), the implementation of LP practices and principles has been adapted and expanded to different sectors, such as healthcare (Zepeda-Lugo et al. 2020), logistics (Trakulsunti et al. 2023, forthcoming), education (Waterbury 2015), and government (Radnor 2010). The benefits of LP implementation reported in various industry settings indicate the pervasiveness and versatility of its practices and principles, validating its relevance in supporting the achievement of more competitive performance levels.

A true LP implementation is characterised by many key success factors. For instance, Dora, Kumar, and Gellynck (2016) argued that the size of the plant, existing setup times, and layout flexibility influence LP implementation, especially in food-processing firms. Marodin and Saurin (2015) highlighted the importance of proper human and/or financial resources and employees' problem-solving skills. Schulze and Dallasega (2023) emphasised that the importance of these key success factors may vary according to the characteristics of the productive system, i.e. an engineer-to-order

productive system might value different factors than a make-to-order or make-to-stock.

Regarding its configurational approach, many researchers have dedicated efforts to defining the proper bundles of practices for a systemic LP implementation. Shah and Ward (2003) initially conceptualised LP as 22 interrelated practices grouped into four bundles, later expanded to 41 practices divided into ten internally consistent operational constructs (Shah and Ward 2007). Bortolotti, Boscari, and Danese (2015) complemented these studies by suggesting organisational and soft bundles for LP implementation. Finally, Galeazzo and Furlan (2018) examined whether different configurations of LP bundles could lead to successful financial performance, exploring their complementarities. Despite some specificities, literature on LP practices and their configuration is prolific and tends to converge on the implementation patterns observed in companies.

Lean has been examined at the intersection of various relevant concepts and themes. Examples include reviews by Pagliosa, Tortorella, and Ferreira (2019) on the interfaces between lean and Industry 4.0, and by Kumar and Mathiyazhagan (2020) on sustainability in lean manufacturing. In Section 2.3, we further explore works that investigate lean in the context of resilience development, which is central to our propositions.

2.2. Resilience and disruptive events

Various definitions of resilience are found in the literature, each with its own limitations (Kassa et al. 2023). For instance, from the management point of view, resilience is the organisational ability to respond and recover normal operations after a disruption occurs (Carpenter et al. 2001). However, this definition misses the point that organisations may not return to the same state after disruptions but to a different, sometimes improved one (Wieland and Durach, 2021), i.e. resilience is a matter of degree rather than a dichotomy of performing or not in a resilient manner. Although such an interpretation is commonly implicit, some researchers (e.g. Wieland 2021; Wiedmer et al. 2021) have explicitly acknowledged this view of resilience as not necessarily bouncing back to the same pre-disruption state.

A resilient system can restore an acceptable operating pattern within a reasonable time after a disruptive event (Brandon-Jones et al. 2014). Adapting to unplanned disruptions is a characteristic of resilience (Krause, Vachon, and Klassen 2009) obtained via continuous monitoring of the context in which the organisation is inserted so that it can reconfigure itself (Ambulkar, Blackhurst, and Grawe 2015). The development of resilience has been carried out through the proposition of various capabilities, such as collaboration between partners (i.e. customers, suppliers, and stakeholders), development of redundant suppliers, preservation of production capacity slack, determination of a pool demand, and an adequate balance between outsourcing and vertical integration (Pettit, Fiksel, and Croxton 2010; Scholten and Schilder 2015; Tang 2006; Wieland and Wallenburg 2013).

A resilient system differs from a robust system. The former adapts to disruptions and expands its original boundaries of acceptable performance, while the latter only withstands a predetermined range of disruptions (Bhamra, Dani, and Burnard 2011; Ivanov and Dolgui 2019). Another important distinction is between the concept of resilience and efficiency and effectiveness. While efficiency is the ability to prevent wasting resources in achieving a targeted result, effectiveness refers to the success level during the production of this targeted result (Jeong and Phillips 2001; Mouzas 2006). Although resilience development may be interrelated with achieving efficiency and effectiveness, they are not necessarily correlated. The organisation can be efficient and effective, but if not resilient, such efficiency and effectiveness will not be observed during (or even after) a disruptive event.

An indicator commonly used to assess an organisation's resilience is its ability to cope with disruptions, i.e. absorb, adapt, and restore after a disruptive event (Hosseini, Ivanov, and Dolgui 2019). Disruptions can occur in different forms, varying from the operational to the strategic level, including delays, quality obstacles in the production process, accidents, or equipment failure, as well as pandemics and natural hazards (Habib Rad, Mojtahedi, and Ostwald 2021). Disruptions can be classified in various ways. Chopra and Sodhi (2014) categorised disruptions according to their sources into nine groups: (*i*) disasters (e.g. natural disasters, terrorism, war), (*ii*) delays (e.g. inflexibility of supply source), (*iii*) systems (e.g. information infrastructure breakdown), (*iv*) forecast (e.g. inaccurate forecast, bullwhip effect), (*v*) intellectual property (e.g. vertical integration), (*vi*) procurement (e.g. exchange rate risk), (*vii*) receivables (e.g. number of customers), (*viii*) inventory (e.g. inventory holding cost, demand and supply uncertainty), and (*ix*) capacity (e.g. cost of capacity). Other criteria, such as frequency (Tang and Tomlin 2008), type, intensity, duration (Dolgui, Ivanov, and Rozhkov 2020), and impact level (Yu et al. 2019), are also often used to categorise disruptive events.

2.3. LP and resilience development

Research on the relationship between LP and resilience is relatively recent (see Table 1). Most scholars (e.g. Alemsan et al. 2022; Gayer, Saurin, and Anzanello 2022; Ivanov 2022) have suggested a positive association between LP practices and resilience capabilities. Nevertheless, some of the measures used by organisations to enhance resilience may conflict with LP principles (De Sanctis, Ordieres Meré, and Ciarapica 2018). For instance, LP prioritises the production of what is needed when it is needed, consequently minimising waste in the production system. Such inventory reduction may impair the system's ability to absorb unexpected disruptions related to an interruption in the materials flow (Ruiz-Benítez, López, and Real 2018). LP practices may also affect specific resilience capabilities differently, being an additional point of practical concern and theoretical questioning (Ahmed and Huma 2021).

Table 1. Works on the relationship between LP and resilience.

