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On Bullwhip in Supply Chains ~ Historical Review, Present Practice and Expected Future Impact

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Abstract

Demand amplification (or "bullwhip" as it is now called) is not a new phenomenon, since evidence of its existence has been recorded at least as far back as the start of the twentieth century and is well known to economists. Yet industry worldwide still has to cope with bullwhip measured not just in terms of the 2:1 amplification which is frequently quoted, but sometimes it is as high as 20:1 from end-to-end in the supply chain. This can be very costly in terms of capacity on-costs and stock-out costs on the upswing and stockholding and obsolescence costs on the downswing. In this paper we have identified 10 published causes of bullwhip, all of which are capable of elimination by re-engineering the supply chain. We offer evidence on the present "health" of a family of supply chains, and pinpoint much good practice. This is in anticipation that such excellence will become normative in the near future as the learning experience gathers momentum and provided that human factors are properly addressed.

Keywords

Bullwhip Reduction, Supply Chains, BPR.

1. Introduction

Jay Forrester (1958) has been rightly viewed in many quarters as a pioneer of modern day supply chain management. His seminal work on demand amplification as studied via Systems Dynamics simulation demonstrated phenomena which many practising managers had experienced. This included such events as demand waveforms being propagated upstream in the supply chain, the inducing of "rogue seasonality" in the order patterns and the consequent wrong-footing of decision makers. Such demand amplification as shown in Figure 1 (Fisher, 1997) is not new phenomena, since evidence of its existence has been recorded at least as far back as the start of the twentieth century. The situation facing much of industry worldwide is exacerbated because "bullwhip", Lee et al (1997), tends to be either misunderstood, or ignored (McCullen and Towill (2002). Familiar arguments include that such "whiplash" behaviour (Hayes and Wheelwright, 1984) is someone else's problem, or it does not cost anything to this particular "player", or it is an unavoidable fact of life. But industry, in the meantime, has to cope with bullwhip measured not just in terms of the frequently quoted 2:1 amplification which is bad enough, but 20:1 and even higher (Holmström, 1997). This behaviour can be very costly in terms of capacity on-costs and in stock-out costs (Metters, 1997). Equally, because there are consequential downturns in demand stock-holding and obsolescence costs will also increase.

If effective supply chain management is now seen as a move towards "Swift and Even Material Flow" (Schmenner, 2001), then another major contributor to our present day understanding of bullwhip is Jack Burbidge, who during his lifetime was in turn an experienced production manager, consultant, and then a distinguished academic. Even prior to the "Japanisation" of much of US and European industry via the "Lean Thinking" Paradigm, he was arguing against the Economic Batch Quantity concept and in favour of the "Batch of One" supply (Burbidge, 1981). Hence, if we traditionally manufacture in large batches then his solution to queuing problems was to reduce these long set-up times, and aim for small batches as a way of life. So

much so that even 40 years ago he was postulating "only to make in a week what you can use in a week". In the present operating environment we would simply substitute "day, or even hour", for "week", and his "5 Rules for Avoiding Bankruptcy" would thus have an amazing relevance to modern pipeline controls. Historically the bullwhip problem has also been of considerable interest to economists via their study of trade cycles (Mitchell, 1923). In this context the little-known paper by Zymelman (1965) provided an interesting proposal to reduce bullwhip in the cotton industry via a control law he established via analogue simulation.

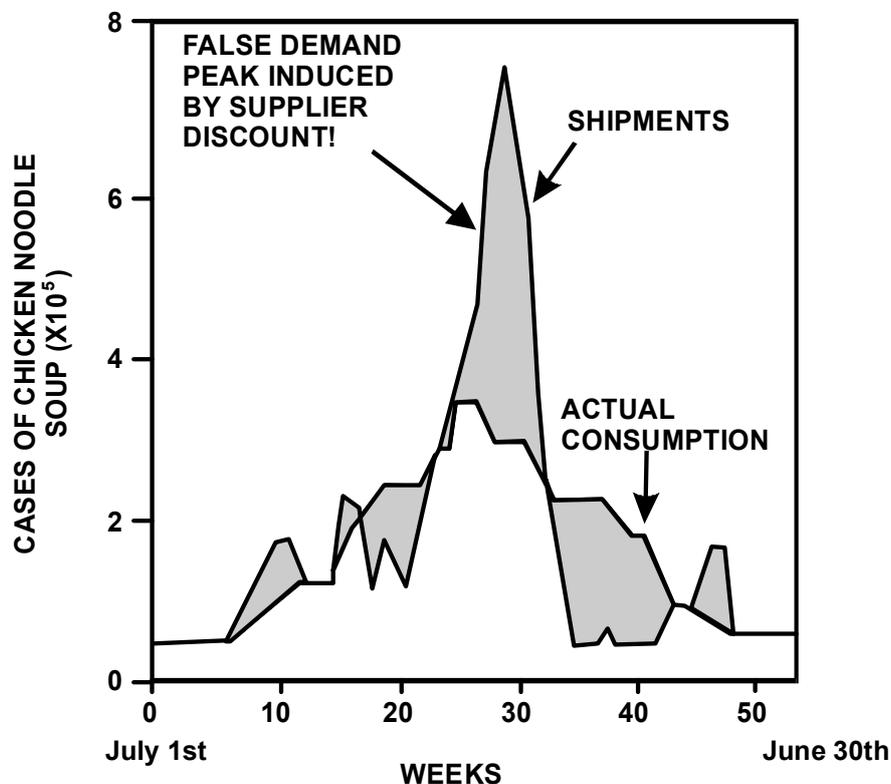


Figure 1. Who Bears the On-Costs? Example of Bullwhip Generated via Price Promotion
(Source: Fisher et al, 1997)

Fortunately the writings of both Forrester and Burbidge considered a range of possible solutions to the bullwhip problem. These may have been brought together to form a coherent set of streamlined Material Flow Principles which have been termed the FORRIDGE approach. These have been shown to produce substantial industrial benefits, via studies of BPR Programmes. This improvement has been recorded despite the many barriers to change which

may be encountered as the historically entrenched “functional silos” react to the holistic approach. More recently in a move to further improve on the FORRIDGE Principles bullwhip has become a topic for concurrent formal study. This has brought together a number of previously separate strands of research, namely OR (Lee et al, 1997), control theory (Disney and Towill, 2002) and filter theory (Dejonckheere et al, 2002). These topics underpin the essentially empirical studies of bullwhip via simulation (Forrester, 1958 and van Ackere et al, 1993).

In this paper we shall demonstrate that these approaches can be brought together via simulation packages as their focal point, thus providing diagnostic tools and design guidelines which will assist supply chain designers. The methodology has been validated on industrial data which is representative of present day operations. But, because the framework is based on sound theoretical principles it can also be exploited to test the new supply configurations needed to underpin the era of mass customisation. In addition to our historical review, and illustrations from present industrial practice, we shall contemplate the future bullwhip scenario. This will involve assessing a wide range of impacting factors, and is far from being an IT issue alone. Our perceptions are based on over two decades spent by the current authors as analyst, synthesist, modeller, observer, auditor, change manager and implementer roles in real-world value streams. As output from this combined experience we posit that bullwhip is merely one phenomenon (amongst many) associated with poor material flow. Furthermore our actions are based on identification and eradication of root causes.

2. Historical Review of Supply Chain “Best Practice”

A brief history of supply chain “best practice” is summarised in Table 1 (Towill et al, 2002). The example of the design and construction of the Crystal Palace is noteworthy for the very

short total cycle time from conception to completion. This was partly due to the modular iron-and-glass design which greatly simplified erection on site. However the then relatively recent arrival of the Birmingham to London railway also meant that the component parts could be delivered directly to the site Just-In-Time, (Wilkinson, 2000). The Crystal Palace was built as a home to a huge exhibition of art and industry. But the Victorians recognised it as something extraordinary. As Wilkinson (2000) concludes, it was a magnificent logistics exemplar as was visibly apparent during the erection process and which was itself regarded as a spectacle to behold ahead of final commissioning.

