A Simulation Model of a Tandem Coordinated Supply Chain

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December 2010
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ABSTRACT: This paper presents a study of a coordinated production inventory-system. In the proposed model, any echelon considers its successors as part of its inventory system and generates the replenishment order on the basis of operational information of its partners. We show that the coordinated decision making allows elimination of information distortion along the chain. Furthermore, we show how the bottom-up transmission of inefficiencies, typical of traditional supply chains, is avoided.

KEYWORDS: Tandem production/inventory, collaboration, bullwhip effect, differential equations, statistical analysis, continuous simulation.

JEL Code: C0, C1

1. INTRODUCTION

A classical problem of Supply Chain (SC) is the bullwhip effect (Lee et al. 1997). It refers to the tendency of replenishment orders to increase in variability as one moves up the SC from retailer to manufacturer (Disney and Lambrecht 2008). From 1919, the year in which the phenomenon was recognised at P&G, academics and practitioners from all over the world have explored one of the most fascinating enigmas of Operation Management.

A taxonomy used to classify the countermeasures which can be undertaken to dampen or avoid the bullwhip effect is presented in Van Ackere et al. (1993). The framework identifies three different solving approaches: (1) redesigning the physical process, (2) redesigning the information patterns, and (3) redesigning the decision process. With respect to the latter, we add redesigning the number and position of decision making points in a chain, something that impact on the nature and entire process of decision making. An example is when a retailer delegates inventory replenishment decisions to supplier, like vendor managed inventory (VMI).

Dejonckheere et al. (2004) suggest that the first approach could be realised through two of the bullwhip reduction principles: “time compression” and “echelon elimination”. (Geary et al. 2006). Echelon elimination can be physical but when is virtual it refers to the change of decision making position, elimination of a decision making point. Both are strictly linked: the echelon elimination technique allows, by its own nature, the achievement of time compression purpose. Disney and Lambrecht (2008) suggest that lead-time reduction is generally provided by two techniques: by eliminating channel intermediaries, such as the “Dell Model”, and by coordinating the supply operations. Redesigning the information patterns and redesigning the decision process can be conjointly realised by implementing supply chain coordination mechanisms. Supply chain coordination allows transforming suboptimal solutions of individual links into a comprehensive solution (Cannella and Ciancimino 2009). At the operational level, supply chain coordination mechanisms concern with the alignment of decision making amongst supply chain partners in their planning and inventory management. This alignment is enabled by the exchange of information in the supply chain (Stadtler 2009). This paper wishes to contribute to the bullwhip literature, by presenting a supply chain tandem coordination model and a numerical study to assess the efficiency of the production-distribution system. To perform the study, a differential equation modelling approach is adopted. Results show how sharing real-time point-of-sales information, sales forecasts, inventory order policies and inventory reports to support multi-tiers integration decision rules represent the key element to achieve bullwhip dampening ability. Furthermore we show how the bottom-up transmission of inefficiencies, typical of traditional supply chains, is avoided.

The article is organized as follows. Section 2 reports a literature review on the impact of the coordination mechanisms and of information transparency in term of bullwhip effect. The simulation model is presented in section
3. Section 4 presents the design of the experiment, the supply chain performance metrics, the simulation output analysis and discussions. Section 5 presents conclusions and future directions.

2. LITERATURE REVIEW

Although the supply chain literature frequently proclaims the virtues of coordination mechanisms and information sharing, only in the last decades an easily implementable, effortlessly updatable and economically accessible information technology was developed to allow the realisation of the effective large-scale collaboration project. As reported by Butner (2010), though more information is available, proportionally less is being effectively captured, managed, analysed, and made available to people who need it. Therefore more research has been advocated on modelling and analysing coordination-level issues by several practitioners and academics (Dooley et al. 2010, Flynn et al. 2010, Lu et al. 2010, Yu et al. 2010, Cannella et al. 2010).


