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Safety stock or safety lead time: coping with unreliability in demand and supply

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Abstract

Safety stock and safety lead time are common measures used to cope with uncertainties in demand and supply. Typically, these uncertainties are studied in isolated instances, ignoring settings with uncertainties both in demand and in supply. The current literature largely neglects case study based contexts and, often, single product situations are investigated in which machine set-ups are not considered. Based on the problems and findings in a case study, we investigate the effects of safety stock and safety lead time on delivery performance in a multi-product setting. The outcomes of the extensive simulation study indicate that utilising a safety lead time results in a higher delivery performance where there is a variable supply, whereas having a safety stock results in a higher delivery performance where there is unreliable demand information. In contrast to earlier findings in the single product situation, this study shows that managers facing the combination of unreliability in demand information and supply variability in a multiple product situation should opt for a safety lead time as the most effective way of improving their delivery performance.

Keywords: advance demand information; material requirements planning; safety lead time; safety stock; simulation.

1. Introduction

Typically, production stages in a process industry are tightly coupled, with only a small amount of intermediate inventory available relative to the production speed (Taylor et al. 1981). In such a situation, these systems are vulnerable to machine breakdowns and last minute order changes. The process industry is capital-intensive, and hence production capacity is highly utilized. In the absence of excess production capacity, safety stock and safety lead time are common measures used to deal with supply variability and unreliable demand information (e.g. Buzacott and Shanthikumar 1994). The use of safety lead time provides planners in such systems with mix flexibility. This is especially helpful in dealing with supply uncertainties, such as machine breakdowns. On the other hand, having a safety stock increases the system responsiveness, which is helpful in dealing with short-term changes in demand. The presence of both types of uncertainty, however, tends to complicate matters in terms of the trade-off between the benefits of safety stock and safety lead time. Based on an industrial case study, we have conducted an extensive simulation study that addresses this trade-off and investigates the real life situation with both supply variability and demand uncertainty.

We found similar problems being studied in two fields. The literature on Material Requirements Planning (MRP) discusses planning and controlling production and inventory levels of various products and materials (e.g. Koh et al. 2002, Dolgui and Prodhon 2007). In this field, uncertainties in demand and supply are typically studied in isolation. Further, those papers that do investigate uncertainties in both demand and supply largely restrict uncertainty in demand information to volume changes. Not surprisingly, the need for further research on supply planning under simultaneous demand and lead time uncertainties is acknowledged in a recent review by Dolgui and Prodhon (2007).

While the relevant literature we found on MRP tends to stress *intra-company* tuning of activities, other researchers have considered the way Advance Demand Information (ADI) may be beneficial for improving *inter-company* activity tuning. Here, research efforts are aimed at improving insights into the costs and benefits of acquiring more reliable demand information for company planning (e.g. Karaesmen et al. 2004, Kunnumkal and Topaloglu 2008). In this field, various types of demand variability are considered such as changes in volume, product type and due date. Again, only very few papers combine supply uncertainty and demand uncertainty. Further, the papers that do combine these uncertainties address only a single product situation.

Given the fact that both these fields largely ignore supply planning when there are uncertainties in demand and production, the question remains as to what buffer measure to use under which circumstances. The question whether to use safety stocks or safety lead times to cope with uncertainties in demand and supply has been considered over the years (see e.g. Guide and Srivastava 2000, pp. 227-228) but findings are inconclusive as to when safety stock or safety lead time is the better option.

The aim of this study is to investigate the effectiveness of safety stocks and safety lead time in the presence of both demand and supply uncertainties. More precisely, we investigate the ability of different levels of safety stock and safety lead time to cope with (1) supply variability, (2) alternative types of unreliability in demand information and (3) the combined effect of unreliability in demand information and supply variability. The effects of safety lead time and safety stock are measured along two dimensions: delivery performance and average inventory level in the system. An extensive simulation study has been used to obtain insights in a range of situations which can aid planners to choose between these two alternatives.

