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Steel supply chain management by simulation modelling

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Abstract

Purpose – The aim of this paper is to propose a simulation study of the "steel supply chain" to demonstrate the effect of inventory management and demand variety on the bullwhip effect mitigation.

Design/methodology/approach – The relevant literature is reviewed, and then the simulation model proposed.

Findings – This study identifies reasons for sharing information under varying levels of demand and some variants, and demonstrates the benefits of mitigating the bullwhip effect by applying a design of experiment. It is shown that the information sharing is able to mitigate the bullwhip effect in the steel supply chain by extending the order interval and minimising the order batch size.

Research limitations/implications – This study explores the factors associated with the bullwhip effect. This research is focused on built-to-order simulation, so the results are only oriented on the basis of orders; hence a simultaneous order- and forecast-based steel supply chain should be carried out in the future.

Practical implications – This framework is expected to provide a convenient way to measure the optimum inventory level against a limited level of demand uncertainty, and thus enterprises can promote the supply chain coordination.

Originality/value – An innovative simulation model of the "steel supply chain" is proposed, which includes information sharing in the simulation model. Furthermore, dynamic scheduling is shown by applying a continuous ordering and order prioritization rule to replace traditional scheduling methods.

Keywords Simulation, Modelling, Steel supply simulation, Supply chain management

Paper type Research paper

1. Introduction

The pace of change and growing uncertainty about the way in which markets will evolve has made it increasingly important for companies to be aware of supply chain management (SCM). In general, SCM can be defined as a process of integrating a chain of entities (such as suppliers, manufacturers, warehouses, and retailers) in a manner which ensures the production and delivery of goods in the right quantities and at the right time, while minimising costs and satisfying customers.

The supply chain itself can be understood as a network of autonomous (or semi-autonomous) business entities involved in various business activities which produce and deliver, through upstream and downstream links, goods and/or services to customers. Lin and Shaw (1998) emphasised the notion of value in seeing a supply chain

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as a series of activities which delivers value to its customers, in the form of a product or a service (or a combination of the two), whereas Moon and Kim (2005) emphasised the notion of core flows, describing a supply chain in terms of flows (of information, cash, and materials) through a series of processes, beginning with suppliers of raw materials and finishing with the end customers.

If a supply chain is understood in the second sense (that is, in terms of information and material flows), a so-called "bullwhip effect" can occur over time as the dynamics of the flows change. The "bullwhip effect" is a phenomenon whereby a small change in demand among end customers is amplified as it progresses upstream along the supply chain. This has the potential to cause cycles of excess inventory, severe backlogs, inadequate product forecasts, unbalanced capacities, poor customer service, uncertain production plans, high backlog costs, and lost sales (Lee *et al.*, 1997; Zhang *et al.*, 2004; Law and Ngai, 2007; Hong *et al.*, 2010).

The successful management of a supply chain is thus essentially concerned with the management of flows among entities, with a view to delivering value. Indeed, Christopher (1998) defined SCM as simply being the management of upstream and downstream relationships with suppliers and customers in such a way as to deliver superior value to customers at less cost to the supply chain as a whole. SCM thus involves an integration of various business processes. Many systems have been developed in an attempt to integrate business processes in various sectors of industry, for example, enterprise resource planning (ERP) is one such attempt to integrate several data sources and processes into a unified database system within an organisation. By analogy, it might be supposed that the integration of individual resource entities within a supply chain could provide overall integration of the supply chain itself. However, resource planning of the various organisational components that constitute a supply chain is inherently likely to be more demanding than a similar process within a single organisation – simply because resource planning would be need to be carried out simultaneously within (and between) all the entities in the supply chain.

There are many examples of business process improvement through radical changes (Hammer and Champy, 1993; Davenport, 1994; Levine, 2001; Sandhu and Gunasekaran, 2004; Sandhu, 2005). However, there are also many reports of the failure of attempts to produce radical business process improvement – mainly due to lack of tools for evaluating the effectiveness of the designed solutions before their implementation (Tumay, 1996; Paolucci *et al.*, 1997; Barber *et al.*, 2003; Greasley, 2003). There are also some studies to improve supply chain process in the steel industry, like Xiong and Helo (2008) discuss supply chain and win-win path in visibility across all participants, from steel producers to customer demand. However, the benefits of simulation modeling have been ignored. In this regard, simulation modelling appears to have great potential for analysing business processes in a variety of industries (Hlupic and Vreede, 2005). Simulation models can incorporate the changing levels of such dynamic parameters as demand variation, production variation, arrival rates, and service intervals; these can be used to identify process bottlenecks and to assess suitable alternatives. Simulation models can also provide graphical displays of process models which can be interactively edited and animated to show the process dynamics of such phenomena as the "bullwhip effect".

Simulation has been applied to multi-agent supply chains to investigate the dynamics of the systems against sudden deviations in parameters, with a view to optimising lead times and minimising total costs (Swaminathan *et al.*, 1998). Similarly, Wilkner *et al.* (2007)

used simulation to investigate order book effectiveness against demand uncertainty, and Towill (1996) studied the "bullwhip effect" by applying control theory to inventory and lead time minimisation. Our arguments are in line with Dale (2001), who indicated that simulation modelling has helped the aerospace industry.

Some guidelines for supply chain simulation have been suggested for application in the steel industry (Naylor *et al.*, 2007; Dawande *et al.*, 2004). However, the authors focus on production scheduling to minimise the on-hand inventory. Other contributions, for instance, Djamila (2003) add a multi-agent simulation into the steel supply chain in order to improve the design and performance of steel production and scheduling. Hafeez *et al.* (1996) use a system dynamic simulation to control the material inventory. However, fewer data are available on the use of information sharing by means of simulation analysis in the steel industry. Indeed, the failure to share information tends to retain greater inventory than is required for actual demand (Holweg and Bicheno, 2002). In view of this, the objective of the present study is to offer a simulation tool which management can use as a guide in determining inventory levels and the "bullwhip effect" at each level in the supply chain. The present study thus extends previous theory in SCM by using a simulation modelling approach to demonstrate that the optimisation of business processes needs to be complemented by corresponding computer simulation analysis. The research question guiding the study is:

RQ1. How does information sharing reduce the bullwhip effect?

