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Systems dynamics modelling of a manufacturing supply chain system

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Abstract

Supply chains are multifaceted structures focusing on the integration of all the factors involved in the overall process of production and distribution of end products to the customers. Growing interest in supply chain systems has highlighted the need to adopt appropriate approaches that can ensure the efficient management of their complexity, enormity and broadness of scope. With the main aim of supply chain management being to optimise the performance of supply chains, attention is mainly drawn to the development of modelling frameworks that can be utilised to analyse and comprehend the dynamic behaviour of supply chains. While there have been only a few supply chain modelling attempts reported in the literature, this paper proposes a modelling framework that is used to simulate the operation of a supply chain network of moderate complexity. The proposed model comprises four echelons and is build around a central medium-sized manufacturing company operating as a typical Make-to-Order (MTO) system. The developed model was built using a systems dynamics (SD) approach. The operations performed within a supply chain are a function of a great number of key variables which often seem to have strong interrelationships. The ability of understanding the network as a whole, analysing the interactions between the various components of the integrated system and eventually supplying feedback without decomposing it make systems dynamics an ideal methodology for modelling supply chain networks. The objective of the paper is to model the operation of the supply chain network under study and obtain a true reflection of its behaviour. The modelling framework is also used to study the performance of the system under the initial conditions considered and compare it with that obtained by running the system under eight different scenarios concerning commonly addressed real-life operational conditions. The modelling effort has focused on measuring the supply chain system performance in terms of key metrics such as inventory, WIP levels, backlogged orders and customer satisfaction at all four echelons. The study concludes with the analysis of the obtained results and the conclusions drawn from contrasting the system's performance under each investigated scenario to that of the benchmark model.

Keywords: Manufacturing supply chain; Systems dynamics; Simulation modelling; Make-to-Order systems

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1. Introduction

Fierce global competition over sophisticated customers demanding increasing customisation and constantly faster response in addition to advancements in information and communication technology have resulted in making supply chain networks critical contributors in the production and distribution of goods in contemporary markets. The growing interest in supply chain networks has in turn pointed out the importance of relying on efficient management practices specially designed to manage the complexity, enormity and breadth of scope of the supply chain structures. Supply chain management (SCM) has evolved to one of the most prevailing 21st century manufacturing paradigms focusing on the design, organisation and operation of supply chains.

A supply chain is defined as a network of organisations that are involved in processing a business function such as manufacturing, distribution, supplying, subcontracting and so on, at any stage of the value chain. In a supply chain there are three types of flow, that of materials, information and finance. In each case the flow is a two-way process, for example the downstream flow of materials which refers to the flow of products and parts results in the upstream flow of, for instance re-work parts. Information going downstream can be related to production capacity, delivery schedules, etc. whereas upstream information flow may refer to sales forecasts, orders and point of sales data. Examples of financial downstream flow can be invoices, pricing and credit terms while an example of upstream financial flow can be payments. Without any of the aforementioned organisations and their functions, the supply chain would not be complete. The aim of supply chain management (SCM) is to improve the overall performance of the network by creating a series of coordinated activities and efficient control and management of the three flows taking place across the supply chain network.

The objective of this work is to model a manufacturing supply chain, which is assumed to have a moderate complexity of four echelons, to measure its performance under different operational conditions and finally identify and understand its dynamic behaviour. A systems dynamics approach is used to build the model and measure the system's performance. Systems dynamics (SD) is a methodology that is capable of studying and modelling complex systems as it is the case for supply chain networks. The operations performed within a supply chain are a function of a great number of key variables which often seem to have a strong interrelationship. Systems dynamics aims to provide a holistic view of the system and to identify how these interrelationships affect the system as a whole [1]. The ability of understanding the whole system as well as analysing the interactions between various components of the integrated system and eventually supplying feedback without breaking it into its components make SD an ideal methodology for modelling supply chain networks. A structure is provided to transform the system from a mental model to a computer-based level and rates model. Further experimentation is then carried out on the model involving a number of designed scenarios. Conclusions are drawn on the behaviour displayed.

The rest of the paper is organised as follows: a background discussion is presented in the next section to remind the reader of the latest developments in supply networks and supply chain management. Section 3 discusses the supply chain problems addressed in the literature as well as the attempts made to model and analyse the behaviour of supply chain systems. The characteristics of the supply chain network considered in this work and the methodology followed to build the systems dynamics model are presented in Section 4. Section 5 presents the simulation of the system under the initial conditions considered to benchmark the performance of the supply chain network under study. The section in question also discusses the proposed eight experimentation scenarios built around a number of real-life operating conditions. The performed experimentations and analysis of the obtained results are further discussed in Section 6. The paper concludes with the major findings and lessons learned from the supply chain model developed, that are presented in Section 7.

2. Background

The different functions within a company, focus on different goals and in the pursuit to fulfil them, they do not consider their implications to other departments. At the same time, decisions made by particular functions about the product or process could have an effect on the goals of other functions even if they have no direct interest in or control over the process or goal. In most supply chains, an increase in customer service could result in higher inventory levels and lowering the inventory levels could consequently result in lower customer service. If inventory and customer service are the responsibility of different functions (which usually appears to be the case) then they would compete each other to achieve their goals. This is known as the 'silo' mentality and can result in costly swings in inventory levels and customer service. These two responsibilities should not be separate rather they should be controlled by a single function, so that the most beneficial trade offs can be made for the benefit of the company. Strategies can be applied to the supply chain that can move the inventory-service level curve as a whole. In other words, these strategies lower the inventory levels without reducing customer service or improve the customer service without increasing inventory levels [2]. As an example of this, if lead times are reduced, customer service can then be increased without maintaining higher inventory levels.

It is common for supply chains to seek the optimisation of their operations by substituting inventory/material flow for information flows. The benefits are clear, as information is less costly than inventory and much can be gained by pursuing this technique. The adoption of such strategy however, is heavily dependent on the level of demand uncertainty. In particular, this strategy can play an important role when the demand uncertainty is low as it will reduce the responsiveness of the chain. However, if the demand uncertainty is high then a strategy, which aims to increase the responsiveness is rather preferable [3]. Uncertainty and variability are the most significant threats to the optimisation of a supply chain network [4]. Both uncertainty and variability refer to demand, process and supply. Demand variability is often due to the Bullwhip effect, which is when small variations in demand downstream are amplified upstream of the supply chain [5]. This causes inefficiency in inventory management, manufacturing and logistics across the entire network. Common reasons for the Bullwhip effect are information distortion, order batching, promotions and allocation gaming [6].

The performance of supply chain systems can be measured from various different perspectives. These can be put into three main categories: customer service metrics, asset metrics, and time/speed/flexibility metrics [7]. All the aforementioned metrics tend to be implemented at the company level. However, metrics that measure the performance of the entire supply chain are becoming more widely used. The major benefit of these metrics is that the performance of the overall supply chain can be compared to that of the competitors [8].

3. Literature review

The area of supply chain management (SCM) is being increasingly investigated by both academia and industry. The successful implementation of supply chain improvement programs has pointed out the benefits of efficient SCM. All supply chains are different and a lot of companies struggle to understand the dynamics of their supply chain.

The traditional supply chain problems studied in the literature are more related to location/allocation decisions, demand planning, distribution channel planning, strategic alliances, new product development, outsourcing, supplier selection, pricing, and network structuring at the strategic level. The tactical level problems cover inventory control, production distribution coordination, order/freight consolidation, material handling, equipment selection and layout design. The problems addressed at the operational level include vehicle routing/scheduling, workforce scheduling, record keeping, and packaging [9].

A considerable amount of the literature related to supply chain management (SCM) has accumulated since the first papers appeared in the early 1980s. Recently, a number of comprehensive surveys of the supply chain literature have been published, amongst which those by Lambert and Cooper [9–11].