Author(s)	Objective	Findings
Birkie (2016)	To investigate synergy/trade-off relationships between LP and operational resilience paradigms upon disruption.	Synergetic relations between operational resilience and LP in mitigating performance losses outweigh the trade-off. Just-in-time and total productive maintenance appear to be major sources for the trade-off; there is limited-synergy leveraged on the anticipative (sense) capability of operational resilience.
Azadeh et al. (2017)	To conduct performance assessment from integrated resilience engineering and LP points of view.	Results showed that the pull system from lean and fault tolerance from resilience engineering have been implemented inappropriately, while other factors are either suitably executed or ineffective.
De Sanctis, Ordieres Meré, and Ciarapica (2018)	To develop a model able to calculate the resilience of a lean organisation while considering the organisational topology as well as the learning capacity and attitudes of its workforce.	The proposed methodology allows quantification and prediction of the local and global impacts of unexpected and expected events in companies undergoing lean implementation.
Ruiz-Benítez, López, and Real (2018)	To investigate the relationship and links between lean and resilient supply chain practices and their impact on performance.	Lean practices lead to a higher performance improvement than resilient practices, due to the fact that resilient practices do not exert influence over all performance metrics as it occurs with lean practices.
Rosso and Saurin (2018)	To discuss the joint use of principles of LP and resilience engineering.	Eight design propositions that support the framework application were developed. Both the framework and its corresponding propositions can contribute to the design of socio-technical systems that are at the same time safe and efficient.
Ruiz-Benítez, López, and Real (2019)	Lean and resilient practices applied to supply chains are studied in order to evaluate their impact on the three dimensions of sustainability.	Results reveal synergetic effects between lean and resilient practices. The former practices act as drivers of the latter practices. Hence, lean practices lead to direct and indirect effects in achieving supply chain sustainability.
Hundal et al. (2021)	To investigate how lean may help mitigate the impact of COVID-19 within healthcare environments.	Results report that personal safety is the primary subject, followed by supporting dimensions of process redesign, and telemedicine.
Ivanov (2022)	To present a framework that consolidates different angles of efficient resilience and renders utilisation of resilience capabilities for creation of value.	Ten future research areas for lean resilience integrating management and digital platforms and technology were identified.
Alemsan et al. (2022)	To identify the relationship between lean practices and resilience capabilities in the healthcare supply chain through a scoping review.	Three research directions are proposed: empirical validation of the contribution of lean practices to resilience capabilities in the health-care supply chain; systemic implementation of lean practices across tier levels of the health-care supply chain; and complementary approaches to lean implementation towards a more resilient health-care supply chain.
Tortorella et al. (2024)	To empirically examine how lean supply chains have coped with the disruptive effects of the COVID-19 pandemic from the normal accidents' theory perspective.	Results indicated that lean might effectively and quickly adapt to keep interactions as linear as possible through transparent information flows and collaborative work while at the same time temporarily reducing tight-couplings through inventory increases.

When managing the trade-off between LP and resilience development, some organisations undergoing LP implementation opt for prioritising resilience and keep high inventory levels to cope with disruptions (Sahu et al. 2022, forthcoming; Sezen, Karakadilar, and Buyukozkan 2012). To achieve a more balanced trade-off, Costantino et al. (2014) suggested inventory replenishment policies based on information sharing, increasing resilience when LP practices are implemented. Moreover, Lotfi and Saghiri (2018) argued that a higher level of leanness might result in faster recovery time and, hence, higher organisational resilience. In the same vein, Ruiz-Benítez, López, and Real (2018) indicated that LP practices act as drivers for resilience, suggesting that both approaches are closely interrelated. Nevertheless, guidelines to develop resilient organisations based on LP implementation in different disruptive scenarios are still missing, reinforcing our study's relevance.

3. Method

The proposed method is comprised of five steps: (*i*) data collection from practitioners, (*ii*) data collection from experts, (*iii*) consistency analyses, (*iv*) consolidation of relationship matrices, and (*v*) direct and reverse analyses using relationship matrices. These steps are described in the following subsections.

3.1. Data collection from practitioners

To determine the adoption level of LP practices, we considered the 10 LP operational constructs a_i $(i = 1, \ldots, 10)$ proposed by Shah and Ward (2007) as proxies, namely: a_1 – supplier feedback, a_2 – just-in-time (JIT) delivery, a_3 – developing suppliers, a_4 – involved customers, a_5 – pull, a_6 – flow, a_7 – low setup, a_8 – controlled processes, a_9 – involved employees, and a_{10} – productive maintenance. The constructs have been widely acknowledged among researchers and their rationale is well understood by practitioners (Bhamu and Sangwan 2014; Bortolotti, Boscari, and Danese 2015). Further, the consolidation of LP practices into these constructs facilitates the utilisation of experts' opinions (subsequent step of our method) and supports a more reasonable discussion of our findings, justifying our choice.

Respondents indicated the adoption level of each LP practice in their companies using a scale from 1 (no adoption) to 5 (full adoption).

The following selection criteria were established to collect data from practitioners regarding the adoption levels of LP practices: First, to align with the purpose of our study, all respondents needed to work for manufacturers that are currently implementing LP practices in the automotive industry. This criterion was set to ensure that our findings could be more readily generalised to organisations within this sector. The automotive industry has been implementing LP for over three decades (Marodin et al. 2016, 2019), indicating a high level of LP maturity. This extensive experience provides a suitable context for conducting this research effectively. Second, all companies should be based in the same country (i.e. Brazil) to control for socio-economic context effects (Erthal and Marques 2018). Third, all respondents should hold key leadership positions (e.g. middle or senior managers) within their companies. This ensures they have a comprehensive view of the organisation, legitimising their perceptions. Finally, we aimed to include participants from various tiers of the automotive industry to obtain a more comprehensive sample, which would enable us to accurately assess the readiness of the Brazilian automotive supply chain.

The data collection instrument was comprised of two parts: one that collected demographic information about the respondents to establish the sample profile, and another that asked about the implementation level of LPs within companies. Since 2008, the researchers have been conducting professional education courses on LP at leading universities in Brazil. This has enabled the establishment of an extensive database containing contacts and information from Brazilian practitioners and companies, predominantly from the South and Southeast regions, which are the most industrialised. We screened this database to identify respondents who met the selection criteria. In May 2022, an email with the questionnaire was sent to 350 potential respondents, resulting in 135 completed responses (a 38.57% response rate). The characteristics of the respondents are shown in Table 2. Most companies were large-sized (65.19%) and from tiers 3 and 4 (51.11%). Respondents were predominantly supervisors or coordinators (54.81%) with more than five years of experience.

3.2. Data collection from experts

Twelve experts with at least 15 years of both practical and academic experience in LP (see Table 3) were invited to individually evaluate the relationships displayed in two correspondence matrices. We determined the number of experts based on Boddy (2016), who suggests that saturation in qualitative data collection may be achieved with samples of 12 respondents if they are homogeneous. Despite some variations in their backgrounds (e.g. management or engineering), all experts have taught, researched, and conducted consultancy activities, and/or held leadership roles related to LP.

