Achieving lean supply through agile manufacturing

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Abstract
Drawing on results from supply chain modelling and dynamic simulation, presents four material flow principles which can be employed to reduce the bullwhip effect. A case study from the precision mechanical engineering sector is employed to illustrate the effect of rapid response manufacturing and supply chain integration. Analysis of six years of time-series data indicates bullwhip reduction of up to 58 per cent. These results serve to validate the four material flow principles of selecting appropriate control systems, time-compression, information transparency, and echelon elimination. They also raise interesting questions concerning the relationship between manufacturing agility and lean supply. For, by attenuating bullwhip the studied company was able to reduce their global inventory by 45 per cent. Thus, by viewing manufacturing in the context of the supply chain as a whole, it is possible to see how agile manufacturing can eliminate sources of variability induced waste; particularly inventory. In this way it is argued that agile manufacturing can subsume the paradigm of lean production.

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The bullwhip effect

In this paper we consider the effect of an agile manufacturing strategy on company A's global supply chain. The supply chain has three echelons, consisting of:

1 overseas warehouses;
2 a central finished goods warehouse; and
3 a UK factory.

Each echelon procures products from its immediate upstream echelon. The original information flow from the overseas warehouses to the central warehouse consisted of a stream of purchase orders, and the central warehouse communicated with the factory through demand forecasts and a jointly agreed master production schedule (MPS). The poor performance of the company's original supply chain can be explained in terms of the "bullwhip effect":

> ... information transferred in the form of orders tends to be distorted and can misguide upstream members in their inventory and production decisions ... the variance of [replenishment] *orders* may be larger than that of *sales* [to end customers], and the distortion tends to increase as one moves upstream – a phenomenon termed "the bullwhip effect" (Lee *et al*., 1997).

Typical amplified and distorted demand patterns have been documented in many market sectors, for example, relating to paper making, nappies, automotive component supplies, retailing, and confectionery products (Towill and McCullen, 1999). These observations are broadly in line with theoretical predictions obtained from simulation models representing real world supply chains. Simulation models have been employed by the Cardiff Logistics Systems Dynamics Group (LSDG) in order to develop material flow principles to guide supply chain actors wishing to reduce the bullwhip effect, and thus to improve supply chain competitiveness (Towill and McCullen, 1999). The paper demonstrates that application of these principles, as part of a supply chain re-engineering package, does indeed significantly reduce bullwhip in a global supply chain.

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Four material flow principles

The Cardiff LSDG has been involved in a large-scale project on improving the dynamic performance of supply chains. A fundamental aspect of the project's methodology has been to simulate real world supply chains using improved and validated versions of the Forrester (1961) and other supply chain models, as typified by Del Vecchio *et al*. (1987). The orientation of the research has been to discover rules and design principles which lead to the optimum supply chain structure. The project has therefore concentrated on modelling the serial interactions, which determine the dynamic performance of the supply chain, and has employed modelling and simulation to obtain guideline benchmarks for comparing the various strategies for improving supply chain performance. Towill *et al*. (1992) show that steps to providing effective damping of the bullwhip effect fall into four major categories, which appear sufficiently general to be termed material flow principles, and can be considered appropriate to all those supply chains bearing a reasonably close resemblance to the multi-echelon Forrester model. These are:

1 *Control systems principle*. This involves selection of decision support systems, which contribute to the dynamic stability of the total supply chain (if process lead times are reliable and operations information of high quality, then good, robust control systems can also be simple).

2 *Time compression principle*. This involves the re-engineering of business processes in order to slash material flow and information flow lead times (reduction of these is within the technological and organisational remit of individual echelons).
3 *Information transparency principle*. This involves sharing high integrity information between supply chain actors (however, the quality and quantity of data available throughout the supply chain from end customer to raw materials source remain a commercially sensitive issue).
4 *Echelon elimination principle*. This involves the elimination of echelons and functional interfaces (this reduces time delays and the information distortion which precipitates demand amplification, but may lead to a substantially different channel of distribution).

A global supply chain

Company A is a UK manufacturer of precision mechanical engineering products, which they distribute globally via a network of overseas subsidiaries, as shown in Figure 1. A total of 80 per cent of the products are exported with the largest markets in Japan and the USA. The company's internal supply chain consisted of three echelons:
1 a UK factory;
2 the company's head office and central finished goods warehouse; and
3 a number of overseas subsidiary operations.

