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Inventory record inaccuracy in supply chains: the role of workers' behavior

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Abstract

Purpose – The purpose of this paper is to explore the effect of inventory record inaccuracy due to behavioral aspects of workers on the order and inventory variance amplification.

Design/methodology/approach – The authors adopt a continuous-time analytical approach to describe the effect of inbound throughput on the inventory and order variance amplification due to the workload pressure and arousal of workers. The model is numerically solved through simulation and results are analyzed with statistical general linear model.

Findings – Inventory management policies that usually dampen variance amplification are not effective when inaccuracy is generated due to workers' behavioral aspects. Specifically, the psychological sensitivity and stability of workers to deal with a given range of operational conditions have a combined and multiplying effect over the amplification of order and inventory variance generated by her/his errors.

Research limitations/implications – The main limitation of the research is that the authors model workers' behavior by inheriting a well-known theory from psychology that assumes a *U*-shaped relationship between stress and errors. The authors do not validate this relationship in the specific context of inventory operations.

Practical implications – The paper gives suggestions for managers who are responsible for designing order and inventory policies on how to take into account workers' behavioral reaction to work pressure.

Originality/value – The logistics management literature does not lack of research works on behavioral decision-making causes of order and inventory variance amplification. Contrarily, this paper investigates a new kind of behavioral issue, namely, the impact of psycho-behavioral aspects of workers on variance amplification.

Keywords Arousal, Behavioural operations, Bullwhip effect, Inventory record inaccuracy, Workload pressure

Paper type Research paper



Nomenclature*Material flow variables*

W_t	Work in progress at time t
I_t	Physical inventory of finished materials at time t
S_t	Sales to market at time t
F_t	Physical throughput at time t

Information flow variables

\hat{d}_t	Customer demand forecast at time t
O_t	Replenishment order quantity at time t
B_{t-1}	Existing backlog of orders at time t
TI_t	Target inventory at time t
TW_t	Target work in progress at time t
FR_t	Work in progress record at time t
SR_t	Sales to market record at time t
IR_t	Inventory record at time t
TIR_t	Target inventory record at time t
IRI_t	Inventory record inaccuracy at time t
σ_D^2	Customer demand variance
σ_O^2	Order quantity variance
σ_I^2	Inventory variance

Behavioral variable

WP_t	Work pressure due to throughput level at time t
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Parameters

F_1^*	Ideal throughput level under which the workers are prone to oversights
F_2^*	Ideal throughput level over which the workers are under pressure
FR^*	Ideal throughput range length
ω	Magnitude of data entry errors
T_p	Physical production/distribution lead time (the time between order placement and the arrival of raw material supply and over the production lead time)
T_w	Work in progress proportional controller
T_I	Inventory proportional controller
SSF	Safety stock factor
α	Forecast smoothing factor

Introduction

The awareness that human beings are a critical factor in business models is not new: in the 1950s, Simon (1957) stated that people suffer from “bounded rationality” and therefore have a limited capability of solving complex problems and are often irrational or emotional. Disciplines such as economics, marketing, and finance, and later, in the 1990s, operations management, have accepted the removal of regulatory theories about the behavior of human subjects, enclosing theories from psychology and sociology. The result of this integration in operations management research is called Behavioral Operations Management (BOM), “an emergent approach to the study of operations which explicitly incorporates social and cognitive psychology theory” (Gino and Pisano, 2008).

In BOM several theories of social psychology, cognitive psychology, and organizational behavior are applied to several operations management fields, including inventory and supply chain management. Despite the quickly increasing number of papers recently published within this nascent behavioral supply management research stream, very few studies deal with behavioral aspect related to worker operations. For example, Cantor *et al.* (2012) recently investigated how employee perceptions of management practices influence employee engagement in environmental behaviors such as participating in environmental management activities. Also, Ellinger *et al.* (2005) empirically explored how warehouse workers’ satisfaction and performance is influenced by different the coaching behaviors of their supervisor.

However, most research in this field has concerned behavioral aspects related to decision makers. Katsikopoulos and Gigerenzer (2013) recently stated that “BOM aims at understanding the decision-making of managers and at using this understanding to generate interventions that improve the operation of the supply chain.” For example,

Kaufmann *et al.* (2012) empirically analyze debiasing variables of managers in the supplier selection process. Jin *et al.* (2013) analyze supply chain integration decisions under a “planned behavior” theory perspective. Carter *et al.* (2007), by reviewing extensive literature on judgment and decision-making biases, create an exhaustive taxonomy of decision biases which can affect supply managers.

One of the most addressed issues of behavioral supply chain management, related to decision-making biases, is the bullwhip effect, which according to Lee *et al.* (1997) refers to the “phenomenon where orders to the supplier tend to have larger variance than sales to the buyer” (p. 546). Many authors (Sterman, 1989; Croson and Donohue, 2002; Fildes *et al.*, 2009; Oliva and Watson, 2009; Croson *et al.*, 2014) track behavioral causes of the order and inventory variance amplification. The current theoretical literature about the behavioral causes of the bullwhip effect is, indeed, based primarily on the search and description of all cognitive biases and rules of thumb which affect the decision maker.

This paper, instead, investigates the effect of behavioral aspects of workers on the bullwhip effect. Specifically we focus on the specific issue of inventory record inaccuracy (IRI) generated due to behavioral aspects related to supply chain workers’ operations and the generation of the bullwhip effect itself. IRI (i.e. the deviation between the inventory record level and the physical inventory) has been identified as one of the main causes of supply chain uncertainty and performance deterioration (van der Vorst and Beulens, 2002). Also, it has been empirically demonstrated that there is an association between the environmental complexity which the worker has to face and the level of record inaccuracy (DeHoratius and Raman, 2008).

In this paper we propose an analytical model of a single-echelon supply chain where workers involved in the recording activity of inbound flow items make data entry errors because of workload pressure. We measure how such errors influence the bullwhip effect. The proposed analytical models are numerically analyzed through simulation, the parameters are set according to a full factorial design of experiment (DOE) and the simulation results are analyzed with statistical methods. The main contribution of this study is twofold:

- (1) *In primis*, we investigate a new kind problem in behavioral supply chain management. The model proposed in this paper focusses on cognitive psychology of workers and not of decision makers. Our findings suggest that further research is needed in this field. Recent research efforts have indeed been put on the analysis of the closed-loop among operations environment, decision makers’ behavior, and operations performance. The closed-loop relation among operations environment, workers’ behavior, and operations performance surely deserves further investigation.
- (2) *In secundis*, and more specifically, our model describes a situation in which an operation variable (the inbound throughput level) impacts workers’ behavioral aspects (workload pressure and arousal), which in turn impacts operations performance (inventory inaccuracy and supply chain performance). This kind of model and the simulation results can be used to think of new inventory and order management practices properly designed for dampening the negative effects of errors due to psycho-behavioral aspects.