The remainder of this paper is arranged as follows. Following this introduction, the next section reviews the literature on SCM, computer simulation, steel supply chains, and steel supply chain simulation. The following section describes the proposed simulation model. The paper then reports a simulation experiment and its results. Finally, the paper concludes with a discussion of the way in which this simulation can enhance the management of very varied demand. Future trends and challenges in steel supply chain simulation modelling are discussed and some conclusions are drawn.

2. Theoretical background

2.1 Supply chain management

As noted above, a supply chain consists of several entities (including customers, distributors, manufacturers, and suppliers), each of which contributes materials, resources, and activities to the chain. To produce an optimal result, managing a supply chain thus requires integration of the entities at the structural level and integration of their individual systems. The benefits of effective SCM include:

- *Throughput improvements*. Better coordination of materials and capacity prevents loss of utilisation while waiting for parts.
- *Cycle time reduction*. Consideration of constraints and alternatives in the supply chain helps to reduce cycle time.
- *Inventory cost reductions*. Knowledge of when to buy materials (based on accurate assessment of customer demand, logistics, and capacity) reduces the need for high inventory levels to guard against uncertainty.
- *Optimised transportation*. Effective SCM optimises logistics and vehicle loads.
- *Increased order fill rate*. Real-time visibility across the supply chain (alternate routings, alternate capacity) enables order fill rates to be increased.

- *Enhanced responsiveness to customers*. Improved capacity to deliver (based on the availability of materials, capacity, and logistics) enhances responsiveness to customer needs.

In capital-intensive industries, such as steel-making, the maintenance of a high utilisation rate is a key success factor (Hill, 1994). However, the scheduling problem in the steel industry is acknowledged to be among the trickiest of several industrial scheduling problems (Lee and Murthy, 1996). The complexity lies in the need to synchronise several processes so as to create a flow through plants in which minimal work in process is allowed (Park *et al.*, 2002). In these circumstances, improved scheduling has the potential to create significant economic gains. As Lee and Murthy (1996) put it:

> In an industry where a single new manufacturing unit, such as a continuous caster, can cost more than $250 million, and where the annual production of the unit is measured in hundreds of millions of dollars, an expenditure in software development to improve production even by a few percent is worthwhile.

2.2 SCM simulation

Computer simulation has become a useful form of modelling in many systems, including economics, social sciences, manufacturing, and engineering. Simulation typically uses a mathematical model to predict the behaviour of the system from a set of parameters and initial conditions. The technique is often used for modelling systems in which simple closed-form analytical solutions are not possible. Although there are different types of computer simulation, the feature common to all is the generation of a sample of representative scenarios for a model in which the complete enumeration of all possible states of the model would be prohibitive or impossible.

The application of simulation in supply chains has tended to emphasise a multi-agent approach which takes account of the fact that supply chains are composed of autonomous or semi-autonomous agents (Swaminathan *et al.*, 1998). However, the main issue in such multi-agent simulation is uncertainty regarding the distribution of supply chain activities among the various agents (Fox *et al.*, 2000). Simulation of a decision-support environment for complex problem solving has been used in the space industry (Rabelo *et al.*, 2006). Nevertheless, Fu *et al.* (2000) has used such a multi-agent simulation to enhance collaborative inventory management and Towill and Del Vecchio (1994) applied a similar technique with a view to eliminating the "bullwhip effect". These studies suggest that multi-agent simulation promises significant improvement in SCM.

According to Chang and Makatsoris (2003), the benefits of supply chain simulation include:

- Improved understanding of the overall supply chain processes and characteristics by the provision of graphics/animation.
- Capturing of system dynamics through probability distribution (including the modelling of unexpected events in certain areas and their impact on the supply chain).
- Minimisation of the risk of changes in the planning process through the utilisation of what is called "what-if" simulation, which enables the user to test various alternatives before changing a plan.

2.3 Steel supply chains and the "bullwhip effect"

Figure 1 shows the functions of a typical steel supply chain from the mining of the iron to the finished product. The present paper concentrates on the "make-to-order" steps shown in Figure 1 because the steps from iron mining to slab-casting production ("make-to-stock") produce a homogeneous bulk product in a continuous production process (rather than as a series of discrete processes). The difference is significant. A continuous process ensures smooth production, whereas discrete processes are characterised by numerous setups and stock points, with an increased likelihood of overstocking or stock-outs.

The "bullwhip effect" has long been a significant problem in steel supply chains. Possible solutions for reducing the effect were originally proposed by Forrester (1961) (based on a "DYNAMO" simulation model) and more recently by Burbidge (1984) (based on his shop-floor observations, supplemented by industrial engineering analysis). According to Forrester (1961), "bullwhip effects" can broadly be identified as continuous changes in the echelon time series with respect to demand, orders, shipments, production, and inventory. These "Forrester effects" generally exhibit long-wavelength periodicity, which can sometimes be related to the time delays in the feedback paths used to correct inventory discrepancies. According to Burbidge (1984), "bullwhip effects" arise from the batching of demand and production, and can therefore be identified by discontinuous (or sharp-edged) changes in the time series. These "Burbidge effects" are generally of shorter wavelength, although infrequent re-ordering or large batch sizes can be expected to produce longer wavelength fluctuations.

In the years since Forrester (1961) and Burbidge (1984) proposed their ideas, research into the "bullwhip effect" have been greatly extended and further refined. McCullen and Towill (2002) have claimed that variations in the steel supply chain can be minimised, but that it is important to identify the particular causes of "bullwhip" in each instance.

