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Evidence of bullwhip in the blood supply chain

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Abstract

This paper presents an empirical investigation of the bullwhip effect in the Scottish blood supply chain. The purpose is to identify the causes of bullwhip and its impact on inventory performance in terms of age at transfusion and time expiry waste. For a range of red cell blood products we find that bullwhip is evident at both an aggregate level and at individual hospital level. The causes are rooted in hospital ordering practice and we find that stock on hand, age of product at transfusion and waste due to time expiry are all correlated with hospital order pattern volatility.

Keywords: Bullwhip, Blood, Inventory performance

Introduction

The Scottish National Blood Transfusion Service (SNBTS) is a division of the NHS National Services Scotland (NSS). The key objective of SNBTS is to ensure availability of blood, cells and tissues for patients throughout Scotland. The irregular supply of donor blood and the perishable nature of blood products call for a sophisticated blood supply chain (Beliën & Forcé, 2012) and a robust approach to inventory management (Stanger, et al., 2012). The objective is to ensure 100% availability whilst minimising wastage through time expiry. Red blood cell units have a shelf-life of 35 days from the time of donation; if not transfused within this time the product must be discarded.

The bullwhip effect is known to cause excess inventory (Lee et al. 1997) which in turn can increase the wastage rate of perishable products; hence this research seeks to identify the causes of bullwhip in the blood supply chain and to understand how bullwhip impacts inventory performance at the customer location.

This paper begins with a brief review of relevant literature on the bullwhip effect, its causes, impacts and countermeasures. We then present our method of investigation before presenting and discussing our findings. Finally we offer our conclusions and ideas for further research into the bullwhip phenomenon in the blood supply chain.

Literature Review

The bullwhip effect refers to “*the amplification of end-customer order signals, whereby upstream replenishment demand and physical shipments exceed the original order quantity.*” (McCullen and Towill, 2002, p. 165.) Bullwhip is not a new concept in supply chain management; first identified by Forrester in his seminal work, *Industrial Dynamics* (1961), the past half a century has seen a plethora of research emerge to demonstrate its various proofs, interpretations and mitigation. A substantial body of empirical and analytical research has explored the causes of bullwhip and how it creates supply chain inefficiencies such as excess inventory, poor customer service, lost sales and ineffective transportation and production schedules (Lee et al., 1997). As the distorted demand signal travels up a supply chain, it disrupts production schedules and capacity plans as suppliers are forced to respond to the volatile demand pattern. The result is additional costs from overtime, shift premiums, extra transportation, handling and storage charges (McCullen and Towill, 2002). How these additional costs are borne by different supply chain actors is outlined by Ma et al. (2013) who surmised that upstream costs are caused by inflated operational costs, whilst the downstream costs are due to large inventory costs as a result of inventory oscillations requiring high safety stock levels. Research by Metters (1997) found that eliminating bullwhip could increase the profitability of a product by 10–30%. In terms of the impact on inventory, bullwhip causes excess inventory throughout the supply chain as each party needs to protect themselves against demand oscillations by holding high safety stock (Cachon et al., 2007) as well as “*successive upswings and downswings*” in supply chain inventories (McCullen and Towill, 2002, pp. 165)

Whilst surplus stock is never desirable, managers of perishable products face the additional challenge of wastage due to time expiry and hence bullwhip in a perishable product supply chain can increase wastage rates as well as operational costs. The major problem for perishable goods is that product value (and often quality) deteriorates over time in the supply chain (Blackburn and Scudder, 2009). Food items are also subject to stringent health, safety and quality regulations (Minner and Transchel, 2010) and once these items are no longer compliant, must be discarded. In the blood supply chain, failure to ensure sufficient product availability can potentially lead to patient death, whilst holding surplus stock will lead to wastage of the donor’s gift and surplus costs to the healthcare system (Stanger et al., 2012). Therefore, the existence of bullwhip in a perishable supply chain, such as the blood supply chain, would indicate that opportunities for improvement and costs savings could be significant – especially given the productivity challenges faced by the UK health service.