The remainder of this work is organized as follows: Section 2 collects the review of relevant literature about behavioral operations and about behavioral supply chain management; in Section 3 we describe and operationalize our conceptual model, linking

worker behavior and supply chain performance; Section 4 reports the research methodological approach and the analytical model we use to conduct our study; the DOEs and the numerical results are described in Section 5; Section 6 provides findings and contributions of the research while conclusions are reported in the final section.

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supply chains

Behavioral operations, logistics, and supply chain management

Behavioral operations

We found that in recent years a lot of papers reviewing the literature of BOM have been published (Bendoly *et al.*, 2006; Bendoly and Hur, 2007; Gans and Croson, 2008; Gino and Pisano, 2008; Bendoly *et al.*, 2010; Tokar, 2010). For this reason, it is out of the scope of this paper to report an additional literature review on this topic. Our intention is just to give an overview of the recent research on this topic in sufficient detail in order to clearly position our research within the field, show how this paper fits in, fills in gaps, and advances the body of knowledge.

We observe that a wide variety of areas of logistics and operations management were analyzed under a behavioral lens or by using behavioral variables. Among them, the following can be cited: revenue management (Bearden *et al.*, 2008; Su, 2009; Bendoly, 2011); logistics and marketing coordination (Keller *et al.*, 2006); human resource management (McAfee *et al.*, 2002; Dal Forno and Merlone, 2010; Huckman and Staats, 2011); manufacturing process innovation (Azadegan and Dooley, 2010); service operations management (Bitran *et al.*, 2008; Veeraraghavan and Debo, 2011); knowledge management (Siemsen *et al.*, 2008); security management (De Koster *et al.*, 2011); process planning and scheduling (De Snoo *et al.*, 2011); and performance management (De Leeuw and van den Berg, 2011).

But, overall, undisputedly the most studied domain in the BOM is inventory and supply chain management (Powell Mantel *et al.*, 2006; Wu and Katok, 2006; Li and Wang, 2007; Su, 2008; Gavirneni and Isen, 2010; Oliva and Watson, 2011). The research of this paper falls into the same area. The following section deepens the analysis along this specific research domain.

Behavioral logistics and supply chain management

The link between logistics management and behavioral aspects has been studied with a focus on the study of human behavior in inventory and ordering processes, on the details of human interactions in supply chain relationships and on the decision biases which can affect supply managers (Carter *et al.*, 2007). Donohue and Siemsen (2011) identify two main research areas: individual decision making in supply chains and interaction in supply chains. In individual decision making the interest is directed toward the individual errors and biases in several contexts, such as judgmental forecasting, inventory management, and also product development. Regarding the interaction in supply chains, scholars apply behavioral theories (Amaral and Tsay, 2009), social exchange theory (Narasimhan *et al.*, 2009), and marketing theories (Keller *et al.*, 2006), to buyer-supplier interactions, multi-echelon inventory systems, the procurement market, and inter-functional marketing-logistics interactions (Ellinger *et al.*, 2006), to internal buyer-supplier interactions (Keller *et al.*, 2006), and to logistics employee-firm interactions (McAfee *et al.*, 2002).

Tables I and II present a summary of articles belonging respectively to the two above-mentioned research areas, and classify them according to the behavioral theories they use, the behavioral variables they treat, and their research methodology.

Table I.
Individual decisions
in supply chain
management

Article	BOM Theory/variable	BOM Body of knowledge	Methodology
Su (2008)	Bounded rationality	Cognitive psychology	Math modeling
Schweitzer and Cachon (2000)	Anchoring, minimizing <i>ex post</i> inventory errors	Cognitive psychology	Controlled experiment
Bolton and Katok (2008)	Feedback, experience	Social psychology	Controlled experiment
Croson <i>et al.</i> (2008)	Overconfidence, overprecision	Cognitive psychology	Math modeling
Bostian <i>et al.</i> (2008)	Bounded rationality, anchoring and insufficient adjustment, minimizing anticipated <i>ex post</i> inventory error, chasing and demand	Cognitive psychology	Controlled experiment
Carter <i>et al.</i> (2007)	Judgment bias, decision-making bias	Cognitive psychology	Review
Gavirneni and Isen (2010)	Overage risk, underage risk	Cognitive psychology	Controlled experiment

The most common topic within the area of “individual decision making” is the newsvendor problem. Most articles study the causes and consequences of several decision-maker biases, such as the overconfidence (Croson *et al.*, 2008), anchoring and desire to minimize *ex post* inventory error (Schweitzer and Cachon, 2000), and the pull-to-center effect (Bostian *et al.*, 2008); many authors also describe the behavior and learning dynamics in the newsvendor model (Bolton and Katok, 2008).

On the other side, within the area of “interactions in supply chains” the focus is more frequently on the bullwhip effect (Croson and Donohue, 2006; Wu and Katok, 2006; Syntetos *et al.*, 2011; Croson *et al.*, 2014). In the reviewed works the phenomenon is mainly studied from the point of view of cognitive psychology. Wu and Katok (2006) demonstrate that showing information or providing extra hand experience (through a program of targeted training) does not mitigate the variability of the supply chain; in contrast, the combined use of communication and training brings some improvements. Croson and Donohue (2006) test for the existence of a cognitive bias, under-weighting of the supply line, elimination of all operational causes of the bullwhip effect, as demand signal processing, inventory rationing, order batching, and price variations (Lee *et al.*, 1997). The work of Syntetos *et al.* (2011) provides an assessment of the positive impact of judgemental adjustments of the orders and demand forecasts on the dynamics of the supply chain and the authors analyze the influence of behavioral variables, such as the decision-maker optimism or pessimism when she/he carries out forecasting and ordering adjustments, on the entire supply chain. Croson *et al.* (2014) perform a set of laboratory experiments with a serial supply chain which test behavioral causes of the bullwhip effect. In particular they analyze the influence of the coordination risk on the demand amplification.

The literature review clearly shows that efforts to identify the causes of the bullwhip effect are concentrated on the area of cognitive psychology and the decision-maker subject. Personality issues, judgments, biases, and behavior of decision-makers are definitely analyzed more than the worker’s. Also, the most adopted research methodology is controlled experiment.