The first matrix ($\mathbf{M}^1$) maps the relationships between LP practices (rows) and resilience capabilities (columns). Eight capabilities proposed by Tortorella et al. (2022a) are adopted; they are listed in the columns of Table 4. The relationship intensity m_{ij}^1 indicates to what extent resilience capability j benefits from adopting LP practice i. The second matrix ($\mathbf{M}^2$), presented in Table 5, maps the relationships between the same resilience capabilities analysed in $\mathbf{M}^1$ (rows) and four disruptive scenarios (columns) obtained by combining two factors, each at two levels: impact intensity level (Yu et al. 2019) and duration of the implications (Dolgui, Ivanov, and Rozhkov 2020). The disruptive scenarios are (*i*) mild impact with temporary implications (i.e. $\leq$ one year), (*ii*) mild impact with permanent implications (i.e. $>$ one year), (*iii*) high impact with temporary implications, and (*iv*) high impact with permanent implications. The relationship intensity m_{jk}^2 indicates to what extent the development of resilience capability j prepares the company for disruptive scenario k, in terms of mitigating its effects.

Relationship intensities in $\mathbf{M}^1$ and $\mathbf{M}^2$ are measured using a scale varying from 0 (no relationship between the pair of elements) to 9 (strong relationship between the pair of elements). In $\mathbf{M}^1$, 80 pairs of elements were evaluated by each expert; in $\mathbf{M}^2$, 32 pairs of elements were assessed. In section 3.4, we present the strategy adopted to combine assessments from all experts into two consolidated matrices $\overline{\mathbf{M}}^1$ and $\overline{\mathbf{M}}^2$ (see Tables 4 and 5, respectively).

3.3. Consistency analyses

Data collection from practitioners used a survey; therefore, the quality of survey items and the consistency of responses were assessed using traditional method bias verifications and reliability metrics. The following actions suggested by Podsakoff et al. (2003, 2012) to address common method bias were adopted: (*i*) randomisation of items in the questionnaire to avoid associations of those belonging to the same construct, (*ii*) use of a study sample that only included respondents directly related to lean implementation in the companies, and (*iii*) make respondents aware that responses would be kept anonymous and that there were no right answers. Common method bias was statistically verified

Table 2. Respondents' characteristics (left) and experts' profiles (right).

Company size			Tier level		
$\leq$ 500 employees	47	34.81%	1 and 2	66	48.89%
$>$ 500 employees	88	65.19%	3 and 4	69	51.11%
Role			**Work experience**		
Supervisor or Coordinator	74	54.81%	$\leq$ 5 years	32	23.70%
Manager or Director	61	45.19%	$>$ 5 years	103	76.30%

Table 3. Experts' profiles.

Expert	LP experience	Background	Expert	LP experience	Background
E_1	20 years	Engineering	E_7	23 years	Management
E_2	28 years	Management	E_8	16 years	Management
E_3	17 years	Engineering	E_9	27 years	Engineering
E_4	15 years	Engineering	E_{10}	25 years	Engineering
E_5	16 years	Management	E_{11}	17 years	Management
E_6	18 years	Engineering	E_{12}	35 years	Management

Table 4. Compromise matrix $\overline{\mathbf{M}}^1$

		$\overline{\mathbf{M}}^1$	Resilience capabilities (j = 1,…,8)							
Lean practices (i = 1,…,10)		Adoption level	Learning from experience	Financially adept to proactively meet contingencies	Always maintain high situational awareness	Provide a quick response to disruption	Cope with changes brought by disruption	Adapt to disruption easily	Recovery to normal operations speedily after disruption	Easy and fast access to knowledge when facing an operational failure
Supplier related	Supplier feedback	a_i	6.23	5.00	7.32	5.76	5.43	5.60	5.09	6.32
	JIT delivery		4.42	5.25	5.68	7.09	5.77	6.25	5.32	4.33
	Developing suppliers		5.50	5.17	5.49	6.74	7.00	7.42	6.58	5.17
Customer related	Involved customers		6.50	5.27	6.99	6.26	6.84	6.67	5.95	5.93
Internally related	Pull		5.17	5.76	5.01	6.75	6.85	7.00	6.91	5.25
	Flow		5.76	6.61	6.45	6.92	6.52	6.17	5.49	5.16
	Low setup		5.25	5.84	5.42	7.41	6.99	7.17	5.66	4.17
	Controlled processes		5.06	4.83	6.07	6.66	6.83	5.58	5.59	5.41
	Involved employees		7.07	4.77	6.51	6.67	6.42	6.93	6.50	7.57
	Productive maintenance		5.83	5.57	5.27	5.33	5.02	5.51	6.59	6.49
Development of resilience capabilities						d_j				

using Harman's single factor test. Since 26.54% of the variance was loaded into the first factor, below the 50% threshold established by Malhotra (2016), common method bias was disregarded as a problem. Responses' consistency was verified through the Cronbach alpha calculation. An alpha result of 0.805 suggested the ten-item perceptual scale was reliable.

Data collected from experts comprised pairwise comparisons of items. To assess the quality of responses, we applied the Statis method originally proposed by Escoufier (1987). Statis is based on the Hilbert-Schmidt scalar product, which is a multivariate distance metric between pairs of data tables (in our case, relationship matrices), given by:

$$\langle \mathbf{X}_b | \mathbf{X}_{b'} \rangle_{HS} = Tr(\mathbf{X}_b \mathbf{X}_{b'}), \tag{1}$$

where $\mathbf{X}_b = \mathbf{M}_b \mathbf{M}_b^t$ and b and b' designate the pair of matrices whose distance is being calculated, containing assessments from experts b and b'. If $\langle \mathbf{X}_b | \mathbf{X}_{b'} \rangle_{HS} = 0$, tables $\mathbf{M}_b$ and $\mathbf{M}_{b'}$ are not significantly correlated.

When using normalised matrices $\mathbf{X}_b$ in Equation (1), scalar product results correspond to vector correlation coefficients between pairs of tables, which are organised in a square matrix $\mathbf{S}$ diagonalisable through principal component analysis. A graphic representation of the distances between matrices $\mathbf{X}_b$ is obtainable by projecting them onto factorial plans whose coordinates are given by:

$$\mathbf{c}_{b,i} = \sqrt{\lambda_i} \mathbf{v}_i, \tag{2}$$

where $\mathbf{c}_{b,i}$ gives the coordinates of data table b on the i-th factorial axis, and λ_i and $\mathbf{v}_i$ are the corresponding eigenpair associated with the i-th principal component of $\mathbf{S}$.