Causes of bullwhip

Lee et al. (1997) and Disney and Towill (2003) identify the four main operational causes of demand amplification including:

- Demand signal processing. Small variations in the original demand signal are amplified due to a combination of over responsive forecasting and information time lags. It has long been understood that delays in information and material flow (i.e. lead-time) are key drivers of demand amplification (Forrester 1961 and Lee et al. 1997).
- Order batching. Batched orders are the result of ordering practices; most notably the periodic review process and attempts to minimise transaction costs. In an ideal scenario, customer orders are spread out evenly over time to minimise bullwhip. In reality orders are likely to be randomly spread out or overlap, with several customers simultaneously placing orders at once, i.e. at the end of the week/month, thus creating a surge in demand upstream.

- Price fluctuation. Fluctuations in the price of products can impact purchase behaviour whereby buyers capitalise on short-term discounts by forward buying.
- Order inflation or rationing and gaming. A recognised driver of order variation is limited supply (or a perception of) where customers order more than required 'just in case'. Retailers protect themselves against perceived shortages by exaggerating their real needs or placing duplicate orders (Lee et al., 1997). When demand returns to normal levels or reduces, order cancellations can follow. This is problematic for suppliers who base operational decisions on their customers' orders which do not reflect consumer demand.

Bullwhip countermeasures

McCullen and Towill (2002) developed a bullwhip mitigation framework based on four material control principles, including:

- Control system principle - involving the use of decision support systems to synchronise and avoid a batch and queue scenario, such as 'just-in-time' and level scheduling. Several authors have also modelled allocation policies that promise to reduce order inflation and the practice of 'rationing and gaming' between supply chain members. For example, Chen et al. (2013) suggest allocation according to some predetermined priority sequence whereas Cachon and Lariviere (1999) carry out allocation based on past sales;
- Time compression – shorter time delays of material and information flows that will allow organisations to adjust their inventory and reduce inventory discrepancies;
- Information transparency – the provision and sharing of quality end to end supply chain data to provide a common platform from which each supply chain actor can based their operational decisions upon. Lee et al. (1997) identified demand information sharing as a bullwhip countermeasure where end consumer demand is shared directly with all supply chain members, who then use that information to improve their forecasts rather than depending on distorted, i.e. amplified, orders that lag behind real consumer demand.
- Echelon elimination – removing redundant supply chain echelons and functional interfaces. This also facilitates the reduction in time delay and information distortion but can lead to significantly different distribution channels.

Fundamentally, the literature identifies sharing timely information along the supply chain as being a key method to mitigate the bullwhip effect (Lee et al., 1997, McCullen and Towill, 2002, Giard and Sali, 2013). Disney and Towill (2003) show how Vendor Managed Inventory (VMI) can reduce bullwhip by counteracting several causes of demand amplification. VMI is a form of information sharing between two echelons in a supply chain whereby the supplier is given visibility of the customer's inventory and the responsibility to replenish stocks automatically as required. In effect this removes a decision echelon in the supply chain thus reducing the risk of information distortion and demand amplification. As the customer no longer needs to place orders on the supplier, the possibility of 'order inflation' is eliminated.

Method

Case studies and empirical analysis based on firm-level rather than industry-level data have the ability to offer more insights on the incentives of demand amplification (Wang and Disney, 2016). Zotteri (2013) noted that case studies tend to focus on single products and Sucky (2009) pointed out that the literature is dominated by examples of two stage supply chains. This empirical investigation is based on a single case study encompassing

the four stage supply chain of the Scottish blood supply chain stretching from blood donors to final consumers, i.e. patients, in which we consider a range of eight blood products from a single product family (red blood cells). A vertically integrated supply chain from product extraction (donation) to final consumption (transfusion) the Scottish supply chain includes the SNBTS, comprising Donor Services and Production (processing & testing), and NHS Hospital customers throughout Scotland as illustrated in Figure 1.