Minegishi and Thiel [12] developed a systems dynamics model for a food supply chain system. This work sheds light on the complex nature of this specific type of supply chain and in particular on the coordination of variables controlling the food production. Zimmer [13] investigates on a possible way of coordinating the supply chain system over a single period order and delivery planning model within a just in time setting. This paper also attempts to evaluate the performance of the supply chain network while at the same time considering the cost implication of several key parameters that affect the supply chain. In another model proposed by Beamon [14] to measure the performance of a supply chain system, two different performance measures predominantly associated to cost, i.e. cost and the combination of cost and customer responsiveness have been utilised. In the context of the aforementioned work, cost includes inventory and operating cost whereas, the customer responsiveness measure includes lead time, stockout probability, and fill rate. Chan et al. [15] outline a rough modelling approach to investigating logistics networks. The close relationship between WIP and manufacturing lead time is discussed, and it is argued that if production rate is maintained, then a reduction in WIP will result in a proportional reduction in lead time. Min and Zhou [9] synthesise past supply chain modelling efforts and identify key challenges and opportunities associated with contemporary supply chain modelling. The paper identifies supply chain drivers, customer service initiatives, monetary value, information/knowledge transactions, risk elements, supply chain constraints, and supply chain decision variables as the key components of supply chain modelling. Lee et al. [16] suggest that supply chains are neither completely discrete nor continuous but a mixture of the two and therefore should be modelled appropriately to reflect this situation. Gunasekaran et al. [17] discuss the need for selecting the appropriate measures in the evaluation of supply chain performance. Their work concludes by providing a long list of metrics such as cost per operation hour, information carrying cost, capacity utilisation, total inventory in different forms, supplier rejection rate, etc. that can be used to assess the supply chain performance at the operational level.

In a special issue dedicated on supply chain management published by one of the most reputable journals in the area [18], it is stressed that there is a great gap in the relevant literature as only a few attempts have been made in the direction of developing appropriate frameworks and models for integrated supply chains. It is furthermore identified that the vast majority of the already published works can be classified as traditional operations research models specifically dedicated to solving solely capacity or inventory problems. The work in question concludes by pointing out the need to propose more sophisticated and efficient supply chain frameworks that can be used in modelling the operation of supply chains with respect to a selection of performance measures and metrics. Acknowledging the contribution of modelling to the optimisation of the constantly evolving supply chains, our work, proposes a modelling framework developed by adopting a systems dynamics approach. The proposed model aspires to contribute to the supply chain research by shedding light on the operations and dynamics of supply chains and studying its performance globally with respect to a range of key performance measures.

4. Supply chain model development

A model built around a Make-to-Order (MTO) medium-sized organisation that serves as the central manufacturer operating within a broader supply chain network is developed in the present paper. The overall supply chain model considers only four echelons: suppliers, manufacturers, distributors and retailers and its dynamics are studied from the operational perspective. None of the companies that form the network has a partnership with any of the companies of the network; in addition, the companies forming the echelons of the supply chain modelled in this work are assumed to have no interactions whatsoever with any company outside of the supply chain considered and hence no dedicated supply system is available for any of them. The central company cooperates with warehouses and distribution centres, which drive the company's demand. The demand at the retailers' level is determined by a normal distribution that represents customer demand while all other demand rates are dependent on the order policy of the echelon downstream. Demand refers to 10 different end products and it is over the year open to consumers' seasonal or any other statistically defined patterns of behaviour.

The production capacity of the manufacturer is 50 components per week. Production time follows a normal distribution and there are no assembly operations. Each inventory within the system has an order policy such that in each period, the stock is replenished to a pre-set safety stock. The suppliers order and receive raw materials from an external source. The model only includes information and material flows. Cash flow is not considered in this work due to the added complexity. The system was simulated for one year, i.e. 52 weeks using the widely known systems dynamics software Stella®.

4.1. Logic of influence diagrams

The high level model identifies each echelon and the links between them that need to be incorporated into the model. For labelling purposes in the model the four echelons, i.e. suppliers, manufacturer, distributors and retailers are abbreviated to s, m, d and r, respectively.

The next step in the modelling process is to construct the influence diagrams. Variables are very rarely independent as they usually have strong interrelationships and the influence is in most of the cases one-way. This causes a loop in which variables influence one another.

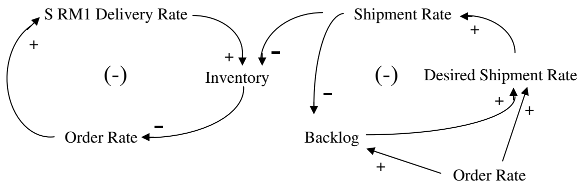

Fig. 1. Suppliers, distributors and retailers influence diagram.

There are two distinct loops in Fig. 1, one controlling the inventory and the second one controlling the backlog of orders. The first loop shows that the inventory has a counteractive effect on the order rate. Therefore, when inventory is low the order rate will be high. The order rate in turn has a positive influence on the delivery rate as, when the order rate increases so does the delivery rate. Finally, the delivery rate has a positive influence on the inventory level. The loop is negative as it controls the inventory level to a predetermined policy.

The second loop represents the desired shipment rate and backlog, which are influenced by the order rate. This is because the desired shipment rate is the order rate plus any backlogged orders and the backlog is the difference between the order and shipment rates. As Fig. 1 suggests, the backlogged inventory influences the desired shipment rate in the same direction (+). Therefore, as the number of backlogged orders increases the desired shipment rate will also be increased. As the desired shipment rate increases the influence on the shipment rate is again positive. Finally, the shipment rate has a counteractive (negative) effect on the backlogs. The above loop is negative as it involves a counteractive influence. The overall influence of the loop can be also be checked by multiplying the individual influences $(-)(+)(+) = (-)$. As the loop is negative it will always try to reduce the backlog to zero. Outside of the loop the shipment rate has a negative influence on the inventory represented in the first loop.

In the manufacturing influence diagram represented in Fig. 2, three distinct loops can be observed, which control the *m* gap. The term *gap* is the difference of inventory and backlog of orders. Therefore if the gap is positive it represents inventory, if it is negative then it represents backlogged orders. This performance criterion shows the ability of each echelon to meet demand. Customer satisfaction is expressed as the percentage of orders fulfilled by the retailers to the final customer. This shows the supply chain's ability to satisfy the customer, which should be the central goal of any supply chain. The performance of the supply chain will be measured using the criteria: suppliers' gap, manufacturer gap, distributors' gap, retailers' gap denoted as *s gap*, *m gap*, *d gap* and *r gap*, respectively. The last performance measure considered is customer satisfaction.

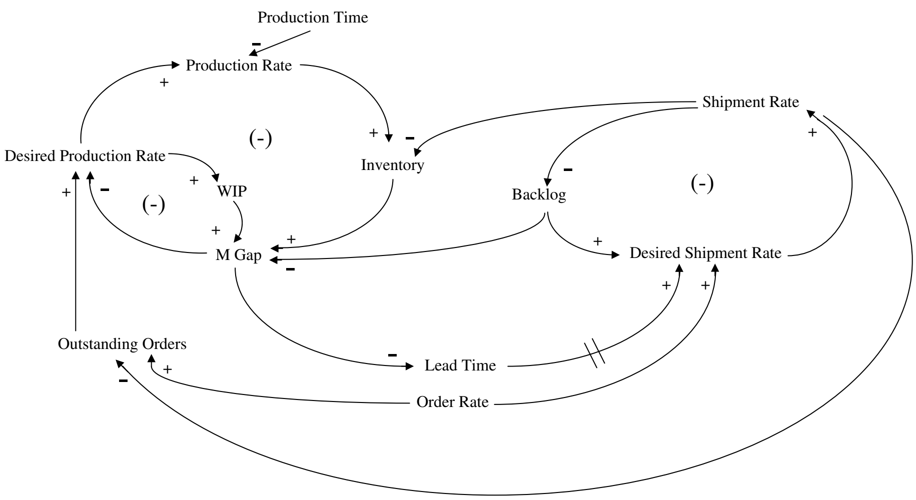

Fig. 2. Manufacturing influence diagram.

The loop which controls the backlogged orders has already been explained, the only difference now is that the desired shipment rate is the order rate delayed by the lead time plus any backlog. The second loop is counteractive and aims to reduce the *m gap* (inventory if positive, backlog if negative) to zero. The desired production rate is negatively influenced by the *m gap* but positively influenced by the outstanding orders. This has a positive effect on the production rate that is negatively influenced by the production time. The production rate has a positive effect on the inventory as the greater the production rate the more parts enter the stores. The inventory has a positive influence on the *m gap*. The third loop controls the WIP and shows that the desired production rate positively influences WIP, which in turn positively influences the *m gap*. The *m* gap then has a counteractive effect on the desired production rate, resulting in the whole loop being counteractive. This means that as the WIP increases it causes the desired production rate to decrease, therefore controlling the WIP.

4.2. Logic of rate and level diagrams

The next stage in the modelling process is to convert the influence diagrams to rate and level diagrams by utilising the systems dynamics program used in the context of this work. The model constructed for the distribution section is shown in Fig. 3 and is identical in structure to that of the suppliers' and retailers'. According to the logic of the model the order policy controls the order rate to fill the deficit between the inventory level and the safety stock. If the safety stock is 70 and the *d gap* is 60, then 10 units will need to be ordered to maintain the safety stock of 70. Note that, if *d gap* was minus this would have indicated backlog in orders and therefore the safety stock value plus the backlog would need to be ordered. By *outstanding orders* we refer to the orders that need to be subtracted to ensure that any parts that have been ordered but not yet arrived are taken into account.