In conclusion, most of the studies explore the link between behavioral constructs related to supply chain managers and supply chain performance. The literature about

Article	BOM Theory/variable	BOM Body of knowledge	Methodology
McAfee <i>et al.</i> (2002)	Relational-transactional relationships	Organizational culture, strategic fit	Conceptual paper
Wu and Katok (2006)	Learning, communication, training, bullwhip effect	Cognitive psychology, group dynamics, organizational behavior	Controlled experiment
Powell Mantel <i>et al.</i> (2006)	Strategic vulnerability	Cognitive psychology	Controlled experiment
Ellinger <i>et al.</i> (2006)	Inclusive communication, joint accountability for outcomes, senior management involvement	Cognitive psychology, constituency-based theory	Interviews and critical incident technique
Keller <i>et al.</i> (2006)	Human workplace interaction, interdepartmental customer orientation	Cognitive psychology, organizational behavior	Survey, questionnaire
Amaral and Tsay (2009)	Hidden actions, hidden information, misaligned incentives	Cognitive psychology	Controlled experiment
Narasimhan <i>et al.</i> (2009)	Social exchange theory, power, dependence, justice	Social psychology	Controlled experiment
Crosron and Donohue (2006)	Bullwhip effect, dynamic decision making, information sharing	Cognitive psychology	Controlled experiment
Lee <i>et al.</i> (2011)	Motivation, coordination, incentives	Social psychology	Math modeling
Oliva and Watson (2011)	Cross-functional conflict, misaligned incentives, engagement	Organizational behavior	Case study
Syntetos <i>et al.</i> (2011)	System dynamics, inventory forecasting, human judgment, bullwhip effect	Cognitive psychology, system dynamics	Simulation
Ho <i>et al.</i> (2010)	Reference dependence, pull-to-center bias, aversion to leftovers and stockouts	Cognitive psychology	Controlled experiment
Fildes <i>et al.</i> (2009)	Heuristics and biases, judgmental adjustments, accuracy, optimism	Cognitive psychology	Survey
Crosron <i>et al.</i> (2014)	Coordination risk, coordination stock	Cognitive psychology, system dynamics'	Laboratory experiment

the behavioral causes of the bullwhip effect is based primarily on the search and description of all cognitive biases and rules of thumb which affect the decision maker. In respect to this extensive research exploring the link between supply chain management and behavioral variables, there is a lack of psycho-behavioral studies focussed on the workers conducting actual supply chain operations (e.g. inbound and outbound physical logistics, inventory recording, etc.). While, for example, in the manufacturing contexts the relationship between work pressure and errors of the shop-floor workers has been empirically analyzed (Bertrand and van Ooijen, 2002), in the context of supply chain management no work has studied the link between the workers' behavioral facets and the bullwhip effect. Exploring this link could reveal to be very relevant for supply chain managers who are, indeed, not only asked to dampen, *ex post*, the negative effects of order and inventory variance amplification, but also and overall to avoid such an amplification *ex-ante*, by designing the logistics system (including order and inventory policies) in a manner to take into considerations all possible causes of it. Being aware of the effect of workers' behavior on the supply chain performance is no doubt a great advantage for the effectiveness of supply chain management practices.

The research presented in this paper is thus positioned within the field of exploring behavioral causes of the bullwhip effect, but differentiates from existing studies because it wishes to fill the gap above mentioned.

Conceptual framework

The conceptual model proposed in this study (Figure 1) wishes to fill the literature gap discussed in the previous section. Specifically, the goal of our research is to explore the impact of behavioral aspects of workers on supply chain performance.

Indeed, as already argued, despite the numerous and detailed discussions on the influence of human beings as decision makers on the performance of the supply chain, no work has studied the link between the psychology or behavior of workers and the bullwhip effect yet. Bertrand and van Ooijen (2002) find a relationship between work pressure and human error level in a manufacturing context. The origin of this relation is the Yerkes-Dodson law (1908) (inverted-*U* theory), according to which some stress is necessary to motivate optimal job performance and is, therefore, desired. A person carrying out a given task is characterized by a certain level of arousal, i.e., the level of psychophysiological activation at that time. When arousal increases, the worker perception, information sharing, decision making, and also actions improve; but beyond a certain level of arousal, performance gets worse. From this point, stress damages performance and increasing levels of stress are increasingly detrimental (Muse *et al.*, 2003). There is an optimal level of arousal for each subject, which decreases when the complexity of a task or workload rises (see Figure 2).

In the context of inventory management, DeHoratius and Raman (2008) show that high levels of inventory and a high volume of transactions increase the environmental pressure for employees who work in a crowded space and can't detect stockout and thus inaccuracies in data. We, thus, operationalize the main constructs of our

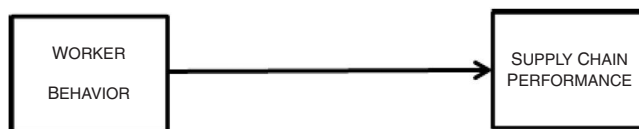


Figure 1.
Conceptual model

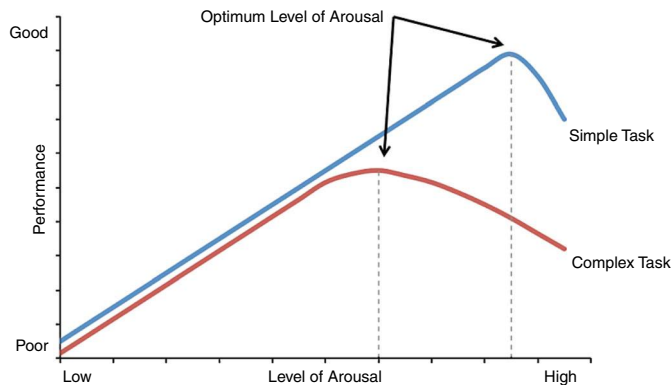


Figure 2.
Inverted-*U* theory

conceptual model by looking at this specific problem – the IRI. IRI measures how the inventory record level deviates from the physical inventory. IRI is actually a widespread phenomenon both in the context of manufacturing and retailing (Raman, 2000). DeHoratius and Raman (2008) analyze 37 retail stores and show that more than 65 percent of 370,000 inventory records are inaccurate. The main causes of IRI can be grouped into four types of errors: shrinkage errors (Fleisch and Tellkamp, 2005), misplacement errors (Fleisch and Tellkamp, 2005; Delaunay *et al.*, 2007), supply errors, and transaction errors (Raman, 2000; Delaunay *et al.*, 2007; Sarac *et al.*, 2010).