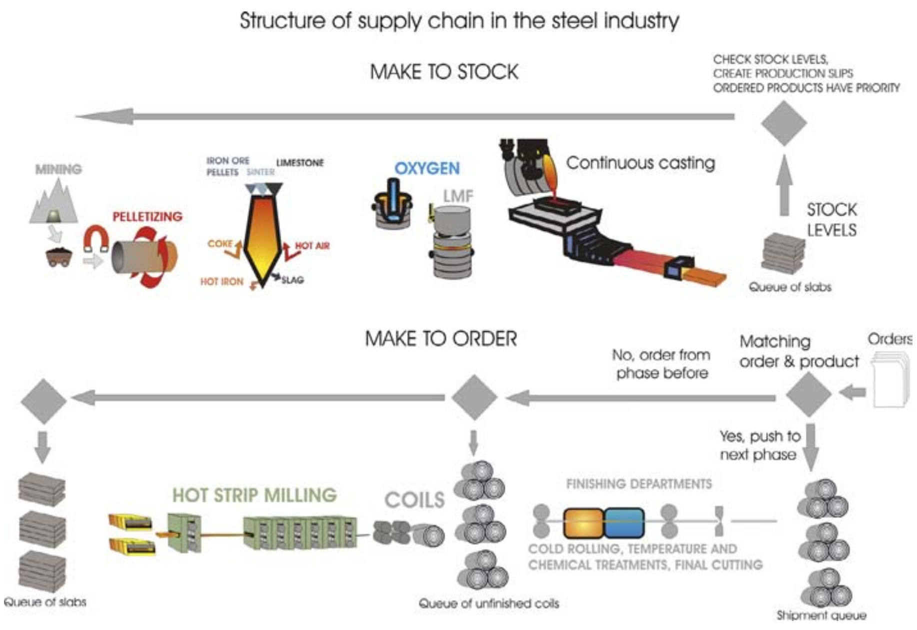

Figure 1.
Functional structure of steel supply chain

Metters (1997) has built up a sophisticated model for estimating the cost of "bullwhip" using a form of dynamic programming which models the optimum supply chain response to a number of demand patterns. Towill's *et al.* (2002) result is an interesting one. He shows that the Forrester effect causes the amplification of the supply chain demand or bullwhip effect. The interesting result is that this factor is dependent of the information confidence level of both supplier and buyer. Kelle and Milne (1999) investigate how the (s, S) policy parameters, the demand parameters, and the cost coefficients influence the variability of the orders by using approximations to the exact quantitative models. It is shown that correlated demands can reduce demand variability of aggregate orders and smaller and more frequent order up to (OUT) policy can reduce the order variability and thus reduce the bullwhip effect. Partially, Cachon (1999) supports the previous contribution (Kelle and Milne, 1999) by suggesting a scheduled ordering policy at smaller batch size by taking risks of higher backorders and balanced ordering policy where either the supplier or the buyer may have different order interval to minimize the buyer and the supplier demand variances. Similarly, this present article use information sharing where either the buyer or the supplier will order if the current stock below a certain level s and fills the inventory by ordering the supplier as much as the predicted future demand, to represent balanced ordering policy. While Forrester (1961) idea and the last two contributions (Kelle and Milne, 1999; Cachon, 1999) are contradictive one of another, it is necessary to resolve the conflict by combining the balanced ordering rule and longer order interval without loosing the customer service level. In this article, we use information sharing to distribute the demand information to the supplier and the buyer and at the same time to give signal to them time to deliver.

Our model, furthermore use balanced supply to run OUT policy based on the the demand forecast. The demand forecast is centralized so as to minimize the magnification of customer demand information. Furthermore, we use coefficient of variation (CV) as the metric of the bullwhip effect to accommodate the effect of demand correlation where the bullwhip effect is measured by calculating the ratio of order variance against OUT level. The order interval is represented by using different level of initial inventory where the higher level of initial inventory signifies the longer ordering interval and vice versa. The performance measure of the ordering policy is the customer service level.

The Bullwhip effect is also caused by price fluctuation from the supplier that motivates the buyer to order in larger quantities than the actual customer demands (Kaipia *et al.*, 2002). However, Reiner and Fichtinger (2009) model the effect of different forecast model by including price effect. It is shown from the case study of a two stage supply chain with weekly empirical sales and pricing data that different forecast model might have different accuracy of predicting the future demand. The reason is that different forecast method has a difference level of responsiveness against price fluctuation that is defined as an offset of reference and observed prices. It is also showed that the forecast accuracy about customer demands is also determined by the supply chain responsiveness in terms of delivery response.

In considering the importance of demand forecast and supply chain responsiveness to mitigate the Bullwhip effect, Towill and Del Vecchio (1994) use filter theory and simulate this mechanism through a series of closed loop Fourier analysis and first order transfer functions from retailer to supplier. The adequacy of the filter is determined by the signal amplification from each echelon. Similar ideas are also proposed by Dejonckeere *et al.* (2000, 2002) who use automatic-pipeline, inventory and order-based production control system (APIOBPCS) and Z-transform to eliminate noise. It is clear that demand information is smoothed, since no effort is made by the supplier to intervene in an order decision. Given this situation, without assigning information access to the supplier, it is possible to end up with a non-optimum and trivial solution.

Second, information is batched and smoothed in an order book before it is released to a producer. For instance, in a work by Wilkner *et al.* (2007), they used an order book with two options. The first option was to maintain stability in the delivery level by having flexible production capacity. In contrast, the second option is to maintain production stability by letting demand fluctuate. The order book represents lists of waiting orders which must be fulfilled as promise. This paper makes no distinction between standard modules and customized modules and emphasizes analysis of ways to manage a fixed customer order decoupling point (CODP) and its influence in leading time management issues. The CODP concept in system dynamics is a gate between high variety and smooth demand pattern (Jones *et al.*, 2000). It is clear that demand information is still smoothed since efforts are made to reduce manufacturers' lead time. Hence, without moving from make-to-forecast to build-to-order, it is possible to end up with an unrealistic and impractical solution.