The quoted review of the early use of "Japanese" methods of Value Stream Management (VSM) (and *keirutsu*) and their "invention" in the USA is due to Drucker (1995). Thus according to this source VSM was developed *circa* 1914 and practiced at GM for a period of some 40 years until US trade union opposition put an end to this approach. However during this period VSM practice expanded into the retail sector, most notably in Sears Roebuck (in the USA) and Marks and Spencer (in the UK). Significant progress was also made during this time on exploiting the principles of "Lean Production" in the manufacture of Spitfires during World War II (Burbidge, 1995), only to be discarded when peacetime resumed to his obvious chagrin. Meanwhile in Japan the Toyota material flow control system was in place by around 1970. Some progress was made in transferring their approach to Western companies, a process accelerated by Schonberger (1982). The final proof for the success of lean production applied in the right way at the right time was given by Womack et al. (1990). The impact of their book is due to the lessons learned being transmitted via especially simple metrics; significant differences recorded according to these metrics; and finally the metrics selected being unambiguous and hence readily transferable between countries (Towill, 1999).

| | |
|------------------|--|
| 1851 | JIT effectiveness demonstrated in construction of the Crystal Palace, London |
| 1916 | Value stream management (and <i>Keirutsu</i>) invented in USA by William Durant of GM |
| 1919 | Successful action taken by Proctor and Gamble (USA) to damp down bullwhip in their supply chains. |
| 1925 | Value stream management concepts exploited in the retail sector by Sears Roebuck |
| 1940 | Parts of UK WWII fighter aircraft industry implements "lean production" and hence smoothes material flow. |
| 1946 | UK heaves a sigh of relief, abandons lean production and reverts to "comfort levels" of stock throughout the chain |
| 1955 | Value stream management hits the GM rocks of "unionisation" |
| 1961 | Smooth material flow logic published by Jack Burbidge as "The New Approach to Production" |
| 1970 | Toyota exploit smooth material flow control principles via the "Understand Document Simplify and Optimise" concept of Edwards Deming |
| 1980 | Some Western firms follow suit, impressive results are achieved, but in many cases regression follows progression |
| 1982 | Richard Schonberger published "Japanese Manufacturing Techniques: Nine Hidden Lessons in Simplicity" |
| 1990 | <i>The Machine That Changed The World</i> unambiguously benchmarks performance improvement obtained by adopting smooth material flow control principles. |
| Mid 1990s | Estimated that only 7% (Joseph Andraski, US retail) to 10% (Jack Burbidge, UK Manufacturing) of supply chains are effective. |
| 2000 | Audit of European automotive value streams shows just 10% are World Class "Exemplars" |

Table 1. Some Notable Events in the "Boom-and-Bust" Development of Smooth Material Flow

However, it is also noted in Table 1 that despite the foregoing examples of good practice of good material flow control, that there are still many value streams which do not perform as well as they should. Nor has the situation necessarily been any better in the past when,

arguably, operating scenarios were somewhat simpler. For example here is an excellent description of an example of bullwhip and its promulgation.

“Retailers find that there is a shortage of merchandise at their sources of supply. Manufacturers inform them that it is with regret that they are able to fill their orders only to the extent of 80 per cent: there has been an unaccountable shortage of materials that has prevented them from producing to their full capacity. They hope to be able to give full service next season, by which time, no doubt, these unexplainable conditions will have been remedied. However, retailers, having been disappointed in deliveries and lost 20 per cent or more of their possible profits thereby, are not going to be caught that way again. During the season they have tried with little success to obtain supplies from other sources. But next season, if they want 90 units of an article, they order 100, so as to be sure, each, of getting the 90 in the pro rata share delivered. Probably they are disappointed a second time. Hence they increase the margins of their orders over what they desire, in order that their pro rata shares shall be for each the full 100 per cent that he really wants. Furthermore, to make doubly sure, each merchant spreads his orders over more sources of supply.” (Mitchell, 1923)

It may come as some surprise to many that this quotation is attributable to Mitchell (1923) and cited by Sterman (1986). As a descriptor of the bullwhip effect it has a potential impact at least as great as that made by the classic description of the jeans clothing supply chain by Stalk and Hout (1990). But not only was bullwhip historically known (but not defined), so were some little publicised proposed solutions. For example, Zymelman (1965) tested a control law for damping down the aggregate cotton industry supply chain cycle based on proportional feedback of inventory error and WIP error. His verification was via an analogue computer

simulation since at that time digital simulation was still in its infancy. Even earlier, Metzler (1941) had provided an analytic solution to one particular inventory cycle problem which established stability boundaries according to his assumptions. This latter paper is also noteworthy because of his criticism of researchers who draw generic conclusions (sometimes wrongly) from numerical solutions, which can subsequently be disproved via algebraic analysis. We agree with this comment, but would emphasise that in supply chain design analytical tools have a limited (but admittedly very important) role to play e.g. Vendor Managed Inventory (VMI) systems are analytic under particular operating conditions (Disney and Towill, 2002). Modern day software greatly assists obtaining such solutions via elimination of the need for tedious algebraic manipulation.

3. Bullwhip and the Economy

Bullwhip (under any other name) has long been of interest to economists. For example the foregoing description of the behaviour of the retail supply chain as described by Mitchell (1923) is remarkably similar to the classic clothing value stream described by Stalk and Hout (1990). Since it is reckoned that problems in supply chains are "80% people centred and 20% technology centred" (Andraski, 1994) this is hardly surprising. It is our experience that if supply chains can possibly find a way of inducing bullwhip, then they surely will, which is an alternative view of the Burbidge Law of Industrial Dynamics (Towill, 1997). At the national economy level, bullwhip is frequently observed, reproduced in Table 2 (Blanchard, 1983). These results are for American automobile manufacturers at the OEM Divisional level. This Table therefore aggregates the data for a number of current models some of whose individual bullwhip effects, according to the Central Limit Theorem, are likely to be much higher. Also note that although Table 2 suggests bullwhip is present, further analysis leading to improved indicators as recently advocated by El-Beheiry et al (2004) may well be justified.

| Car Manufacturing Division No. | Production Deviation Sales Deviation | | | Total Car Inventory Sales (in months) |
|--------------------------------|--------------------------------------|----------|---------|---------------------------------------|
| | Raw Data | Seasonal | Remnant | |
| 1 | 1.42 | 1.65 | 1.23 | 2.49 |
| 2 | 1.43 | 1.76 | 1.29 | 2.10 |
| 3 | 1.27 | 1.76 | 1.30 | 2.02 |
| 4 | 1.38 | 1.63 | 1.30 | 2.04 |
| 5 | 1.35 | 1.94 | 1.37 | 1.40 |
| 6 | 1.42 | 1.38 | 1.37 | 2.38 |
| 7 | 1.23 | 1.31 | 1.30 | 2.94 |
| 8 | 1.34 | 1.96 | 1.22 | 3.04 |
| 9 | 1.35 | 1.33 | 1.44 | 4.45 |
| 10 | 1.43 | 1.47 | 1.53 | 4.08 |

N.B. The deviations given are the square root of the sum of the squares divided by (N-1)

Table 2. Historical Record of Bullwhip Recorded in the USA Automobile Industry
(Source: Blanchard, 1983)