In our model we consider the last category and we treat this problem from a behavioral operations point of view, i.e., by considering the psycho-behavioral causes of such a phenomenon and by evaluating the impact of them on the operations themselves. We thus provide an explanation of an operations management problem, namely, the IRI, in order to highlight the link between the human factor (worker behavior), the operation the worker performs (item record keeping), the performance of the specific operation (IRI), and supply chain performance.

Even low discrepancy between physical inventory and recorded inventory produces suboptimal system performance in terms of service level delivered to customers (Ettouzani *et al.*, 2012), stockouts (Ehrenthal and Stölzle, 2013), and inventory costs (Fleisch and Tellkamp, 2005; Kang and Gershwin, 2005; DeHoratius *et al.*, 2008). Also, IRI is one of the main causes of unsuccessful supply chain information sharing projects (Angulo *et al.*, 2004; Uçkun *et al.*, 2008). Finally, IRI creates critical distortions in order placement, as almost every order policy uses information on current inventory level. For this reason it damages supply chain performance (Sahin and Dallery, 2009; Sari, 2010). There are several performance measures for supply chain management practices; in this paper we are interested in those specifically linked to inventory and order management. We thus consider the following two measures:

- (1) Order variance amplification (Chen *et al.*, 2000), expressed as the ratio of the variance of the order rate to the variance of the demand rate, is the most common bullwhip metric.
- (2) Inventory variance amplification (Disney and Towill, 2003), defined as the ratio of the variance of the net stock (inventory) over the variance of demand, is necessary to control fluctuations in serviceable inventory which result in higher holding and backlog costs.

Summing up and going back to our conceptual model shown in Figure 1, the human factor we study in this work is the worker reaction to the workload pressure dependent on the inbound throughput level (Figure 3). Existing research has predominantly concentrated on the negative effect which coping with time pressure has on the quality of decision making (Maule *et al.*, 2000; Kocher and Sutter, 2006; Thomas *et al.*, 2011). However, the impact of these time pressure coping mechanisms on operations performance has been largely ignored. In our conceptual model, the operation which we take into consideration is the recording of the items arriving in the inventory, and the source of inventory inaccuracy is the data entry errors due to workload pressure. Consider for example the error which occurs during the purchase of common, identically priced items, such as a lemon- and a strawberry-flavored yogurt, in which case the grocery cashier may scan one flavor twice. Thus, the store experiences a positive, one-unit inventory error for the scanned flavor and a negative, one-unit inventory error for the unscanned flavor (Raman *et al.*, 2001). Nachtmann *et al.* (2010) analyzed the impact of this kind of error on the fill rate and average inventory level, while in this paper we measure its effect on the amplification of order and inventory variances. Please notice that, while in real processes there may be many sources of data entry errors (e.g. incomplete data or unreadable data), in our model we assume that the only source of error in the incoming item recording is worker stress. Also, while in real processes there may be many sources of worker stress, we assume that the only source of stress is the time pressure due to the variation in the inbound throughput level.

Methodological approach and supply chain models

We develop a behavioral supply chain model through differential equations. We assume that the source of inventory inaccuracy is the transaction recording error due to the level of arousal of the worker and, thus, it is due to an over-load or an under-load of work pressure. The proposed analytical model is numerically solved through simulation with the Euler integration method with a time step equal to 0.25; the parameters are set according to a full factorial DOE and the simulation results are analyzed with statistical methods. This kind of research method to study supply chain phenomena is the same as adopted by Torres and Maltz (2010) who modeled a multi-echelon supply chain to investigate financial consequences of the bullwhip effect, and by Turrisi *et al.* (2013) who modeled a mono-echelon supply chain to investigate the impact of reverse logistics on performance.

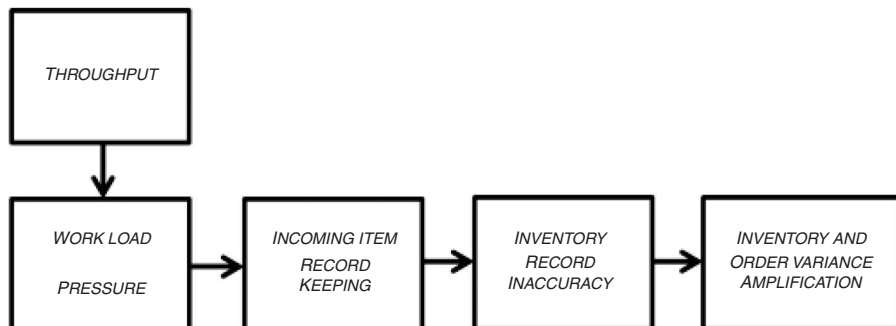


Figure 3.
Detailed conceptual model

We report in Table III the analytical model describing the mono-echelon supply chain. The main assumptions are:

- (1) The customer demand pattern, as in Dejonckheere *et al.* (2003), is normally distributed.
- (2) The forecast method is the Simple Exponential Smoothing technique.
- (3) The order policy is the Automatic Pipeline Inventory and Order Based Production Control System (APIOBPCS) replenishment rule (see Equation (6)), defined as “the quantity ordered is equal to the sum of forecasted demand plus a fraction $1/T_i$ of the difference between the actual and target stock level of serviceable inventory plus a fraction $1/T_w$ of the discrepancy between target and the actual WIP” (John *et al.*, 1994). T_i and T_w are, respectively, the inventory proportional controller and the WIP proportional controller and represent the fraction of the gap between the target and the actual value to recover with a single echelon. In this work we use the Deziel and Eilon (1967) rule according to which $T_i = T_w$; this reduces the problem dimension, and thus the solutions space, keeping the solutions stable (Disney *et al.*, 2004). We use the APIOBPCS archetype because:
 - It is the policy most commonly used in behavioral supply chain research. In fact, according to John *et al.* (1994) the APIOBPCS structure directly