Migrating from a make-to-forecast to a built-to-order is not a winning strategy for everyone. But all companies need to rigorously assess each of their functions to determine whether or not they have sufficient capacity to perform this action. Greater focus on synchronized supply can improve a company's strategic position by reducing lead times, streamlining the inventory cost and improving revenue. Finding optimum lead times and inventory level usually allows companies to enhance the core capabilities that drive competitive advantage in their industries.

2.4 Simulation of SCM in the steel industry

Supply chain simulation to reduce the "bullwhip effect" has been undertaken in the automotive steel industry by Holweg and Bicheno (2002), who used a lean processing program applied to three tiers of the supply chain (slab-casting, hot rolling mills (HRM), and finishing coils) prior to component manufacture. The authors investigated an information-distortion effect to demand magnification in two rounds of simulation. This differed from the well-known "beer game" simulation in using a "lean leap" logistics game – because the "beer game" is not appropriate for application to a manufacturing process that consists of multiple stages and significant capacity constraints. Holweg and Bicheno (2002) concluded that synchronisation within the supply chain is influenced by three factors:

(1) demand visibility;

(2) process visibility; and

(3) an appropriate time buffer.

Steel supply chain simulation has also been undertaken in the context of business strategy development by Hafeez *et al.* (1996), who analysed and modelled two echelons of a steel supply chain for the construction industry. The authors adopted a system-dynamics approach similar to that of Holweg and Bicheno (2002) to minimise lead times and inventory levels. Two kinds of model were utilised:

(1) a conceptual model (to determine the dominant factors that influence system performance); and

(2) a quantitative model (representing a closed-loop system).

The study, which used supply lead times as disturbance for the modelled system, produced a steel industry competitiveness index according to various competitive criteria. The authors concluded that this tool can serve as a management information system to measure competitiveness in the industry.

Supply chain simulation using a system-dynamics approach was also developed by Dawande *et al.* (2004), who used heuristic optimisation to satisfy an order book. The methodology involved the minimisation of slab inventory and scrap, such that output was in accordance with a targeted order weight. The authors concluded that this heuristic approach could be used to minimise slab "overweight" and cut total costs significantly.

Steel supply chain simulation has also been used as an educational tool in metallurgy (Naylor *et al.*, 2007). These authors developed an e-learning facility which enabled students to learn how to manufacture steel from an electric furnace to a continuous casting run.

3. Developing a simulation model

Steel production is an extremely complex process and determining coherent schedules for the wide variety of production steps in a dynamic environment, where disturbances frequently occur, is a challenging task. In the steel production process, the blast furnace continuously produces liquid iron, which is transformed into liquid steel in the melt shop. Most of the molten steel passes through a continuous caster to form large steel slabs, which are rolled into coils in the hot strip mill.

The scheduling system of these processes has very different objectives and constraints. It operates in an environment where there is a substantial quantity of real-time information concerning production failures and customer requests. The steel-making process, which includes steel-making followed by continuous casting, is generally the main bottleneck in steel production. Therefore, comprehensive scheduling of this process is critical for improving the quality and productivity of the entire production system.

Specific problem areas in steel production planning and scheduling include inventory management; slab, plate and cast design; and melting shop, hot strip mill and finishing-line scheduling. Optimizing each problem area independently can result in savings for a steel manufacturer. However, even greater gains can be achieved by simultaneously optimizing all of these interrelated areas. The combination of these scheduling issues with the instability of market conditions makes production planning in the steel industry one of the most challenging problems facing manufacturers today. Thus, a central demand forecast is proposed to support the production process in the supply chain. The forecast is distributed across the supply chain which minimises the inventory investment. The expected results are lower backorders and a lower inventory level across the supply chain. Figure 2, details the features of the simulation model, as follows.

4. Simulation methodology

The research was funded by the European Union (EU) and was investigated by the research team at Slovakia and Finland. Simulation data collection has been performed in Košice, Slovakia and the process has included several companies along the supply chain. The research conducted contains model parts from the mine, processing division and production of iron (Fe) pellets, transport to the steel manufacturing company, reloading raw materials and storing inputs in materials stores and Fe production in three blast furnaces, Fe transport to the steel works, continued casting works of the slabs, repairing hall and storing in the cold store, modeling of charging into the push

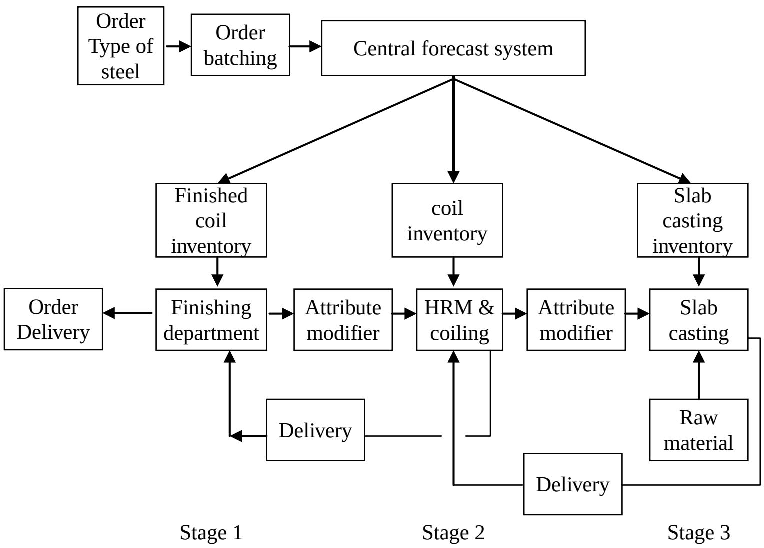

Figure 2.
The three stage steel supply chain model

furnaces, rolling on the wide hot rolling mill, and creating the tin coils at the cutting workshop. We define inputs and inputs as follows.

4.1 Inputs

Stock levels, varieties (sizes, length, thickness and width), production time and its standard deviation, transportation average delay, etc.