Shang et al. (2004) via discrete event simulation and Taguchi technique study three multi-layer supply chains. The authors state that integration of suppliers helps cutting cycle times and reducing inventories. Chatfield et al. (2004) present two four-echelon supply chains studied via object-oriented simulation: a traditional and an EPOS (Electronic Point Of Sales). The authors show that information sharing decelerates the bullwhip effect in the upstream direction. More specifically, information sharing scenarios exhibit a linear trend with echelon, whereas non-information sharing scenarios exhibit a quasi-exponential increase of order variance amplification. Kim et al. (2006) quantify bullwhip effect under stochastic lead time, different forecasting methods and customer demand information sharing for a traditional and an EPOS five-layer supply chain. They affirm that the bullwhip effect is attenuated from exponential to linear when information is shared. Byrne and Heavey (2006), via discrete event simulation, present a traditional and an EPOS supply chain and show how the use of improved information sharing techniques has a more significant impact on the supply chain costs than the forecasting technique. To assess the supply chain performance, the authors adopt costs of transportation, ordering, production, setup, inventory and backorder. Hosoda and Disney (2006) study via optimisation methods a traditional supply chain and a Vendor Managed Inventory supply chain. The authors show the benefit of information sharing in terms of inventory variance. Kelepouris et al. (2008) present a traditional and an EPOS two-echelon supply chain, both studied via spreadsheet simulation. They show how information sharing results in a 21% order variability reduction, on average, and in a 20% mean cycle inventory decrease. Hosoda et al. (2008) study via statistical modelling an EPOS supply chain. The authors show how sharing data reduces the second echelon’s holding and backlog costs by 8–19%. Agrawal et al. (2009) show in the discrete time domain the benefit of customer demand information sharing in term of Order Rate Variance Ratio and Inventory Rate reduction. Nevertheless, they state that part of the bullwhip effect will always remain even after sharing both inter- as well as intra-echelon information. Chaharsoghi and Heydari (2010) present a four-echelon EPOS supply chain simulation model, showing the impact of lead time reduction provided by information sharing in term of Order Rate Variance Ratio, inventory, stock out size stock out number diminution. Yuan et al. (in press) study the impact of different collaboration strategies like Vendor Managed Inventory (VMI), Jointly Managed Inventory (JMI), and a Collaborative Planning, Forecasting & Replenishment (CPFR) model using system dynamics based simulation and compare the results with a non-collaborative chain. The results indicate that the manufacturer of a high-tech product would be much better-off increasing the share of inventory risk with distributor.

3. THE COORDINATED SUPPLY CHAIN MODEL

In this section we detail modelling assumptions and mathematical formalism of the coordinated supply chain presented in this work. Our model is a multi-tier structure, composed by \( K \) serially-linked echelons. We model this as a SC line synchronized through tandem production/inventory entities. Each entity has knowledge of the total downstream inventory. External demand is met from the available finished goods inventory maintained in front of the most downstream entity; unsatisfied demand is backlogged. In other words, each echelon in the system has a single successor and a single predecessor. We assume that in our study there is not constrained production-distribution capacity (no quantity limitations in production, buffering and transport are considered). We adopt the single-product/aggregate production plans modelling assumption, widely used in supply chain analysis (Simon 1952; Vassian 1955, Forrester 1961; Sterman 1989; Lee et al. 1997; Chen et al. 2000). Our consideration of backlog provides a good indicator to measure performance improvement due to coordination. Unlimited raw material supply is assumed, i.e. orders from producer are always entirely fulfilled in time. To model the coordinated order policy we assume that market demand is visible to all echelons. Furthermore, as in a coordinated supply chain the aim of a generic tier is not to satisfy the order generated by the subsequent adjacent stage but the demand coming from market, in the determination of the replenishment quantity any echelon considers its successors as a part of its inventory system. Consequently a generic echelon \( i \) receives information about order quantity from the downstream adjacent echelon, information on the up-to-date market demand and on cover time for the inventory control, lead times, inventory levels, and work in progress levels from all downstream echelons. In Table 1 the model notation is reported.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( W_{i} )</td>
<td>work in progress (includes incoming transit units) in echelon ( i ) at time ( t )</td>
</tr>
<tr>
<td>( Inv_{i} )</td>
<td>inventory of goods at echelon ( i ) at time ( t )</td>
</tr>
</tbody>
</table>
Equation (4) defines the item delivery from one echelon to its successor modelling the non negativity condition of inventory.