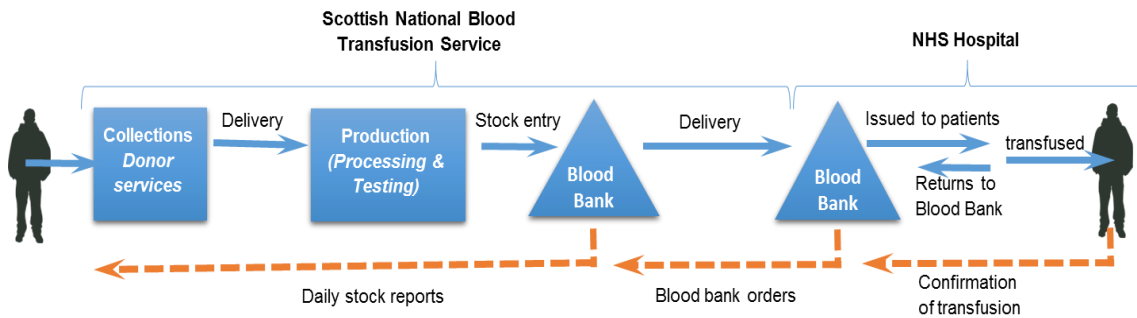


Figure 1 – Schematic of the end to end blood supply chain in Scotland

Data collection

Transaction data indicative of demand at different echelons of the supply chain (Table 1) were extracted from the SNBTS archival database and analysed using Microsoft Excel. The data cover a 12 week period from 10/11/2014 to 01/02/2015 for each of 8 RBC blood components at individual hospital and aggregated to national level. Each transaction data set was aggregated into daily time buckets for time series analysis.

Table 1 – Transaction data indicative of demand at each echelon of the blood supply chain

Supply chain echelon		Transaction data
1	Patient	Units transfused
2a	Hospital Blood Bank	Units issued to theatre/patient
2b	Hospital Blood Bank	Units ordered from SNBTS
3	Production (SNBTS)	Units entered to central SNBTS stock
4	Donations (SNBTS)	Units donated

Semi-structured interviews were used to collect qualitative data concerning inventory control practice for a large hospital blood bank in central Scotland where bullwhip was clearly evident in historic time series data.

Data analysis

Incomplete and anomalous data were removed before applying statistical analysis to calculate the degree of bullwhip at different echelons in the supply chain. Demand amplification can be measured by comparing the variance between demand and orders (or issues) at each echelon in the supply chain. This can be achieved using an amplification ratio where bullwhip is indicated by a ratio larger than one (Cachon et al., 2007). Contrarily, a ratio less the one indicates smoothing of the demand signal. Following Zotteri (2013) we measure the degree of bullwhip using the classic amplification ratio (AR):

Equation (1):

$$AR_{B/A} = \frac{CoV_B}{CoV_A}$$

CoV = Coefficient of variation

A,B = supply chain echelons where A is closest to the end consumer

The amplification ratio was determined between each echelon in the aggregate national blood supply chain for the eight RBC products. For more in-depth analysis of hospital level data we compared transfused demand per hospital with both internal issue quantities and orders placed on SNBTS. An example hospital located in the central belt of Scotland exhibiting bullwhip was identified for more in-depth analysis. Key informant interviews with managerial staff were conducted to explore the causes of bullwhip identified in the ordering process.

Findings and discussion

Evidence of bullwhip can be seen in product level time series data, for example figure 2 clearly illustrates amplification of transfused demand in the aggregate OPOS RBC supply chain. The amplification ratio between transfused demand and donations ($AR_{4/1}$) is 2.21, i.e. the volatility in the demand signal for OPOS RBC is more than doubled as it moves up the supply chain.