4.2 Output

Service level (percentage of on-time delivery), final inventory levels and fill rate (the number of completed orders per time unit, which can be formulated as follows:

$$fill\_rate = \frac{Finished\_coil(FC)\_output}{Completion\_time} \tag{1}$$

$$Completion\_rate = \frac{Finished\_coil(FC)\_output}{Demand} \tag{2}$$

In pursuit of these objectives, the simulated system took orders from the order database, and then prioritised them. Scheduled production was then simulated and the outputs were analysed. These outputs included inventory levels, production throughput-time, and customer satisfaction (proportion of orders produced on time). Order batching was used to represent economic production quantity, and the simulation model was run under three replications.

The model was able to generate production slips to the steel factory, based on orders. These orders were placed in a queue, and orders were fulfilled according to priority. The priority order was as follows:

- *Stock of finished coils.* If steel type and size matched from shipment queue.
- *Stock of coils.* If steel type and thickness and width matched or if it were possible to cut ordered width size from coils of the finished department queue.
- *Stock of raw slabs.* If steel type and order weight size matched or if it were possible to cut ordered weight size from slabs of furnace and HSM queue.
- *Raw material.* If steel type did not match any stocks of smelting queue.

The model was able to generate orders to raw material suppliers, if:

(1) the actual inventory level of the raw material was below the safety stock limit of raw material orders; and

(2) there were backorders, where, after orders were matched against available stocks, the unfilled orders still remained in the orders queue.

4.3 System implementation

The specific problem areas in steel production planning (as described above) were simulated in a so-called "Simulsteel" model using Extend simulation software (Figure 2). The objectives of this simulation were:

(1) to identify the relationships between external factors (such as variety of customer demand) and internal factors (such as inventory levels);

(2) to note the effects of these relationships on system performance indicators (such as final inventory level, order completion rate, and production rate); and

(3) to investigate the influence of information sharing on reducing the bullwhip effect.

Extend simulation software requires the assumption that the model parameters and model logic can be changed, making it easier to restate the problems. The Extend simulation models are constructed with library-based iconic blocks, which each describe a calculation or a step in a process. It is also possible to transfer the simulation results into the Excel worksheet for further analysis. Thus, the solution is connectable and extendable to other applications. Most importantly, the Extend software offers visual transparency with no programming necessary (Krahl, 2002).

The detailed steps of the simulation are introduced as follows:

(1) Demands arrive according to M/M/1 distribution and the sales department prioritize them according to their priority and stock availability. Order scheduling by prioritization is used by considering the process commonality across the entire factory. It is assumed that product varieties have different processing times and the highest priority is given to the one with the least processing time. Prioritization is done manually, using Microsoft Excel.

(2) In a simulation model with information sharing, customer order is transmitted directly to HRM department. This decision is taken in order to short cut information flow from finishing department to HRM department and to reduce inventory level in finishing department. Afterward, each stage delivers the order according to the demand information by considering the delivery lead times and the availability of stock in the downstream. In this model (s, S) is not applied, rather dynamic batch size is implemented to meet the customer demands at lower backorders and holding costs.

(3) In addition to this production scheduling, an evolutionary optimizer is applied to optimize manufacturing time which consists of machining time, holding time in inventory and transportation time as it is formulated as follows:

$$\begin{aligned}\text{Max Profit} = {} & \text{Num Shipped}*5000 - \text{Num Machines}*100000 \\ & - \text{Num Holding Prods}*10000 - 5000000/(\text{TransportTime}\hat{}2)\end{aligned}$$

This optimization is operated separately from the simulation.

(4) The same processes are then followed by HRM and the slab-casting departments on the assumption that the processes are entirely similar.

(5) To investigate the effect of information sharing, the simulation model is then modified by changing the order information path from the finished coil manufacturer directly to the hot rolling mill factory.

The above steps are then simulated by providing some inputs and outputs to investigate the performance of the supply chains. The choice of input and output parameters is made carefully to focus on the objective of this simulation, that is, to investigate the effect of inventory level on service level and the effort of mitigating the bullwhip effect.

5. Simulation results and analysis

Qualitative analysis is implemented to detect the existence of the bullwhip effect. The design of experiment (DOE) is used for making the analysis, by considering the following reasons:

- DOE is used to gather all information by considering process variation, whether or not it is under the full control of the experimenter.
- DOE is used to investigate the effect of intervention; some objects, for instance, demand variety and an inventory level up to the service level. In this paper, we wish to investigate whether both factors give co-intervention to the experiment outputs.

DOE is the only way to test the model when the variable is not fully under control. For example, the experimenter cannot assume that the beginning inventory level and demand variety as a fully non-correlated factor or, at the other extreme, closely correlated. Mathematical modelling in this case can replace DOE in situations where the experimenter knows exactly whether or not they are correlated. Finally, DOE can be summarized as follows:

Run number: 27.

Independent variables: demand, beginning inventory level.

Demand level: three levels (low (75), medium (100) and high (125)).

Inventory level: three levels (low (60), medium (120) and high (180)).

Replication number: 3.

Dependent variables: final inventory, completion rate and fill rate.

Dependent variables: final inventory, completion rate and fill rate.

Number of stages: three.

In considering the limitation of the space, Table I exhibits an example of Stage 1 simulation results. Next, similar operations are applied to Stage 2 and 3 (Table II).

5.1 Simulation model validation and verification

Table I is then analysed as performed in the ANOVA for detecting the bullwhip effect with a different level of demand and opening inventory. In the first observation, Figure 3 shows the impact of inventory level on its variance. It is clear that a high inventory level gives no advantage because a company should put a higher safety stock on this level. The reason can be retrieved from Table III. The higher level of inventory in Table III indicates that the supply chain has no precise demand information. This imprecision in the information encourages the supply chain to install a higher level of inventory. Furthermore, it affects the fill rate (delivery) variation. This combines imprecision in the demand information with that on the delivery.

A similar DOE is also conducted to the supply chain with information sharing included and is benchmarked against the previous result, as shown in Table III.

Table II shows the different performance levels between the supply chain with and without information sharing. It shows that the level of production rate and fill rate are two dependent variables affected by the demand and the beginning inventory.

