BI-CRITERIA AND SIMULATION ANALYSIS OF REVERSE BULLWHIP EFFECT IN A HIGH-TECH COMPANY

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RESUMO

A maior parte da literatura sobre o efeito chicote está focada nos efeitos de amplificação produzidos pela variabilidade da demanda no nível do varejo, que se propaga e aumenta a montante em uma cadeia de abastecimento. Na última década, um novo fenômeno foi identificado como o efeito chicote reverso (RBWE, as siglas em inglês), que é a amplificação progressiva downstream produzida pela variabilidade de produção em um sistema de manufatura. Embora diferentes fatores tenham sido propostos como causas para esse fenômeno, muito pouco se sabe sobre a relação entre RBWE e retrabalho. Este artigo apresenta as lições de análise e gestão obtidas a partir de um estudo de caso em uma empresa de alta tecnologia no Brasil que mostra um alto nível de retrabalho e a falta de informações oportunas para gerenciar uma de suas linhas de produção. Usando simulação e análise de dois critérios, a dinâmica da linha de produção é descrita mostrando que um tipo de retrabalho e o aumento do lead time causam RBWE. Uma discussão sobre os resultados e os desafios futuros para controlar a RBWE são destacados.

PALAVRAS CHAVE. efeito chicote reverso, retrabalho, bi-critérios, simulação

ABSTRACT

Most of literature regarding the bullwhip-effect is focused on the amplification effects produced by the demand variability at the retail level, which propagates and increases

upstream in a supply chain. The last decade a new phenomenon has been identified as the reverse bullwhip-effect (RBWE), which is the progressive downstream amplification produced by production variability in a manufacturing system. Although different factors have been proposed as causes for this phenomenon, very few is known about the relationship between RBWE and rework. This paper presents the analysis and management lessons obtained from a case study in a high-tech company in Brazil which shows a high level of rework and the lack of opportune information to manage one of its production lines. By using simulation and bi-criteria analysis, the production line dynamics is described showing that one type of rework and increasing lead time both cause RBWE. A discussion about results and future challenges to control RBWE are highlighted.

KEYWORDS. reverse bullwhip effect, rework, bi-criteria, simulation

1. Introduction

The "bullwhip-effect" is an undesired progressive amplification, phase lag and oscillation in production and inventory, caused by the demand variability at the retail level of a supply chain [Wang and Disney, 2016]. Although different reasons are frequently reported in the literature [de Almeida et al., 2015], one important reason is that decision-makers (DMs) are unable to find the feedback structure of the management system nor can they adequately deal with delayed information flow through the supply chain [Sterman, 2006]. The last decade a new phenomenon has been identified as the reverse bullwhip-effect (RBWE), which is the progressive downstream amplification produced by the order variability pushed into the manufacturing system, from the raw material stage downstream up to the exit stage (delivery to customer) [Jeong and Hong, 2019]. Among origins of RBWE, literature includes supplier capacity challenges, inadequate and/or distortion of information at the supplier level [Rong et al., 2009]. Supply disruption is mentioned as a key factor producing RBWE. However, very few has been studied regarding this phenomenon and different inventory management policies. ? studied the reverse bullwhip effect focusing on how wholesaler prices affect the price variation downstream. Özelkan et al. [2018] studied a more complex version, adding prices decisions and inventory policies decisions are jointly made. Simulation is used in order to analyze the behavior and define under which conditions RBWE is detected.

Although rework in supply chains have been studied at least for a couple of decades [Love et al., 1999], there are very few papers relating it to the bullwhip effect. Rework happens when parts and products are erroneously manufactured, caused by wrong engineering, improper manufacturing, defective supplies or low quality standards. It impacts in the general performance of supply chains [Chen, 2017] by increasing costs and lead-times, inducing alterations in the work-in-process and the production rates [Chen, 2013; Chiu et al., 2017; Sofiana et al., 2019]. As important as it is, to the best of our knowledge, research about rework and RBWE is not yet available.