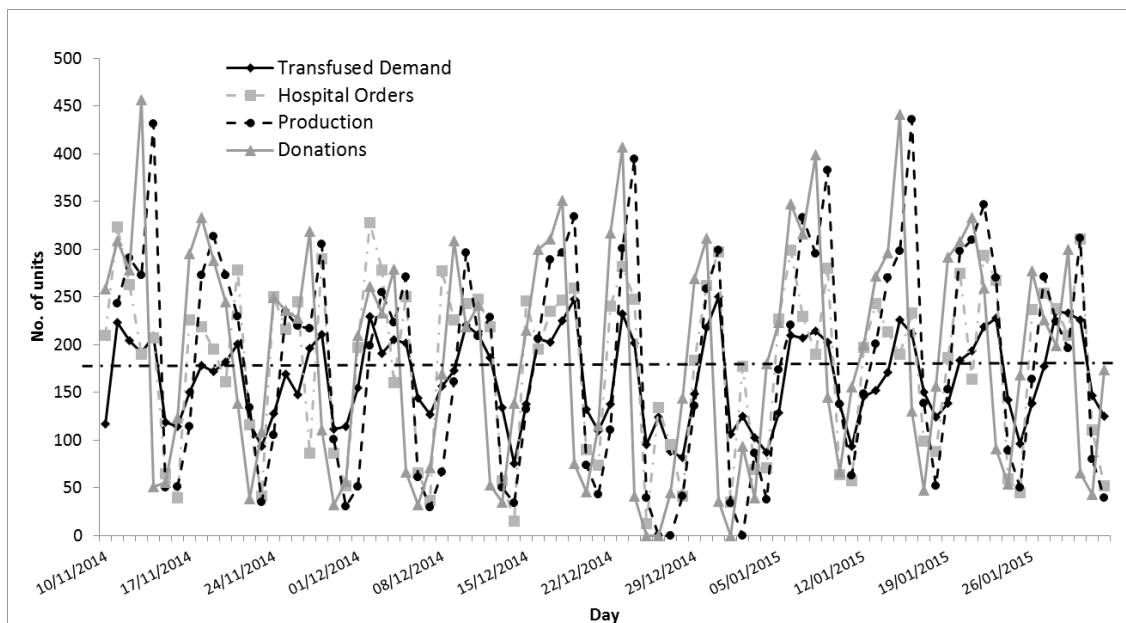


Figure 2 – Amplification in the demand signal for OPOS Red Blood Cells

Unlike traditional supply chains the original demand signal does not pass sequentially upstream through each echelon of the blood supply chain. Daily production quantities were found to be dependent on the previous day's donations (evident in figure 2) and are not directly driven by downstream demand patterns, i.e. donated units are pushed through production to central SNBTS storage. However, daily inventory reports are used to inform donor collection requirements; if for example a particular RBC product falls below a pre-defined stock level, then specific donors are contacted by Donor Services and invited to donate bringing the inventory back to an acceptable level. For this reason subsequent analysis omits the production echelon as shown in figure 3. The data presented in Figure 3 illustrate that the severity of demand

amplification varies between different blood products and supply chain echelons. Most amplification is introduced by hospital blood bank ordering; this is true for all products with the exception of ABNEG red cells where smoothing of the original transfused demand occurs rather than amplification.

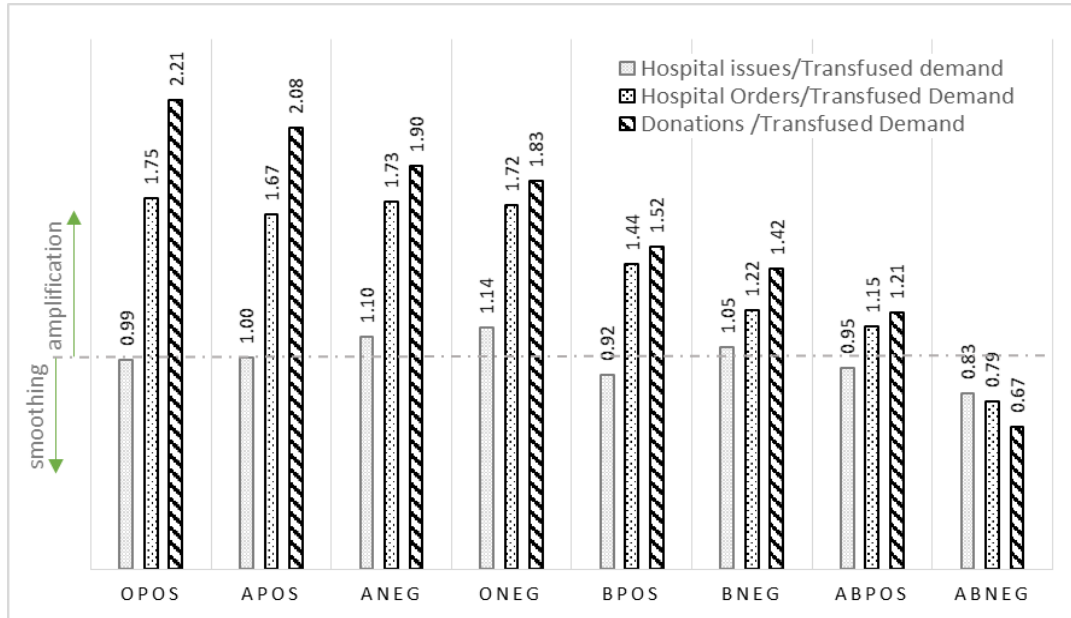


Figure 3 – Bullwhip ratios between supply chain echelons for different RBC products

ABNEG is a very slow moving product accounting for just 0.37% of transfused demand (table 2.) Average national demand for ABNEG RBC is 1.5 units/day with an intermittent demand pattern and as such demand is volatile (CoV = 1.29) (figure 4). The aggregate hospital ordering pattern for ABNEG is smoother than this and hence we observe an amplification ratio of less than one.