Input			Output				
Run	Demand	Beginning inventory	Final inventory	Production time	FC output	Fill rate (product/hour)	Completion rate (%)
1	75	60	23	109	73	0.69	97
2	75	60	12	147	64	0.51	85
3	75	60	33	144	72	0.52	96
4	100	60	26	246	92	0.41	92
5	100	60	31	114	93	0.88	93
6	100	60	30	282	97	0.35	97
7	125	60	23	329	125	0.38	100
8	125	60	12	294	119	0.43	95
9	125	60	33	286	121	0.44	97
10	75	120	79	141	74	0.53	99
11	75	120	60	159	66	0.47	88
12	75	120	72	183	72	0.41	96
13	100	120	36	226	99	0.44	99
14	100	120	53	270	99	0.37	99
15	100	120	78	272	91	0.37	91
16	125	120	79	126	125	0.99	100
17	125	120	60	85	123	1.47	98
18	125	120	72	219	121	0.57	97
19	75	180	139	123	65	0.61	87
20	75	180	128	75	71	1.00	95
21	75	180	143	117	67	0.64	89
22	100	180	116	237	99	0.42	99
23	100	180	107	276	97	0.36	97
24	100	180	97	243	100	0.41	100
25	125	180	123	309	122	0.40	98
26	125	180	75	322	123	0.39	98
27	125	180	117	231	122	0.54	98

Table I.
Simulation results

Source	Dependent variable	Without information sharing *F*	Sig.	With information sharing *F*	Sig.
Demand	Final inventory	2.229	0.136	1.561	0.532
	Fill rate	2.086	0.153	6.032	0.028
	Production rate	4.777	0.022	6.773	0.023
Beginning inventory	Final inventory	100.155	0	0.956	2.867
	Fill rate	0.822	0.456	0.998	1.439
	Production rate	0.427	0.659	1.009	1.284
Demand * beginning inventory	Final inventory	2.096	0.124	1.224	0.553
	Fill rate	4.859	0.008	5.194	0.072
	Production rate	0.773	0.557	5.386	0.018

Table II. Tests of between-subjects effects of Stage 1 in the supply chain with and without information sharing

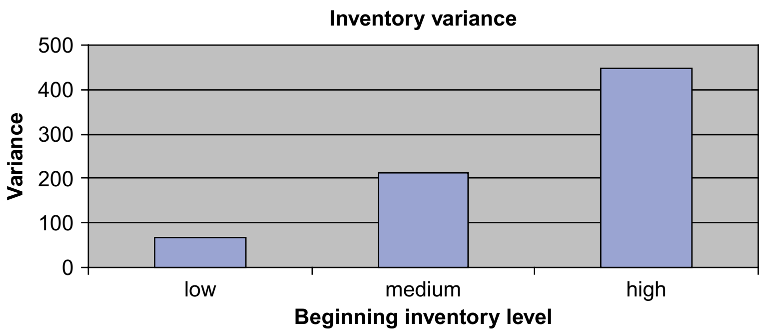

Figure 3. Inventory variance as a function of beginning inventory level

	Stage 1 With information sharing	Stage 1 Without information sharing	Stage 2 With information sharing	Stage 2 Without information sharing	Stage 3 With information sharing	Stage 3 Without information sharing
D = 75	1.18	1.21	1.02	2.32	1	3.19
D = 100	1.18	1.37	1.02	2.67	1	2.52
D = 125	1.27	1.76	1.04	2.89	0.99	2.82

Table III. Bullwhip effect of the supply chain at different demand levels

This implies that information sharing is capable of hedging the adverse effect of the variation in the demand by adjusting the fill rate and production rate. Thus, balanced ordering rule should be appropriate to the supply chain with information sharing.

For providing information about the level of demand magnification across the supply chain, the bullwhip effect is measured. The bullwhip effect is measured as the quotient of the demand CV generated in a given supply chain level and the demand CV received by that same level (Fransoo and Wouters, 2000), since it explicitly measures the relative variability of order against demand as an explicit representation of the bullwhip effect:

$$\text{Bullwhip(B)} = \frac{\sigma_{q_n(t)}(\mathrm{t}, \mathrm{t} + \mathrm{L}_{d(n)})/q_n(t)(t, t + \mathrm{L}_{d(n)})}{\sigma_{D(t)}(\mathrm{t}, \mathrm{t} + \mathrm{L}_{d(n)})/D(t)(t, t + \mathrm{L}_{d(n)})} = \frac{R_{out}}{R_{in}}. \tag{3}$$

For $\sigma_{q_n}(t)(\mathrm{t,t} + \mathrm{L}_{d(n)})$ represents standard deviation during Ld, the lead times of delivery, $q_n(t)(t,t + \mathrm{L}_{d(n)})$ represents the delivery rate according to the demand at time t, $\sigma_{D(t)}(\mathrm{t,t} + \mathrm{L}_{d(n)})$ represents standard deviation demand during the delivery lead time Ld and $D(t)(t,t + \mathrm{L}_{d(n)})$ is the demand during the lead times.

Table III shows that the imprecision of the demand signal is eliminated, such that variation in the delivery lead times has no significant impact on magnifying demand.

The EU, as the primary funder of this research, and the research teams in Slovakia and Finland verified the model through joint efforts between the research team and the case factory. The simulation was presented before both the EU and the company representatives. After undergoing some corrective actions, finally the result was acceptable.

6. Discussion

This experiment is intended to answer *RQ1* about continuous replenishment and the effect of the inventory level on the order fulfilment rate (product output rate and order completion rate) and also the effect of information sharing on mitigating the bullwhip effect. Multivariate analysis of variance (MANOVA) is used in order to assess the effect of demand imprecision on the generation of the bullwhip effect. The demand and the beginning inventory level are used to indicate whether or not the information of the demand is imprecise. Thus, the final inventory level, the fill rate (delivery rate) and production rate are used as the performance indicators. Finally, demand magnification is measured through the quantification of the bullwhip effect.