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Demand forecast	$\hat{d}_t = \hat{d}_{t-dt} + \alpha(d - \hat{d}_{t-dt})$	(1)
Sales to market	$S_t = \min\{d_t; I_t\}$	(2)
Throughput	$F_t = O_{t-T_p}$	(3)
Inventory	$I_t = I_{t-dt} + dt \times (F_t - S_t)$	(4)
Work in progress	$W_t = W_{t-dt} + dt \times (O_t - F_t)$	(5)
Order quantity	$O_t = \hat{d}_t + \frac{I_t - TIR_t}{T_i} + \frac{TW_t - W_t}{T_w}$	(6)
Non-negativity condition of order quantity	$O_t \geq 0$	(7)
Backlog	$B_t = B_{t-dt} + dt \times (d_t - S_t)$	(8)
Target inventory	$TI_t = SSF \times \hat{d}_t$	(9)
Target WIP	$TI_t = SSF \times \hat{d}_t$	(10)
Alignment	$\varphi = IF THEN ELSE(\frac{t}{26} = INT(\frac{t}{26}); 1; 0)$	(11)
Throughput record	$FR_t = F_t + Er_t$	(12)
Sales to market record	$SR_t = S_t$	(13)
Inventory record	$IR_t = IF THEN ELSE(\varphi = 1; I_t; IR_{t-dt} + dt \times (FR_t - SR_t))$	(14)
Target Inventory record	$TIR_t = TI_t$	(15)
Inventory record inaccuracy	$IRI_t = \left \frac{I_t - IR_t}{I_t} \right $	(16)
Underload range	$F_t < F_1^*$	(17)
Overload range	$F_t > F_2^*$	(18)
Optimal range	$F^*Range = F_2^* - F_1^*$	(19)
Errors magnitude	$\omega_t = IF THEN ELSE(F_t < F_1^*; (1 - F_t/F_1^*); IF THEN ELSE(F_t > F_2^*; (F_t - F_2^*)/F_1^*; 0))$	(20)
Errors sign	$S = UNIF(-1; 1)$	(21)
Data entry errors	$Er_t = \omega_t \times F_t \times S$	(22)
Under- and over-load curves slopes	$e_2 = e_1$	(23)
Midpoint of the optimal range	F^*	

Table III.
Equations of the model

corresponds to Sterman's (1989) Anchoring and Adjustment algorithm, which fits the decision maker behavior when playing the Beer Distribution Game.

- It is demonstrated to avoid demand variance amplification and generate smooth ordering patterns in the supply chain, damping the operational causes of the bullwhip effect.

- (4) Backlogging is assumed and the backlog is fulfilled once the on-hand inventory becomes available (8).
- (5) The retailer adopts an inventory management system and thus uses the inventory record information to set the order (6).
- (6) Every six months an alignment between the virtual and the physical inventory is carried out (11). The unit of time t is the week.

As prescribed by the inverted- U theory, the performance of workers does not get worse just with the increase of workload. When the level of throughput is very low, workers are relaxed or bored and commit errors due to inattention. As the throughput approaches the ideal level F_1^* , the magnitude of the errors decreases with a linear law (20). This representation of error magnitude uses the psychological theory about stress called positive linear theory, based on the belief that stress and anxiety present challenges to the individual, which, in turn, improve performance (Meglino, 1977). Studies which have found support for the positive linear theory include Arsenault and Dolan (1983), Kahn and Long (1988), and Hatton *et al.* (1995).

Beyond the level of F_2^* , individuals come into the work-overload region, and the errors increase with a linear law (20). This representation of error magnitude uses the psychological theory about stress called negative linear theory, based on the premise that stress consumes an individual's time, energy, and attention, taking away from the task at hand and consequently inhibiting performance (Jamal, 1984). The negative linear theory has multiple studies supporting it, among which are Allen *et al.* (1982) and Friend (1982).

We suppose that the negative and positive slopes are equal ($e_2 = e_1$). Also, we suppose that the maximum magnitude of the errors is $\omega_{max} = 1$. The data entry errors happen when there is work pressure and are computed as the product of the physical throughput and the magnitude of errors (22). This representation of data entry errors is very similar to the one suggested in the works of Angulo *et al.* (2004), Waller *et al.* (2006), and Sari (2008, 2010).

Errors reach zero in the range for (19). This representation of error magnitude reproduces a generalized version of the inverted- U theory. In fact, this theory represents a merger of the negative and positive linear theories by suggesting that increasing stress is good to a point, beyond which it becomes bad. Graphically, this optimal stress level is depicted by the center of the inverted- U curve where stress, along the X -axis, is moderate, and performance, along the Y -axis, is at its peak. We substituted the optimal point with an optimal range. We made this choice for two reasons. The first is that a point is just a particular case of a range, i.e., when the range width is zero; as will better explained in the experimental design section, this setting allows testing of the effect of different range width on performance. The second is that we believe this modified version of the U -theory is more realistic and, as will better described in the next section, allows us to introduce a behavioral variable called worker stability to stress. We assume that, analogously to the final customer demand pattern, that throughput has a certain probability distribution which is comparable to a Gaussian dispersion. Depending on how

the optimal range is positioned and how big it is, the overall magnitude of the errors changes. This idea is graphically depicted in Figure 4.

The mathematical formulations of the selected performance measures are shown in Table IV.

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Experimental design and data analysis

To analyze the math models, we conduct numerical simulations. We initialize the parameters with the values shown in Table V. Before carrying out the statistical analysis, a logarithmic transformation of the outputs of the simulations was applied to obtain normally distributed residuals.

The factors tested in this model are: the throughput optimal range width, F^*Range ; the midpoint of throughput optimal range, F^* . We selected these two factors because of their relevance respect to our behavioral model. The width of the interval F^*Range can be considered a proxy of worker psychological stability to stress, and thus to workload pressure. The larger is this range the more the worker is stable respect to variations of throughput level. On the other side, the midpoint F^* of throughput optimal range represents a proxy of worker psychological sensitivity to stress, and thus to workload pressure. The higher is this value, the less sensitive is the worker respect to variations of throughput level. This is because we assumed that the maximum error magnitude is 1 and thus higher values of F^* mean lower values of the slope $e_2 = e_1$.