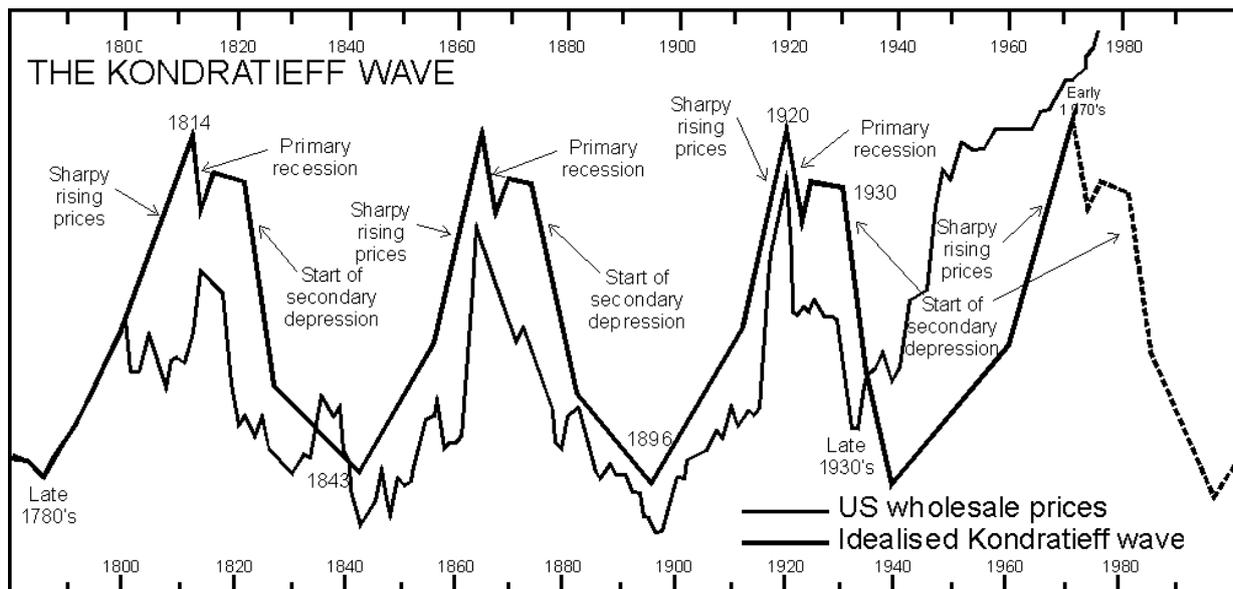


Figure 2. Periodicity in the Economy ~ an Example of a Kondratieff Wave
(Source: Kondratieff (1984) <http://www.angelfire.com/or/truthfinder/index22.html>)

A major area of study in economics is concerned with bullwhip observed in the total economy. This is the phenomenon known as the “long wave” or the Kondratieff (1984) cycle. An excellent summary from our perspective is given by Sterman (1986). He says;

"The long wave is characterised by successive waves of overexpansion and collapse of the economy, particularly the capital-producing sector. Overexpansion means an increase in the capacity to produce and in the production of plant, equipment, and goods relative to the amount needed to replace worn-out units and provide for growth over the long run. Overexpansion is undesirable because, eventually, production and employment must be cut back to below normal levels to reduce the excess.

How does the long wave arise? In particular, how does overexpansion of the capital-producing sector of the economy arise? The explanation can be divided into two parts. First, the internal structure and policies of individual firms tend to amplify changes in demand, creating the potential for oscillation in the adjustment of capacity to changes in the desired level. Second, a wide range of self-reinforcing processes significantly amplifies the response of individual firms to changes in demand, increasing the amplitude and lengthening the period of the fluctuations generated by each firm."

Establishing the Systems Dynamics National Model provided a representation of the US economy via which the long wave phenomenon could be studied. Sterman (1986) thereby produces two findings of particular interest to bullwhip analysts. He argues that waves are produced in economic systems because there are;

- *Inherent oscillatory tendencies within firms.* Due to the inevitable lags in acquiring factors of production and reacting to changes in demand, firms tend to amplify unanticipated changes in demand, creating the potential for oscillation in the adjustment of production capacity to demand.

- *Self-reinforcing processes between firms further amplify the volatility.* Though individual firms are likely to be stable, a wide range of positive feedback loops is created by the couplings of individual firms to one another, to the labour markets, and to the financial markets.

Such mechanisms substantially amplify the fluctuations in the demand for capital created by individual firms, boosting the amplitude and lengthening the period of the inherent oscillatory tendencies of firms. The major self-reinforcing processes involve capital self-ordering, labour market interactions and real interest rate dynamics. A practical example of the impact of economic factors on the behaviour of the machine tool supply chain is given by Anderson et al, (2000). There is extreme volatility therein caused by the “multiplier effect” which in this case is the high gearing (say 10 to 1) of changes in percentage annual replacement of the capacity of the customer (product manufacturer) on the number of orders placed on the machine tool suppliers. Hence if due to an economic downturn the product manufacturer decides to reduce his capacity by 10%, this could mean zero orders placed. But if later he decided to compensate and increase his capacity by 10%, then this would double the number of orders passing up stream to the machine tool producers.

4. Clearing Up the “Mess”

In the language of Russell Ackoff (1999) a supply chain exhibiting bullwhip is a “mess” in the sense that the problem to be solved must be abstracted from that situation in order that a solution be proposed. The final outcome, following the Understand-Document-Simplify-Optimise (UDSO) routine proposed by Watson (1994) should be a more effective supply chain exhibiting a greatly reduced bullwhip in the real-world. An example of the complete procedure is that describing the Business Process Re-Engineering of a real-world global mechanical

precision products supply chain (Towill and McCullen, 1999). At the conclusion of the Glosuch Rapid Response Programme the bullwhip as measured over a sample product range had been reduced by 50%. Furthermore the stock turns had concurrently increased by 2 to 1 and were on track to ultimately reach 4 to 1. As expected, customer service levels simultaneously improved dramatically with the standard deviation of delivery variation reduced by 70%. However the Glosuch learning curve dynamics are of particular interest here since month-on-month improvements were still occurring some two years after BPR completion.

These results are typical of the benefits accruing from supply chain re-design and properly engineered implementation. It is important to emphasise that just reducing bullwhip is not the only positive impact since many other performance metrics are thereby simultaneously improved. In terms of bullwhip induced production on-costs at the factory gate, these are estimated by Metters (1997) to attract a penalty of between 20% and 50%. Since these estimates are for a production schedule which is optimum for the order pattern as received, and the factory is unlikely to perform so well, these estimates are to be regarded as conservative. Note also that the estimates cover only those costs incurred by the factory. The resulting on-costs between the factory and the marketplace are additional and for such cases as those shown in Figure 1 are quite substantial.

Miragliotta (2004) has examined the bullwhip phenomenon with the intention of producing a classification system which identifies "amplifiers" and "triggers". This is based on a control theoretic approach in analogy with systems theory. Our view is that bullwhip reduction is best enabled via implementation of the principles of smooth material flow. So the intention in a practical BPR Programme is to identify and eliminate all causes of poor material flow and

eliminate them ~ to good effect, as demonstrated in the real-world Glosuch supply chain (Towill and McCullen, 1999). The Miragliotta (2004) framework may well have a practical use in providing a "layered" framework for the design of BPR programmes to reduce bullwhip. What we can say is that in practice, businesses tend to first put their own house in order then use this expertise to bring suppliers into the system: exploit this "best practice" working with our customers: and improve control during each phase according to the current *modus operandi* (Towill et al, 2002).

5. Five Routes to Bullwhip Knowledge

Assuming that a real-world "mess" has been identified as a bullwhip problem, how has our knowledge of potential solutions been acquired? Five routes are shown in Fig. 3, together with sample supporting references. These routes are mutually supportive, and indeed some references qualify under more than one heading eg Sterman (1989). This is hardly surprising, since in the analytic routes the mathematics may well be similar, even if the insight offered by the particular methodologies is different depending on the "eye of the beholder". Broadly speaking the five routes may be summarised as follows;

OR Theory. The problem is expressed as a difference equation, with some parameters variable. The solution sought is one that explicitly minimises a cost function (or a surrogate), for an assumed set of operating conditions (Deziel and Eilon, 1967). The dynamic performance is *implied* by the mathematical solution to the problem.