Following the suggestion of Guide and Srivastava (2000) to model real environments, the experimental settings in the simulation study are based on an industrial case study concerning a can supplier in a dairy supply chain. Essentially, the activities of the can supplier are aligned to a packaging firm, where the processes are decoupled within a warehouse. Decoupling the processes by using safety stock or safety lead times makes the system less vulnerable to machine breakdowns in the can factory (supply variability) and demand changes from the packaging firm (demand unreliability).

This paper is structured as follows. Section 2 reviews related literature. Next, Section 3 discusses the case study which motivated our research. The main focus will be on the system characteristics and the dilemmas faced by the planner in realising an effective supply. Together these underpin the design of the simulation study, described in Section 4. In Section 5, the results of the study will be presented, and subsequently discussed in Section 6. Finally, Section 7 summarises the main conclusions and makes suggestions for further research.

2. Literature review

In this paper, we are studying the use of safety stocks and safety lead times as a way of aiding the operational planning of tightly coupled manufacturing stages with uncertainties in both supply and demand information. We define safety stock as the average amount of inventory kept in hand to allow for short-term uncertainty in demand and variability in supply (Silver et al. 1998). In line with Hariharan and Zipkin (1995), we define safety lead time as the difference between the release time and the due date minus the supply lead time of the product, where supply lead time is defined as the time that is required to produce the order (Hariharan and Zipkin 1995). Variability in supply occurs because the output is not constant for a range of reasons including equipment failures. Demand variability is related to uncertainty in the volume, product type, or the timing of incoming orders, which may cause last minute changes to operational production plans.

Various authors have studied the use of safety stocks and safety lead times, but their findings are inconclusive with respect to the question as to whether it is better to use safety stock or safety lead time. Liberopoulos et al. (2003) show that in cases with limited capacity, safety stock and safety lead time are fully interchangeable. On the other hand, Buzacott and Shanthikumar (1994) show that safety lead time is usually only preferable to safety stock when it is possible to make accurate forecasts of requirements over the production lead time. Guide and Srivastava (2000) review the use of safety stock and safety lead time and conclude that there are no methodologies that provide a general solution. They further suggest that future research should focus on models that reflect real environments.

The required amount of safety stock or the length of a safety lead time is influenced by the level of uncertainty experienced in a production unit. If the uncertainty in demand information (e.g. Karaesmen et al. 2004) or supply variability (e.g. Karaesmen 2003) is reduced, the delivery performance will improve or, alternatively, the safety stock or safety lead time can be decreased. Such reductions in uncertainty can lead to cost reductions (Kunnumkal and Topaloglu 2008, Wei and Krajewski 2000).

Three recent reviews on managing uncertainties in MRP environments show that, to date, studies have been largely restricted to a single source of uncertainty, related to either supply or demand. Dolgui and Prodhon found that 22 out of the 26 papers reviewed considered either demand or lead time uncertainty (Dolgui and Prodhon 2007, Tables 2-4 pp. 274-275). Mula et al. distinguished six different types of uncertainty in their review, and 64 out of 87 papers considered only one type of uncertainty (Mula et al. 2006, Tables 5-8 pp. 275-281). Koh et al. distinguished four types of uncertainty in their review, and 21 out of 37 papers considered only one of these (Koh et al. 2002, Figure 3&4 pp. 2403-2412). A limited number of papers in the MRP field do combine supply uncertainty and demand uncertainty. In these papers, demand uncertainty is often related to volume changes (e.g. Schmitt 1984, Ho 1993, Brennan and Gupta 1996, Molinder 1997, Ho and Ireland 1998, Thompson and Davis 1990). Alternatively, Koh and Saad combine volume changes with changes in product specification (2003) or in due-dates (2006). Given the findings from the reviews, it is not surprising that Dolgui and Prodhon (2007) and Mula et al. (2006) conclude that planning under different types of uncertainties is a promising area for further research.