In this paper, a case study regarding rework and RBWE in a high-tech company in Brazil is presented. The company uses a push-type policy in which the customer demand defines the quantity of supplier items to be manufactured from an initial stage up to a final-product stage from which products are sent to the delivery to customer section. High level of rework and low visibility of the supply-chain operation are the main problems described by managers in this supply-chain, pleading that these potentially delay deliveries and increase costs of production. By using simulation, the supply-chain and the management rules are modeled to present the production system dynamics. Simulation is used to describe the current situation, showing the impact of rework and push policies on the reverse bullwhip effect. Bi-criteria analysis is performed to evaluate the consequences of rework on the supply-chain when a push or a pull policy is applied by managers, in terms of two criteria: amplification of order and amplification of inventory on each stage of the production line. Results show that, when rework interacts with order policies, RBWE is observed. Countermeasures are ineffective discussed and future research is proposed.

This article is organized as follows. In Section 2, the supply chain model and the main equations defining the system dynamics are presented. The high-tech company and the main problem are introduced in Section 3. In Section 4, rework and its impact on the RBWE is analyzed. Section 5 presents a discussion about results. Finally, conclusions and future research are presented in Section 6.

2. Production line model

Let us consider a four-stage supply chain, as shown in Figure 1 in which a unique product flows from left to right, represented with right-oriented black arrows. At the far right of the chain a delivery Del_t represents the actual costumer's consumption. At the far left, the inventory of input provided by a supplier, I_t, is represented. In this case a push policy is considered in which each stage is in charge of the immediately upstream inventory. This means that a stage receives an order and its purpose is to control the upstream in-process inventory.

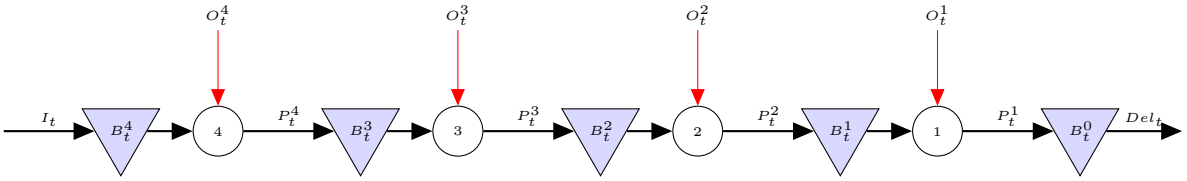


Figura 1: Production line model

Each stage manages the stock to the left of the stage. For instance, the Stage 1 keeps inventory with level B_t^1 at time t. The quantity to manufacture in each stage, per period, is defined by an order. For instance, to the Stage 1 corresponds the O_t^1 at time t. Each stage needs to consume units from the left inventory to produce units that are sent to the inventory on the right side. For instance, the Stage 1, in the range $[t, t+1)$, consumes units to produce P_t^1. The model can be formalized with equations that relate the variables and allow to build a simulation model, for $(i = 1, \ldots, 4)$:

$$B_t^i = \begin{cases} B_{t-1}^0 + P_{t-1}^1 - Del_{t-1}, & i = 0, \\ B_{t-1}^4 + I_{t-1} - P_{t-1}^4, & i = 4, \\ B_{t-1}^i + P_{t-1}^{i+1} - P_{t-1}^i, & i \neq 0, 4 \end{cases} \quad (1)$$

$$P_t^i = \min\{B_{t-L}^i, O_{t-L}^i\}, \quad (2)$$

$$I_t = D_t, \quad (3)$$

$$WIP_t^i = \sum_{j=1}^{L} O_{t-L-1+j}^i, \quad (4)$$

$$O_t^i = \max\{0, P_{t-1}^{i+1} + (B_t^i - S^i) + (SL^i - WIP_t^i)\}, \quad (5)$$

where WIP_t^i is the work-in-process level of orders at the stage i; S^i is the expected level of inventory B_t^i; SL^i is the expected level of work-in-process in stage i; and L is the production lead time. The variable B_t^0 corresponds to the final product inventory, while B_t^4 can be considered the raw material inventory, which is replenished by the input rate I_t. If production stages have enough capacity, there is upstream inventory units available and no rework is present, one can establish $P_t^i = O_{t-L}^i$, which means that items picked-up from the upstream inventory are all transformed into products sent to the downstream inventory. However, if rework is necessary, there is a lack of inventory or the stage capacity is not available, $P_t^i \leq O_{t-L}^i$. In which follows, rework and lack of inventory are modeled, but capacity is assumed to be infinite.