The first factorial plan coordinates of matrices $\mathbf{M}_b^1$ $(b = 1, \ldots, 12)$ and $\mathbf{M}_b^2$ $(b = 1, \ldots, 12)$ are given in Table 6 (*top*), along with the amount of variability accounted for by the first two components in each case. Table 6 (*bottom*) provides the graphical representations using those coordinates. Both graphs present a homogeneous distribution of experts on the first factorial plan, which is an indicator of agreement. Note that the first PC accounts for most of the information in matrices $\mathbf{M}^1$ and $\mathbf{M}^2$, which is indicative of alignment in assessments from experts.

3.4. Consolidation of relationship matrices

In this step, we create relationship matrices $\overline{\mathbf{M}}^1$ and $\overline{\mathbf{M}}^2$ that combine experts' assessments using the amount of information in matrices and the degree of agreement between experts as importance weights. For that, we use the concept of compromise matrix from Statis, which is given by the weighted sum of matrices $\mathbf{M}_b$; for example, $\overline{\mathbf{M}}^1 = \sum_{b=1}^{12} w_b^1 \mathbf{M}_b^1$. Weights w_b^1 and w_b^2 are obtained from the first eigenpair of $\mathbf{S}^1$ and $\mathbf{S}^2$, respectively, i.e.:

$$w_b = \left| \left(1/\sqrt{\lambda_1} \right) \mathbf{v}_1^{(b)} \right|, \tag{3}$$

where λ_1 is the first eigenvalue of $\mathbf{S}$ and $\boldsymbol{v}1(b$ is the b-th element of the eigenvector associated with λ_1. Normalised importance weights for the experts used to obtain matrices $\overline{\mathbf{M}}^1$ and $\overline{\mathbf{M}}^2$ are given in Table 6. Note that experts' weights

Table 5. Compromise matrix $\bar{\mathbf{M}}^2$

$\bar{\mathbf{M}}^2$			Development of resilience capabilities	Types of disruptions ($k = 1, \ldots, 4$)			
				Mild impact – Temporary	Mild impact - Permanent	High impact - Temporary	High impact - Permanent
Resilience capabilities ($j = 1, \ldots, 8$)	Absorptive capabilities	Learning from experience	d_i	3.91	6.16	4.82	6.99
		Financially adept to proactively meet contingencies		5.49	5.41	6.07	6.17
		Always maintain high situational awareness		4.82	6.00	5.41	6.35
	Adaptive capabilities	Provide a quick response to disruption		6.10	5.78	6.42	6.02
		Cope with changes brought by disruption		5.16	5.84	6.18	7.02
		Adapt to disruption easily		5.66	6.76	6.35	6.96
	Restorative capabilities	Recovery to normal operations speedily after disruption		5.50	5.29	6.16	5.86
		Easy and fast access to knowledge when facing an operational failure		5.33	6.33	5.85	6.94
Ability to cope with disruptions					h_k		

are inversely proportional to their distances from the main clusters of experts in Table 6 (*bottom*); e.g. $b = 1$ has the lowest weight in $\overline{\mathbf{M}}^1$ and $b = 1, 6$, and 7 have the lowest weights in $\overline{\mathbf{M}}^2$. Matrices $\overline{\mathbf{M}}^1$ and $\overline{\mathbf{M}}^2$ correspond to the central portion of Tables 4 and 5, respectively.

3.5. Direct and reverse analyses using relationship matrices

We propose two analyses with the relationship matrices. The first is the direct analysis. Consider the transposed vector $\mathbf{a}^t = [a_1, \ldots, a_{10}]$ containing average adoption level scores for the ten lean practices obtained from practitioners' responses. Consider $\overline{\mathbf{M}}^1 = \left[\overline{\mathbf{m}}_1^1, \ldots, \overline{\mathbf{m}}_8^1\right]$, such that vector $\overline{\mathbf{m}}_j^1$ contains the compromise scores for the j-th resilience capability obtained from experts. The development score d_j of resilience capability j is given by:

$$d_j = \mathbf{a}^t \overline{\mathbf{m}}_j^1, j = 1, \ldots, 8 \tag{4}$$

Organise development scores d_j in a transposed vector $\mathbf{d}^t = [d_1, \ldots, d_8]$. Consider $\overline{\mathbf{M}}^2 = \left[\overline{\mathbf{m}}_1^2, \ldots, \overline{\mathbf{m}}_4^2\right]$, such that vector $\overline{\mathbf{m}}_k^2$ contains the compromise scores for the k-th disruption type obtained from experts. The score that measures the ability to cope with disruption type k, denoted as h_k, is obtained by:

$$h_k = \mathbf{d}^t \overline{\mathbf{m}}_k^2, k = 1, \ldots, 4 \tag{5}$$

The direct analysis of relationship matrices allows identifying the types of disruptions the company is best prepared to cope with, given a vector $\mathbf{a}^t$ of lean practices' adoption scores. As an intermediate result, the analysis also gives development scores for the set of eight resilience capabilities in Table 5.

The relationship matrices' reverse analysis objective is to identify which lean practices best prepare a company to cope with disruptions of a given type. For that, it uses a simulated vector $\overleftarrow{\mathbf{h}}$ with entries $\overleftarrow{h}_k$ set to 1 or 0, according to the disruption type of interest. For example, if the analyst is interested in identifying lean practices that best prepare a company to cope with mild-impact/temporary disruptions, the vector to be used is $\overleftarrow{\mathbf{h}} = [1, 0, 0, 0]$. Vector $\overleftarrow{\mathbf{h}}$ is used in the first reverse calculation using matrix $\overline{\mathbf{M}}^2$, as follows (Fogliatto, Silveira, and Royer 2003):

$$\overleftarrow{\mathbf{d}} = \left(\overline{\mathbf{M}}^2 \overline{\mathbf{M}}^{2^t}\right)^{-1} \overline{\mathbf{M}}^2 \overleftarrow{\mathbf{h}} \tag{6}$$

In Equation (6), $\left(\overline{\mathbf{M}}^2 \overline{\mathbf{M}}^{2^t}\right)^{-1} \overline{\mathbf{M}}^2$ is the pseudo inverse of matrix $\overline{\mathbf{M}}^2$. The operation in Equation (6) allows identifying which resilience capabilities are important to cope with the disruptions whose scores were set to 1 in vector $\overleftarrow{\mathbf{h}}$. The resulting vector $\overleftarrow{\mathbf{d}}$ scores are zero-centered, and large positive scores are associated with important capabilities.