Table 2 - Red blood cell products: proportion of transfused demand

Product	OPOS	APOS	ONEG	BPOS	ANEG	BNEG	ABPOS	ABNEG
Proportion of total demand	41%	27%	12%	8.2%	6.9%	2.4%	1.6%	0.37%

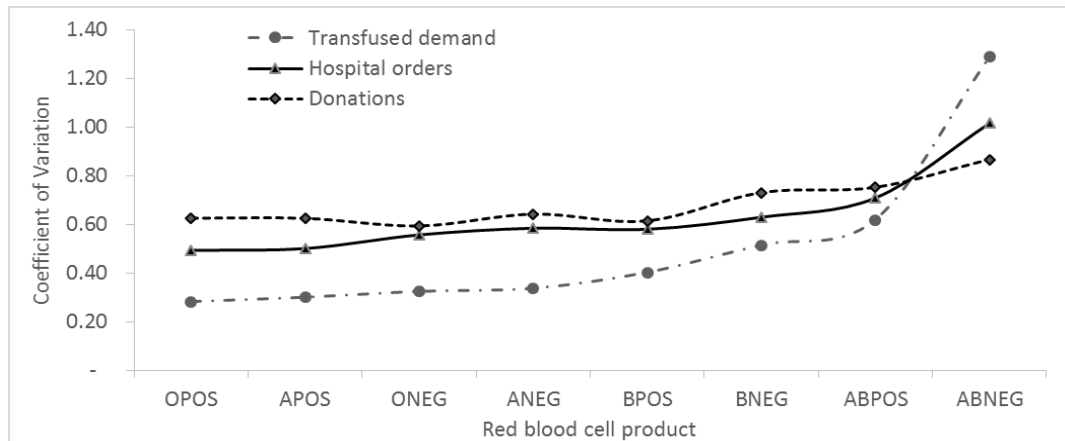


Figure 4 – Variation in aggregate demand signals at different supply chain echelons

The variation in demand, order and donation patterns is similar for fast moving products, however for the slowest movers the volatility in transfused demand increases sharply. In the case of ABNEG we find that demand is progressively smoothed with each supply chain echelon.

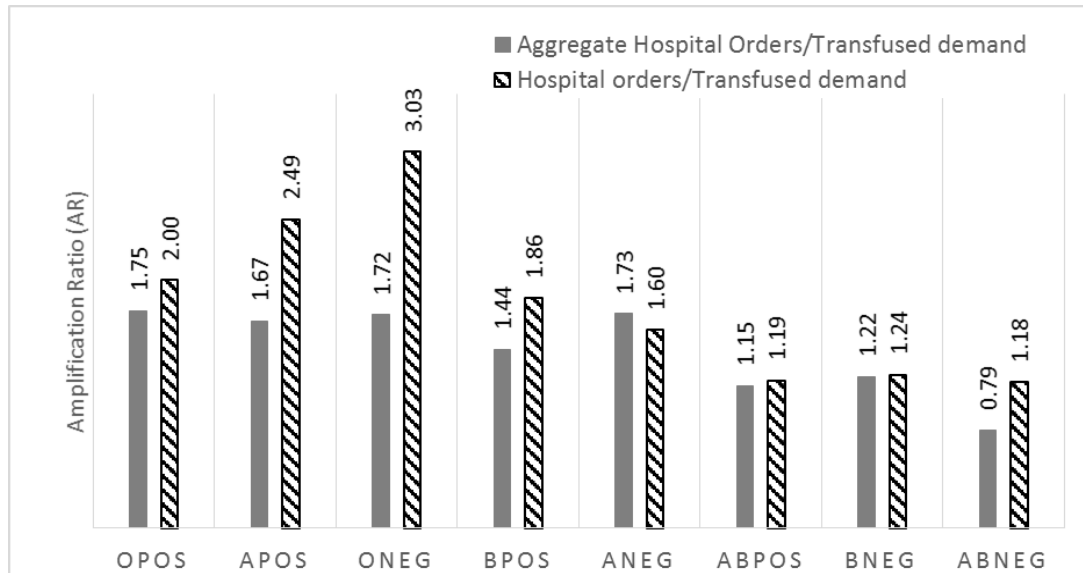


Figure 5 – Amplification ratios for different RBC products at aggregate and hospital level