The levels of the factors are shown in Table VI. We set three levels for the F^* factor: the middle one is equal to the average inbound throughput (100, which is equal to the

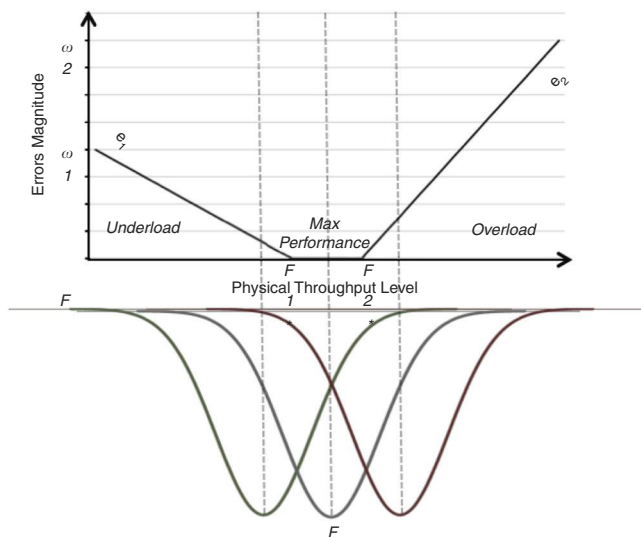


Figure 4.
Qualitative representation
of the arousal theory
applied to data entry
errors

Performance measure

Formulation

Order variance amplification

$$OvarA = \sigma_0^2 / \sigma_D^2 \quad (24)$$

Inventory variance amplification

$$IvarA = \sigma_I^2 / \sigma_D^2 \quad (25)$$

Table IV.
Supply chain performance
metrics

average demand as the process is stationary) and the minimum and maximum values are, respectively $\pm 2\sigma$, of the customer demand. We fixed these two values according to the results of a preliminary numerical analysis. We also tried $\pm 3\sigma$ and $\pm 1\sigma$ but in the first case we basically fell into the traditional negative (or positive) linear theory (see Figure 4); in the second case, the results were less evident given our initial data setting reported in Table V.

We set two levels for the *F*Range* factor: the lower value ultimately means we are using the classical inverted-*U* theory (no range), and the higher value is again $+2\sigma$ of the customer demand. Again, we arranged these two values according to the results of a preliminary numerical analysis. By using these values, the maximum magnitude of errors we get generates an average level of inventory inaccuracy of 27 percent, a value consistent with that verified by Raman (2000) for the records in the Gamma Corporation, considering that the company was affected by transaction errors both in throughput and in sales recording.

We conducted a full factorial DOE and we thus have six experimental points. For each experimental point, $n = 10$ replications have been performed.

We verify the significance of factors and their interactions through the generalized linear model (Minitab software has been used) with a significance level $\alpha = 0.05$. Tables VII and VIII show that the factors and their interaction are significant with a p -value = 0.000 and the midpoint of throughput optimal range accounts for 83 percent

Table V.
Initial values of
model setting
parameters

Parameter	Value	Units
Mean of the customer demand	100	units/week
SD of customer demand	10	units
Exponential smoothing factor	0.33	–
Target inventory	$TI_t = SSF \times \hat{d}_t$	units
Target WIP	$TI_t = SSF \times \hat{d}_t$	units
Target inventory record	$IR_t = SSF \times \hat{d}_t$	units
Experiment's time length	$T = 1,000$	week

Table VI.
Levels of the factors
of the second model

Factor	Levels		
<i>F*Range</i>	2	20	–
<i>F*</i>	80	100	120

Table VII.
Output of the
general linear model
for the inventory
variance
amplification

Source	df	Analysis of variance for LogIvarA			<i>F</i>	<i>p</i>
		Seq SS	Adj SS	Adj MS		
<i>F* Range</i>	1	1.8947	1.8947	1.8947	143.84	0.000
<i>F*</i>	2	15.3697	15.3697	7.6848	583.41	0.000
<i>F* Range</i> × <i>F*</i>	2	0.3444	0.3444	0.1722	13.07	0.000
Error	54	0.7113	0.7113	0.0132		
Total	59	18.3201				

Notes: $S = 0.114770$; $R^2 = 96.12$ percent; $R^2(\text{adj}) = 95.76$ percent

of the variance of IvarA and for 74.7 percent of the variance of OvarA. The graphs, shown in Figures 5 and 6, put into evidence that both the variance of the order and the variance of inventory decrease with the widening of the throughput optimal range. The trend of IvarA and OvarA at varying of F^* , which is the factor that gives the major contribution to the variance of the output parameters, is quite expectable: the two measures have the highest values for the lowest level of F^* ($F^* = 80$) and the lowest values for the average level of the factor ($F^* = 100$).

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Source	df	Analysis of Variance for LogOvarA			F	p
		Seq SS	Adj SS	Adj MS		
F^* Range	1	0.22422	0.22422	0.22422	59.23	0.000
F^*	2	1.59641	1.59641	0.79821	210.86	0.000
F^* Range $\times F^*$	2	0.11266	0.11266	0.05633	14.88	0.000
Error	54	0.20441	0.20441	0.00379		
Total	59	2.13771				

Notes: $S = 0.0615259$; $R^2 = 90.44$ percent; $R^2(\text{adj}) = 89.55$ percent

Table VIII.
Output of the general
linear model for the order
variance amplification

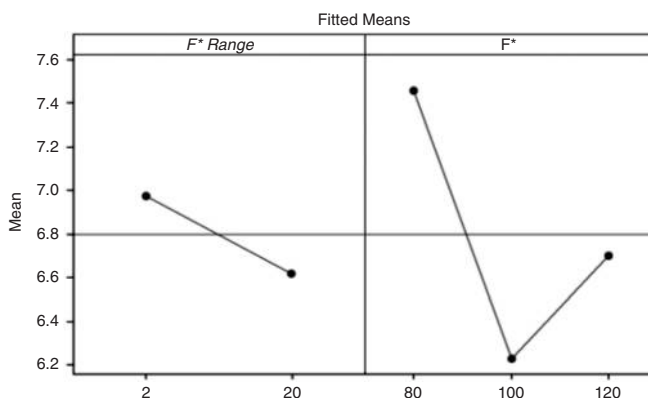


Figure 5.
Main effects plot for IvarA

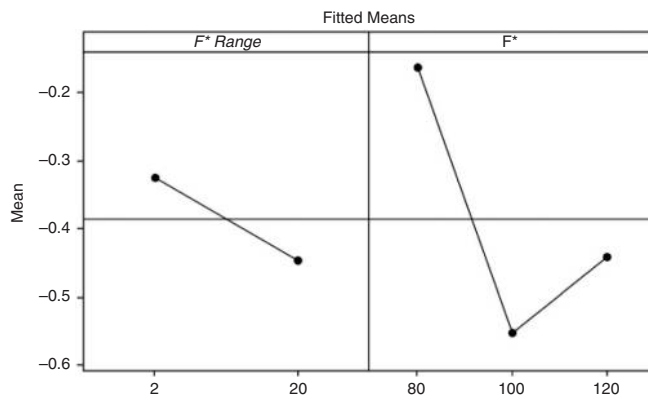


Figure 6.
Main effects plot for
OvarA

On the other side, the interactions plots (Figures 7 and 8) show that the effect of F^*Range decreases when the midpoint F^* is at the average level. We use two paired t -tests to see if the results differ from that of a mono-echelon supply chain with a perfect accuracy in inventory record. Specifically, we tested that the mean of output in our model is lower than the one of the model with perfect inventory record accuracy, with a confidence level of 0.05. In such tests, we use the output of our model with the factor F^* set at the medium level (100) and the F^*Range at the highest level (20). In both the paired t -tests, the hypothesis that the mean of output in our model is lower than the one of the model with perfect inventory record accuracy has been accepted with a p -value < 0.005 .