The second reverse calculation follows the same rationale, although using matrix $\overline{\mathbf{M}}^1$:

$$\overleftarrow{\mathbf{a}} = \left(\overline{\mathbf{M}}^1 \overline{\mathbf{M}}^{1^t}\right)^{-1} \overline{\mathbf{M}}^1 \overleftarrow{\mathbf{d}} \tag{7}$$

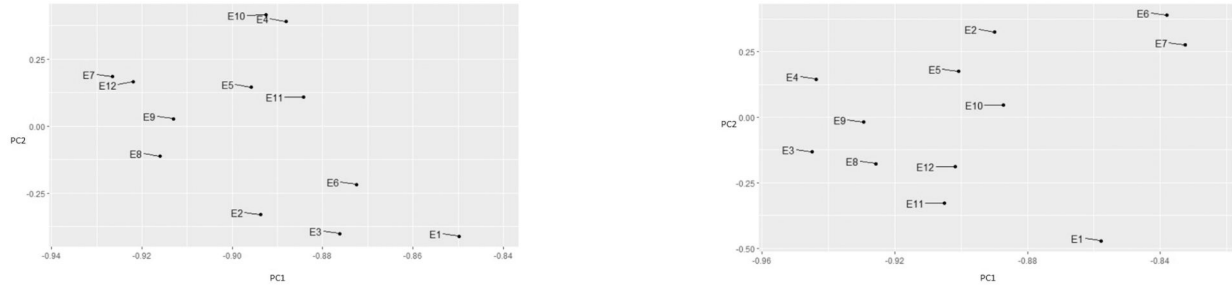
Vector $\overleftarrow{\mathbf{a}}$ scores are also zero-centered, and large positive scores identify lean practices whose adoption has the greatest impact on the ability to cope with the disruption type of interest. Following the guidelines from Tortorella and Fogliatto (2014), scores deviating negatively or positively from the average row score by one or more standard deviations were considered highly critical and were analysed and discussed. These scores are highlighted with black shading in Tables 7 and 8. Scores deviating positively from the average row score by 0.5 to 0.99 standard deviations were deemed critical, with the corresponding table cells shaded in grey.

4. Results

We first present the results of the analysis using responses from Brazilian automotive supply chain practitioners. We tested for paired differences in the means of the ten LP constructs obtained from practitioners in tiers 1&2 and 3&4, which resulted not significant. We, therefore, inputted in matrix $\overline{\mathbf{M}}^1$ the average of the implementation levels of lean practices overall companies surveyed. Results from applying Equations (4) and (5) are given in Table 7.

Table 6. *Top*: coordinates of the first factorial projection of matrices M^1 and M^2 (top). *Bottom*: projection of experts E1 to E12 on the first factorial plan of S^1 (left) and S^2 (right).

	M^1			M^2		
b	$c^1_{b,1}$	$c^1_{b,2}$	w^1_b	$c^2_{b,1}$	$c^2_{b,2}$	w^2_b
1	−0.850	−0.411	0.079	−0.858	−0.471	0.080
2	−0.894	−0.331	0.083	−0.890	0.325	0.083
3	−0.876	−0.401	0.082	−0.945	−0.132	0.088
4	−0.888	0.390	0.083	−0.944	0.145	0.088
5	−0.896	0.145	0.083	−0.901	0.174	0.084
6	−0.872	−0.218	0.081	−0.838	0.388	0.078
7	−0.926	0.184	0.086	−0.833	0.275	0.077
8	−0.916	−0.112	0.085	−0.926	−0.177	0.086
9	−0.913	0.027	0.085	−0.929	−0.019	0.086
10	−0.893	0.414	0.083	−0.887	0.046	0.082
11	−0.884	0.108	0.082	−0.905	−0.328	0.084
12	−0.922	0.166	0.086	−0.902	−0.189	0.084
% of variance explained by principal component (PC)		$PC_1 = 80\%$ $PC_2 = 8\%$			$PC_1 = 80\%$ $PC_2 = 7\%$	



The average lean practices adoption levels are similar. However, *supplier feedback* and *involved customers* stand out as the most extensively adopted, while the adoption of *JIT delivery* and *developing suppliers* are the least prominent. These four lean practices are externally related (Shah and Ward 2007), either referring to customers or suppliers. Regarding resilience development, two capabilities were prominently developed in the sample of companies from the Brazilian automotive supply chain: *provide a quick response to disruption* and *adapt to disruption easily*. In turn, the adoption level of lean practices in the sample of companies makes them not *financially adept to proactively meet contingencies*. Based on its current LP maturity, the Brazilian automotive supply chain seems to be more prepared to cope with disruptions that present high impact and permanent implications and less ready to deal with disruptive scenarios with temporary implications and mild impact.

We now report the results of the relationship matrices' reverse analysis. We simulated four scenarios obtained by combining two factors (impact intensity and duration of the implications) at two levels, as follows: (*i*) high ability to cope with mild-impact disruptions of temporary nature (i.e. input vector $\overleftarrow{\mathbf{h}} = [1, 0, 0, 0]$); (*ii*) high ability to cope with mild-impact disruptions of permanent nature (i.e. input vector $\overleftarrow{\mathbf{h}} = [0, 1, 0, 0]$); (*iii*) high ability to cope with high impact disruptions of temporary nature (i.e. input vector $\overleftarrow{\mathbf{h}} = [0, 0, 1, 0]$); and (*iv*) high ability to cope with high impact disruptions of temporary nature (i.e. input vector $\overleftarrow{\mathbf{h}} = [0, 0, 0, 1]$). The reverse analysis yielded vector $\overleftarrow{\mathbf{d}}$ as intermediate result and vector $\overleftarrow{\mathbf{a}}$ as final result. Table 8 presents results for scenarios (*i*) and (*ii*), and Table 9 presents results for scenarios (*iii*) and (*iv*). Scores in each row that positively deviated from the average row score by 0.5 to 0.99 standard deviations were deemed critical, while those that positively deviated by 1.0 or more standard deviations were regarded as highly critical for the corresponding disruptive scenario.

When mild-impact disruptions occur, the duration of their implications does not appear to be an influential factor since the most critical lean practices and resilience capabilities are the same in both temporary and permanent scenarios. *Involved customers* is the most critical lean practice to cope with mild-impact disruptions, followed by *pull*, *involved employees*, and *JIT delivery*. With regards to resilience, automotive manufacturers that develop capabilities such as *provide a quick response to disruption*, *easy and fast access to knowledge when facing an operational failure*, and *cope with changes brought by disruption* seem to be more prepared to face these disruptions.