\[ DO_i^t = \min (RV_i^t; Inv_i^t + Th_i^t) \]  

Eq. (5) represents the production/delivery lead time delay, represented by the parameter \( T_p \)

\[ Th_i^t = DO_{i-1}^t \]  

Equation (6) models the exponential smoothing formula to forecast demand (Makridakis et al. 1982), where \( d_{i,t} \) stands for the end customer demand and \( \alpha \) is the smoothing parameter. The market demand forecast equation is shared by all the echelons.

\[ d_i^t = \alpha T_{d_{i-1}} + (1 - \alpha) d_i^{t-1}; \quad 0 < \alpha \leq 1. \]  

Equation (7) models the variable virtual work in progress, which is obtained by the sum of orders-in-the-pipeline at stage \( i \) plus the work in progress of downstream echelons (Work in Progress in echelon \( i \) plus Work in Progress of all downstream echelons \( i+1 \ldots K \)).

\[ VirtWip_i^t = \sum_{j=1}^{K} Wip_j^t \]  

Virtual inventory is modelled by equation (8). For an individual echelon, virtual inventory is the sum of the Inventory at stage \( i \) and Inventory of all subsequent echelons. (Inventory level in echelon \( i \) plus inventories levels of all downstream echelons \( i+1 \ldots K \)).

\[ VirtInv_i^t = \sum_{j=1}^{K} Inv_j^t \]  

Target Virtual Wip (9) and Target Virtual Inventory (10) are two further elements that enable the inclusion of information of the downstream members’ operations in the replenishment rule of an individual echelon. They are generated by two operational parameters and the forecasted demand. Target Virtual Work in Progress (equation 9) is the forecast of market demand multiplied by the sum of lead times from echelon \( i \) to the echelon \( K \). The sum of lead times \( T_{d_i} \) from echelon \( i \) to echelon \( K \) is the time period needed to deliver the finished product from the generic echelon \( i \) to the final customer \( K+1 \).

\[ TVirtWip_i^t = \sum_{j=1}^{K} T_{d_j}^t \]  

Target Virtual Inventory (equation 10) is the forecast of market demand multiplied by the sum of cover times for the inventory control from echelon \( i \) to echelon \( K \).

\[ TVirtInv_i^t = \sum_{j=1}^{K} T_{c_j}^t \]  

Equation (11) models the order rule adopted in our model. It is a well-known variant of a periodic review Order-Up-To (OUT), namely a smoothing replenishment rule (Boute et al. 2008-2009, Lin et al. 2010). The features of smoothing replenishment rules were studied and popularised by the Cardiff Business School (see Towill 1982, John et al. 1994, Disney and Towill 2006). It has been shown in the literature that properly tuning the value of the smoothing parameters of this order policy offers an opportunity to reduce bullwhip (Disney and Towill 2003). At every review time the ordered quantity is equal to the forecasted demand, plus a fraction of
the discrepancy Target Virtual Wip and actual Virtual Wip (regulated by 1/Tw), plus a fraction of the gap between Virtual Inventory and actual Inventory (regulated by 1/Ty). The main feature of these smoothing replenishment rules is that the entire deficit between the OUT level and the available inventory is not completely recovered in a review time (Cannella et al. in press).

\[ R_i^* = \tilde{d} + \frac{1}{T_w} (TVirtWip_i^* - VirtWip_i^*) + \frac{1}{T_y} (TVirtInv_i^* - VirtInv_i^*) \] (11)

Finally, equation (12) defines the non negativity condition of order quantity.

\[ R_i^* \geq 0, \forall i \] (12)

Figure 1 summarises the information used by a generic echelon to generate the order quantity.

![Figure 1 Operational information for the replenishment at a generic echelon i](image)

4. NUMERICAL ANALYSIS AND DISCUSSION

To perform our numerical study the parameters of the coordinated order policy are varied for each echelon according to a standard Latin Square Design (Kleijn 2008). More specifically, we set up nine experimental sets, obtained by varying three parameters three key variables of production inventory control systems: lead time, demand forecast factor and proportional controller of the replenishment rules.

In table 2 the three parameters are detailed.