The manufacturing section has some additional logic, which is represented in Fig. 4. The difference here is that the desired shipment rate is calculated as the order rate being delayed by the lead time plus any backlogged orders. This means that the orders are shipped for their promised delivery date, for example if the lead time, Eq. (1), was one week then the present order rate should be the desired shipment rate a week later plus any backlog.

$$m \text{ lead time}(t) = m \text{ lead time}(t - \mathrm{d}t) + (m \text{ lead time adjustment}) * \mathrm{d}t \tag{1}$$

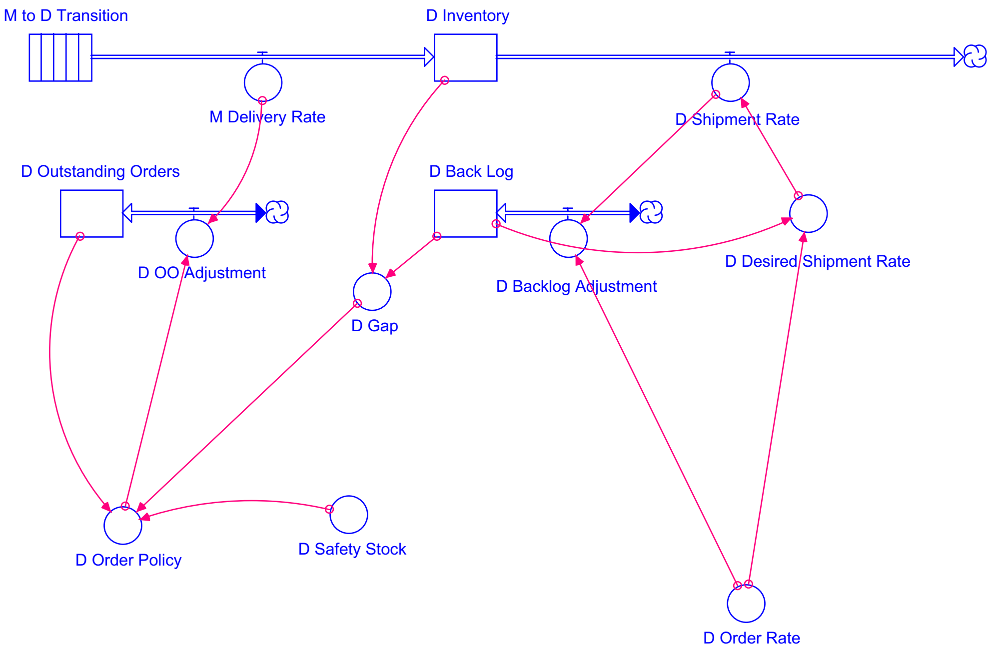

Fig. 3. Distribution model.

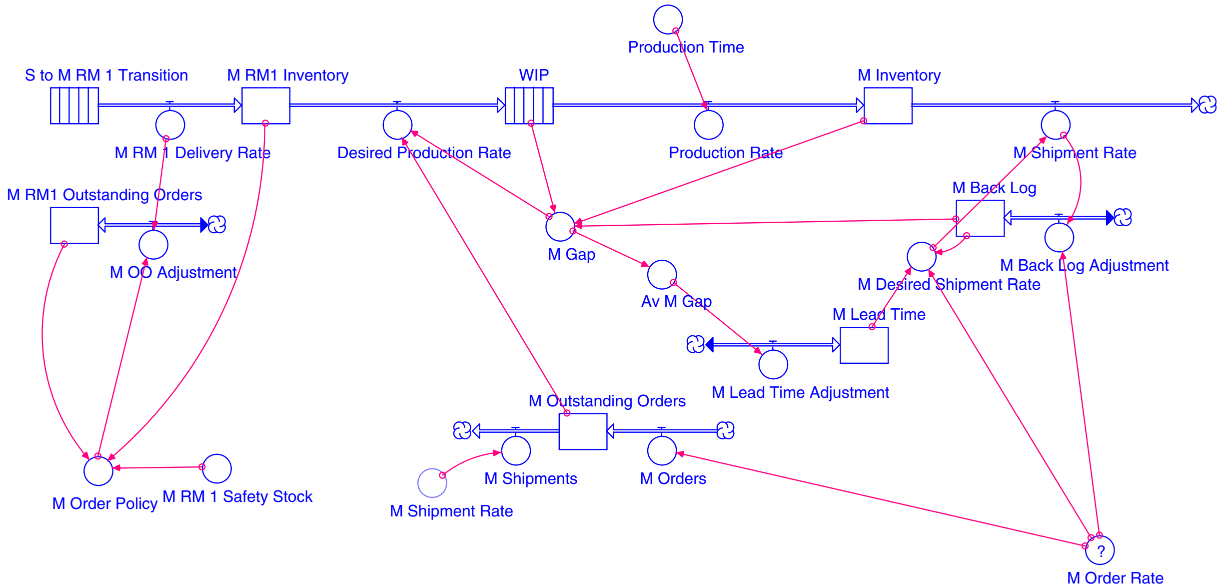

Fig. 4. Manufacturing model.

The lead time is adjusted based on the value of Av *m gap*, which is the average of the last five *m gaps*, Eq. (2). If the Av *m gap* is greater than 40 then the lead time is reduced by 20% (i.e. 1 day assuming that the system operates 5 days in a week). If the Av *m gap* is less than minus 40 (case of backlog) then the lead time should be increased by 20%. Finally, if the Av *m gap* is anywhere in between, then there is no difference to the lead time. This means that if the average inventory is above 40 then the lead time will be reduced by a day; if there is a backlog greater than 40 then the lead time will be increased by a day but anything in between will result in no change to the lead time.

$$m\text{ lead time adjustment} = \text{if Av } m\ gap > 40 \text{ then } -0.2 \text{ else (if Av } m\ gap < -40 \text{ then } 0.2 \text{ else } 0) \qquad (2)$$

The desired production rate equals the outstanding orders. The *m gap* is subtracted from this value to take into account any inventory already in the production system. Therefore, the desired production rate aims to fulfil all the outstanding orders but also to reduce the inventory in the production system to zero, Eq. (3)

$$\text{Desired Production Rate} = m \text{ Outstanding Orders} - m\ gap \qquad (3)$$

As shown in Eq. (4), WIP is derived from the previous value of WIP plus the desired production rate (Eq. (3)) minus the actual production rate for the current dt period.

$$\text{WIP}(t) = \text{WIP}(t - \mathrm{d}t) + (\text{Desired\_Production\_Rate} - \text{Production\_Rate}) * \mathrm{d}t \qquad (4)$$

5. Modelling conditions and experiments

5.1. Initial operating conditions

The system was first simulated under normal conditions, whereby the production time and customer demand rate were assumed to follow normal distributions with a certain average and variation figures. The results obtained by modelling the system under these initial conditions will be used as a benchmark for comparing the system's performance under a number of experimentation scenarios presented further in the section.

The system's performance under the normal conditions is shown in Fig. 5. As the graph suggests inventory levels for the retailers, distributors and suppliers remained above zero and therefore there were no late deliveries during the entire modelling period. However, in the manufacturer's case, backlogs were observed at two points during the year. The latter is understandable as the manufacturer aims to hold no inventory and production