When disruptions present a high impact, the criticality of lean practices and resilience capabilities varies according to the duration of implications. To deal with high-impact, temporary disruptions, three lean practices appear to be more critical; they are: *developing suppliers*, *supplier feedback*, and *flow*. In addition, the critical resilience capabilities for this scenario are *financially adept to proactively meet contingencies*, and *always maintain high situational awareness*. In turn, for high-impact, permanent disruptions, lean practices such as *involved customers*, *pull*, *involved employees*, *JIT delivery*, and *low setup* are the most critical. In terms of the resilience capabilities necessary for this scenario, *provide a quick response to disruption*, *cope with changes brought by*

Table 7. Direct analysis results using LP adoption levels informed by practitioners.

Lean practices	Supplier feedback	JIT delivery	Developing suppliers	Involved customers	Pull	Flow	Low setup	Controlled processes	Involved employees	Productive maintenance
Avg adoption level	**3.22**	**2.35**	**2.27**	**3.10**	2.58	2.85	2.50	2.64	2.79	2.74
Resilience capabilities	Learning from experience	Financially adept to proactively meet contingencies	Always maintain high situational awareness	Provide a quick response to disruption	Cope with changes brought by disruption	Adapt to disruption easily	Recovery to normal operations speedily after disruption	Easy and fast access to knowledge when facing an operational failure		
Development level	155.0	**146.2**	164.6	**176.4**	171.6	**173.0**	160.8	152.5		
Disruption type	Mild impact - Temporary	Mild impact - Permanent	High impact - Temporary	High impact - Permanent						
Ability to cope	**6,839.5**	7,740.1	7,698.7	**8,501.5**						

Note: Bolded gray cells indicate scores that negatively deviated from the average row score by one or more standard deviations. Black cells indicate scores that positively deviated from the average row score by one or more standard deviations.

disruption, and *easy and fast access to knowledge when facing an operational failure* are the most critical to be developed. Our results are consolidated in Figure 1.

5. Discussion

The relationship matrices' direct analysis outcomes indicated that the Brazilian automotive supply chain is likely to cope more effectively with disruptions that have high-impact and permanent implications, e.g. bounce back to sustained enhanced performance by using the crisis as an opportunity to develop innovative processes, enhance the workforce's problem-solving capacity, and strengthen collaborative networks at the supply chain level. Although high-impact, permanent disruptions are usually less frequent than the other types, they inevitably demand a response while allowing for learning over time based on several continuous improvement cycles (Akkermans and Van Wassenhove 2018). As a drawback, it is difficult to predict such disruptions, given the non-linear and low visibility nature of the underlying complex interactions (Roh et al. 2022; Taleb 2007). Responses to this type of disruption vary according to the level of analysis, i.e. inter- or intra-organisation. Between organisations, trust and dependence tend to be the main driving forces; within organisations, prior experience may be one of the most relevant aspects (Bode et al. 2011).

According to Zhu et al. (2017), supply chain collaboration stands out as a remedy for high-impact and permanent disruptions, positively affecting performance. Our results suggested that the Brazilian automotive supply chain has extensively adopted externally related lean practices that foster communication and trustworthy relationships, such as *supplier feedback* and *involved customers*. As a result, adaptive capabilities such as *provide a quick response to disruption* and *adapt to disruption easily* are more developed, contributing to the ability to cope with high-impact, permanent disruptions. In turn, absorptive capabilities that proactively promote resilience, such as *financially adept to proactively meet contingencies*, seem less prominent, highlighting a source of brittleness.

Findings from the relationship matrices' reverse analysis provide three main streams for discussion. First, when mild-impact disruptive events happen, the criticality of lean practices and resilience capabilities does not seem to alter according to the duration of the consequences. A possible interpretation for that relates to the necessary effort for setting up some practices and capabilities. Once they are deployed in case of mild impacts, the costs of maintaining the practice or capability may not be significantly affected (or may not grow linearly) whether they are sustained for the short or long term. Another possible and complementary interpretation is that mild impacts might be normalised in the sense that they reoccur frequently and become part of everyday work, whether their implications are short or long-lasting (de Vries, Erumban, and van Ark 2021; Roh et al. 2022). If mild disruptions frequently reoccur, even with short-lived implications, they might resemble the patterns of disruptions with long-lasting implications, thus blurring the distinction between both situations. In this scenario, lean practices that promote both customers' and employees' involvement, pull production system, and JIT delivery with suppliers seem to be critical, contributing to the provision of a quick response and coping with the disruption. In particular, pull systems are well-suited to mild-impact disruptions because lean companies typically have standardised inventory caps designed to accommodate relatively small

Table 8. Reverse analysis results simulating high ability to cope with mild-impact disruptions of temporary (top) and permanent (bottom) nature.

Scenario (*i*): high ability to cope with mild impact disruptions of temporary nature										
Lean practices	Supplier feedback	JIT delivery	Developing suppliers	Involved customers	Pull	Flow	Low setup	Controlled processes	Involved employees	Productive maintenance
Avg adoption level	-1,006	**584**	-2,184	**1,342**	**968**	-808	414	42	**800**	-206
Resilience capabilities	Learning from experience	Financially adept to proactively meet contingencies	Always maintain high situational awareness	Provide a quick response to disruption	Cope with changes brought by disruption	Adapt to disruption easily	Recovery to normal operations speedily after disruption	Easy and fast access to knowledge when facing an operational failure		
Development level	104	-784	-512	**408**	**296**	16	124	**304**		
Disruption type	Mild impact - Temporary	Mild impact - Permanent	High impact - Temporary	High impact - Permanent						
Ability to cope	1.00	0	0	0						
Scenario (*ii*): high ability to cope with mild impact disruptions of permanent nature										
Lean practices	Supplier feedback	JIT delivery	Developing suppliers	Involved customers	Pull	Flow	Low setup	Controlled processes	Involved employees	Productive maintenance
Avg adoption level	-705	**420**	-1,542	**962**	**671**	-570	298	12	**554**	-139
Resilience capabilities	Learning from experience	Financially adept to proactively meet contingencies	Always maintain high situational awareness	Provide a quick response to disruption	Cope with changes brought by disruption	Adapt to disruption easily	Recovery to normal operations speedily after disruption	Easy and fast access to knowledge when facing an operational failure		
Development level	74	-544	-352	**272**	**184**	7	68	**192**		
Disruption type	Mild impact - Temporary	Mild impact - Permanent	High impact - Temporary	High impact - Permanent						
Ability to cope	0	1.00	0	0						

Note: Gray cells indicate scores that positively deviated from the average row score by 0.5 to 0.99 standard deviations (i.e. critical). Black cells indicate scores that positively deviated from the average row score by one or more standard deviations (i.e. highly critical).

variations in demand. In addition, the involvement of customers and employees is key to reducing uncertainty in decision-making. This is particularly important during mild-impact events, where the implications of disruptions may not be as clear-cut as in high-impact disruptions. This aligns with the findings of Tortorella et al. (2015, 2020).