3. Case study

3.1. Problem

A manufacturing company in Brazil produces high-tech products for the industrial and scientific high-technology fields. This company produces fiber optical cables and connectors for clients operating telecommunications companies in Brazil and elsewhere. The manufacturing operations are placed in Rio de Janeiro. One of the production lines in this plant is called the "drop cable area", focused on the production of optical fiber cable connectors, which have a special component used to connect cables into transfer boxes carrying the digital signal through wired telecommunications networks. Each drop cable unit is produced in a sequence involving 24 different steps.

Figure 1 may represent a sub-model of the real production line. It is complete in the sense that it allows the modeling and testing of management policies and performances. The Stage 4 corresponds to the operation position where the raw cable units are picked-up, according to production orders stamped on each unit. These units enter the system to be successively processed downstream, up to the final stage. The Stage 3 can be considered a standard operation stage. The Stage 2 corresponds to an inspection stage in which tests are applied to the cable connectors. The Stage 1 stocks the final product, from which the products are taken to the customer delivery section (out of the production line model).

The main problems reported by managers of the drop cable section are the low visibility they have regarding the operations in the production system and the high level of rework, which has a negative impact in both the production planning and the time to costumer. Low visibility is due to the lack of opportune information about manufacturing, in all stages of the production line. Causes for high rework may be multiple, but information about it is not available at opportune time either. Thus, the purpose of this paper is to analyze the management policies applied in the supply chain and the way that the rework interacts with them to induce the RBWE.

3.2. Simulation setting

The company uses a push system in the sense that the demand D_t pushes production by defining the input rate I_t as a function of the demand process. This initiates manufacturing through the stages up to reach the final product inventory B_t^0, where drop cable units are ready to be taken to the customer delivery section. In order to simulate the demand behavior, we consider a first order autocorrelated process. This represents a stochastic demand that seems to be common in many high-tech industries [?Disney et al., 2006]. We choose to model an AR(1) (first-order autocorrelated) demand process, which is usual in simulation studies [Boute et al., 2014]. Then, let us define$D_t = \lambda D_{t-1} + (1-\lambda)\mu + a_t$, where λ is the first-degree autocorrelation level; $a_t \sim N(0, \sigma^2(1-\lambda^2))$ is a normal distributed random error; and μ, σ are the mean and standard deviation values, respectively, of the demand process.

In Figure 2, results of simulation using Vensim Software are shown when $S^i = SL^i = \mu L; L = 1; \mu = 10; \sigma = 2; \lambda = 0.5$. In this ideal situation, a stage "follows" the demand process, delayed by the lead time on each position, showing a synchronization between the demand and the stage production rates. The system structure propagates the demand signal through the supply chain.

3.3. Rework

Whenever a defective unit being manufactured is detected, the involved stage stops working on the product, which is entered in a specific rework-in-process queue indicating

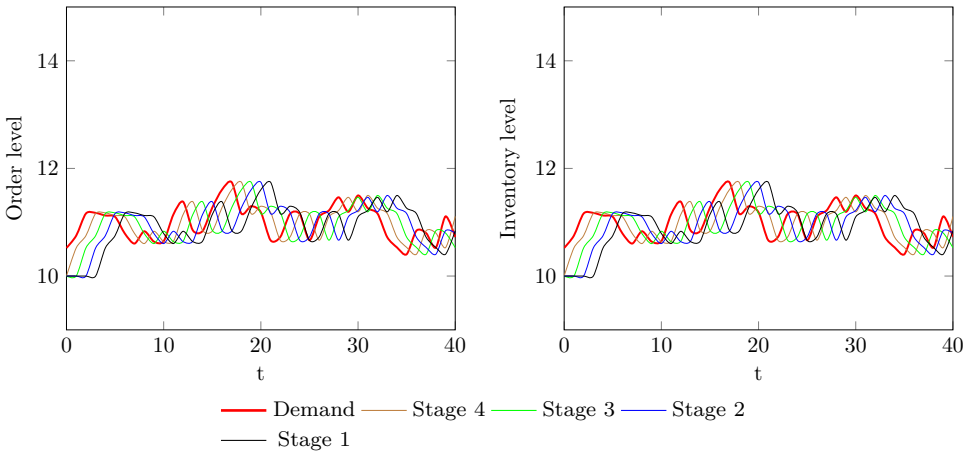


Figura 2: Orders and inventory in an ideal situation, without rework

the number of items that need to be re-scheduled at the beginning of the production line. Figure 3 illustrates how the items are re-scheduled, in the case where rework is produced by Stages 4, 3 and 2. Given that all the enqueued rework units directly go to the beginning of the supply chain, the expression (3) needs to be modified as follows

$$I_t = D_t + R^4_{t-L^4} + R^3_{t-L^3} + R^2_{t-L^2}, \tag{6}$$

where $R^i_{t-L^i}$ is the rework level and L^i equals the time the system takes to re-schedule an item that was previously chosen for rework in the stage $i \in \{2, 3, 4\}$. Stage 1 is not considered for rework because Stage 2 (Inspection) is the last position in which a defective item can be detected.