<table>
<thead>
<tr>
<th>SUPPLY CHAIN PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>The forecast smoothing factor α</strong></td>
</tr>
<tr>
<td>Suggested by Disney and Lambrecht (2008) we have selected exponential smoothing as it is well understood and popular among practitioners. As reported by the two authors, it was the preferred option from among 24 other commonly used time series methods</td>
</tr>
</tbody>
</table>

| The physical production/distribution lead time \( T_p \) |
| Suggested for the incoming transit time at echelon \( i \) from supplier plus the production lead time. It is recognised in the literature as one of the variables that most impact on the efficient operations of the supply chain, as it is identified as one of the principal causes of bullwhip effect (Lee et al. 1997). In the bullwhip field several studies underline the importance of the lead time compression to avoid bullwhip effect (Towill et al. 1996, Geary et al. 2006). |

| The smoothing inventory and work in progress parameter \( T_w = \frac{T_p}{\alpha} \) |
| These parameters are recognised as one of the most important topic in the bullwhip avoidance literature as order smoothing is an effective solution to several causes of bullwhip identified by Lee et al. (1997): demand signal processing, order batching and production distribution lead time. The philosophy behind the smoothing parameters consists of decreasing the tiers’ quantity in presence of possible market demand distortion. As reported by Disney and Lambrecht (2008), when \( T_p = T_w < 1 \) bullwhip is created (variance amplification) and for \( T_w = T_p > 1 \) a smoothed replenishment pattern is created (dampening). The optimal values of the two controllers are obviously sensitive to the economics of the supply chain in question. |

Table 2 The three analysed supply chain parameters

<table>
<thead>
<tr>
<th>( \alpha )</th>
<th>( T_p )</th>
<th>( T_i )</th>
<th>( T_w = T_p/\alpha )</th>
<th>( Wip_i^* )</th>
<th>( Inv_i^* )</th>
<th>( B_i )</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>1/6</td>
<td>1</td>
<td>3</td>
<td>( 2^1 )</td>
<td>100</td>
<td>300</td>
</tr>
<tr>
<td>#2</td>
<td>1/3</td>
<td>1</td>
<td>3</td>
<td>( 3^1 )</td>
<td>100</td>
<td>300</td>
</tr>
<tr>
<td>#3</td>
<td>2/3</td>
<td>1</td>
<td>3</td>
<td>( 4^1 )</td>
<td>100</td>
<td>300</td>
</tr>
<tr>
<td>#4</td>
<td>1/6</td>
<td>2</td>
<td>3</td>
<td>( 3^1 )</td>
<td>200</td>
<td>300</td>
</tr>
<tr>
<td>#5</td>
<td>1/3</td>
<td>2</td>
<td>3</td>
<td>( 4^1 )</td>
<td>200</td>
<td>300</td>
</tr>
<tr>
<td>#6</td>
<td>2/3</td>
<td>2</td>
<td>3</td>
<td>( 2^1 )</td>
<td>200</td>
<td>300</td>
</tr>
<tr>
<td>#7</td>
<td>1/6</td>
<td>3</td>
<td>3</td>
<td>( 4^1 )</td>
<td>300</td>
<td>300</td>
</tr>
<tr>
<td>#8</td>
<td>1/3</td>
<td>3</td>
<td>3</td>
<td>( 2^1 )</td>
<td>300</td>
<td>300</td>
</tr>
<tr>
<td>#9</td>
<td>2/3</td>
<td>3</td>
<td>3</td>
<td>( 3^1 )</td>
<td>300</td>
<td>300</td>
</tr>
</tbody>
</table>

Table 3. Parameter settings

To set the market demand, we adopt Towill et al.’s (2007) shock perspective. They presented a creative classification framework for bullwhip studies, suggested by the Morecroft “lens” concept (1983). They identified three “observer’s perspectives” to analyse the bullwhip effect: Variance lens, Shock lens and Filter lens. In this paper, the research approach selected to study the supply chain is the bullwhip shock lens. Using a mathematical modelling (Kleijn 2005), the bullwhip shock lens aims at inferring on the performance of supply chains for an unexpected and intense
change in market demand. The demand signal from market changes from 100 items per time unit to 200 items/time unit in the tenth simulation period. The model runs are for a total of 100 time units, with a time step equal to 0.25. The Euler-Cauchy method with order of accuracy $\Delta t=0.25$ is adopted to approximate the solution for the initial-value problem (Ciancimino and Cannella, in press).