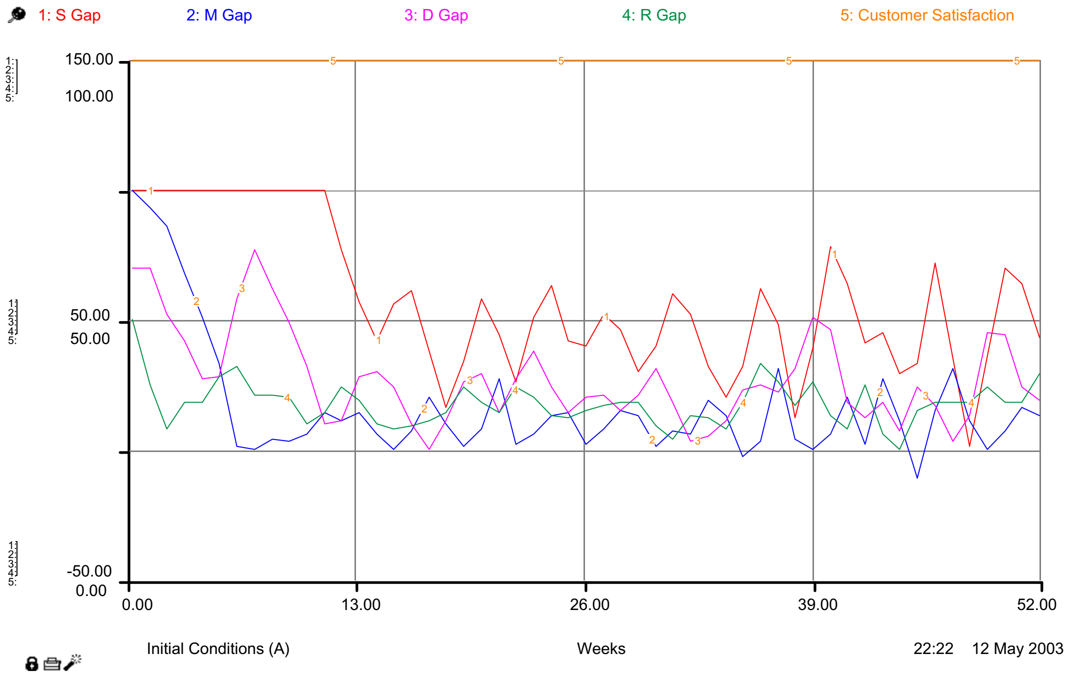

Fig. 5. Initial performance graph.

times can often exceed the specified lead times. Therefore, the results suggest that the further away from the customer the more the accumulation of inventory is. In other words, the bullwhip effect is amplified mainly in the upper echelons since these are the most vulnerable to the uncertainty and variability of customer demand.

5.2. Experimented operating conditions and design of scenarios

Considering that demand is one of the most decisive factors affecting the network's performance, four out of the overall eight scenarios considered in this study concentrate on customer demand. The first two scenarios investigate on the effect that an increase/decrease in demand will have on the system's performance whereas the third and fourth scenarios focus on demand variability and its impact on the supply chain network. Demand level for the cases of the first two scenarios was manipulated by altering the mean of the normal distribution (as discussed in the initial conditions) while keeping the standard deviation constant. Changes in demand variability were introduced by altering the standard deviation for the experimentations performed as part of investigating scenarios 3 and 4. The fifth scenario involves changes in lead time; in particular it considers the worst case i.e. that of lengthened lead time. The issue of working with reliable partners and more specifically manufacturers and suppliers is considered in scenarios 6 and 7, respectively. Finally, the impact of efficient information sharing on the overall network's performance is studied in scenario 8.

5.2.1. Scenario 1 – high demand

The customer demand rate is very influential to the system; therefore, it is important to understand the effect that a sharp increase in the average demand rate will have on the system's performance. The experimentations carried out as part of this scenario involved a step-by-step increase of the average demand rate up to 68% while the deviation remained the same as that described in the initial conditions.

5.2.2. Scenario 2 – low demand

As demand can be highly unpredictable, scenario 2 explores the effect of the opposite case occurring, i.e. demand rate falls step-by-step down to 58%.

5.2.3. Scenario 3 – high demand uncertainty

In the modern manufacturing environment demand is becoming increasingly more uncertain. Therefore, it is important to understand how a particular supply chain responds to such changes. This scenario shows the effect of increased demand uncertainty on the performance of the supply chain network. The experimentations performed considered the case of 100% increase in demand variability.

5.2.4. Scenario 4 – low demand uncertainty

This scenario is the opposite of scenario 3 and is simulated to show the effect of fairly stable demand on the network's performance. For this purpose, demand variability was assumed to be lower by 50%.

5.2.5. Scenario 5 – increased production time

This scenario in fact considers the case whereby the manufacturer faces considerable lengthening of the production lead time. In particular, a 100% increase in the production time was considered. Since the manufacturer operates as a Make-to-Order (MTO) system it ideally holds no finished stock and production is supposed to be strictly governed by orders. This means that there is a considerable time lag (lead time) between the order being placed and the delivery of products. Obviously, if the production time is increased then the lead time will be longer. This scenario investigates on the effect of an increased production time on the network as a whole.

5.2.6. Scenario 6 – unreliable manufacturer

Variability in production capacity due to machine breakdowns is a common problem in any manufacturing supply chain. This scenario considers the case whereby the manufacturing organisation encounters some machine failures in week 14. The underlying logic for choosing to consider the machine breakdowns in this specific point in time is that by the week 14 the system is fully operational and free from the effect of the initial conditions. At the same time, considering that the system is modelled for 52 weeks in total, there is more than half of the modelling horizon left to study the effects of capacity changes on the system.

5.2.7. Scenario 7 – working with unreliable suppliers

It is a frequently experienced problem that suppliers may not be fully cooperative or efficient in meeting the requests of procuring companies because of their own priorities and conditions in their work environments. This common problem is considered in this scenario; supplier unreliability will be encountered randomly in weeks 16 and 17 causing some serious material shortages and production delays to the manufacturer.

5.2.8. Scenario 8 – information enriched supply chain

In a traditional supply chain as it is the case in this work, only the retailer sees the true customer demand. The other echelons only see the demand from the sector ahead of them and this can lead to demand uncertainty amplification. In this scenario, the production and order decisions are made based on actual customer demand. This scenario is based on the assumption that real time information sharing between companies is increasingly possible due to the utilisation of advanced communication and computer technology.

6. Experimentations and analysis of results

6.1. Scenario 1 – high demand

The effect of a sharp increase in demand by 68% on the inventory gaps for each echelon can be seen in Fig. 6. As the figure suggests, the safety stocks are not adequate and all the sectors have large increases in the time they have backlogged orders. Customer satisfaction is only at 100% for 15 weeks of the year and drops as low as 20% in week 17. The results show a direct link between the demand rate and the stock levels required to meet the demand.

Fig. 7 shows that the stock levels would have to be increased by 18% to bring customer satisfaction level back to 100%. Such a result was obtained by increasing the demand level by 50%. In fact, the increased by 18% inventory level, turned out to be the threshold point in our cost analysis as, further increase in inventory caused by considering higher demand levels would have no additional improvement on customer satisfaction.

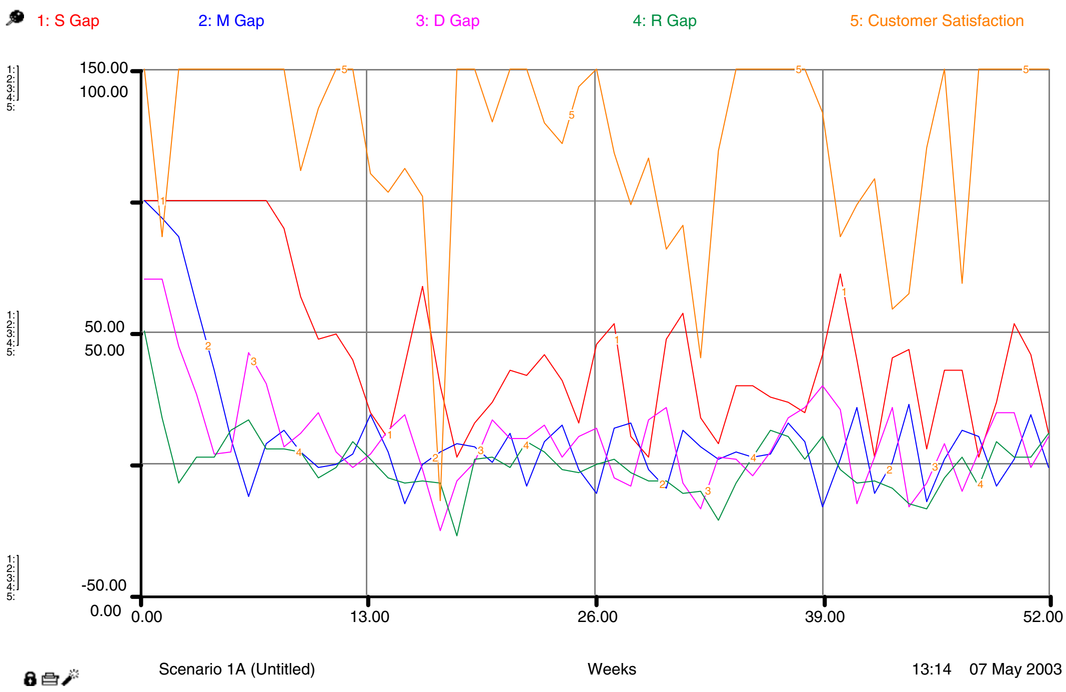

Fig. 6. Scenario 1 – performance graph.