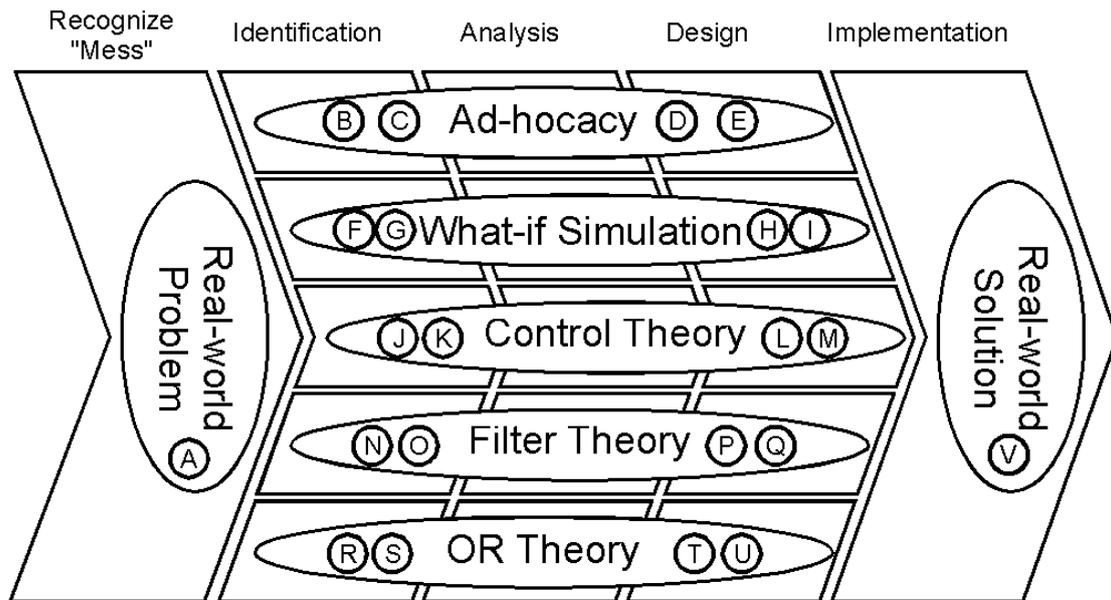


Figure 3. Five Routes to Bullwhip Reduction ~ from Real-World Problem to Real-World Solution

(Source: Authors)

Key

- | | |
|--------------------------------|---------------------------------------|
| (A) Ackoff (1999) | (B) Schmenner (2001) |
| (C) Zymelman (1965) | (D) Lee and Billington (1992) |
| (E) Holmström (1997) | (F) Lambrecht and Dejonckheere (1999) |
| (G) Sterman (1989) | (H) Forrester (1958) |
| (I) van Ackere et al, (1993) | (J) Vassian (1955) |
| (K) Deziel and Eilon (1967) | (L) Riddalls and Bennett (2002) |
| (M) Axsäter (1985) | (N) Towill and del Vecchio (1994) |
| (O) Burns and Sivazlian (1978) | (P) Adelson (1996) |
| (Q) Towill et al (2002) | (R) Chen et al, (2000) |
| (S) Lee et al, (1997) | (T) Thonemann (2002) |
| (U) Holt et al, (1960) | (V) McCullen and Towill (2002) |

Filter Theory. The problem is expressed in the frequency domain where value judgements are made on spectrum widths of the “message” and the “noise”, or “disturbances”. Using an assumed control law the solution is obtained by shaping the system frequency response to suit the needs of the user (Towill and del Vecchio, 1994). The dynamic performance is *explicit* from inspecting this response, whereas the cost performance is implicit.

Control Theory. The problem is expressed in transfer function form and concentrates on system structure, initially to guarantee stability, and then to shape the desired response. A substantial data base of possible supply chain structures is available, especially from hardware system analogues ('Towill, 1982). The dynamic response is *explicit* from studying "rich pictures" obtained via solution of the difference equations for test demands.

"What If" Simulation. System dynamics type modelling where causal loop diagrams are transformed into simulation models and studied via test demands arbitrary. There is a large data base of such models available (Lyneiss, 1980). For the design eventually selected via this "what if" procedure the dynamic response will be *explicit*.

Ad-Hocacy. This is included because as we have seen by reference to Mitchell (1923), or indeed Devons (1950) and Sterman (1989) it is possible for experienced managers or observers to get a good feel for what is causing poor behaviour within the real-world "mess". Hence practical experience in observing amplification caused by an echelon, subsequent action to re-engineer the chain to remove the echelon, and assessing the subsequent improvement certainly adds to the bullwhip knowledge base. Such an approach is *conjectural* with regard to the dynamic response.

We now proceed to examine the "ground rules" that have accumulated over the years via these five routes. It will provide a reasonable summary of "where we are now" regarding bullwhip in supply chains. As we have already stipulated earlier these routes are not mutually exclusive. For example Deziel and Eilon (1967) and Adelson (1966) are all OR specialists. Yet the

former paper has discernable elements of control theory therein, and the latter paper points towards filter theory.

6. What We Now Know About Bullwhip Reduction ~ the Ten Principles

At this stage we must again emphasise that the twin pioneers of “modern” supply chain knowledge are Jay Forrester and Jack Burbidge. They “opened up” the subject, laid bare many of the problems, and showed the way to possible solutions. Many of the researchers cited in this paper owe both Forrester and Burbidge a great debt since they generated the following four supply chain design principles;

- **Control System Principle.** There is a need to select the most appropriate control system best suited to achieving user targets. In turn this will necessitate accessing important supply chain “states” thus taking unnecessary guesswork out of the system.
- **Time Compression Principle.** Every activity in the chain should be undertaken in the minimum time needed to achieve task goals. In practice this means removing non-value added time or “muda” from the system. It also means delivering on time what is actually required i.e. this Principle covers process capability.
- **Information Transparency Principle.** Up-to-the minute data free of “noise” and “bias” should be accessed by all “players” in the system. This simultaneously removes information delays and “double-guessing” other “players”. Because inventories, WIP, flow rates, and orders are now visible throughout the chain, holistic control via a suitable DSS is now enabled.
- **Echelon Elimination Principle.** There should be the minimum number of echelons appropriate to the goals of the supply chain. The aim is to have not only the

optimum level of inventories (maybe in some instances actually zero) but to have these minimum stocks in the right place at the right time.

There is a fifth Principle which was implied by Forrester but proven (by example) by Burbidge. This is the

- **Synchronisation Principle.** In Forrester simulations all events are synchronised so that orders and deliveries are visible at discrete points in time. Burbidge showed by reference to multiple customers working on EBQ re-order principles that this produced an emphatic bullwhip effect subsequently eliminated by continuous ordering synchronised throughout the chain.

Additionally as demonstrated by Wikner et al (1992) there is a sixth Principle inherent in the original Forrester supply chain model. This is very important as a source of bullwhip as demonstrated in the machine-tool industry (Anderson et al, 2000). It is the

- **Multiplier Principle.** There can be situations where orders directly multiply in a knock-on effect, usually between product manufacturers and their capital equipment suppliers. So if a product manufacturer replaced all its machine tools on a 10 year cycle, it might choose to increase planned capacity by 10% one year, leading to its machine tool orders being doubled, a "multiplier" of 10 to 1.

There are four further principles emerging from extensions to the Forrester approach, as published by Lee et al (1997), and which have been shown by them to be significant bullwhip generators;

- **Demand Forecast Principle.** Forecasts may well be a problem simply because they are so rarely right. But attempts to improve the situation by building in safety factors and trend detection capability may result in bullwhip generation. Furthermore demand forecasts need to cope with such phenomenon as “product substitution” where what is actually available is sold in place of stock-out items.
- **Order Batching Principle.** Time phased aggregation of orders (the bane of the EBQ so deplored by Burbidge) lead to “lumpy” deliveries, and hence come back around the ordering loop as “lumpy” orders, which is a certain cause of bullwhip.
- **Price Fluctuation Principle.** Marketing programmes may deliberately be designed to empty over-full pipelines. As Fisher (1997) has ably demonstrated, this effect may cause a backlash by over-ordering so as to take advantage of discounts on offer. When the retailer has enough stock, their orders drop to zero in a typical boom-and-bust scenario.
- **Gaming Principle.** As Mitchell (1923) described in an actual (or perceived) shortage situation, there will be orders placed to “hedge” against unpredictable supply. Both suppliers and customers may be involved in this game, followed by double-guessing of the form “X has ordered 1000, but I bet he only needs 400” followed by “Y is slow with his deliveries; I really need 500 but I’d better order 1200 just in case”, and so on.

As this review shows, BPR programme managers are not short on guidelines to follow when designing supply chains for improved performance. In theory it seems quite straightforward to just apply UDSO (Understand ~ Document ~ Simplify and Optimise) according to the steps suggested by Watson (1994), and a better supply chain will automatically result. This is the

theory; sometimes the practice is just a little different. It may not be rocket science, but it is definitely rocket engineering in terms of the inputs required, especially during the analysis and design phases.