The supply chain performance is measured via a set of metrics, whose reduction reflects improved cost effectiveness of members’ operations as followings: (I) the Order Rate Variance Ratio proposed by Chen et al. (2000), (II) the Inventory Variance Ratio, proposed by Disney and Towill (2002), (III) the Backlog (Kleijnen and Smits 2003) as customer service metric.

Table 4 details the performance metrics Order Rate Variance Ratio, Inventory Variance Ratio and Backlog.

### Table 4. Supply chain performance metrics

The results are presented for a four-echelon supply chain in which $i=1$ stands for the producer, $i=2$ stands for the distributor, $i=3$ stands for the wholesaler and $i=4$ stands for the retailer. The numerical experiment output is presented in the following. The Order Rate Variance Ratio and the Inventory Variance Ratio measures are reports in Table 5 and Table 6, respectively. Figure 2 reports the Backlog. In Figure 3 the Order Quantity values for the four echelons for each parameter set are plotted over the time span. Finally, table 7 provides the results from the statistical analysis on the Backlog and Average Inventory, obtained using Minitab.

### Table 5. Order Rate Variance Ratio

<table>
<thead>
<tr>
<th>Order Rate Variance Ratio</th>
<th>Retailer</th>
<th>Wholesaler</th>
<th>Distributor</th>
<th>Producer</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1 2.924</td>
<td>6.283</td>
<td>7.147</td>
<td>4.934</td>
<td></td>
</tr>
<tr>
<td>#2 1.464</td>
<td>2.444</td>
<td>3.128</td>
<td>3.281</td>
<td></td>
</tr>
<tr>
<td>#3 1.478</td>
<td>2.417</td>
<td>3.186</td>
<td>3.478</td>
<td></td>
</tr>
<tr>
<td>#4 1.654</td>
<td>2.956</td>
<td>3.417</td>
<td>2.878</td>
<td></td>
</tr>
<tr>
<td>#5 1.863</td>
<td>3.366</td>
<td>3.988</td>
<td>3.438</td>
<td></td>
</tr>
<tr>
<td>#6 6.995</td>
<td>15.058</td>
<td>15.382</td>
<td>6.421</td>
<td></td>
</tr>
<tr>
<td>#7 1.956</td>
<td>3.771</td>
<td>4.285</td>
<td>3.022</td>
<td></td>
</tr>
<tr>
<td>#8 10.079</td>
<td>21.162</td>
<td>20.177</td>
<td>5.792</td>
<td></td>
</tr>
<tr>
<td>#9 6.149</td>
<td>13.170</td>
<td>14.387</td>
<td>6.643</td>
<td></td>
</tr>
</tbody>
</table>

### Table 6. Inventory Variance Ratio

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>DF</th>
<th>SS</th>
<th>MS</th>
<th>F</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_p$</td>
<td>2</td>
<td>6379.7</td>
<td>3189.9</td>
<td>44.86</td>
<td>0.022</td>
</tr>
<tr>
<td>$T_{pe}=T_{re}$</td>
<td>2</td>
<td>345.6</td>
<td>172.8</td>
<td>2.43</td>
<td>0.292</td>
</tr>
<tr>
<td>$a$</td>
<td>2</td>
<td>486.4</td>
<td>243.2</td>
<td>3.42</td>
<td>0.226</td>
</tr>
<tr>
<td>error</td>
<td>2</td>
<td>142.2</td>
<td>71.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>8</td>
<td>7353.9</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Figure 2. General linear model for Backlog

Numerical experiments quantify the impact of coordination mechanism on supply chain performance, i.e. the elimination of bullwhip effect, the stability of inventory and the enhancing of customer service level.

Firstly, Order Rate Variance Ratio values show that, unlike a traditional serially-linked supply chain, in the coordinated supply chain there is no geometric increase of the bullwhip with the level in the chain (Dejonckheere et al. 2004). In other words, unlike in traditional supply chain can a node-to-node 20:1 and even higher amplification be recognised (Geary et al. 2006), in our model the average increases is less than 1:2.