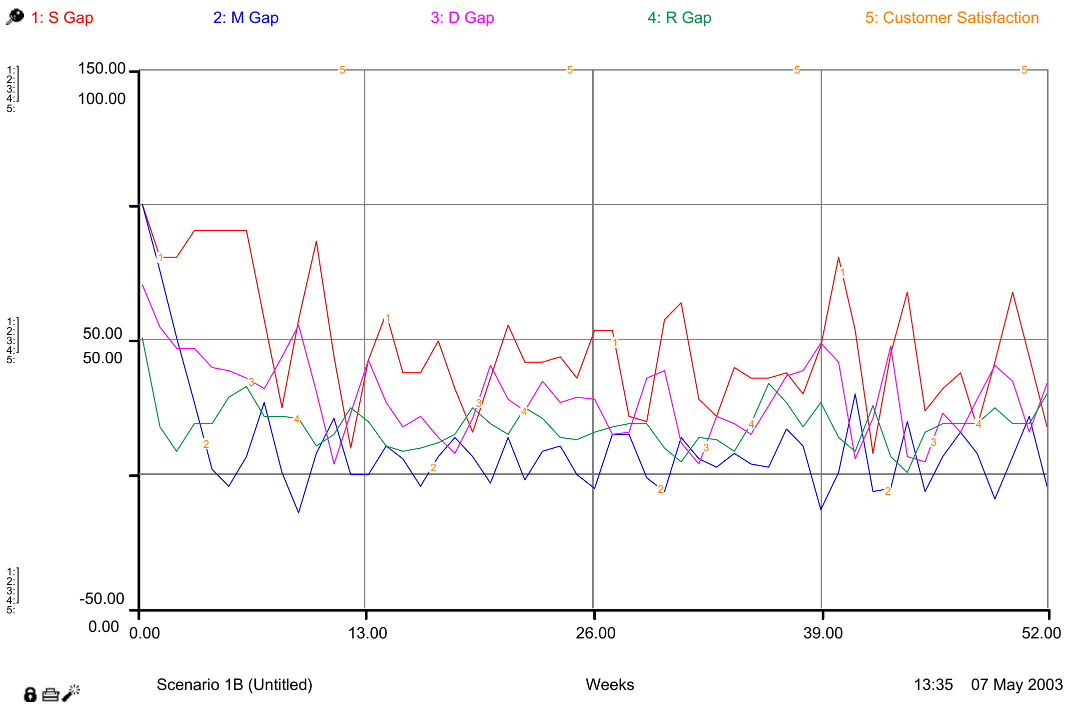

Fig. 7. Scenario 1 – adjusted performance graph.

There is also an increase in revenue that resulted from the increase in sales, in this situation the 50% increase in demand resulted in the need for an 18% increase in inventory levels. Ideally, inventory levels are aimed to be as low as possible but increased inventory may be justified on the grounds of meeting the increased demand. The amount of increased inventory would have to be calculated on an individual basis and would depend on the unit cost, profit margin and the consequences of having a stockout. Increasing the stock levels would, in that sense, be justifiable if all of the following conditions are true; unit cost is low, profit margin is high and a stockout means failure to meet customer demand and potential loss of good faith on behalf of the customer.

6.2. Scenario 2 – low demand

The second scenario simulates the system by considering a 58% decrease in demand and the results are shown in Fig. 8. The results are exactly the opposite of those obtained by experimenting with scenario 1; lower demand results in excessively high inventory levels. This is due to the stock levels being too high, confirming the fact that there is an invert relationship between demand and stock levels.

During the experimentations performed for scenario 2, it turned out that a 42% reduction in demand, results in a 16% reduction in inventory with the customer satisfaction remaining at 100%. Fig. 9 shows the inventory and backlog levels when the stock levels are reduced down to 16%. The danger with the reduction in demand is that its effect on stock levels is realised in later periods. This increases the risk of ending up holding obsolete stock, therefore, it is essential that the stock levels are set as low as possible so that maximum customer satisfaction is maintained.

6.3. Scenario 3 – high demand uncertainty

Scenario 3 considers the effect that an increase in demand uncertainty has on the inventory and backlog levels. As Fig. 10 shows, doubling the demand uncertainty resulted in the average inventory level also getting increased and backlogs becoming more frequent in the system. The latter points out that, there is a direct link between demand and inventory level variability. In other words, as demand uncertainty increases there is a need to hold higher inventory levels to maintain 100% customer satisfaction.

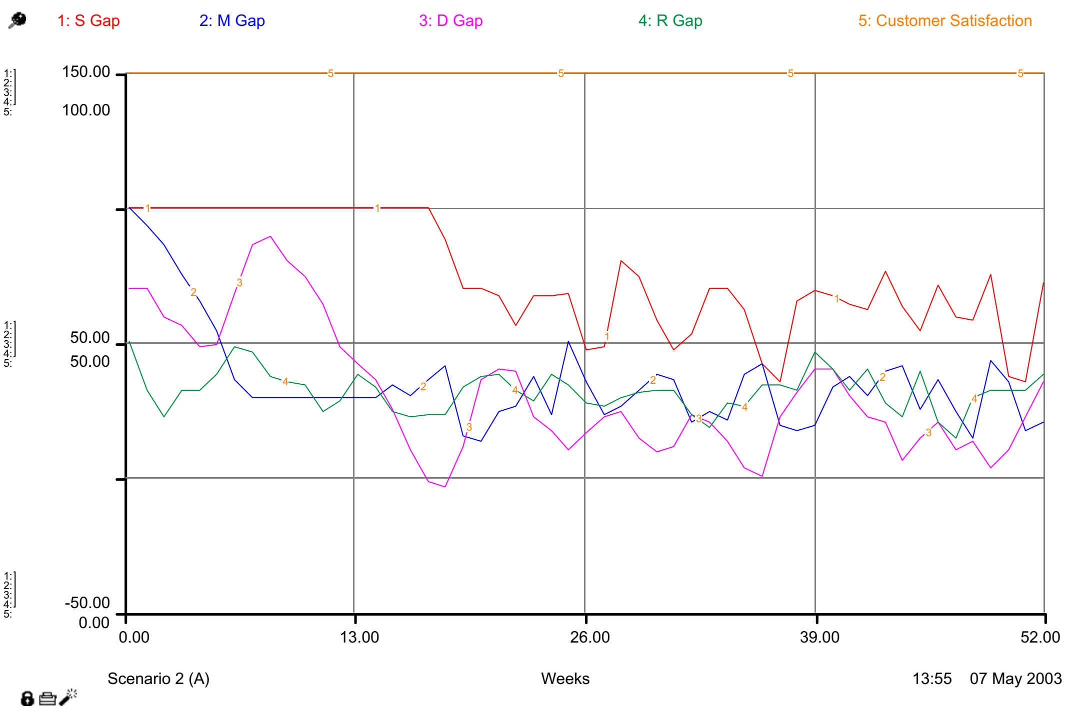

Fig. 8. Scenario 2 – performance graph.

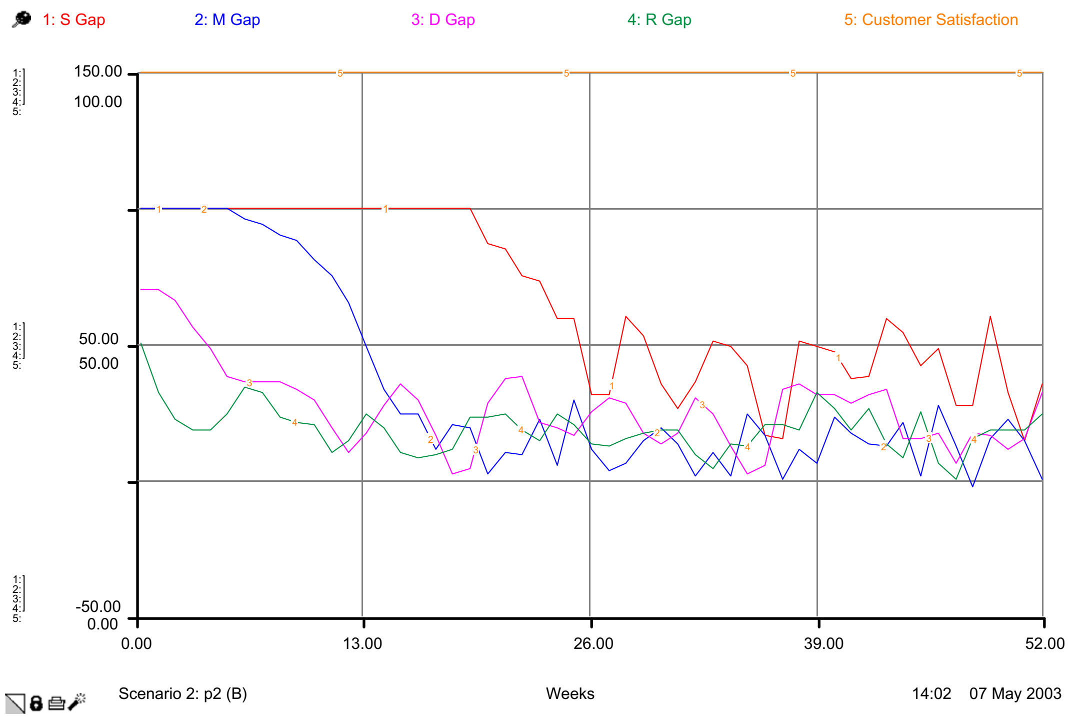

Fig. 9. Scenario 2 – adjusted performance graph.