Findings, contribution, and implications

The paper investigates an unexplored issue, namely the contribution to the order and inventory variances of the IRI caused by data entry errors due to workers behavior.

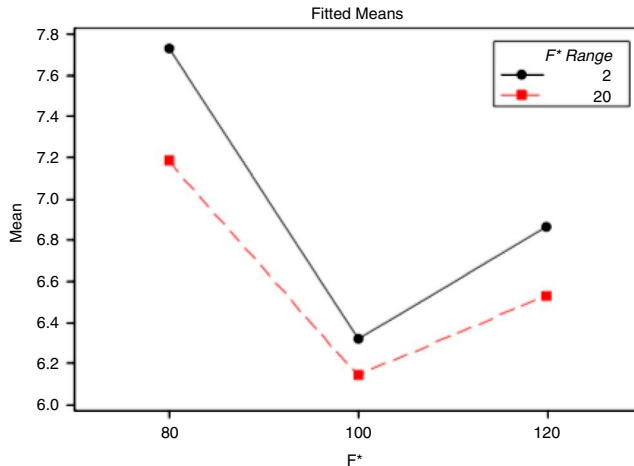


Figure 7.
Interactions plot for IvarA

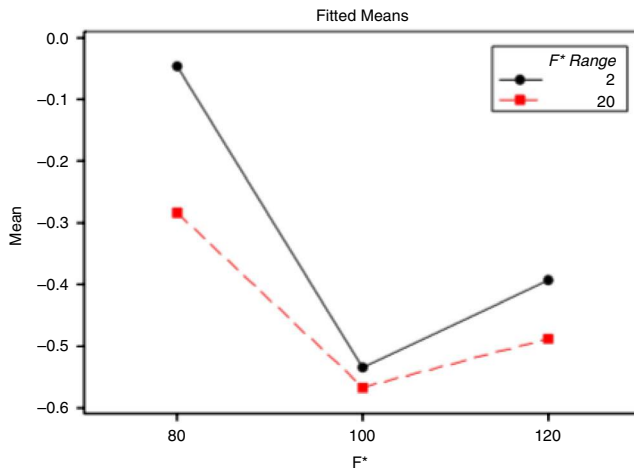


Figure 8.
Interactions plot for OvarA

The developed model, the experimental simulations, and the ANOVA on obtained results have produced interesting findings which let us argue that the proposed research brings significant contributions to the literature and implications for managerial practice. They are summarized as follows:

- (1) We registered the presence of bullwhip effect. Although we were adopting a smoothing replenishment rule (namely APIOBPCS) and a six-month counting policy, the order and inventory variances amplified. This let us argue that order and inventory management policies, traditionally used for dampening the bullwhip effect, are not effective if a certain level of inaccuracy is generated due to workers' behavioral aspects.
- (2) Inventory and order variance amplifications are very sensitive to the main factors. This means that, *ceteris paribus*, the damages on supply chain performance generated by the IRI are highly influenced by behavioral aspects of workers. This finding is quite interesting and asks researchers to rethink traditional supply chain models explaining and linking material and information flows' dynamics along the chain. Such models, in fact, do not take into consideration workers' behavior in reaction to physical system variables (e.g. the inbound throughput level) that contrarily, we have demonstrated, influence the dynamics of the system.
- (3) By using the Yerkes-Dodson law to model behavioral aspects of workers we were able to investigate the effect of the worker psychological stability (besides her/his sensitivity) to stress, and thus to workload pressure. The results of the analysis on the single factors were rather expectable since the record inaccuracy due to workload pressure depends on the psychological stability of the workers in dealing with a given range of throughput values and on the probability that the actual value of the throughput falls within such a range. On the other hand, the analysis on the interaction of factors reveals some findings which are not so obvious. By observing Figures 7 and 8, we notice that, the parameters of the Yerkes-Dodson law describing the behavioral reaction of the worker against a workload pressure or arousal being equal, the width of the *U*-shape of the bullwhip decreases when the stability of the worker decreases. This means that the psychological sensitivity of the worker to her/his level of arousal and her/his psychological stability to deal with a given range of operational conditions (throughput level) have a combined and multiplying effect over the amplification of order and inventory variance generated by her/his errors. This finding is quite interesting. We, in fact, could have expected that the two curves in Figure 7 (or Figure 8) were just vertically translated. This would have meant that workers which are more sensitive to arousal/stress simply make more errors when subject to workloads they are not used to dealing with, and workers which are scarcely stable against variations make still more errors; once again, these effects increase the record inaccuracy, which in turns creates the bullwhip effect. However, our results tell us that things are more complicated. The deteriorating effect of psychological sensitivity with respect to the bullwhip effect is strongly influenced by the psychological stability of the worker with respect to the changing operational conditions.

In fact, these findings bring interesting practical implications for managers.

On the one hand, when fixing the average inbound throughput level of material entering the inventory, managers should be well acquainted with the different sensitivities of workers with respect to positive or negative variations in the workload. The effect that a variation in the current throughput value with respect to its average value (the one the workers are more likely to be used to dealing with) may have very different effects on worker performance depending on the sign of the variation. In other words, workers may be more sensitive to a decrease of throughput (their level of arousal decreases too much) or to an increase of it (their level of stress increases too much). Depending on the behavioral characteristics of the workers (namely, the slopes of the two legs of the *U*-curve), the manager should more likely prefer to under- or over-settle the average level of inbound throughput level in such a way as to diminish the times its current value is higher or lower with respect to the fixed value. These considerations apply when the logistics manager has some leeway to regulate and set the inbound throughput thanks to different ordering policies, order arrival frequencies, re-order points, security stock levels, etc. Contrarily, when she/he has little leeway with regard to throughput levels, which instead are set based on business needs and capacity utilization, she/he should schedule labor according to expected levels of throughput and worker sensitivities. However, workload balancing through labor scheduling is not always easy to apply. Labor laws generally prohibit differential treatment (i.e. different workload expectations) for workers performing the same functions while receiving same compensation. Furthermore, depending on the number of workers involved in the inbound items recording, micromanaging overall workload (in terms of throughput) for individual workers may be unrealistic. In this case, the logistics manager should evaluate the option of delegating tasks based on worker experience such that workers who are more suited for certain tasks can handle greater throughput without experiencing detrimental effects of over-arousal.