7. Bullwhip Clichés ~ Why the Problem Isn't Tackled as Well as it Should Be

There is much anecdotal evidence available on present day supply chain operations. The attitude with respect to bullwhip varies widely according to the observer's perception, their position within the supply chain, and the power associated with their particular function. For example, McCullen and Towill (2002) list the following clichés:

- *Ignorance cliché* *Bullwhip? Doesn't exist in the real world*
- *Arrogance cliché* *Bullwhip? Is just an academic invention*
- *Negligence cliché* *Bullwhip? Doesn't cost me any money*
- *Indifference cliché* *Bullwhip? The customer can wait*
- *Transference cliché* *Bullwhip? So what? – the suppliers can cope. That's what service level agreements are for!*
- *Acceptance cliché* *Bullwhip? It's like tax – always with us*
- *Despondence cliché* *Bullwhip? It's a systems problem – nothing I can do about it*
- *Decadence cliché* *Bullwhip? It's old hat – surely it's been eradicated by now?*
- *Intolerance cliché* *Bullwhip? Japanese solutions don't work here*
- *Avoidance Cliché* *Bullwhip? Those solutions are all very well – but not in my industry*

All of these attitudes have been met experientially in real-world scenarios by McCullen and Towill (2002). These comments cover a wide range of sentiment. This is not unexpected given the earlier comment by Andraski (1994) that supply chain problems are "80% people and 20% technology" in origin. So the "actors" making the foregoing remarks are just going

through normal routines of “turf protection” and “buck passing”. In the meantime, as the Campbell’s Soup example, coupled with the Metters (1997) cost model, show, the ramp-up/ramp-down production on-costs, and stock-holding/stock-out costs add significantly to the price paid by the customer. Nor are these added costs spread equitably throughout the chain. Since the classic Marshall Fisher paper was published in 1997, the influence of the retailer has increased yet further. So their “mark-ups” tend to have risen significantly with the on-costs being disproportionately borne upstream. As Levy (1995) has shown, this situation may be worsened, not bettered, when adopting third world outsourcing.

8. Present Operational Status of Supply Chains

Our contention is that supply chains designed to be seamless in operation should seek to avoid these on-costs arising in the first place. So to provide more scientific evidence on the operational status of real-world supply chains, an investigation was undertaken into the behaviour of 32 trans-European value streams, mostly from the automotive market sector. The successful launch of the so-called “Lean Production” description of Japanese practice by Womack et al (1990) led us to expect that many of these value streams would score well in this exercise. The investigation required extensive field work as described by Naim et al (2002). It was based on the concept of assessing the extent of smooth material flow (arguably the inverse of bullwhip). For consistency the comparison between value streams was made on the basis of perceived uncertainty against the observed occurrence of particular phenomena. These were monitored via the physical situation in the plant(s), operational features, organisational features, and dynamic behaviour perceived from numerical data.

To obtain a single index of performance the codified audit output was based on Likert scale ratings of the uncertainty levels in the value streams. Four individual scores were estimated for each value stream according to the perceived uncertainty arising from the following sources:

- **Process uncertainty.** Process uncertainty affects an organisation's internal ability to meet a production delivery target.
- **Supply uncertainty.** Supply uncertainty results from poorly performing suppliers' not meeting an organisation's requirements and thereby handicapping value-added processes.
- **Demand uncertainty.** Demand uncertainty can be thought of as the difference between the actual end-marketplace demand and the orders placed within an organisation by its customers.
- **Control uncertainty.** Control uncertainty is associated with information flow and the way an organisation actually transforms customer orders into production targets and supplier raw materials

The single index of performance is then calculated as the Euclidean Norm of these four individual uncertainty scores. The sample may then be ranked according to this score which has a theoretical range from the "traditional" (functional silo) supply chain right through to internal and external seamless operation. The stages of the Stevens (1989) Supply Chain Model are then used as "Benchmarks" against the degree of integration achieved by the sampled value streams.

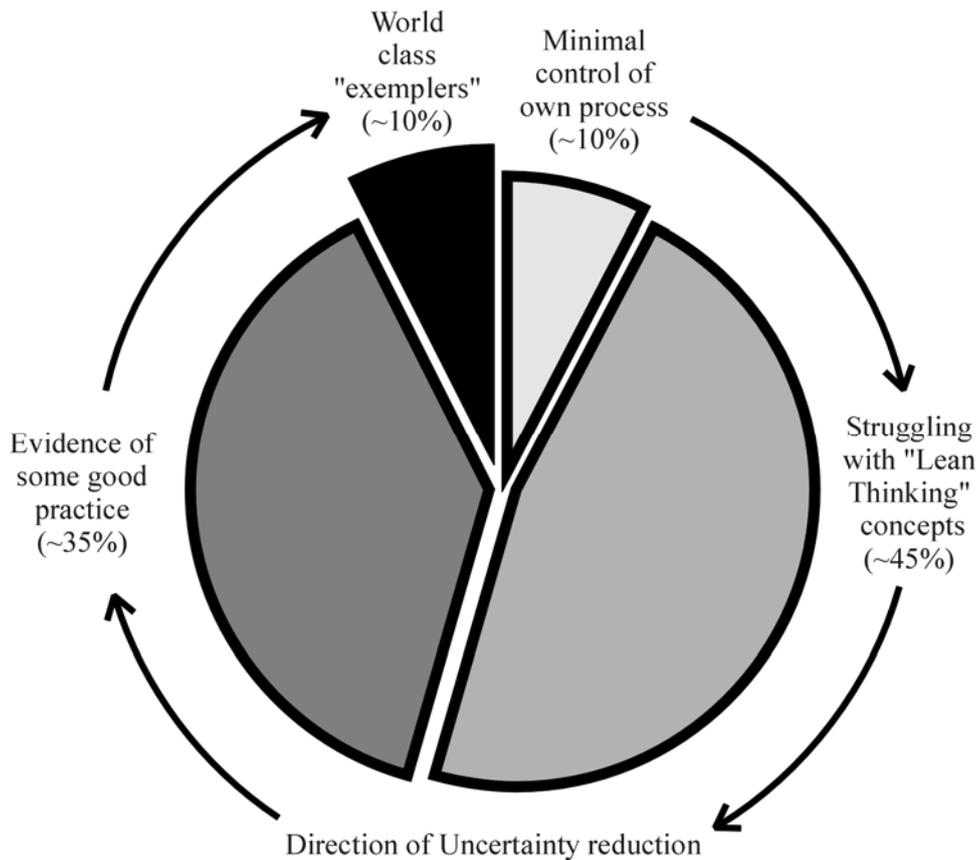


Fig. 4. Present Practice ~ Supply Chain Audit Results Based on Uncertainty Scores
(Source: Childerhouse, 2002)

9. Value Stream Audit Results

The result of the audit is shown in Fig. 4. The pie chart classifies the supply chain value streams according to their uncertainty scores. About 10 percent of the value streams studied demonstrated minimal control over their own processes and had not successfully applied material flow and lean thinking concepts even to their operations. Another 45 percent still had major uncertainties. They were in various stages of implementing lean thinking concepts but had already reduced some of the uncertainty in their value stream. Approximately 35 percent had reduced their uncertainty levels even further and were already engaged in supply chain practices that went significantly beyond internal integration as defined by the Stevens (1989) model. Finally, 10 percent of the organisations in the audit can be regarded as rapidly approaching the seamless supply chain. They can be regarded with confidence as exemplars of

world-class performers. So we may surmise that nearly half the sample exhibit some good practice worth emulating and furthermore the top 10 percent are identified as worthy benchmarks to exploit in identifying "best practice". In other words any volatility experienced by the company was due to the marketplace behaviour and not to the value stream dynamics.

| PERFORMANCE METRIC | OBSERVED | BENEFIT |
|---------------------------|-----------------|------------------|
| Lead Time | Down | 7 to 1 |
| Set-up Time | Down | 3 to 1 |
| Production Runs/Annum | Up | 4 to 1 |
| Rejects/Million Parts | Down | 2.5 to 1 |
| Overdue Orders | Down | 4 to 1 |
| Annual Sales | Up | by $\frac{1}{3}$ |
| Return on Investment | Up | by $\frac{1}{3}$ |

Table 3. Typical Performance Improvements Obtained Via Smooth Material Flow
(Source: Burbidge and Halsall, 1994)

That BPR based on such streamlined material flow is effective can be seen from Table 3 which shows the bottom line improvement for a first-tier automotive supplier to both OEM and Autospare customers (Burbidge and Halsall, 1994). A detailed Case Study also shows that such BPR Programmes can substantially reduce bullwhip (typically by 50 percent with associated increase in stock-turns from two to four-to-one) as happened in a real-world mechanical precision products global supply chain (McCullen and Towill, 2002). As the value stream moves closer to the goal of the seamless supply chain, it becomes more in tune with both its customers and the marketplace, providing competitive advantages to participants across the entire chain.