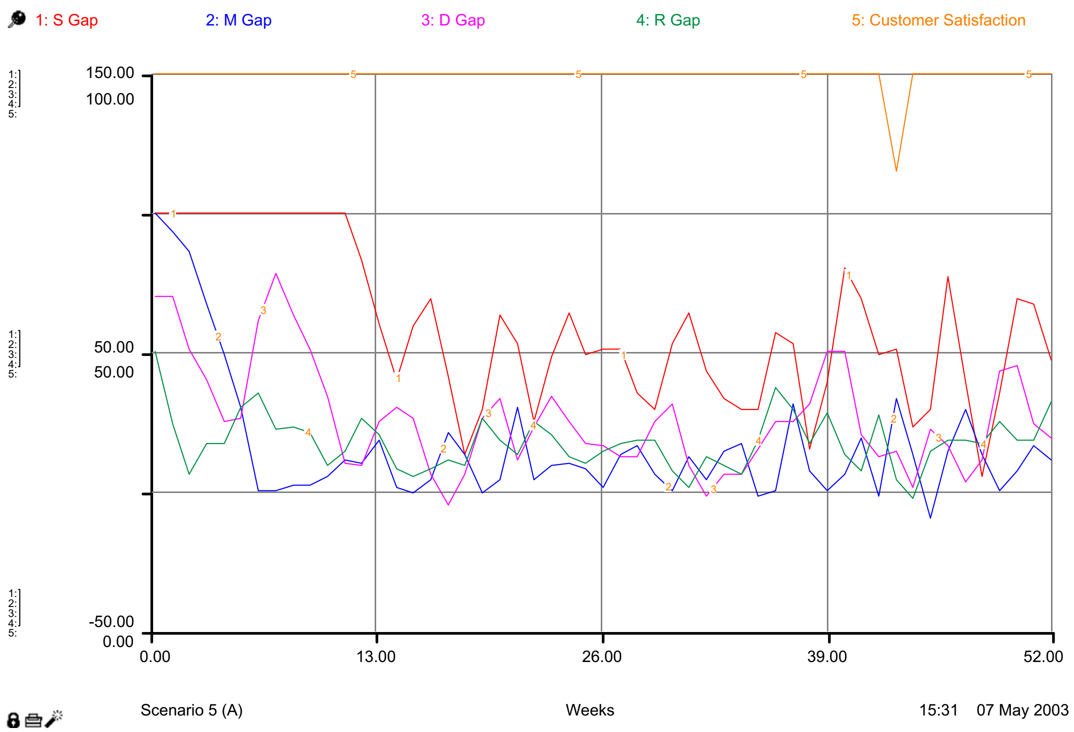

Fig. 10. Scenario 3 – performance graph.

Due to the stock levels being particularly low as a result of the doubled demand, there is a stockout at the retailers' echelon in week 44, resulting in customer satisfaction falling to 82%. To prevent this from occurring further in the modelling horizon, inventory levels at the retailers level would have to be increased by 2%. The only safe way to ensure that higher demand uncertainty does not result in stockouts is to increase the safety stocks. The supply chain can become more responsive by sharing information and reducing lead and delivery times. This alternative will be investigated further in scenario 8. However, the retailers will always require enough inventories to cope with the demand uncertainty. If the reasons for the demand uncertainty are understood then the variations in demand can be forecasted and therefore the inventory held can be reduced.

6.4. Scenario 4 – low demand uncertainty

Scenario 4 simulates the system with a 50% reduction in demand variability. Fig. 11 suggests that stock levels can be reduced with customer service remaining at 100%. Considering that this scenario is investigating the opposite case of that studied in scenario 3, the results obtained highlighted that the more the demand uncertainty is reduced the further safety stock levels can be lowered without any compromise on customer satisfaction. This again shows the direct link between demand and inventory levels required to meet demand. The analysis has further revealed that the safety stocks can be reduced by 5% with no impact on customer satisfaction which is therefore remaining at 100%.

Supply chains with low demand variability are unlikely to operate as MTO systems. Due to the demand certainty this supply chain would better suit an MTS system where the production rate is more or less constant and the inventory levels would absorb any fluctuations in demand.

6.5. Scenario 5 – increase in production time

Fig. 12 shows the effect on the inventory and backlog levels for an increase in production time. Among the significant drawbacks of increased production time we should perhaps note the negative impact on the

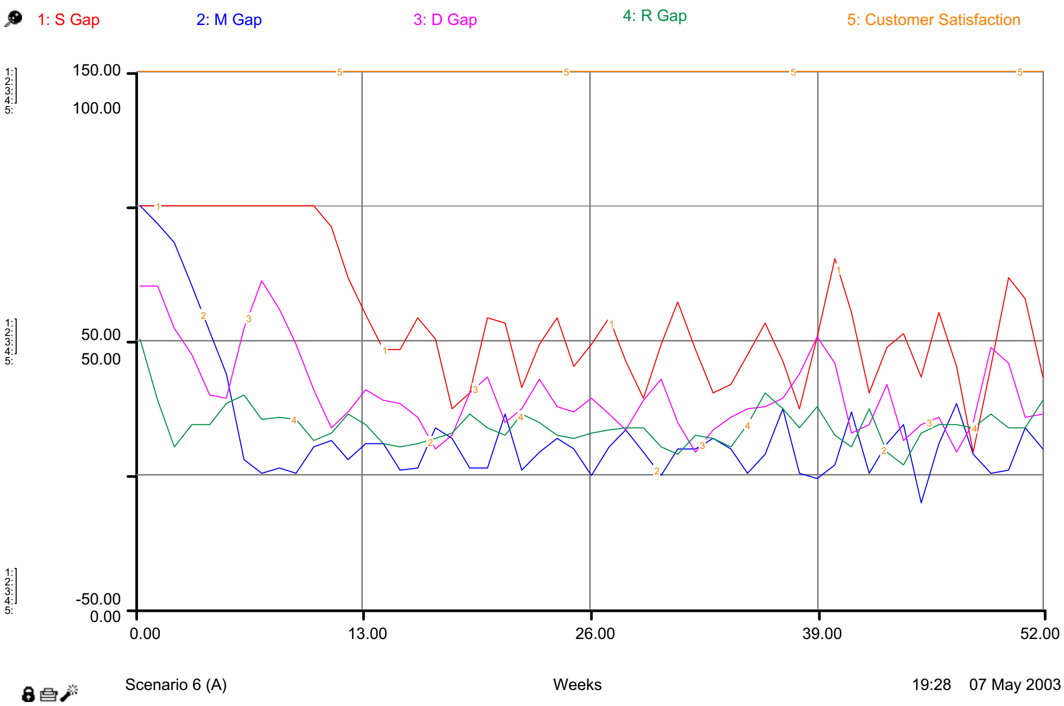

Fig. 11. Scenario 4 performance graph.