Each echelon had its own control system, illustrated in Figure 2, and relied on the serial transfer of logistics information from one echelon to the next. The entire system was forecast driven, with territory sales re-forecasts transformed into a demand plan by Commercial Administration, and worked into an MPS by factory materials management. During the 1980s these planning processes involved spreadsheet analysis with data frequently transmitted by fax and re-keyed at the next echelon. The quarterly planning process was supplemented by a monthly cycle of re-ordering by overseas subsidiaries, and feeding into a joint process of MPS adjustment by commercial administration and materials management. Further mid-month MPS changes were negotiated with materials management in response to order exception reports thrown out by Commercial Administration's "available to promise" (ATP) system.

Problems with the original supply chain

During the mid- to late 1980s the company experienced very strong sales growth and decided to increase capacity on several occasions. Behind the success story, however, supply chain actors were experiencing considerable stress, brought about by a number of problems, as illustrated in the Ishikawa diagram shown in Figure 3. The problems were as follows:

Figure 1
Original supply chain and organisation

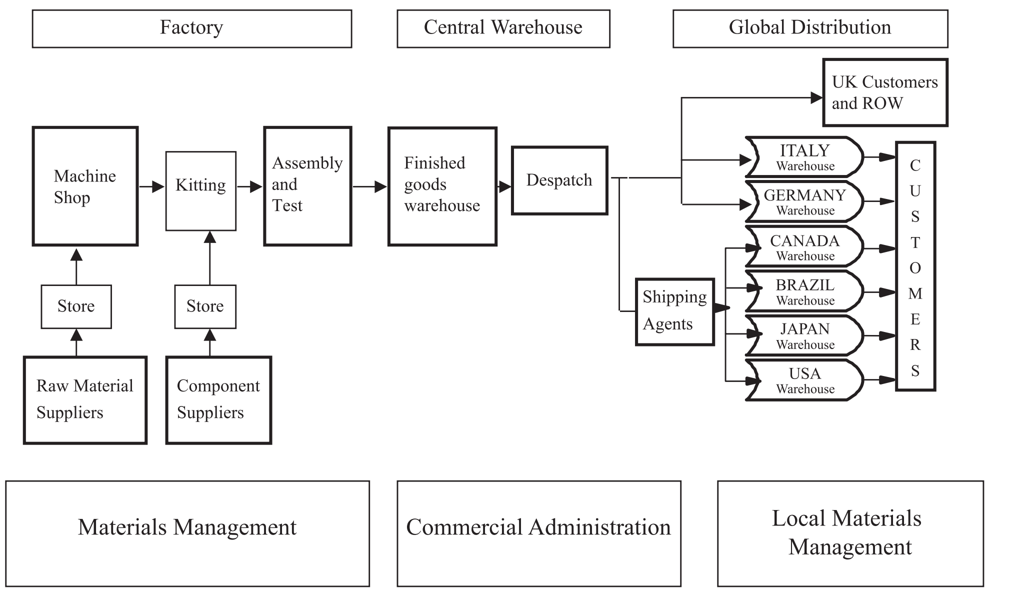


Figure 2
Original information flow and control systems

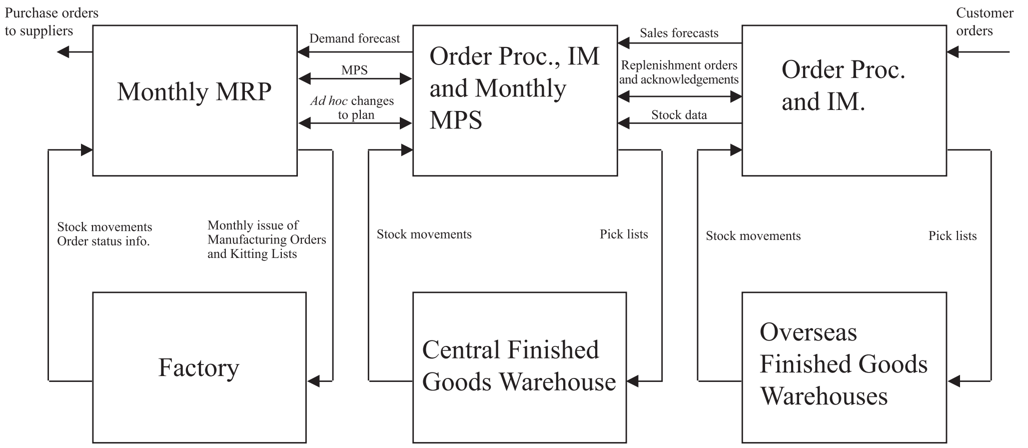
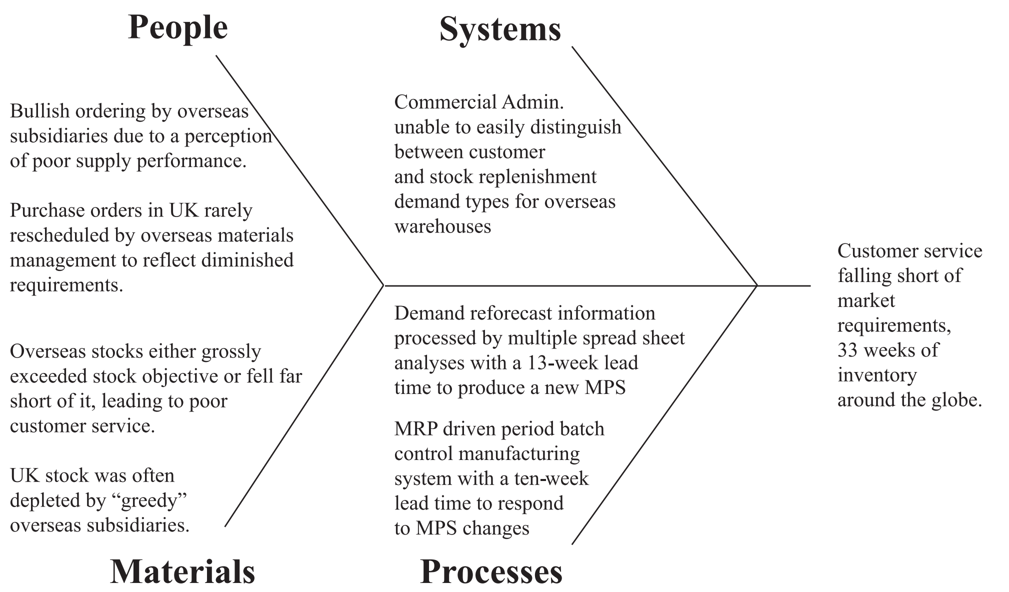


Figure 3
Ishikawa diagram summarising problems with the original supply chain



- central warehouse safety stock was often depleted by apparently greedy overseas subsidiaries;
- overseas subsidiaries either grossly exceeded stock objective or fell far short of it;
- Commercial Administration sometimes could not identify true end-customer requirements amongst a "sea" of back-orders, and found it difficult to advise Materials Management on priorities and optimum product mix;
- the overall supply chain was unresponsive to changes in customer demand, with a cumulative lead time of 23 weeks to react to changes in the sales forecast;
- some products, on back-order due to above-forecast demand, and with consequently increased production, would suffer from a phenomenon, whereby, just at the point when UK stocks were recovering, overseas demand would collapse, leading to excess stock and cuts in future production.

Rapid response manufacturing programme

The company recognised that these problems were fundamentally due to the company's forecast-driven supply chain, and the implicit assumption that everything would be OK, if forecast accuracy could be improved. The operations director believed that the solution was therefore to reduce manufacturing's dependence on forecasts by slashing lead times. The factors affecting forecast accuracy have been outlined by Watson (1994):

> . . . if you map the sales process to the forecast accuracy, you will find that the sales representatives know very accurately what sales they will close within a month. They have a fairly good idea how qualified and ready to order their prospects are within the two-month window. As for month three and beyond – well, you may as well flip a coin . . .