Having looked at the aforementioned studies within the MRP context, we concluded that they tend to display a somewhat *intra-company* focus, and often consider demand information as an exogenous factor. However, some researchers have discussed the way in which Advance Demand Information (ADI) could be beneficial for *inter-company* tuning of activities. Here research efforts are aimed at improving insights into the costs and benefits of acquiring more reliable demand information for company planning (e.g. Karaesmen et al. 2004). Product ADI concerns the amount, the product type or the timing, and reduces demand uncertainty. ADI becomes more beneficial when its unreliability is reduced (Tan et al. 2007). Greater accuracy in demand information can reduce the need for inventory (e.g. Bourland et al. 1996, Ozer and Wei 2004), improve reliability (Bourland et al. 1996) and reduce the need for excess supply capacity (Ozer and Wei 2004).

The literature on ADI often assumes perfect demand information and few papers address uncertainties in demand. The papers that do study demand uncertainty relate uncertainty to due-date setting (Tan et al. 2007), order cancellations (Thonemann 2002, Liberopoulos et al. 2003, Tan et al. 2007), incomplete order data on product type (Thonemann 2002) or partial schedules, where part of the orders are still unknown (Liberopoulos et al. 2003). We could only find the combination of variability in supply and unreliability in demand in papers by Hu et al. (2003, 2004) and by Toktay and Wein (2001). Here, however, the researchers only studied a single product situation.

The main aim of our research is to evaluate the effectiveness of safety stock and safety lead time in coping with supply uncertainty in combination with three different types of demand uncertainty that we saw in our case study: uncertainty arising from changes in order size, uncertainties arising from changes in order type and uncertainties arising from changes in order sequence. The effectiveness of safety stock and safety lead time has not been reported in the MRP literature in relation to changes in order type or sequence. In the ADI literature, a few papers have considered a combination of unreliable ADI and variable supply, but these papers have focused on a single product. Building on case study findings, we investigate the dilemma facing a planner as to whether to use safety stock or safety lead time in a multiple product situation while taking several real life types of uncertainty into account.

3. Case description

The previous section shows that investigating further the use of safety stocks and safety lead time in real life situations with multiple sources of uncertainty is a potentially promising direction for further research. Pursuing this goal, this study is firmly grounded in, and motivated by, a case study in a can factory delivering to a packaging firm in the food processing industry. The case study helped to explore the types and scales of the uncertainties faced in real life. These uncertainties and other uncovered system characteristics are used in the design of the simulation study, as described in the next section. To obtain the required information, interviews were held with shop floor managers and production planners. Additionally, procedures, planning data and data derived from the MRP system were also studied. The interviews revealed that both supply variability and demand uncertainty have a major influence on the need for safety stock or a safety lead time.

The studied can factory (see Figure 1) has five production lines that produce different types and sizes of cans. Cans are supplied to a packaging firm, where they are filled with condensed milk and subsequently packed into cardboard boxes. The can factory and the packaging firm are tightly coupled in the sense that there is limited intermediate storage capacity relative to the production speed: the maximum stock equates to two days of production. The production lines face regular breakdowns, reducing overall running times by about 20%. Production output is further influenced by the type and size of can, as well as by the set-ups involved.

----INSERT FIGURE 1 AROUND HERE-----

Operations at the can factory and at the packaging firm are aligned through a single, weekly, production plan. The production plan provided by the packaging firm (which is considered as demand information for the can factory) may be adapted during execution. Plan changes are linked to customer order changes, the availability of raw materials and/or the availability of packaging materials. An analysis of production plans for one product size, over a period of 26 weeks, showed that the production plan was modified 82 times (average 3.2 modifications, range 1-8 modifications, per week). Each modification may involve multiple changes to the schedule, to which the can factory has to respond. Over a year, the utilisation of the different production lines in the can factory varied between 56 and 86 per cent.

Based on the case study, we concluded that the level of unreliability in both ADI and production output forces the use of safety stocks or safety lead times in order to guarantee acceptable delivery performance. The choice for, and the amount of, each option is based on the requested delivery performance. The options are restricted by the limited intermediate storage space, and influenced by efficiency considerations with respect to inventory, production and handling costs. Finding a suitable trade-off between restrictions and ambitions is one of the main tasks for the planners; with safety lead time providing more flexibility and safety stock more responsiveness. For the planners it is not clear under what circumstances they should opt for safety stock and when for a safety lead time. The subsequent simulation study helps the planners to choose the right type of buffer for different levels and types of unreliability in both demand information and production outcomes.