Figure 5 shows the degree of demand amplification in hospital orders at the example hospital is more pronounced than at aggregate level for most products, particularly for the ‘universal donor’ ONEG and those products that are fast movers. The hospital level data is based on a single large hospital and further analysis is required at multiple hospitals to determine the significance of these findings. Nevertheless, this initial analysis suggests that aggregation across multiple locations may dampen amplification of the order signal experienced by a central SNBTS blood bank.

Causes of bullwhip

Interviews with hospital blood bank staff revealed a lack of a standardised approach to blood ordering. Ordering is often dependent on an individual’s perception of a “comfortable stock level” and based on “previous experience.” Staff responsible for stock replenishment had no inventory management training and no access to inventory control algorithms or tools to support replenishment decisions. It became apparent that product level forecasting of lead-time demand does not take place at hospital level and hence replenishment decisions are driven by a simple rule to keep stock above “comfortable” levels. This implies that any amplification of demand cannot be caused by demand signal processing. Indeed interviewees reported that they do not have visibility of transfused demand data. The graph in figure 6 shows that the more volatile the original demand signal the less pronounced the bullwhip effect. The opposite would be expected if managers were responding to the volatility of the transfused demand signal. Hence the evidence suggests that demand signal processing is not a cause of the demand amplification observed.

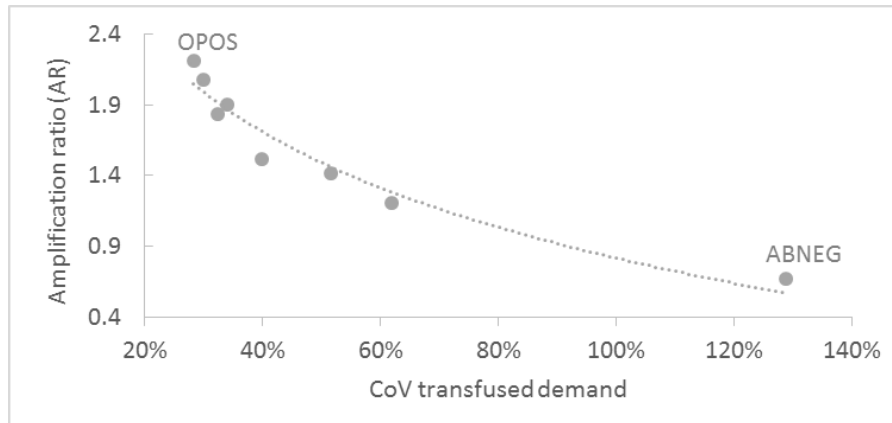


Figure 6 –Amplification ratios and demand volatility

Further analysis of time series data at hospital level revealed a tendency to order in multiples of 10 in an intermittent pattern that typically avoids weekends even though replenishment orders can be placed daily before 7 am for same day delivery by SNBTS. Furthermore, several members of blood bank staff can be responsible for placing replenishment orders; this introduces additional uncertainty and a tendency to order ‘just-in-case’. Interviewees also revealed a lack of visibility of blood stocks held in ward fridges beyond the hospital blood bank resulting in additional uncertainty. The tendency to batch and inflate orders seems to be driven by several factors: a lack of clear responsibility, a lack of understanding of inventory control; the absence of an inventory control system and a lack of visibility of stocks held in remote fridges.

In the case of ONEG blood the volatility in the hospital ordering pattern shown in figure 7 is more pronounced than expected. Interviewees stressed the importance of the ‘universal donor’ product which is routinely held as emergency stock in ward fridges. Interviewees expressed a real fear of stocking out of ONEG RBC recounting anecdotal evidence of incidents requiring significant volumes of ONEG, which in part explains the ‘just in case’ mind-set and the observed ‘order inflation’.