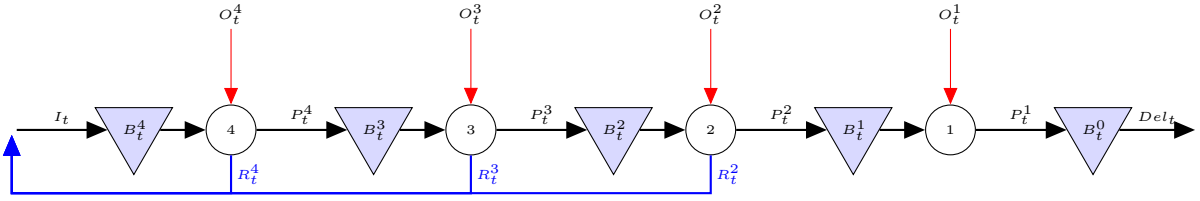


Figura 3: Supply chain model with rework

In Figure 4, the system behavior is shown when rework amounts for 5% of times, relative to the total time of simulation on stages $4, 3, 2$. Two phenomena are observed: 1) amplification both in production and inventory, when compared to the demand process (red line); 2) phase lag, which means that synchronism between the demand process and the production and the inventory processes is lost.

3.3.1. Push policy

If S^i and SL^i are variables that depend on demand forecasting functions and other parameters related to the demand process as the mean value, the standard deviation, and

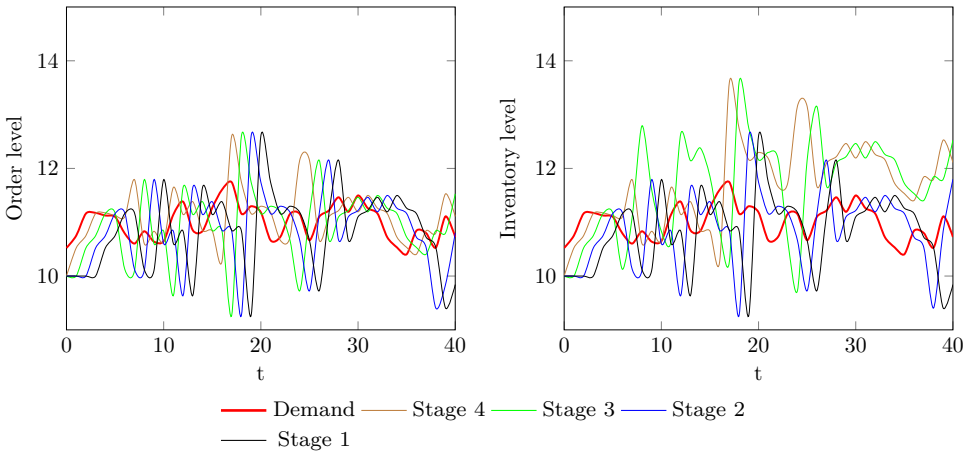


Figura 4: Order and inventory amplification with rework in stages 4,3,2

some order of autocorrelation, the management is adopting a push policy [Pereira et al., 2009]. Usually, push systems re-define these variables according to the demand forecast and dynamics on each stage, which breaks synchronism observed in Figure 2. This can be modeled by an expected WIP value defined as

$$SL_t^i = \sum_{j=1}^{L} \hat{D}_{t,t+j}, \forall i \tag{7}$$

where $\hat{D}_{t,t+j} = \lambda^j D_t + (1 - \lambda^j)\mu$ [Pereira and Paulre, 2001]. Expression (7) could model a centralized decision-making process, which establishes what the expected WIP would be through the production line.

In which follows, the modeled supply chain is simulated in cases of push and pull policies. Results are compared in terms of performance of order and inventory, when rework is observed in stages 4, 3, 2. Simulations are run as if managers apply the management rules without intervention to reduce or alter the negative consequences of their policies on the manufacturing process. This simulates their low visibility of the supply chain and their inopportune action on high rework levels.