Additionally, in two experimental sets, the values of the Order Rate Variance Ratio for the retailer are lower than the values reported by the producer. This phenomenon indicates that potential initial growth of the order stability is promptly smoothed at the higher level of the chain. As the producer benefits from the fully transparent information of all processes in the chain and is enabled to avoid a possible transmission of false demand.
Similarly, the Inventory Variance Ratio shows how a win-win partnership, provided by the coordination model, creates full stability for any inventory in the chain. The bottom-up transmission of inefficiencies, typical of traditional supply chains, is avoided, especially in term of inventory instability. We can observe a monotonous decrement in the inventory instability at each level of the supply chain (from retailer to producer) in every simulation set. In other words, the variance of inventory decreases along the chain in upstream direction, regardless of parameter setting. From a managerial viewpoint, this result converts in a highly beneficial reduction of holding costs for the higher levels of the chain.

Results reassert the study of Yuan et al. (in press): a JMI stock management strategy performs significantly better than other collaboration strategies because it enables the manufacturer and the distributor control their stocks together, in this way, when facing the retailer orders changes, they can adjust quickly the stock and that in turn reduces the adjustment cycle for the jointly managed stocks.

Another noticeable insight on the features of the studied supply chain coordination model can be observed by analysing the customer service metric. The better performance is provided when the supply chain model works under low lead time. Analogously, the same trend can be observed for the two previous process metrics (Order Rate Variance Ratio and Inventory Variance Ratio).

The analysis of variance for Backlog reveals that at \( p<0.004 \) level of significance, none of the analysed factors are significant sources of variation. Nevertheless, the \( p \) level of lead time is one order of magnitude lower than the \( p \) levels of forecasting smoothing factor and the smoothing inventory and work in progress parameter \( (T_s,T_w) \). This is indicative of a relatively higher impact of lead time on customer service level.

These results reassert several statements of the literature on the importance of lead time reduction (Wikner et al. 1991, Towill 1996, Chen et al. 2000, Disney and Towill 2003a, Chatfield et al. 2004, Zhang 2004, Chandra and Grabis 2005, Disney et al. 2006, Kim et al. 2006, Kelepouris et al. 2008, Agrawal et al. 2009, Wang et al. 2010). We can deduce that, although the problem of distortion and delay of information is resolved by default in the coordinated supply chain, production-distribution lead time impact on performance is still very important. Results emphasise that one of the pillars of performance is the production-distribution lead time management. In cases of extreme uncertainty or supply chain break-downs, the lead time compression principle has to be guaranteed, so backup plans should be activated through the use of alternative distribution channels.

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**Figure 2. Order Quantity**
5. CONCLUSIONS

As reported by Lee (2010) is a recent editorial on bullwhip effect and the current world crisis recession, increasing visibility of the supply chain is today even more necessary to avoid being misled by the distorted demand signals. In this work we presented a supply chain coordination model designed to avoid the bullwhip effect. To perform the study, a differential equation modelling approach was adopted and a parameter variation analysis was conducted. We adopted two process performance metrics to assess the model, the Order Rate Variance Ratio, the Inventory Variance Ratio, and the Backlog to evaluate the customer service level. To set the market demand, we adopt the Towill et al.’s (2007) shock lens perspective. We showed how the node-to-node average increase of Order Rate Variance Ratio is less than 1:2, unlike the traditional structure where a 1:20 increase is observed. A further noticeable result is the monotonous decrement in the inventory instability at each level of the supply chain in upstream direction, in counterevidence with the trend that has been reported in the literature of traditional production-distribution systems. Finally, we reconfirm how the production-distribution lead time management continues to be a key factor for internal and customer benefits.

Future research will focus on the impact of imprecise information on collaborative supply chain performance (Wong 2010). Most literature on the benefit provided by IT and supply chain collaboration ‘a priori’ assumes that data sharing is highly accurate (Kappor et al. 2009). On the contrary, it has been shown that errors and failures in IT, also in the innovative RFID technology, cannot be completely eliminated (Zhou 2009).

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