Second, in high-impact, temporary disruptive events, we found that lean practices that foster a closer relationship with suppliers (e.g. *supplier feedback* and *developing suppliers*) appear highly critical. This scenario is highly complex as the short-term and acute implications of the disruption make processes tightly coupled and possibly highly interactive, which can give rise to a non-linear and unexpected sequence of events as the disruption quickly unfolds (Rosso and Saurin 2018). Critical lean practices in this scenario also impact the development of resilience capabilities related to technical preparedness, such as *financially adept to proactively meet contingencies* and *always maintain high situational awareness*. This point can be illustrated by the need for financial reserves to cope with contingencies; this tends to be highly critical when the impact is high, and the consequences play out acutely in the short-term, demanding the quick deployment of large sums of money (Moretto and Caniato 2021). The relevant role of suppliers in this scenario

Table 9. Reverse analysis results simulating high ability to cope with high-impact disruptions of temporary (top) and permanent (bottom) nature.

Scenario (*iii*): high ability to cope with high-impact disruptions of temporary nature										
Lean practices	Supplier feedback	JIT delivery	Developing suppliers	Involved customers	Pull	Flow	Low setup	Controlled processes	Involved employees	Productive maintenance
Avg adoption level	**1,371**	-720	**2,751**	-1,538	-1,292	**977**	-456	-155	-1,238	384
Resilience capabilities	Learning from experience	Financially adept to proactively meet contingencies	Always maintain high situational awareness	Provide a quick response to disruption	Cope with changes brought by disruption	Adapt to disruption easily	Recovery to normal operations speedily after disruption	Easy and fast access to knowledge when facing an operational failure		
Development level	-86	**1,216**	**848**	-656	-496	-59	-204	-536		
Disruption type	Mild impact - Temporary	Mild impact - Permanent	High impact - Temporary	High impact - Permanent						
Ability to cope	0	0	1.00	0						
Scenario (*iv*): high ability to cope with high-impact disruptions of permanent nature										
Lean practices	Supplier feedback	JIT delivery	Developing suppliers	Involved customers	Pull	Flow	Low setup	Controlled processes	Involved employees	Productive maintenance
Avg adoption level	-337	**164**	-667	**410**	**256**	-204	**152**	2	**237**	-30
Resilience capabilities	Learning from experience	Financially adept to proactively meet contingencies	Always maintain high situational awareness	Provide a quick response to disruption	Cope with changes brought by disruption	Adapt to disruption easily	Recovery to normal operations speedily after disruption	Easy and fast access to knowledge when facing an operational failure		
Development level	46	-160	-176	**128**	**80**	-8	28	**64**		
Disruption type	Mild impact - Temporary	Mild impact - Permanent	High impact - Temporary	High impact - Permanent						
Ability to cope	0	0	0	1.00						

Note: Gray cells indicate scores that positively deviated from the average row score by 0.5 to 0.99 standard deviations (i.e. critical). Black cells indicate scores that positively deviated from the average row score by one or more standard deviations (i.e. highly critical).

might stem from the difficulty of seeking alternative suppliers during a short-term disruption. Under these circumstances, the existing suppliers must be reliable and capable of meeting their commitments despite the disruption implications. These goals might be challenging in the Brazilian automotive supply chain, as the adoption level of lean practices may vary according to the tier level of the organisation (Marodin et al. 2016). Nevertheless, the relationship with suppliers is crucial at a supply chain level (i.e. inter-organisation trust and collaboration) and to reinforce the improvement and stability of intra-organisational processes (Marodin et al. 2017), justifying the criticality of these lean practices.

The largest number of lean practices (5) and resilience capabilities (3) are necessary to cope with disruptions of high-impact and permanent implications, reflecting the high complexity and socio-technical nature of this scenario. *Involved employees* and *involved customers* are key to developing resilience capabilities over the long term, as the sustained response is likely to demand several cycles of continuous improvement, management of potentially conflicting goals, and the consequent continuous negotiation between the affected parties (Duong and Chong 2020; Scholten and Schilder 2015; Tortorella et al. 2021). For instance, these lean practices might be useful to address