This heightened proximity to the customer reinforces the movement toward integration beyond our functional walls and much better visibility across the extended supply chain. This increased integration, in turn, leads to lowered uncertainty and improved performance. Thus, the seamless supply chain becomes a self-fulfilling prophecy i.e. a virtuous circle. Hence

lower uncertainty leads to tighter integration, which reduces uncertainty further, and the cycle continues, resulting in smooth material flow and minimal bullwhip. As Wikner et al (1992) demonstrated, what a "player" within the chain needs to know is how his customer orders are constituted. Specifically, knowledge of the "firm orders from the marketplace" plus "buffer store top-ups" plus "forecast future demand" is what is wanted to make an appropriate scheduling decision.

10. How Does Bad Performance Actually Happen?

The Pie Chart ranking of the 32 value stream sample shown in Fig. 3 raises the issue as to how some real-world chains are still operating so poorly in the light of our vast current knowledge of supply chain design as outlined in Section 5. To answer this important question the Quick Scan Audits (Naim et al, 2002) also identified a range of typical problems encountered within the value stream sample. These are listed in Table 4 and classified under the "Process Side": "Supply Side"; Demand Side", and "Control Side" regimen. We have also indicated the supply chain disruption potential associated with each observed weakness. Our surprise comment concerning Table 4 is not that these problems run counter to present day knowledge of what is required of good supply chain practice (which is bad enough), but that some of these factors can be traced to aircraft production in World War II (Devons, 1950), and even as far back as the retail sector scenario cited by Mitchell (1923). We think a major contributor to such intransigence is the "people problem" as identified previously by Andraski (1994).

It is customary to take the optimistic view and think of the human contribution within supply chains to be participating effectively, such as the Production Scheduler in an automotive value stream taking in data from many sources and DSS's and improving on the decision making process by his ability to take an intelligent overview of the current operating scenario (Ols mats

et al, 1988). This is unfortunately an altruistic perspective and the "people factor" really is still a critical issue in changing business processes. For example Loughman et al, (2000) listed the following "people factors" to be properly addressed, otherwise the planned improvements will simply not happen:

| Uncertainty Source | Some Observed Weaknesses | Supply Chain Disruption Potential | | | | |
|--------------------|--|-----------------------------------|----------------|-------------|---------------|------------------|
| | | Data Masking | Data Shortfall | Data Errors | Excess Delays | Excess Variances |
| Process Side | • No measures of process performance | | ◆ | | | |
| | • Reactive rather than proactive maintenance | | | | | ◆ |
| | • Random shop floor layout | | | | ◆ | ◆ |
| | • Interference between value streams | | | | ◆ | ◆ |
| Supply Side | • Short notification of changes to supplier requirements | | | ◆ | | ◆ |
| | • Excessive supplier delivery lead time | | | | ◆ | |
| | • Adversarial supplier relationships | ◆ | | ◆ | | |
| | • No vendor MOPS | | ◆ | | | |
| Demand Side | • No customer stock visibility | | ◆ | | | |
| | • Adversarial customer relationship | ◆ | | | | |
| | • Large infrequent deliveries to customer | | | | ◆ | |
| | • Continuous product modifications causing high levels of obsolescence | | | | | ◆ |
| Control Side | • Poor stock auditing | | ◆ | | | |
| | • No synchronisation and poor visibility during sub-control | ◆ | | ◆ | | ◆ |
| | • Incorrect supplier lead times in MRP logic | | | ◆ | | |
| | • Infrequent MRP runs | | | ◆ | ◆ | |

Table 4. Typical Problems Observed in Real-World Supply Chains
(Source: Geary et al, 2002)

- *People do not always use “rational” methods to make decisions*
- *People have their personal agenda and hence view their world metaphorically and symbolically as well as literally*
- *People will not always do what they are told to do, or even what they know they should do*
- *People can be very creative in sabotaging structures and processes they fear or dislike*
- *The organisational chart inadequately describes how members actually conduct their business*

Sometimes their decisions may be made with the best of intentions as viewed from their narrow parochial perspective. An example is the “Hockey Stick Effect”. Typically a company will attempt to improve its financial reporting figures by manipulating the supply chain. For example, towards the end of the financial year or quarter, it may offer discounts to customers so as to boost the order book. This may also include shipping products to customers that they did not even want so as to reduce our inventory and boost sales in our final financial report. The opposite strategy also applies, when failing to order products from suppliers near milestone dates in order to reduce the stock count and hence holding costs even if it is clear that such items will be needed soon by the next downstream value-added process. Consequently the latter experiences under-supply during the next period.

There is also another related effect caused by the financial reporting mechanism. Over time the stock position in a computer system may well deviate from the actual stock position. It is well known that even major retailers find it difficult to keep track of where goods are actually located within any given store. So what is logged as available stock may not actually be on the

rails for the customer to see (Raman et al, 2001). When the auditors come in and make a physical stock count, they find these errors and they are then rectified but appear as an impulse in the ordering system, thus starting a bullwhip wave which can be compounded via the particular forecasting algorithm used. Hence the importance of educating value stream "players" on the often unintended consequences of their actions, a point readily demonstrated by playing the MIT Beer Game (Senge, 1993) in interactive mode with participants selected from various echelons within the chain.

11. Supply Chains of the Future

Our sample analysis of 32 value streams has thrown up an apparent elite which may be regarded as exemplars. If these are to become the "norm" for future supply chain design and operations it is essential that the lessons to be learnt from these exemplars are readily transferable within and between market sectors. This is the litmus test for deciding if a *real* contribution to management theory has been made (Micklethwait and Woolridge, 1996). Hence Table 5 shows the good practice mined from these exemplars. These are grouped into simplified material flow properties, supply chain relationships, and the over-arching information systems. In our view all three are key factors in enabling good supply chain practice. The output of interest herein is the schedule stability, as defined by Harrison (1997), since this is a direct measure of the bullwhip experienced by the supplier. It is also a surrogate indicator for estimating the likelihood of bullwhip at that level in the chain.

| Observed Area of Good Practice | Exemplar Value Stream Characteristics |
|---------------------------------------|---|
| Simplified Material Flow | <ul style="list-style-type: none"> • Customer orientated operations • Single piece material flow in place • Pull systems based on Kanbans • Use of the shortest possible planning period • Active process time compression |
| Supply Chain Relationships | <ul style="list-style-type: none"> • Generic partnerships with key suppliers • Dominant 'player' i.e. "product champion" who manages the synchronisation and co-ordination of the supply chain • Single point of control |
| Information System | <ul style="list-style-type: none"> • Totally integrated information systems |
| Schedule Stability | <ul style="list-style-type: none"> • Average schedule variability of the three exemplars is 4% over a one-month forecast, compared to 45% for the entire 32 value stream sample. |

Table 5. Supply Chain "Best Practices" Identified Via Audit of European Value Streams
(Source: Childerhouse, 2002)

Using the schedule stability metric, we see that our three exemplars are over 10:1 better than for the sample average. This has been enabled via good business systems engineering techniques to re-engineer material flow and information flow. By entering into appropriate supply chain relationships this infrastructure is exploited on behalf of all "players" in the chain. The single point-of-control ensures that a holistic system results from this opportunity. The impact is then maximised by the presence of the totally integrated information systems which ensures the data required is actually available in a timely, noise free, bias free fashion. Such a seamless supply chain (SSC) minimises the possibility of generating bullwhip via our value added processes, via our supply processes, and via our control processes. In a similar fashion the demand volatility is reduced to the bare essentials because we have marketplace

transparency at all levels in the chain, thus avoiding the double-guessing and wrong-footing associated with traditional value streams.