4. Two criteria for evaluating the production line

Rework causes amplification, phase lag and oscillation, that is, a kind of bullwhip effect, of both order and inventory levels. In this section, two criteria are proposed for measuring amplification, as follows [Muramatsu et al., 1985; Wang and Disney, 2016]:

$$Amp(O_t^i) = \frac{V(O_t^i)}{V(D_t)}, \tag{8}$$

$$Amp(B_t^i) = \frac{V(B_t^i)}{V(D_t)}, \tag{9}$$

where $V()$ is the variance function. Desirable systems satisfy $Amp(O_t^i) \leq 1, Amp(B_t^i) \leq 1, (\forall i)$. It is easy to show that the ideal situation described in Figure 2 satisfies this property.

Let us consider $R_t^4 = R_t^3 = R_t^2, \forall t$, and a uniformly distributed random variable $r \sim U(0,1)$ with cumulative distribution function $P(r)$. In sake of simplicity, we assume that a unit of rework happens each time $P(r) \geq 1 - \alpha$. Initially, let us assume $\alpha = 0.05$, which means that 5% of time working units need some rework in stages 4, 3 and 2. In order to explore the effect of lead time and rework on the amplification levels of order and inventory, we consider a middle level of autocorrelation. In Figure 5 amplification levels of the input rate I_t, the production rates P_t^i and inventory B_t^i $(i = 4, 3, 2, 1)$ are shown for different values of lead time L, for $\lambda = 0.5$ and $\alpha = 0.05$. Three characteristics are observed: 1) if $L = 1$, the amplification levels are very low; 2) if $L \in \{2, 3\}$, RBWE is noted; 3) the more L increases, the more the RBWE is observed in order amplification.

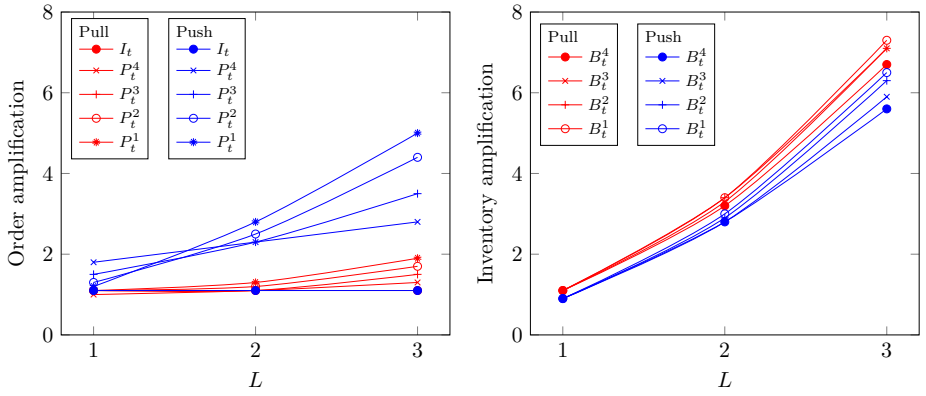


Figura 5: Amplification due to L $(\lambda = 0.5, \alpha = 0.05)$

In this case, the choice of a pull or a push system depends on the priorities established by the management system. For instance, if throughput is more important than inventory, the pull system should be chosen because a less order amplification. Instead, if inventory levels are the priority, the push system could be considered.

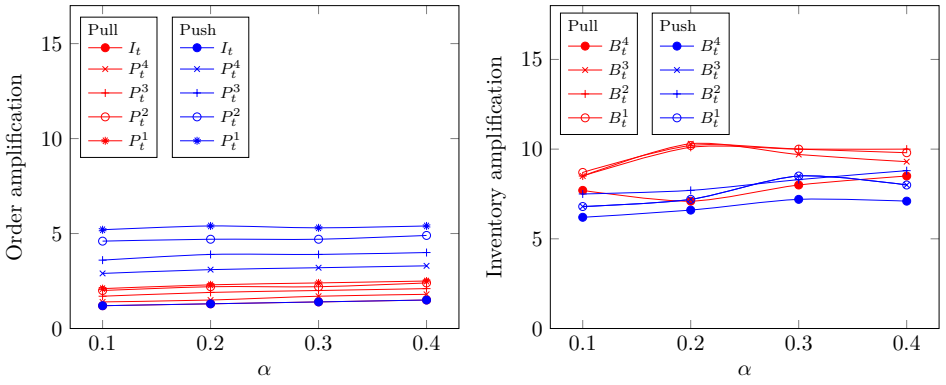


Figura 6: Amplification due to rework $(\lambda = 0.5, L = 3)$

Figure 6 allows us to observe that the amplification of order, when the pull policy

is applied, slightly increases downstream for any rework level. The push policy shows a more important amplification downstream, but it does not depend on the rework level. Amplification of inventory is higher when a pull policy is used, but there are not great differences among the rework levels. The same can be observed in the case of the push policy.