In a make-to-stock environment where the forecasting horizon (the period over which the company is dependent on its forecast of future demand) is determined by manufacturing plus information processing lead times, and where forecast accuracy diminishes according to the length of the forecasting horizon, then manufacturing's exposure to forecast error can be reduced by cutting these lead times. The company's objectives were rapid response manufacturing (RRM) and information systems (IS) integration for material control activities throughout the supply chain. This approach, it was hoped, would buffer both customers and manufacturing from the effects of poor sales forecasts. Agility and rapid response are related, as Kidd (1994) explains:

> Agile manufacturing enterprises will be capable of responding rapidly to changes in customer demand.

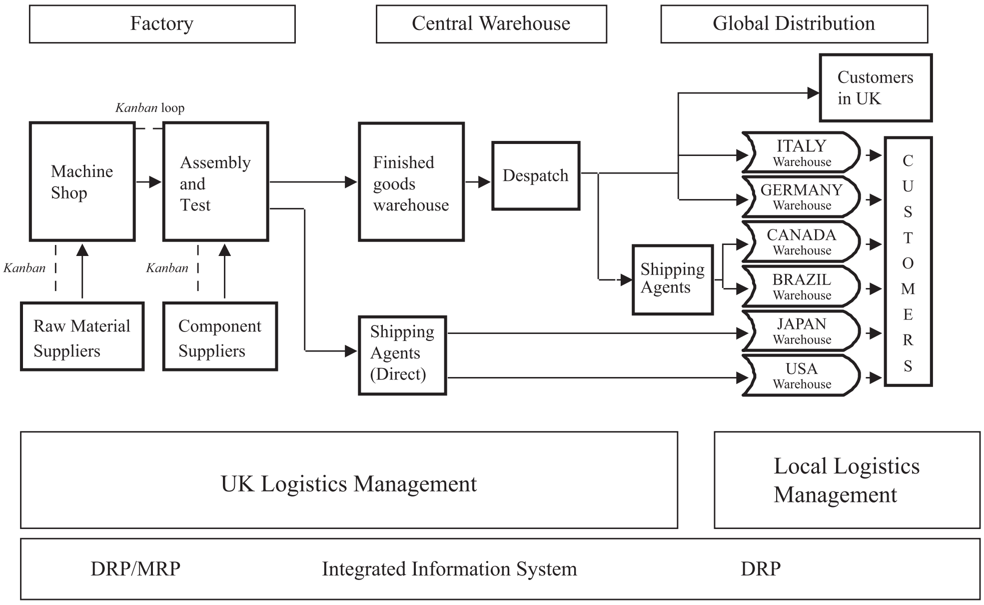
The objectives of the company's rapid response project were as follows:
- slash manufacturing lead times;
- directly link UK factories to international customer demand;
- plan more frequently and rapidly throughout the supply chain;
- physical distribution management (PDM) streamlined in relation to global needs to achieve a more balanced distribution of finished goods inventory.

The company's original manufacturing system was based on a period batch control system (Burbidge, 1991), whereby materials were procured in month 1, machined in month 2 and assembled in month 3. Products were built in batches by skilled fitters on benches (a fixed position layout). Manufacturing planning and control were achieved through a monthly release of manufacturing orders for machining and assembly. Assembly orders were kitted prior to final assembly, with shortages chased in prior to building the batch. The company's RRM strategy involved the following improvements:
- assembly flow lines were developed, which could handle single piece unit flow, i.e. any mix of products in any sequence, with a batch size of 1;
- manufacturing control of the machine shop was switched from a "push" to a "pull" system, driven by *kanban* signals from final assembly;
- partnership arrangements were developed with component suppliers to achieve direct line feed in final assembly, also driven by *kanban* signals;
- similar arrangements were developed with raw material suppliers;
- "backflushing" was employed to update stock records;
- the planning cycle was initially changed from monthly to weekly, and finally from weekly to daily.