On the other hand, the inbound logistic process should be managed according to the psychological stability of workers which, along with their sensitivity to arousal and/or stress, strongly influences the effect that the variation of the inbound throughput level has on the amplification of the variance of orders and inventory itself. If the manager knew the level of stability of her/his workers, she/he might have more degrees of freedom in setting the right value of average throughput entering the inventory and balancing the workload for workers to the line between under- and over-load. However, this is actually not entirely applicable since privacy laws generally forbid employers from evaluating employees and applicants with regard to their psychological stability. Nevertheless, our results suggest that worker psychological stability and her/his sensitivity have a multiplying effect on IRI, resulting in a deterioration of the global performance of the supply chain in terms of order and inventory variance amplification. This calls, on the one hand, for a greater managerial attention to employee well-being to maximize their performance potential. On the other hand, for a greater attention of logistics managers to the minimization of the variance of inventory incoming item flow. They should not just concentrate on avoiding increases or decreases of workers' workload (over- or under-workloading) but also on minimizing the variance of the workload itself.

Summing up, from a theoretical perspective, the principal contribution of our research to existing literature relies on dealing for the first time with behavioral supply chain management by observing the cognitive psychology of workers and not of the decision makers. Specifically, according to Kaufman (1999), the bounded rationality of people can be decomposed into two parts, one part arising from cognitive limitations

and the other from extremes in arousal. Our work applies a fundamental concept of behavioral operations research, i.e., bounded rationality, in a different area to that in which it is ordinarily applied, i.e., decision making. Also, differently from most of the papers dealing with behavioral aspects of supply chain management, this study explores linkages between behavioral aspects and supply chain performance by adopting an analytical modeling approach. This way of investigating behavioral supply chain management opens new frontiers in developing knowledge on this topic.

From a more practical point of view, the results of the research presented in this paper bring interesting managerial implications by suggesting behavioral reasons which underlie supply chain dynamics deterioration despite the use of classical variance dampening practices in forecasting, order placing, and inventory counting. In particular, the results highlight how the response to different levels of work pressure does not only depend on how difficult the task is for workers, but also on the psychological inclinations of individuals. Moreover, the analysis of the interaction of factors shows that the different psychological characteristics of the workers differently affect the dynamics of the supply chain and that when they are co-present their effects are complex and correlated.

Conclusions

More and more frequently we observe situations in which supply chains, despite all operational variables being well designed, show poor performance which is not explainable with the traditional logic. The idea that in companies people make fully rational decisions, fulfill their job without fail and that human beings are not part of the system under analysis is being increasingly abandoned. The analysis of behavioral variables in operational contexts appears to be necessary for two main reasons: first, because it helps to understand the phenomena which cannot be otherwise explained more deeply; second, because it can strongly contribute to the search for solutions or managerial practices which are most suitable, appropriate and effective. The present work fulfills such a dual purpose.

First, it gives an alternative explanation to a widespread and critical phenomenon in supply chains, which is performance deterioration due to the inaccuracy of data, showing that this is connected to how workers react to different levels of workload. A behavioral model, inspired by a psychological theory about stress, has been presented. Through a numerical simulation analysis, a full factorial experimental design, and a general linear model, the research shows that the more the level of physical throughput deviates from the ideal value for the workers, the more the level of the human errors increases and generates an amplification of the inventory and order variance in the supply chain echelon under study.

Second, the analysis of results brings interesting findings and implication for managers who are responsible for designing proper order and inventory policies. The paper gives some hints and suggestion on how to take into account worker behavioral reaction to work pressure and how to avoid this reaction compromising global supply chain performance. Operations and operations management decisions must be designed *ad hoc*, namely, calibrated according to the workload-arousal function of individuals.

This research has several limitations. Two of them are the following. First, we consider a limited number of aspects in the whole behavioral supply chain system: only one operational variable (the throughput level) influences worker behavior, and only two psychological variables (sensitivity and stability with respect to workload pressure and arousal) influence operations performance. Second, we model worker

behavior by inheriting a well-known theory from psychology which assumes a U-shaped relationship between stress and errors. We did not conduct any empirical study (or even a controlled experiment) to validate this relationship when applied to the inventory recording operation. This would also have allowed us to determine or qualifying how much of the transaction error is wholly attributed to worker stress.

Future directions of the research should be directed toward exploring and evaluating logistics, but also human resource management, practices to avoid the negative effect caused by psychological arousal of workers on the whole supply chain dynamics. In the introduction section of the paper we mentioned that BOM not only aims at understanding behavioral phenomena within the operations context, but also at using this understanding to generate interventions that improve the operation of the supply chain itself (Katsikopoulos and Gigerenzer, 2013). The literature review showed that most of the research has been conducted with the first aim, while the design of management practices directed to avoid such behavioral effects has been surely overlooked.

In job analysis and design literature, it is well known, for example, that a variety of factors may moderate psychological arousal, such as the frequency and length of breaks and the presence of external stimuli (e.g. soothing music, ambient temperature, etc.). Inheriting theories from job analysis and human resource management literature would be of great help for identifying proper lines of intervention. Our findings could be interpreted from a human resource management point of view in terms of staffing, training, compensation, and evaluation of employees. McAfee *et al.* (2002) suggest that an important consideration in developing a supply chain strategy is a firm's human resource management strategy and its culture. They also suggest that a firm needs to examine the interaction between its human resource strategy and its logistics strategy. Failure to adequately address this strategic fit can lead to reduced optimization in the effective functioning of the supply chain. In our case, due to the Yerkes-Dodson law behavioral model, the HRM practices could impact supply chain dynamics in a complex way: for example if people are trained, this benefits performance, but if they are trained too much, this may lead to some decrease in performance due to the growth in their arousal level. However, the cognitive load may determine workers' mental fatigue, whereas the benefits of training may be long lasting but mental fatigue fleeting. In general, optimal HRM practices, such as staffing, training, compensation, job analysis, job design, and evaluation of employees, exist and strictly depend on the level of psychological stability of workers, besides their sensitivity model. Future directions of research in BOM should be aimed at deepening such aspects.

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