In order to verify whether the modeled rework worsen the amplification levels or not, amplification for different levels of rework is calculated, when L increases. This helps to explore what happens under the worst conditions. In Figure 7, amplification is shown in the case of $\lambda = 0.5, \alpha = 0.4$ and for different values of L. As before, the bullwhip effect increases downstream and it becomes higher with the increasing lead time. However, the amplification of inventory is almost the same both in pull and push policies. Thus, in a context of high rework and high lead time, the pull policy could be a better option.

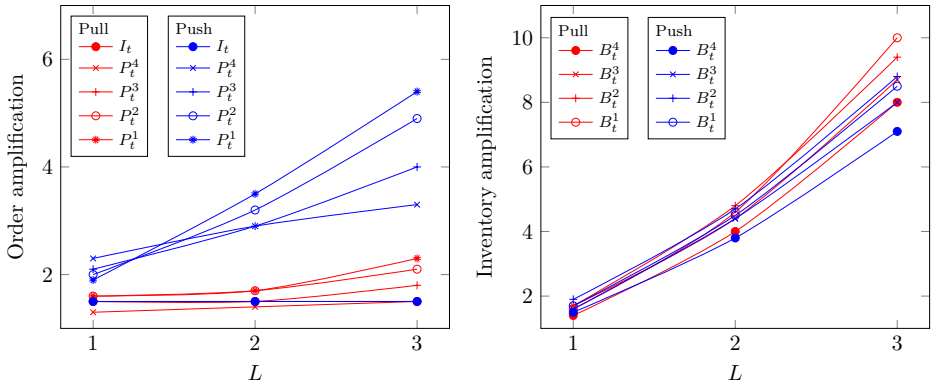


Figura 7: Amplification due to L ($\lambda = 0.5, \alpha = 0.4$)

Note that $\alpha = 0.1$ means that 10% of time, in average, one defective item is found. This could be called the Rework Type I (RTI), due to external uncontrollable variables, for instance defective or previously poorly manufactured supplies. However, other kind of error may be due to systematic internal error produced in a stage because of operation, tools, equipment or human reasons, which could be called the Rework Type II (RTII). This kind of rework can be considered by defining that a proportion β of the upstream in-progress inventory will be defective.

In Figure 8, amplification levels of order and inventory are shown for values $\beta \in \{0.1, 0.2, 0.3\}$ when only the Stage 4 has defective supplies or previously poorly manufactured units, while the other stages have a rework time rate $\alpha = 0.1$. RTII in Stage 4 induces a big amplification both in order and inventory. Amplification of order in a push model increases downstream, showing the behavior already observed in other simulations. Equally, note that inventories are amplified more or less in the same way in the whole production line, both in pull and push models.

5. Discussion

Experiments in Section 4 have been performed assuming that the management rules in the production line are applied in a myopic way, i.e., without intervention on factors leading to rework or high lead time. Thus, potential amplification is observed in

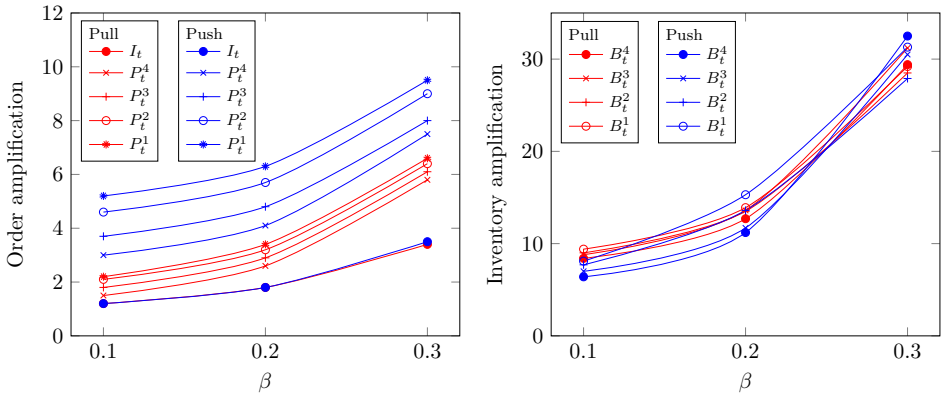


Figura 8: Amplification due to RTII in Stage 4 ($L = 3, \lambda = 0.5, \alpha = 0.1$)