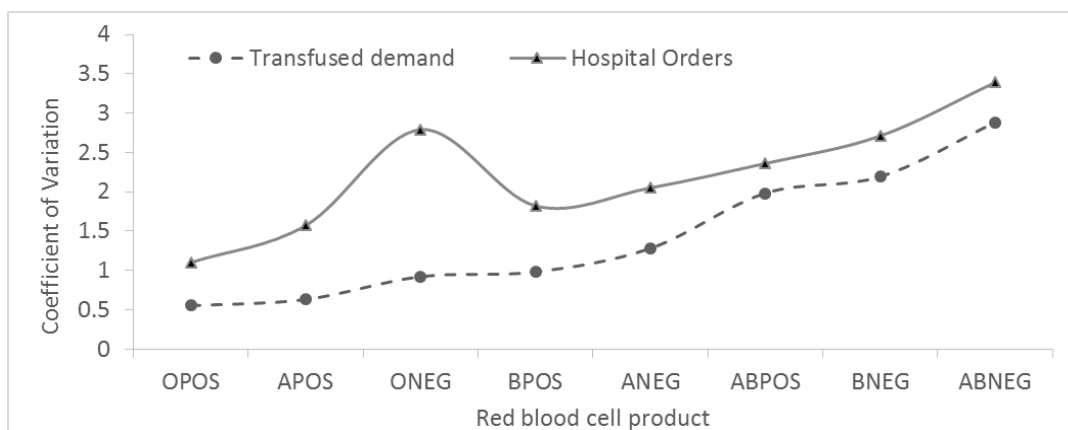


Figure 7 – Variation in demand signals at an example Scottish hospital

Impact on inventory performance

To estimate the possible impact of bullwhip on inventory performance at hospital level we analysed the relationship between demand volatility and days of stock-on-hand, the average age per unit at the time of transfusion and the percentage units wasted due to time

expiry. The coefficients presented in the correlation matrix in table 3 show a strong positive correlation between hospital order volatility and stock-on-hand and age at transfusion. The results also show a very strong positive correlation between stock-on-hand and the percentage of units wasted due to time expiry. Only weak correlations were found between amplification ratios and the different performance statistics considered.

Table 3 - Correlation matrix of hospital level data

	<i>CoV Orders placed</i>	<i>Days of stock-on-hand</i>	<i>Average age at transfusion</i>	<i>% units timex</i>
CoV Orders placed	1			
Days of stock-on-hand	0.8879	1		
Avg. age at transfusion	0.8804	0.7743	1	
% units timex	0.7976	0.9180	0.7357	1

Conclusion

This research provides an initial and unique insight into the bullwhip effect of a vertically integrated supply chain for a critical and perishable range of blood products. Our findings reveal that significant bullwhip is generated by hospital ordering practice caused predominantly by ‘order inflation’ and ‘order batching’ at hospital level. A lack of visibility of transfused demand in hospital blood banks and a lack of lead-time demand forecasting suggests that ‘demand signal processing’ does not contribute to the demand amplification observed.

Differences in bullwhip between products is evident with an increase in amplification related to both an increase in the rate of demand and a decrease in volatility in transfused demand. Inventory performance in terms of time expired waste strongly correlates with days of stock-on-hand which in turn is positively correlated with the volatility of hospital orders.

Our findings highlight the challenges that the SNBTS faces in managing the interface between a central blood bank and individual hospital blood banks. We conclude that efforts to reduce hospital level order inflation and order batching will reduce order volatility and hence the bullwhip effect, resulting in less stock-on-hand, reduced wastage rates and a reduction in the average age of blood at transfusion.

Further research

These initial findings reveal further opportunity to carry out more in-depth research. For example, ONEG RBC is the ‘universal donor’ and is therefore used in emergencies (when there is no time to cross-match a patient’s blood group) as a substitute product. The impact of substitution on bullwhip in supply chains is a new area of research with only one published study to date by Duan et al. (2015). The authors investigate the impact of price variations on bullwhip and acknowledge the challenges in sourcing accurate substitution data in a retail context. In the blood supply chain due to regulations concerning product traceability, accurate substitution data is readily available. This makes the blood supply chain an ideal context to study substitution effects and causal factors not related to price fluctuation. Hence we propose a more in-depth investigation into the impact of substitution of perishable products on bullwhip and inventory performance as an extension of this work.

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