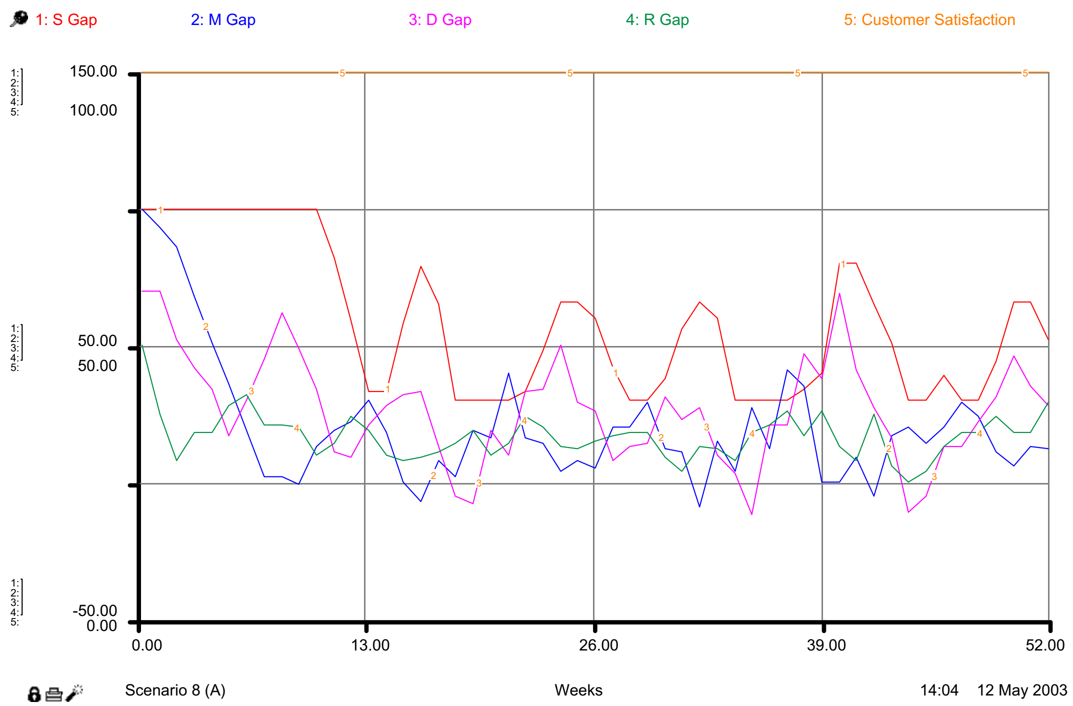

Fig. 12. Scenario 5 – performance graph.

variability of the distributors' inventory levels and consequently on the on-time deliveries to the retailers. Considering the linear relationship between the production time and the manufacturing lead time, an increase in the first will inevitably result in an increase in the second. This, in effect, makes the manufacturer much less responsive and this is also shown by the *m gap* (Fig. 12), which appears to be much more erratic. Poor responsiveness from the manufacturer's side in turn, affects mainly the distributors' inventory levels as the retailers are more able to neutralise the effect of the late deliveries by using safety stocks. Therefore, all the retailers' orders are met and customers remain satisfied at the expense of higher distributor and retailer inventory. The suppliers' inventory levels are shown to vary less, this is due to the smoothening effect the increased lead time has on production. The increase in the lead time means it takes longer to produce a part, this in turn means the desired production rate is, on average, higher. As the manufacturer is not producing to meet the demand but instead always trying to catch up, the production rate varies less. When the production rate varies less, the order rate for the raw material will fluctuate less and the suppliers will be able to reduce the inventory they hold and still fulfil the orders of the manufacturer.

In this scenario the suppliers benefit by being able to hold less stock without this adversely affecting the quality of their service. However, the distributors suffer more as they have to hold high stock levels to maintain the same level of service. This shows that a benefit to one echelon of the supply chain can often cause an adverse effect on another part of the network.

6.6. Scenario 6 – unreliable manufacturer

The effect of a machine breakdowns occurring in week 14 on the inventory and backlog levels of each echelon is illustrated in Fig. 13. In particular, the effect on the manufacturer's gap is shown by the sharp decline in backlog in week 15 which in turn, has a knock on effect on the distributors' gap. The distributors' inventory lasts for 2 weeks because this is the lag between the manufacturer and distributor until they start facing backlogs. Even when the manufacturer starts operating in full capacity, the distributor still experiences a further delay in recovering due to lead and delivery times. The impact on the retailers is minimum as the backlogged orders are mainly absorbed by the distributors.

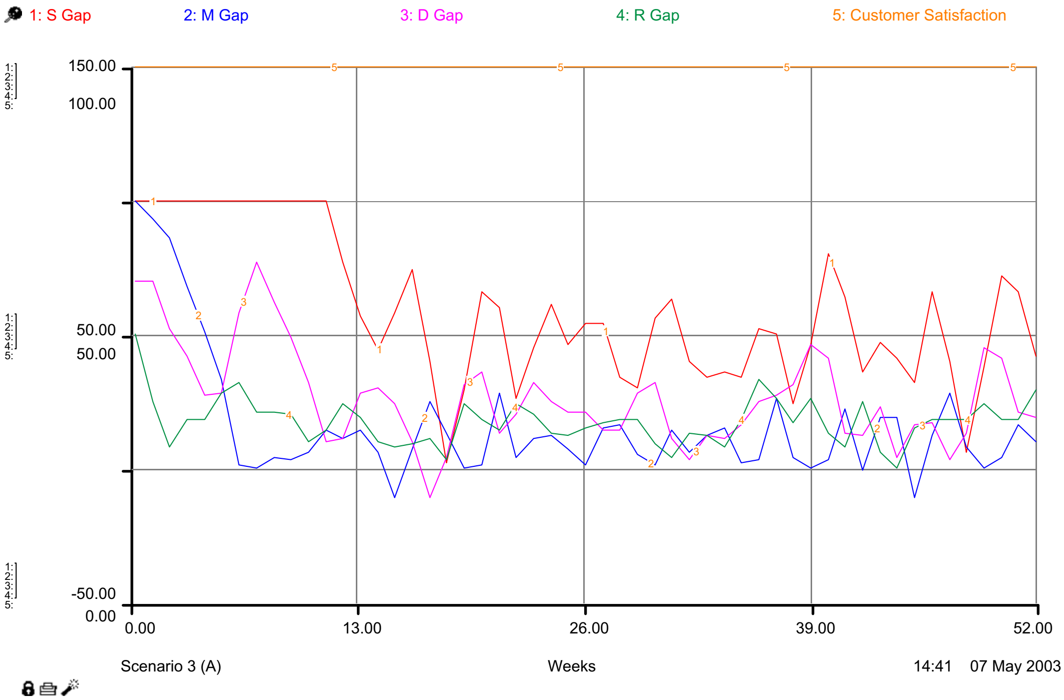

Fig. 13. Scenario 6 – performance graph.

Safety stocks can be used to absorb the effect of the machine breakdown problem occurring at the manufacturer's echelon but this may not always be the case. A production line failure of this kind is very likely to create stockouts as it can cause starvation at the distributors' and retailers' level. Such problem could be avoided by holding larger safety stocks; this is an expensive solution but could be the only option if there is not an alternative supplier. At the manufacturer's level, the effects of machine breakdowns can be eliminated by introducing appropriate preventive maintenance programs. Since this can be a very expensive approach and ultimately add to the product cost it should be used when a loss in production time is very costly, as benefits must always exceed additional costs.

6.7. Scenario 7 – unreliable suppliers

This scenario assumes that the supplier fails to fully fulfil the demand during weeks 16 and 17. This causes the manufacturer to starve for raw materials and experience serious interruptions in production, which eventually may have to stop completely. The large backlogs of orders at the manufacturer's echelon are shown in Fig. 14, which also illustrates the knock on effect that the latter has to the inventory levels of the distributors. This is shown in the figure as a few backlogged orders in the distributors sector. The safety stock held by the distributors is able to absorb some of the effect of the late deliveries from the manufacturer to the retailers. As a result, the retailers only experience two backlogged orders during week 24.

Fig. 14 represents how the wave-like effect of the initial disruption in production occurring at the manufacturer's level is absorbed by each of the echelons downstream as well as the time lag in experiencing that effect. More specifically, the manufacturer encounters the problem in week 16 but the retailers are not affected until week 22. When the retailers start experiencing backlogs the manufacturer will already have recovered and start building inventory for two weeks. The stockout at the retailers' level could have been totally avoided if information about inventory levels and demand was shared across the supply chain network. An information enriched supply chain is discussed in greater detail in the last scenario.