Achieving information systems integration

The company's re-engineered supply chain is represented in Figure 4. The new information system allowed manufacturing logistics to distinguish between: customer orders, forecast demand and safety stock replenishment needs. The new information system also facilitated an organisational change, whereby manufacturing logistics became responsible for its own finished goods stock, effectively eliminating commercial administration as a logistics information processing echelon. Initially the distribution requirements planning (DRP) system was re-run on a weekly basis, but the company soon realised that a daily re-run could provide manufacturing with virtual real-time information on market demand. Whereas PDM had previously been driven by purchase orders placed by overseas subsidiaries, the new system employed a simple re-ordering algorithm, with transfer batches directly related to usage over the transit time. This "pull" distribution system effectively retained stock in the central warehouse until the last possible moment, thus avoiding the global stock imbalances which characterised the original supply chain. Direct shipment from the factory to the port of departure was also implemented for volume products destined for the USA and Japan. The combined effect of RRM and IS integration was to dramatically reduce the combined information and material processing lead time from 23 weeks to two

Figure 4
Re-engineered supply chain, organisation and control system



weeks, thereby achieving time compression of 91 per cent.

Relating the four material flow principles to the bullwhip effect observed in company A

Objectives

Company A's strategy of RRM and IS integration corresponds very closely with LSDG's four material flow principles, as indicated in Table I.

In the light of the correspondence between these four principles and observed practice we would expect company A to experience significant demand smoothing and a reduction in the bullwhip effect. Empirical research was therefore conducted in order to investigate the following questions:

RQ1
- Did company A experience the bullwhip effect in its original supply chain?

RQ2
- If so, was demand amplification attenuated as a result of its strategy of RRM and IS integration?

RRM implies time compression, which, according to findings from industrial dynamics (Wikner *et al.*, 1991), tends to improve the dynamic performance of the supply chain. Thus we might expect smaller variations in demand and inventory, and less inventory to buffer those fluctuations. These considerations lead to a more general question concerning the relationship between rapid response (or agile) manufacturing and lean supply:

RQ3
- Does RRM and IS integration help to reduce variability, thus facilitating inventory reduction and a leaner supply chain?

Methodology

Primary research at company A involved interviews, participant observation and the collection of six years of monthly time-series data on: sales, replenishment demand, production and inventory levels. Time-series were smoothed using three-point moving averages to eliminate random variation, and the existence of a bullwhip effect was ascertained (*RQ1*) by inspecting these time-series. Bullwhip, or amplification, was measured using the average unsigned difference between the time-series for replenishment demand on the central warehouse and actual production. The implementation of DRP followed initial trials of RRM for products 1-6 in month 36, the "supply chain improvement watershed". The degree of attenuation was evaluated (*Q2*) by comparing amplification before and after that date. The effect on variability (*Q3*) was evaluated by measuring the extent of inventory swings using a new time-series for stock. These time-series calculated the coefficient of stock variation (in order to allow for the non-stationary nature of the series) over the previous five months. Once again values were compared before and after the supply chain improvement watershed.

Table I
Correspondence between the company's supply chain improvement strategy and LSDG's four material flow principles

SC improvement	Detail	Control systems	Time compression	Transparency	Echelon elimination
Slash manuf. LT	Single piece unit flow		•		
	Pull scheduling eliminating component lead times	•	•		
	Manufacturing planning cycle changed from monthly to daily		•		
Link factory directly to demand	DRP provides factory with virtually real-time information on international customer demand	•		•	
More frequent and rapid planning	DRP is run first weekly and then daily		•		
	Demand forecasts are automatically generated by DRP instead of Commercial Administration			•	•
Streamlined PDM	Transfer quantities selected to cover distribution lead-time	•			
	Kanban system retains inventory centrally until the last possible moment to minimise global stock imbalances	•			

The leanness of the supply chain was evaluated by measuring global inventory in "weeks cover" for the years following implementation. Secondary sources on lean and agile supply paradigms have been consulted in order to inform the qualitative issues raised by question *RQ3*.

Estimated bullwhip attenuation

For one particular high volume variant of product 1, supplied to an OEM in the USA, it was possible to construct a long-term time-series for sales to the end-customer from months 18 to 77, as shown in Figure 5. When compared with data for actual production, these time-series indicate the degree of bullwhip experienced across three echelons:

1 overseas warehouse;
2 central warehouse; and
3 UK factory.