the system, but none action is taken to control it. Obviously, in a real situation this could not be the case, and managers would be continuously monitoring the system to prevent prejudicious conditions. Unfortunately, the lack of appropriate information technology in the studied company, that could provide opportune and fiable information for decision-making purposes, entails low visibility of manufacturing processes and their dynamics. Most of information received by managers results from analysis on data collected in a manual format, which strongly delays decision-making processes. A company's senior manager calls this approach the rear view management: decisions are made about production problems that happened one day before. The most problematic situations mentioned by the company's senior managers are the high level of rework and the low visibility to timely know what the current state of the production system is. In previous sections, we have explored these situations, assuming two main management policies.

Briefly, simulations above show the following. In all the simulated scenarios, when a pull policy is applied, the amplification of order is lower than the amplification in a push policy. In all the simulated scenarios, when a pull policy is applied, the amplification of inventory is comparable or higher than the amplification in a push policy. This means that a trade-off exists between the pull and push policies. In addition, increasing lead time negatively impacts amplification and it is more importantly observed at the inventory level. RTI negatively impacts amplification, but the production line is not as much sensible to the increasing of the RTI level. Reducing RTI has not a great effect on diminishing amplification. Increasing of RTII has a strong negative impact on amplification.In all the simulated scenarios, a lower lead time and a lower RTII diminish amplification in both order and inventory, in all the supply chain.

Simulations confirm that RTII could have an important negative effect on the production line, which becomes very severe whenever the lead time increases. Results also show that RBWE is observed at the level of order amplification, mainly when the push policy is applied. However, it is also verified in the case of pull whenever RTII increases. Thus, the amplification of order progressively increases from Stage 4 down to the Stage 1. Interestingly, the more the lead time increases, the more this amplification is evident. In which concerns inventory amplification, there is not a clear visualization of RBWE.

Based on these results, some strategies could be identified, with the aim of improving the capacities of the management system to better control potential negative effects on the production line performance. We may assume that inventory of in-progress units needs to be prioritized because the lack of space available to stock WIP between the stages. Actually, in the company's production line, a unit transport system by air rails exists, which allows handling of in-progress units. This makes that a limited area is available for immediately upstream WIP on each stage. This also means that high amplification of inventory must be prevented as much as possible because the whole production line could be compromised because of lack of space.

The cost of using a push policy is the high amplification of order and inventory, which is enhanced by the effects of rework. Thus, reducing RTII is a priority. Analysis of features that cause RTII in the production line seems to be necessary. This encourages the systematic and collaborative collection of information about operations, tools, equipment and human activities in every stage of the supply chain. The main consumer of this information is the quality control area. Multiple causes may induce the lead time increasing, most of them related to manufacturing processes, supplies logistics, material handling, equipment obsolescence, machine performance, etc. In this aspect, opportune information regarding these aspects need to be available for analysis and optimization purposes. The main consumer of this information are the engineering and product design areas. RTI may be difficult to reduce because it considers uncontrollable external variables. However, simulation results show that control of lead time helps to reduce the effect of this kind of rework.

6. Conclusions

This paper presented a case study in a high-tech company in Brazil which has a high level of rework and the lack of opportune information to manage one of its production lines. Using simulation and bi-criteria analysis to simulate a model of the production line, a reverse bullwhip effect is observed. We propose that a cyber-physical production system (CPPS) may be designed to solve the two most prominent problems: high level of rework and low visibility of manufacturing, which in turns incides into the lead time and the delayed delivery to costumer.

Future research regards two features. First, designing of a CPPS which could help decision-makers to have a better visibility and opportune information to make decisions regarding the rework and RBWE levels. Second, at the data analysis level, models can be designed to find patterns that could help managers to design innovative management rules oriented to reduce rework and lead time.

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