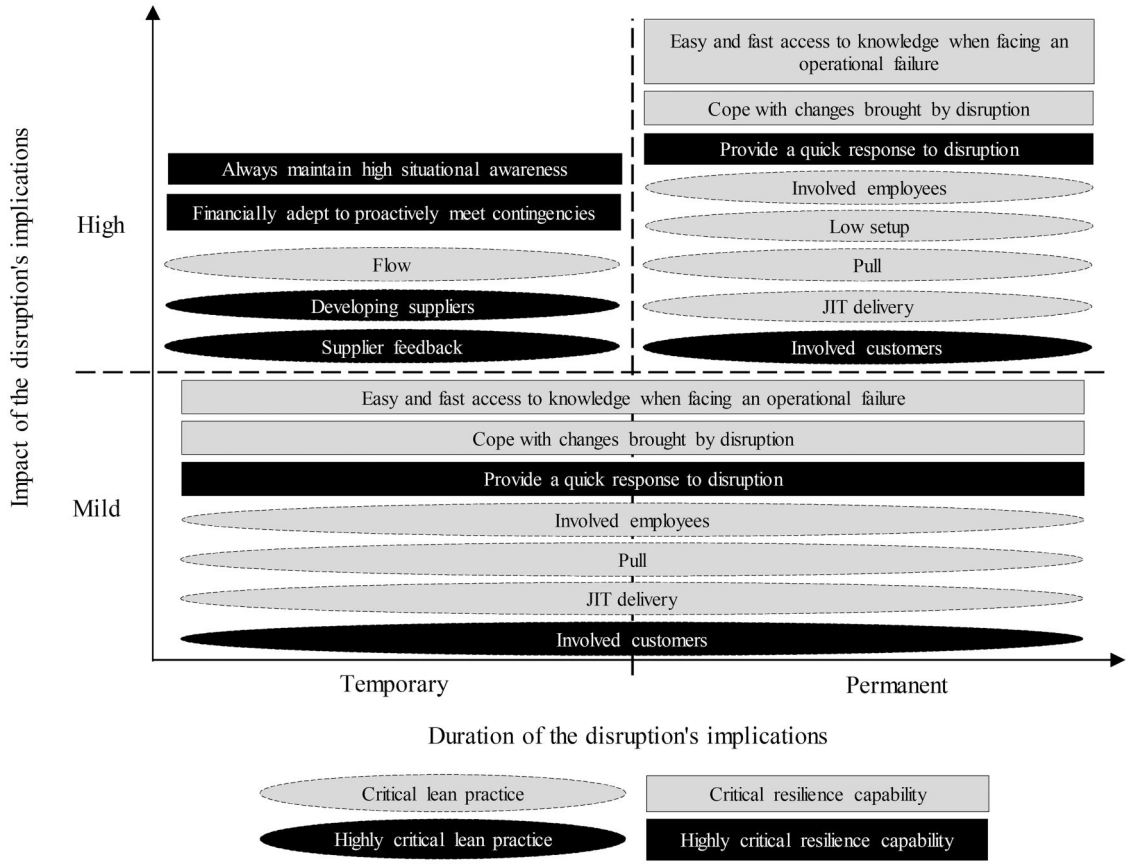


Figure 1. Recommended lean practices and resilience capabilities to cope with different types of disruptions in the Brazilian automotive supply chain.

conflicts related to greater tolerance for customer delivery delays and the willingness of employees to carry out extra activities (e.g. working extra hours and developing additional skills). Complementarily, lean practices that promote process flexibility (e.g. low setup) may help increase the organisation's capability to cope with high-impact, permanent disruptions (Tortorella et al. 2024) – in fact, these practices ultimately imply greater capacity slack, which is a versatile resource that can be used for coping with a wide variety and duration of disruptions. Pull production systems might also be useful in this context, although probably demanding closer monitoring of inventory levels and their frequent readjustment as the disruption unfolds in the long term.

In summary, our findings highlight that different disruptive scenarios, ranging from mild to high intensity with either temporary or permanent duration, require the combination of several different resilient capabilities and lean practices. Altogether these results demonstrate the *fit* between external contingencies and internal practices/capabilities, thus extending previous research on LP, resilience and contingency theory in the operations and supply chain management (e.g. Azadegan et al. 2013; Galeazzo, Furlan, and Vinelli 2021; Kroes and Ghosh 2010). In particular, our results reveal that soft lean practices such as *involved customers* and *involved employees* in combination with adaptive capabilities (i.e. *easy and fast access to knowledge when facing an operational failure*, *cope with changes brought by disruptions* and, most importantly, *provide a quick response to disruption*) are relevant in three scenarios: mild-temporary, mild-permanent and high-permanent. Such results corroborate the central role of the social dimension of LP, demonstrating its ability to develop resilient capabilities in resilient contexts (Bortolotti, Boscari, and Danese 2015). Moreover, contrary to previous literature highlighting the need of keeping high levels of inventory (Sahu et al. 2022, forthcoming; Sezen, Karakadilar, and Buyukozkan 2012), it emerges that the three scenarios are better managed if production processes keep low levels of inventory using JIT delivery and pull systems. Finally, the fourth scenario (high impact and short duration) requires a shift in the combination of LP and resilient capabilities. The focus should be on the supply-side of soft lean practices and on technical and proactive resilient capabilities (i.e. *financially adept to proactively meet contingencies* and *always maintain high situational awareness*). This scenario seems to better comply with the supply chain resilience investigated in prior literature (Costantino et al. 2014; Ruiz-Benítez, López, and Real 2018, 2019).

6. Conclusions

This research proposed a method to assess companies' ability to cope with different types of disruptions based on the development of resilience through LP implementation. The method was based on direct and reverse algebraic operations with relationship matrices. The relationships between pairs of elements in each matrix and their magnitude were assessed by a panel of 12 experts on LP and resilience. Its application was illustrated using responses from a survey

carried out with companies from the Brazilian automotive supply chain. Our results raised valuable insights to theory and practice in the field, as discussed below.

From a theoretical standpoint, this investigation enhances the body of knowledge on LP and its impact on resilience performance. The proposed method facilitates the assessment of companies' resilience capabilities and their ability to handle various types of disruptive events. It enables the analysis of companies' readiness for different disruptive scenarios, identifies lean practices most suitable for supporting them, and highlights the critical resilience capabilities needed. Additionally, we expanded the theoretical discussion on the relationship between LP implementation and the development of resilience capabilities by analysing how this relationship may vary across different disruptive scenarios. To our knowledge, no existing method matches ours in terms of its objectives. Therefore, we assert that this represents an original contribution to the theory.

In practical terms, our study provides managers and organisations with guidance on prioritising their LP implementation efforts to build resilience across various scenarios. The consistent and successful adoption of lean practices is often time-consuming and requires behavioural and technical changes that can be challenging to address. By early identifying the critical practices that can help companies navigate specific disruptive scenarios, organisations may gain competitive advantages when faced with such disruptions. Consequently, companies can develop targeted resilience capabilities that enhance their ability to absorb, adapt, and recover from different types of disruptions through the effective implementation of lean practices. Given that LP has been widely adopted across many industry sectors, particularly in the automotive industry (the context of our study), our findings offer valuable guidelines for leveraging existing approaches to foster resilience in alignment with the organisation's strategic perspective and its susceptibility to disruptive events.

Some limitations of this research should also be mentioned. First, we illustrated the proposed method within a single industry sector (automotive) and a single country (Brazil). While this focus enhances the internal validity and reliability of our findings within that specific context, it limits the generalisability of the results to other sectors and socio-economic settings. Therefore, future studies should incorporate a larger and more diversified dataset to provide broader insights into LP-based resilience. Second, the relationship intensities expressed in both proposed matrices relied on the perceptions of 12 experts, each tasked with the analysis of 112 pairs of elements. In our approach, the statistical significance of these relationships was not assessed. Future studies could focus on that, as these relationships may present different significance levels that could potentially impact the results. Third, we limited our approach to four types of disruptive scenarios classified by the duration and impact level of their implications. Although this classification is relatively common in the literature, other important aspects of disruption categorisation, such as geographical influence (i.e. local or global) and pervasiveness across supply chains, may also be relevant. Additionally, organisations are currently navigating the digital transformation era, which could introduce new implications for the relationship between LP and resilience development. Since our study did not address this, future research could explore this dimension to provide timely insights for both practice and theory.

Disclosure statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability statement

Due to the nature of this research, participants of this study did not agree to have their data shared publicly.

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