These results indicate production lagging and overshooting changes in sales for the periods prior to month 36, when the package of supply chain improvements was first implemented. For the period from months 36 to 57 production mirrors changes in sales more closely, although out-of-phase. From month 57 onwards, once supply chain improvements have "bedded in", production starts to track changes in sales with minimal bullwhip. The time-series for product 1 clearly indicates the existence of a bullwhip effect, which was attenuated by 58 per cent as a result of the company's strategy of RRM and IS integration. Similar data for products 1 to 6, comparing replenishment demand with actual production, also indicate the existence of a bullwhip effect across the central warehouse and factory echelons.

The degree of bullwhip experienced across the central warehouse and factory echelons was estimated using "difference" before and after month 36, the "supply chain improvement watershed", as shown in Figure 6. The results for products 1-6 are shown in Table II.

The improvements were found to be statistically significant for products 1, 2, 4 and 6, and suggest an average bullwhip reduction, across two echelons, of 36 per cent.

Results for stock variability, as shown in Table III, indicate a substantial improvement in five cases, all of which were found to be statistically significant. The increase in stock variability for product 4 may be explained by a change in the pattern of demand. Some customers order this product in large numbers for single consignment letter of credit orders, and there had been an increase in this type of demand since month 36.

The general reduction in variability has allowed the company to reduce its global inventory, as shown in Table IV. Customer

Figure 5
Bullwhip estimated across three echelons: US sales and actual UK production of product 1

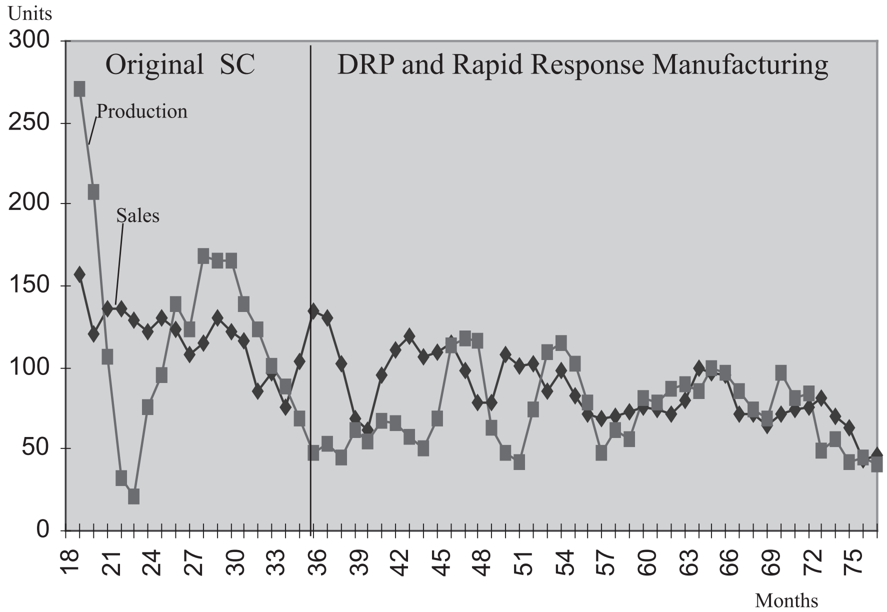
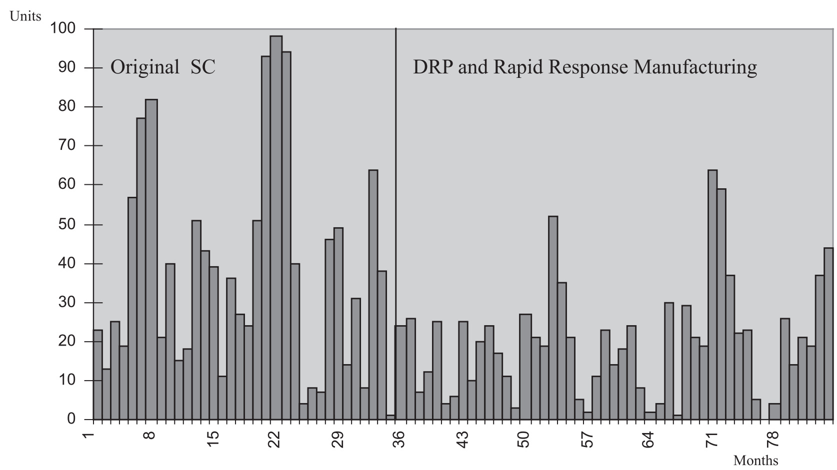


Figure 6
Bullwhip estimated across two echelons: difference between replenishment demand and actual production for product 6



service has also been improved. At the US warehouse, for example, the company measured the average number of days late against customer due date, and the standard deviation of delivery variation. Between months 32 and 43 the first measure improved from an average of ten days to only one day late, and the second from 15 days to four days (McCullen *et al.*, 1995).