The requirements for good supply chain practice which, amongst other benefits, reduces unnecessary bullwhip, as shown in Table 5 may seem a modest target to aim at to ensure that the normative supply chain of the future is as good as the exemplar of today. But as we have already seen, there is unfortunately a large step forward still to be taken. This requires the willingness to properly exploit the existence of IT, rather than just pay lip service to its use. For example, in the critical area of timely, noise free, and bias free information flow, the large US company survey results shown in Table 6 remain disturbing. Nor does the recent survey of 128 Swedish companies present and expected future use of collaborative forecasting techniques make for an better reading (Olhager and Selldin, 2004). The up-to-date status of inventory, capacity, order status, demand history, and forecasts (including the “essential system states” as in the language of Miraglotta, 2004) are pre-requisites to seamless supply chain operations. These survey results suggest that trust still has to emerge in many value stream relationships, the inhibition being the persistence with traditional “adversarial win-lose negotiations” (Clark and Hammond, 1997). Until this situation is resolved into true partnerships unnecessary bullwhip will continue to exist, multiply, and incur significant on-costs.

| Type of Data Made Available | Surveyed In 1998 | Estimated for 2001 |
|--|-------------------------|---------------------------|
| Inventory and Capacity | 50% | 75% |
| Demand History and Forecasts | 30% | 72% |
| Order Status | 30% | 66% |
| Project Design and Specifications | 34% | 54% |
| Financial Information | 3% | 20% |

Table 6. Percentage of Large US Companies Making Specific Information Available to Business Partners

(Results of Price Waterhouse Coopers 1999 Survey reported by Knolmayer et al, 2002)

12. Conclusions

Bullwhip has a long tradition for causing disruptions and massive over-swings and under-swings in demand. The former results in quite unnecessary ramping up of production (usually tried at great speed with the generation of corresponding inefficiencies), and the latter necessitates much pain via paid idle time and possible redundancies. The on-costs incurred include "learning effects" for new labour on the upswing, and lay-off costs on the downswing. Because of this cyclical behaviour (well-known in economic circles as the boom-and-bust scenario), the stocks will also fluctuate out-of-phase with demand. So again on the upswing, there will be stock-outs, whilst on the downswing there will be excess stock with a tendency to incur obsolescence and to damage during excessive storage periods. So business is lost because the products are not available when required, and when they are available they are at a higher cost than need be.

We have identified at least ten major causes of bullwhip. These are in part due to problems in our value-added processes, supplier difficulties, demand volatility, and control processes. A way forward is to re-engineer the supply chain to systematically remove all *avoidable* causes

of uncertainty. This requires the effective application of business systems engineering principles involving technical, cultural, organisational, and financial aspects of the project. It is our view that the underlying themes during the execution of such BPR programmes are smooth material flow, smooth and transparent information flow, time compression of all processes, holistic controls and the abolition of all interfaces, especially those causing functional silos to exist. The consequence is a movement away from traditional, adversarial operations, towards the minimal bullwhip seamless supply chain scenario. In practical terms there appears to be little difficulty in thereby reducing real-world bullwhip by *at least* 50%.

Our perception of future bullwhip lies not in revolutionary new supply chains. Instead we see the promulgation of the present established "exemplar" good practice which has demonstrated that our present knowledge of bullwhip causes can generate effective solutions to be matched to the particular needs of the individual value streams. This move from a few exemplars to a future scenario where their present day exceptional standards have become the new norm needs to be accelerated. But barring the path to such progress are a number of factors which lie outside the technical arena. By far the greatest of these is the elimination of the "functional silo" mentality and its replacement by a new era of interface management. Only then can we fully exploit the versatility of present day IT to improve supply chain competitiveness. This includes avoiding bullwhip on-costs by using proven designs to ensure smooth material flow as needed to satisfy the true demands of the marketplace. We heartily agree with a recent paper which argues that the first step must always be to implement the Time Compression Principle (de Treville et al, 2004) and hence reduce all lead times to their optimum value. It is also axiomatic that these new reduced targets must be consistently achieved if uncertainty is to be reduced.

References

- Ackoff, R.L. (1999) "Ackoff's Best ~ His Classic Writings on Management", John Wiley and Sons, Inc. New York.
- Adelson, R.M. (1996) "The Dynamic Behaviour of Linear Forecasting and Scheduling Rules", *Operational Research Quarterly*, Vol 17, No. 4, pp 447-462.
- Anderson, E.G. Jr, Fine, C.H. and Parker, G.G. (2000) "Upstream Volatility in the Supply Chain: the Machine Tool Industry as a Case Study", *POMS Series in Technology and Operations Management*, Vol. 9, pp 239-261.
- Andraski, J.C. (1994) "Foundations for a Successful Continuous Replenishment Programme", *International Journal of Logistics Management*, Vol.5, No.1, pp.1-8.
- Axsäter, S. (1985) "Control Theory Concepts in Production and Inventory Control", *International Journal of Systems Science*, Vol. 16, No. 2, pp 161-169.
- Blanchard, O.J. (1983) "The Production and Inventory Behaviour of the American Automobile Industry", *Journal of Political Economy*, Vol. 91, Issue 3, pp 365-400.
- Burbidge, J. and Halsall, J. (1994) "Group Technology and Growth at Shalibane", *Production Planning and Control*, Vol. 5, No 2, pp 213-218.
- Burbidge, J.L. 1981, *Britain's Counter Productive Plants*, *Management Today*, November 1981, pp. 86 - 90.
- Burbidge, J.L. (1995) "Back to Production Management", *Manufacturing Engineer*, April, pp 66-71,
- Burns, J.F. and Sivizlian, B.D, (1978), "Dynamic Analysis of Multi-Echelon Supply Systems", *Computers and Industrial Engineering*, Vol. 7, pp 181-193.
- Chen, C., Drezner, Z., Ryan, J.K, and Sunchi-Levi, D. (2000) "Quantifying the Bullwhip Effect in a Simple Supply Chain," *Management Science*, Vol. 46, No. 3. pp 436-443.

- Childerhouse, P. (2002), "Enabling Seamless Market-Orientated Supply Chains" PhD Thesis, LSDG, Cardiff University.
- Clark, T.H. and Hammond, J.H., (1997) "Re-engineering Reordering Processes to Improve Total Supply Chain Performance", *Prod. And Op. Man.*, Vol 6, No. 3, pp 248-65.
- de Treville, S., Shapiro, R.D. and Harmeri, A-P (2004) "From Supply Chain to Demand Chain: the Role of Lead Time Reduction in Improving Demand Chain Performance", *Journal of Operations Management*, Vol. 21, Issue 6, pp 613-627.
- Dejonckheere, J., Disney, S. Lambrecht, M. and Towill. D.R. (2002) "Transfer Function Analysis of Forecasting Induced Bullwhip in Supply Chains" *International Journal of Production Economics*, Vol. 78, pp 133-144.
- Devons, E. (1950) "Planning in Practice: Essays in Aircraft Planning in War-Time", Cambridge University Press.
- Deziel, D.P. and Eilon, S. (1967) "A Linear Production – Inventory Control Rule." *The Production Engineer*, Vol. 43, pp. 93-104.
- Disney. S.M. and Towill, D.R. (2002) "A Discrete Transfer Function Model to Determine the Dynamic Stability of a Vendor Managed Inventory Supply Chain", *International Journal of Production Research*, Vol. 40, No. 1, 179-204.
- Drucker, P. (1995) "The Information That Executives Truly Need", *Harvard Business Review*, Jan/Feb. pp 54-62.
- El-Beheiry, M., Wong. C.Y and El-Kharbotly (2004) "Empirical Quantification of Bullwhip Effect (With Application to a Supply Chain), *Proceedings 13th Working Seminar on Production Economics, IGLS*, Vol. 3, pp 83-95.
- Fisher, M., (1997), "What is the Right Supply Chain for your Product?" *Harvard Business Review*, March/April, 105-116.