Tables I and II reveal the information that enhancing the quality of the demand information gives some advantages. First, it reduces inventory investment. Second, it informs us that the demand variation has no effect on the inventory investment, however, different order interval affects on inventory investment, with or without information sharing. The longer order interval increases the customer service level as indicated in Table I. While the longer order interval increases the service level, however it also increases the requirement about safety stocks (Figure 3). The result support Cachon (2003) conclusion where the increasing of order interval raises the supply chain cost in terms of holding and backorder costs. Furthermore, the longer order interval reduces the fill rate of the supplier as a measure of the batch size. The combination of smaller batch size and longer order interval could reduce the Bullwhip effect (Kelle and Milne, 1999; Cachon, 1999).

The arrangement of the information flow has a significant effect on order completion at the agreed lead times. It is shown that allowing HRM department as supplier to access customer orders benefits the finishing department in terms of order completion rate. It implies that order amplification gives less impact to a supply chain which shares information. This result supports Dejonckeere *et al.* (2000, 2002) in using an APIOBPCS by providing information access to the supplier.

In conclusion, this simulation gives information to readers that a high degree of variety of demand should not cause a bullwhip effect as long as such an order is handled individually by a continuous replenishment policy and information sharing. As a consequence, a flexible production line should be represented.

7. Conclusion

This paper has considered information sharing in the steel supply chain. The proposed model has been successfully applied and has reduced the Bullwhip effect and has obtained related information on the production and fill rates. Moreover, the adaptive production and delivery rate are used to minimise the inventory level. This study uses a quotient of order and demand coefficient of variation, which belong, respectively, to Bullwhip measures and stock and delivery performance, in order to compare the performance of the supply chain with and without information sharing. From observing the results, it appears that the quality of demand information is improved significantly by providing a fill rate according to the demand and by reducing the inventory investment. Thus, the performances of the supply chain with information sharing seems to be better than its performances without information sharing (Table III). In validating the simulation model, we sent the report to the EU commission for review. The EU commission has approved the model with positive comments for the implementation of the results in the society. Further research may want to investigate a number of remaining issues. The steel supply chain must optimise the responsiveness of the production and delivery lead time to minimise the total supply chain cost.

References

Barber, K., Dewhurst, F., Burns, R. and Rogers, J. (2003), "Business-process modelling and simulation for manufacturing management: a practical way forward", *Business Process Management Journal*, Vol. 9 No. 4, pp. 527-42.

Burbidge, J.L. (1984), "Automated production control with a simulation capability", IFIP Working Paper WG5(7), Copenhagen.

Cachon, G. (1999), "Managing supply chain demand variability with scheduled ordering policies", *Management Science*, Vol. 45 No. 6, pp. 843-56.

Cachon, G.P. (2003), "Supply chain coordination with contracts", in de Kok, A.G. and Graves, S.C. (Eds), *Supply Chain Management: Design, Coordination and Operation*, Elsevier, Amsterdam, pp. 229-340.

Chang, Y. and Makatsoris, H. (2003), "Supply chain modelling using simulation", *International Journal of Simulation*, Vol. 2 No. 1, pp. 24-30.

Christopher, M. (1998), *Logistics & Supply Chain Management*, 2nd ed., Financial Times, London.

Dale, R. (2001), "Offline programming and simulation help Boeing use giant automated riveter on C-17 aircraft", *Industrial Robot: An International Journal*, Vol. 18 No. 6, pp. 478-82.

Davenport, T. (1994), *Process Innovation*, Harvard Business Press, Boston, MA.

Dawande, M., Kalagnanam, J., Lee, H.S., Reddy, C., Siegel, S. and Trumbo, M. (2004), "The slab design problem in steel industry", *INFORM*, Vol. 34 No. 3, pp. 215-25.

Dejonckeere, J., Disney, S.M., Lambrecht, M.R. and Towill, D.R. (2000), "Transfer function analysis of forecasting induced bullwhip in supply chains", *International Journal of Production Economics*, Vol. 78, pp. 133-44.

Dejonckeere, J., Disney, S.M., Lambrecht, M.R. and Towill, D.R. (2002), "Measuring and avoiding the bullwhip effect: a control theoretic approach", *European Journal of Operational Research*, Vol. 147 No. 1, pp. 567-90.

Djamila, O. (2003), "A multi agent system for the integrated dynamic scheduling of steel production", PhD thesis, University of Nottingham, School of Computer Science and Information Technology, Nottingham.

Forrester, J. (1961), *Industrial Dynamics*, MIT Press, Cambridge, MA.

Fox, M., Barbuceanu, M. and Teigen, R. (2000), "Agent oriented supply chain management", *The International Journal of Flexible Manufacturing System*, Vol. 12 No. 1, pp. 165-88.

Fransoo, J.C. and Wouters, M.J.F. (2000), "Measuring the bullwhip effect in the supply chain", *Supply Chain Management: An International Journal*, Vol. 5 No. 2, pp. 78-89.

Fu, Y.H., Piplani, R., de Souza, R. and Wu, J. (2000), "Multi-agent enabled modeling and simulation towards collaborative inventory management in supply chains", *Proceedings of the 2000 Winter Simulation Conference*, Vol. 2 No. 1, pp. 1763-71.

Greasley, A. (2003), "Using business-process simulation within a business-process reengineering approach", *Business Process Management Journal*, Vol. 9 No. 4, pp. 408-21.

Hafeez, K., Griffiths, M., Griffiths, J. and Naim, M.M. (1996), "System design of two echelon steel industry supply chain", *International Journal of Production Economics*, Vol. 45 No. 1, pp. 121-30.

Hammer, M. and Champy, J. (1993), *Reengineering the Corporation: A Manifest for Business Revolution*, HarperCollins Publisher, New York, NY.

Hill, T. (1994), *Manufacturing Strategy – Text and Cases*, Palgrave, Basingstoke.