Overall the company's strategy of RRM and IS integration has led to improved dynamic performance, as predicted by independent research from LSDG, and to a leaner supply chain.

Table II
Bullwhip across two observed echelons before and after the supply chain improvement watershed

Products	1	2	3	4	5	6
Months 1-35	62	84	59	84	35	37
Months 36-84	34	62	48	63	30	20
Change (%)	–45	–26	–18	–25	–14	–46

Discussion of lean and agile paradigms

Manufacturing thinking over the last decade has been very much affected by the concept of lean production outlined by Womack *et al.* (1990) in their seminal book *The Machine That Changed the World*. Lamming's (1993) conception of lean supply was initially developed as a description of a supply system that would address the needs of lean producers in the automotive industry. More recently Lamming (1996) has generalised this approach to encompass other industries and, drawing on the lean principle of waste elimination, has defined lean supply as:

> ... an arrangement [which] should provide a flow of goods, services and technology from supplier to customer (with associated flows of information and other communications in both directions) without waste.

According to this global perspective early attempts to implement just-in-time, by passing the burden of inventory to upstream suppliers, did not constitute lean supply.

Womack and Jones (1996) have extended the lean thesis to encompass a vision of "the lean enterprise" and a set of techniques which may be employed in order to bring it to fruition. A central concept of lean thinking is the notion of the value stream, which amounts to a product-oriented disaggregation of the supply chain, which emphasises those activities that add value (as viewed from a customer perspective). Jones *et al.* (1997) have further developed the lean thesis to incorporate lean logistics:

> Lean logistics takes its fundamental philosophy from the Toyota production system (TPS) and is based around extending TPS right along supply chains from customers right back to raw material extraction.

Firms wishing to implement lean logistics must first attempt to understand the sources of waste and inefficiency in existing value streams, for:

> If subjected to a careful review, many of the steps required in the office to translate an order into a schedule and many of the steps required in the factory physically to create the product add little or no value for the customer. [In seminal work dating back to the 1960s] Taiichi Ohno defined seven common forms of waste, activities that add cost but no value: production of goods not yet ordered; waiting; rectification of mistakes; excess processing; excess movement; excess transport; and excess stock (Jones *et al.*, 1997).

The authors list a set of techniques from Toyota's tool box, which may be employed to this end, including level scheduling and elimination of demand amplification, only making or delivering what is pulled from downstream, synchronising work throughout the system to the same rhythm as customer demand (using a common take time for all work processes within the value stream), and logging irregularities in order to conduct root cause elimination to prevent recurrences.

Although the proponents of lean thinking provide examples of lean techniques being employed within industries including bicycle building and soft drinks manufacturing (Womack and Jones, 1996), the greatest diffusion of lean thinking is to be found within the motor vehicle industry, where volumes are high and product life cycles relatively long. The history of the lean movement could perhaps be crudely summarised as follows: the International Motor Vehicle Programme (IMVP) conducted a benchmarking study into vehicle manufacturing; the TPS employed by Japanese car companies was identified as best practice and re-packaged as "lean production" in *The Machine that Changed the World* (Womack *et al.*, 1990). Western vehicle manufacturers and their suppliers took heed of the book's message and have attempted to adopt lean principles in order to compete more effectively. Lean principles have also diffused into some other sectors as reported by the Lean Enterprise Research Centre at Cardiff University (Womack and Jones, 1996).