- Fisher, M., Hammond, J. Obermeyer, W. and Raman, A. (1997) "Configuring a Supply Chain to Reduce the Cost of Demand Uncertainty", *Production and Operations Management*, Vol 6, No. 3, Fall, pp 211-225.
- Forrester, J. (1958) "Industrial Dynamics – a Major Break Through for Decision-Makers." *Harvard Business Review*, Vol. 36, No. 4, pp. 37-66.
- Geary, S., Childerhouse, P. and Towill, D.R. (2002) "Uncertainty and the Seamless Supply Chain" *Supply Chain Management Review (USA)*, July/August, pp 52-61.
- Harrison, A., (1997) Investigating the Sources and Causes of Schedule Instability, *Proceeding of the 3rd International Symposium on Logistics*, Padua, Italy, 155-164.
- Hayes, R.H. and Wheelwright, S.C. (1984) "Restoring our Competitive Edge: competing through manufacturing", John Wiley & Sons.
- Holmström, J. (1997) "Product Range Management: A Case Study of Supply Chain Operations in the European Grocery Industry", *International Journal of Supply Chain Management*, Vol. 2, No. 8, pp 107-115.
- Holt, C.C., Modigliani, F., Muth, J.F and Simon, H.A. (1960). *Production Planning, Inventories, and Workforce*. Prentice-Hall, Englewood Cliffs, NJ.
- Knolmayer, G., Merteus, P., and Zeier, A., (2002) "Supply Chain Management Based on SAP Systems", Springer-Verlag, Berlin.
- Kondratieff, N.D. (1984) *The Long Wave Cycle*, New York: Richardson and Snyder.
- Lambrecht, M. and J. Dejonkheere, (1999) "Extending the Beer Game to Include Real-Life Supply Chain Characteristics", *Proceedings EUROMA International Conference on Managing Operations Networks*, pp 237-243.
- Lee, H.L. and Billington, C. (1992) "Managing Supply Chain Inventory: Pitfalls and Opportunities", *Sloan Management Review*, Spring, 66-73.

- Lee, H.L., Padmanabhan, V. and Whang, S. (1997) "Information Distortion in a Supply Chain: The Bullwhip Effect", *Management Science*, Vol. 43, No. 4, pp. 546-558.
- Levy, D.L. (1995) "International Sourcing and Supply Chain Instability", *Journal of International Business Studies*, 2nd Quarter, pp. 343-360.
- Loughman, T.P., Fleck, R.A. and Snipes, R. (2000) "A Cross Disciplinary Model for Improved Information Systems Analysis, *Industrial Management and Data Systems*, Vol 100 No 8, pp. 359-369.
- Lyneis, J.M. (1980) "Corporate Planning and Policy Design", Pugh-Roberts Associates.
- McCullen, P. and Towill, D.R. (2002) "Diagnosis and Reduction of Bullwhip in Supply Chains" *Supply Chain Management, an International Journal*, Volume 7, Nos. 3 and 4, pp 164-179, 2002.
- Metters, R. (1997) "Quantifying the Bullwhip Effect in Supply Chains", *Journal of Operations Management*, Vol. No 15, pp. 89-100.
- Metzler, L.A. (1941) "The Nature and Stability of Inventory Cycles, *Review of Economic Statistics*, Vol. 23, Issue 3, pp 113-129.
- Micklethwait, J. and Woolridge, A. (1996) "The Witch Doctors – What the Management Gurus are Saying, Why it Matters, and How to Make Sense of it", Mandarin Books, London.
- Miragliotta, G. (2004) "The Bullwhip Effect: A Survey on Available Knowledge and a New Taxonomy of Inherent Determinants and External Triggers", *Proceedings 13th Working Seminar on Production Economics, IGLS*, Vol. 3, pp 259-273.
- Mitchell, T. (1923) *Competitive Illusion as a Cause of Business Cycles*, *Quarterly Journal of Economics*, 38, pp 631-652.
- Naim, M.M., Childerhouse, P., Disney, S.M. and Towill, D.R. (2002) "A Supply Chain Diagnostic Methodology ~ Determining the Vector of Change", *Computers and Industrial Engineering*, 43, pp 135-157.

- Olhager, J. and Selldin, E. (2004) "Supply Chain Management Survey of Swedish Manufacturing Firms", *International Journal of Production Economics*, Vol. 89, pp 353-361.
- Olsmats, C., Edgehill, J. and Towill, D.R. (1988) "Industrial Dynamics Model Building of a Closed-Coupled Production-Distribution Systems", *Engineering Costs and Production Economics*, Vol. 13, pp 295-310.
- Raman, A., de Horatius, N. and Ton, Z (2001) "Execution, the Missing Link in Retail Operations", *California Management Review*, Spring, Vol. 43, No. 3, pp 136-152.
- Riddalls, C.E. and Bennett, S. (2002) "The Stability of Supply Chains", *International Journal of Production Research*, Vol. 40, No. 2, pp. 459-475.
- Schmenner, R.W. (2001) "Looking Ahead by Looking back: Swift, Even Flow in the History of Manufacturing", *Production and Operations Management (USA)*, Spring, Vol. 10, Issue 1, pp. 87-96.
- Schonberger, R.J., (1982) "Japanese Manufacturing Techniques: Nine Hidden Lessons in Simplicity" The Free Press, NY.
- Senge, P.M. (1993) "The Fifth Discipline", Century Business Books, London.
- Stalk, Jr. G.H. and Hout, T.M. (1990), *Competing Against Time; How Time Based Competition is Reshaping Global Markets*, Free Press, New York.
- Sterman, J.D. (1989) "Modelling Managerial Behaviour : Misperceptions of Feedback in a Dynamic Decision-Making Experiment", *Management Science*, 35, (3), pp 321-339.
- Sterman, J.D. 1986, *The Economic Long Wave; Theory and Evidence*, *Systems Dynamics Review*, 2, Summer, pp 87-125.
- Stevens, G.C. (1989) "Integrating the Supply Chain" *International Journal of Physical Distribution and Materials Management*, Vol. 19 No. 8, pp. 3-8.

- Thonemann, U.S. (2002) "Improving Supply Chain Performance by Sharing Advance Demand Information", *European Journal of Operational Research*, Vol. 152, pp. 81-107.
- Towill, D.R, Childerhouse, P. and Disney, S.M. (2002) "Integrating the Automotive Supply Chain: Where are we Now"" *International Journal of Physical Distribution and Logistics Management*, Vol. 32, No. 2, pp 79-95.
- Towill, D.R. (1982) "Dynamic Analysis of an Inventory and Order Based Production Control System" *International Journal of Production Research*, Vol 20, pp 671-687.
- Towill, D.R. (1997) "FORRIDGE – Principles of Good Practice in Material Flow", *International Journal of Production Planning and Control*, Vol. 8, No. 7, pp 622-632.
- Towill, D.R. (1999) "Management Theory – is it of any practical use?" *IEE Engineering Management Journal*, Vol. 9, No. 3, June, pp 111-121
- Towill, D.R. and A. Del Vecchio (1994) "Application of Filter Theory to the Study of Supply Chain Dynamics", *Journal Production Planning and Control*, Vol 5, No. 1, pp 82-96.
- Towill, D.R. and McCullen, P, (1999) "The Impact of an Agile Manufacturing Programme on Supply Chain Dynamics", *International Journal of Logistics Management*, Vol. 10, No. 1, pp 83-96.
- van Ackere, A., Larsen, E.R. and Morecroft, J.D.W. (1993) "Systems thinking and business process redesign: An application to the beer game", *European Management Journal*, Vol. 11, No. 4, pp 412-423.
- Vassian, H.F. (1955) "Application of Discrete Variable Servo Theory to Inventory Control", *Journal ORSA*, Vol 3, No. 3, pp 272-282.
- Watson, G.H. (1994) "Business Systems Engineering: Managing Breakthrough Changes for Productivity and Profit", John Wiley and Sons, Inc. NY

Geary, S., Disney, S.M. and Towill, D.R., (2006) "On bullwhip in the supply chains ~ historical review, present practice and expected likely impact", *International Journal of Production Economics*, 101 (1): pp2-18. DOI: 10.1016/j.ijpe.2005.05.009.

Wikner, J. Naim, M.M. and Towill, D.R. (1992) "The System Simplification Approach in Understanding the Dynamic Behaviour of a Manufacturing Supply Chain", *Journal of Systems Engineering*, Vol. 2, No. 2, pp 164-178.

Wilkinson, P. (2000) "The Shock of the Old: A Guide to British Buildings", Channel 4 Books, MacMillan Publishers, London.

Womack, J.P., Jones, D.T., and Roos, D., (1990) *The Machine that Changed the World*, Mandarin Books, London.

Zymelman, M. (1965) "A Stabilisation Policy for Cotton Textile Cycle" *Management Science*, Vol. 11, No. 5, March, pp572-580.