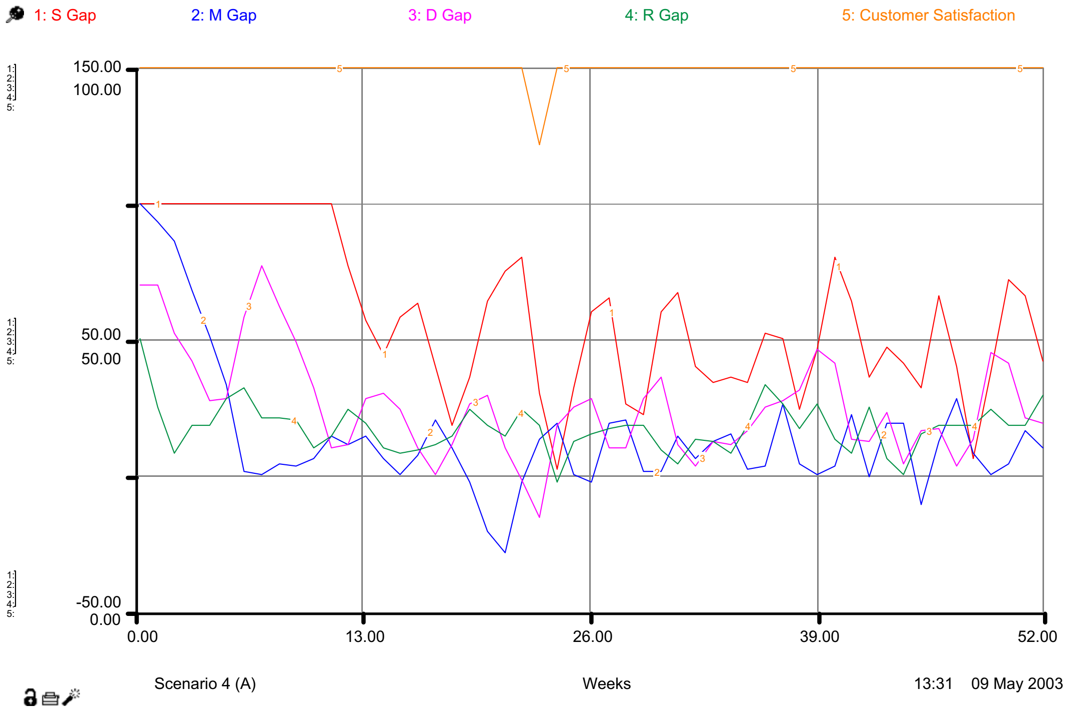

Fig. 14. Scenario 7 – performance graph.

The problem of suppliers being unreliable is a commonly faced problem in supply chain networks. While a possible solution can be sought by increasing the inventory levels, a more cost-effective approach could be to collaborate with a network of alternative suppliers. Production is the bottleneck in any supply chain, due to

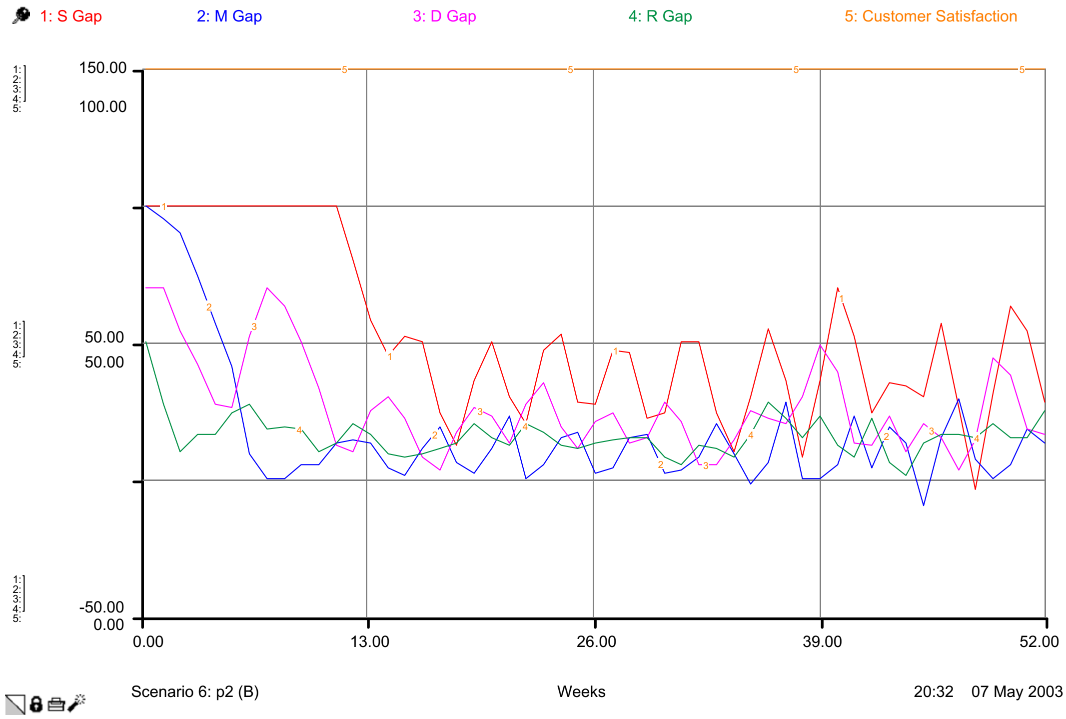

Fig. 15. Scenario 8 – performance graph.

capacity constraints and the time lag of lead time. When the flow of production is interrupted, lead time increases, the system becomes less responsive and the risk of stockout gets higher.

6.8. Scenario 8 – information enriched supply chain

The system originally operated by using forecasted demand data, and each tier was assumed to maintain 20% more inventory than the next lower-level echelon. The information enriched supply chain in this scenario is modelled on the assumption that the inventory level at each echelon is determined based on actual demand. Fig. 15 illustrates the immediate effect of information sharing on the inventory level which has been dramatically reduced at each echelon. This in turn, results in significant reductions in lead time thus making the entire network more agile. Although the advantages of the information enriched supply chain are clear to see there are also disadvantages. There is a cost incurred in setting up the required technology to share information among collaborating companies and not all companies are prepared to exchange information on their demand and inventory levels.

7. Conclusions

A supply chain network has been modelled using systems dynamics. Following a systems dynamics approach enabled the modelling of a complex structure such as that of supply chain networks and shed light on the interactions of its key system parameters. An efficient modelling of these associations and interrelationships is vital as a thorough understanding of the system's dynamics and behaviour is the key step towards the optimisation of its performance. A benchmark model was initially created to represent the operation of the system under normal conditions. The performance of the system was analysed with respect to a number of key performance metrics. Eight alternative scenarios were then designed considering different vital aspects of the supply chain and data were collected on the performance of the system with respect to the same key measures. The results were then compared to those obtained when running the system under the benchmark conditions. The following conclusions were drawn from the aforementioned comparisons.

Half of the designed scenarios focused on investigating the effect of demand on the network's performance. The manipulations of demand were related either to its rate or variability. For both cases, demand was assumed to vary in the positive as well as negative direction. Results obtained by increasing the demand rate and demand variability clearly highlighted that there is an invert relationship between the demand and inventory levels maintained at each echelon. The bullwhip effect applies to this case, and hence, the impact of the demand increase was more intense upstream. Another direct result of the decrease in inventory levels which in turn results in great order backlogs is significant losses in customer satisfaction. Our analysis at that stage was extended to investigate on the appropriate adjustments that need to be made on the inventory levels so as to bring customer satisfaction back to 100% under the conditions of increased demand. Such an analysis concluded by identifying the threshold inventory level, i.e. the inventory level at each echelon that can guarantee maximum customer satisfaction with no further cost increase. The scenarios involving a decrease in demand (affecting either its rate or variability) verified the invert relationship that exists between demand and inventory levels but most significantly highlighted the risk of ending up with obsolete inventory as the effect of demand reduction can be realised at much later periods.

The results obtained by the two scenarios concerning the production time and the manufacturer's reliability mainly affected by the machine breakdowns, impact the network's performance in a similar manner. This is mainly due to the fact that in both cases the normal production flow is disrupted and hence the lead time is prolonged at the same echelon level, i.e. the manufacturer that becomes less responsive to demand and suffers from excessive build up of inventory. The late deliveries and backlogs at the manufacturer's level affect mainly the next echelon, i.e. the distributors that actually absorb to certain extend the impact of the wave-like effect on the retailers at the end of the stream. Perhaps, the only echelon that can benefit under these circumstances is that of the suppliers who can hold less stock without experiencing any adverse impact on the quality of their service.

The major difference between the scenario that considers the case of an unreliable supplier and the aforementioned two is that the material flow is now disrupted one stage upstream, i.e. at the suppliers' tier at the upper end of the network. According to that scenario, the supplier fails to fulfil the demand fully, thus causing the manufacturer to starve for raw material inventory. From this point onwards, the consequences to the rest of the network and at each echelon in particular, are mainly similar to the ones described for the case of interruptions occurring at the manufacturer's level.

Improvements made on the direction of creating an information enriched supply chain resulted in significant reductions in the inventory levels of each echelon, which in turn enabled further reductions in the lead time thus making the overall supply chain more agile.

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