Table III
Central warehouse stock variability before and after the SC improvement watershed

Products	1 (%)	2 (%)	3 (%)	4 (%)	5 (%)	6 (%)
Months 1-35	56	72	57	39	62	53
Months 36-84	37	49	37	45	45	34
Change	–34	–31	–35	+15	–27	–36

Table IV
Global inventory following the supply chain improvement watershed

	Year 0	Year 1	Year 2	Year 3	Year 4
Weeks	31	26	22	20	17
Difference		–5	–4	–3	–2
Change (%)		–17	–14	–12	–11

Manufacturing agility within the agile supply chain

The term "agile manufacturing" can be traced back to the publication of the report *21st Century Manufacturing Enterprise Strategy* (Iacocca Institute, 1991). The origins of the "agility movement" stem from US government concerns that domestic defence manufacturing capacity would be diminished, as defence procurement was reduced following the end of the Cold War in 1989. The

Department of Defense realised that defence manufacturing companies were switching their capacity to commercial products, but wanted to be sure that they could switch back in the event of an emergency (Gould, 1997). Commercial manufacturers, on the other hand, were looking for new ways to compete with Far Eastern firms by taking an approach which could not easily be copied. The Iacocca Institute report (1991) encompassed both of these possibilities in their explanation of the ends and means of agile manufacturing. They argued that a new competitive environment was emerging, in which competitive advantage would be realised by firms that could respond rapidly to demands for highly customised quality products. The means of achieving agility would be to integrate flexible technologies with a highly skilled, knowledgeable and empowered workforce within management structures that stimulated co-operation within and between firms (Kidd, 1994). Agile manufacturing therefore represents a broad business concept which may be defined as: "the ability of an enterprise to thrive in an environment of rapid and unpredictable change" (Gould, 1997). In his book on the subject Kidd (1994) recognises that agile manufacturing encompasses lean techniques, but insists that lean production is a necessary but not a sufficient condition for the achievement of manufacturing agility. Robertson and Jones (1999) make a similar point regarding the means of agile manufacturing when they say:

> Agile manufacturing is based on lean production, although there may be some apparent contradictions between the stability required for low cost and the flexibility required for agility.

While the means of achieving lean production and agile manufacturing may be similar, there is a difference in the strategic intention used to drive through the necessary changes. Whereas the overarching goal of lean supply, lean manufacturing and lean logistics is to eliminate waste, agile manufacturing goes a step beyond by seeking to achieve competitive advantage through rapid response and mass customisation:

> Whereas lean methods offer customers good quality products at low price by removing inventory and waste from manufacturing, agile manufacturing is a strategy for entering niche markets rapidly and being able to cater for the specific needs of ever more demanding customers on an individual basis (Robertson and Jones, 1999).

The difference between lean and agile approaches may be explained in terms of outcomes and strategic intent, as indicated in Figure 7. A surprising similarity between the two approaches is the way in which RRM can actually facilitate waste elimination through bullwhip attenuation. Bullwhip is a major source of unnecessary variability in the supply chain, which is systematically buffered using inventory. RRM reduces bullwhip, which reduces demand variability, leading to diminished safety stock requirements for any given service level objective. The lead time reduction achieved through RRM also serves to reduce safety stock requirements according to the following equation used to calculate safety stock for a given desired service level (Waters, 1992):

$$\text{Safety stock} = Z \times \text{ standard deviation of demand } \times \sqrt{\text{lead time}}$$

where Z is the number of standard deviations from the mean corresponding to the probability of a stock-out specified by the desired service level.

Figure 7
Intentions and outcomes of lean and agile paradigms

	Lean	Agile
Strategic intent	Eliminate waste	Rapid response to diverse requirements
Outcome	Quality and efficient use of all resources	Rapid response, mass customization and selective resource efficiency

Conclusions

The empirical results drawn from the case study serve to validate the four material flow principles of:

1 selecting appropriate control systems;
2 time-compression;
3 information transparency; and
4 echelon elimination,

as these were embedded in the company's strategy of RRM and IS integration, leading to an average 36 per cent reduction in whiplash.

Interestingly, our case study also indicates a connection between lean and agile approaches. Company A's strategic intent was to improve responsiveness rather than to eliminate waste. It is interesting to note that this strategy, while falling short of mass customisation, led to an outcome of increased leanness and improved responsiveness to customers, as suggested in Figure 7. For, by improving the dynamic performance of the supply chain, it was possible to reduce variability-induced waste, leading to a 45 per cent reduction in global inventory. Thus, by viewing manufacturing in the context of the supply chain as a whole, it is possible to see how agile manufacturing can subsume the paradigm of lean production.

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