Hlupic, V. and Vreede, G.J. (2005), "Business process modelling using discrete-event simulation: current opportunities and future challenges", *International Journal of Simulation and Process Modeling*, Vol. 1 Nos 1/2, pp. 72-81.

Holweg, M. and Bicheno, J. (2002), "Supply chain simulation – a tool for education, enhancement and endeavour", *International Journal of Production Economics*, Vol. 78 No. 1, pp. 163-75.

Hong, P., Dobrzykowski, D. and Vonderembse, M. (2010), "Integration of supply chain IT and lean practices for mass customization: benchmarking of product and service focused manufacturers", *Benchmarking: An International Journal*, Vol. 17 No. 4, pp. 561-92.

Jones, R.M., Naylor, B. and Towill, D.R. (2000), "Engineering the leagile supply chain", *International Journal of Agile Management Systems*, Vol. 2 No. 1, pp. 54-61.

Kelle, P. and Milne, A. (1999), "The effect of (s, S) ordering policy on the supply chain", *International Journal Production Economics*, Vol. 59 Nos 1-3, pp. 113-22.

Krahl, D. (2002), "The extended simulation environment", in Yücesan, E., Chen, C.-H., Snowdon, J.L. and Charnes, J.M. (Eds), *Proceedings of the 2002 Winter Simulation Conference*, pp. 205-13.

Law, C. and Ngai, E. (2007), "An investigation of the relationships between organizational factors, business process improvement, and ERP success", *Benchmarking: An International Journal*, Vol. 14 No. 3, pp. 387-406.

Lee, H.L., Padmanabhan, V. and Whang, S. (1997), "The bullwhip effect in the supply chain", *Sloan Management Review*, Spring, pp. 93-102.

Lee, H.S. and Murthy, S.S. (1996), "Primary production scheduling at steel-making industries", *IBM Journal of Research & Development*, Vol. 40 No. 2, pp. 231-53.

Levine, L. (2001), "Integrating knowledge and processes in a learning organization", *Information System Management*, Vol. 18 No. 1, pp. 21-32.

Lin, F. and Shaw, M.J. (1998), "Reengineering the order fulfillment process in supply chain networks", *International Journal of Flexible Manufacturing Systems*, Vol. 10 No. 3, pp. 197-229.

McCullen, P. and Towill, D. (2002), "Diagnosis and reduction of bullwhip in supply chains", *International Journal of Supply Chain Management*, Vol. 7 No. 3, pp. 164-79.

Metters, R. (1997), "Quantifying the bullwhip effect in supply chains", *Journal of Operations Management*, Vol. 3 No. 15, pp. 89-100.

Moon, S.-A. and Kim, D.-J. (2005), "Systems thinking ability for supply chain management", *Supply Chain Management: An International Journal*, Vol. 10 No. 5, pp. 394-401.

Naylor, D.J., Bernhard, C., Green, A.M. and Sjökvist, T. (2007), *Learn How to Continuously Steel on the Internet at Steeluniversity.org*, available at: http://library.mcc-cdl.at/8200.pdf (accessed 12 February 2008).

Paolucci, E., Bonci, F. and Russi, V. (1997), "Redesigning organisations through business process re-engineering and object-orientation", *Proceedings of the European Conference on Information Systems, Cork, Ireland*, pp. 587-601.

Park, H., Hong, Y. and Chang, S.Y. (2002), "An efficient scheduling algorithm for the hot coil making in the steel mini-mill", *Production Planning & Control*, Vol. 13 No. 3, pp. 298-306.

Rabelo, L., Sepulveda, J., Compton, J. and Turner, R. (2006), "Simulation of range safety for the NASA space shuttle", *Aircraft Engineering & Aerospace Technology: An International Journal*, Vol. 78 No. 2, pp. 98-106.

Reiner, G. and Fichtinger, J. (2009), "Demand forecasting for supply processes in consideration of pricing and market information", *International Journal of Production Economics*, Vol. 118 No. 1, pp. 55-62.

Sandhu, M. (2005), "Managing project business development: an inter-organizational and intra-organizational perspective", doctoral dissertation, Swedish School of Economics and Business Administration, Helsinki.

Sandhu, M. and Gunasekaran, A. (2004), "Business process development in project-based industry: a case study", *Business Process Management Journal*, Vol. 10 No. 6, pp. 673-90.

Swaminathan, J.R., Smith, S.F. and Sadeh, N.M. (1998), "Modeling supply chain dynamics: a multi agent approach", *Decision Sciences*, Vol. 29 No. 3, pp. 607-32.

Towill, D.R. (1996), "Industrial dynamics modeling of supply chains", *International Journal of Physical Distribution and Logistics*, Vol. 26 No. 2, pp. 23-42.

Towill, D.R. and Del Vecchio, A. (1994), "The application of filter theory to the study of supply chain dynamics", *Production Planning & Control*, Vol. 5 No. 1, pp. 82-96.

Towill, D.R., Childerhouse, P. and Disney, S.M. (2002), "Integrating the automotive supply chain: where are we now?", *International Journal of Physical Distribution & Logistics Management*, Vol. 32 No. 2, pp. 79-95.

Tumay, K. (1996), "Business process simulation", *Proceedings of the 28th Conference on Winter Simulation*.

Wilkner, J.M., Naim, M. and Rudberg, M. (2007), "Exploiting the order book for mass customized manufacturing control systems with capacity limitation", *IEEE Transactions on Engineering Management*, Vol. 54 No. 1, pp. 145-55.

Xiong, G. and Helo, P. (2008), "Challenges to the supply chain in the steel industry", *International Journal of Logistics Economics and Globalisation*, Vol. 1 No. 2, pp. 160-75.

Zhang, H., Li, H. and Tam, C. (2004), "Fuzzy discrete-event simulation for modeling uncertain activity duration", *Engineering, Construction and Architectural Management*, Vol. 11 No. 6, pp. 426-37.

Further reading

Hammer, M. (2007), "The process audit", *Harvard Business Review*, April.

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