4. Design of the simulation study

Based on the question raised by the case study, namely which buffer measure to use under what circumstances, a simulation study was designed to investigate the effect of different levels of safety stock and safety lead time on the ability to cope with uncertainties in demand and supply. In answering our main research question we evaluated the effectiveness of safety stock and safety lead time in coping, in turn, with (1) supply variability, (2) various types of unreliability in demand information and (3) the combined effect of unreliability in demand information and supply variability. We measure the effectiveness of safety lead time and safety stock on two dimensions: delivery performance and inventory level in the system.

The main variables in our simulation, largely determined from the case study, are summarised in Tables 1 and 2. For all experiments, product supply is modelled as a single machine processing multiple product types (equal product mix), where a change of product type requires a new set-up (assumed to take two hours). The availability of this machine is modelled as 80 per cent due to machine breakdowns. We chose to characterize the mean time to repair by a negative exponential distribution. This choice is motivated by a graphical analysis of company data on machine breakdowns – which lacked the precision for a more profound testing on the fit of the distribution. Furthermore, it is in line with related literature, see, for example Das (2008), Kuhn (1997), and Sulliman (2000). In a similar way we decided to represent the time to failure by a negative exponential distribution. Again this choice is confirmed in earlier research, see, for example, Das (2008), Kuhn (1997), Moinzadeh and Aggarwal (1997), and Sulliman (2000). In the model the mean time to repair represents supply variability (see Table 2) The mean time to failure is derived from the 80 per cent machine availability and the mean time to repair. The initial planned weekly workload of the production machine is constant on 228 units (one unit equates to 6 pallets of cans); however the demand changes during the period with respect to the type, the quantity and the sequence of products contained in the initial schedule. The modelled average supply lead time of one unit is 32 minutes, and 228 units are produced weekly when the utilisation rate is 80 per cent. Based on the modelled workload of the system (228 units per week), individual orders from the packaging firm to the can factory are generated (uniform order size 10-50 units based on case data). These orders are not pre-empted, and are delivered in the demanded sequence.

----INSERT TABLE 1 AROUND HERE-----

Operations in the can factory follow the weekly (seven-day) production plan of the packaging firm including any changes they request. No uncertainties are foreseen in the modelled lead times of the packaging firm. The production plan in the model is generated three days ahead of the start of the new week, and the production orders in the can factory are released based on this plan. The order release time to this machine depends on the planned due date, the machine set-up time, the supply lead time of one unit, and the safety lead time. Once an order in the can factory is finished, the next order is released until all the orders for one period are processed. The production plan may be adapted every 12 hours (the plan evaluation interval) depending on the experimental settings (see Table 2). If modifications in the orders from the packaging firm to the can factory occur, only orders which are known in the production plan but which are not yet started in the packaging firm can be changed. If the demand for an order which has already been released to the can factory increases, a rush order is generated. The basic control rule in the system is that orders are processed in the demanded sequence from the packaging firm unless there is a rush order.

To answer the research question, six series of experiments are carried out (see Table 2). These experiments evaluate safety lead time (ST) and safety stock (SS) on delivery performance and inventory level in alterative settings of uncertainty in demand and supply. Three related pairs of safety stock and safety lead time levels are compared where eight hours of safety lead time is the equivalent of 15 units' production time, assuming no additional set-ups are required. Therefore, in the five product scenarios the use of three units of safety stock of each product type are comparable to the use of 8 hours of safety lead time.

----INSERT TABLE 2 AROUND HERE-----

In the first series of experiments, the effect of utilising safety lead time and safety stock on delivery performance is studied in a situation where the supply is variable. A zero in Column 2 in Table 2 represents a constant supply, and other values represent increasing levels of variability. Supply breakdowns are modelled using a negative exponential function with the chosen supply variability (the mean time to repair) as its mean.

In the second to the fourth series of experiments, the effect of safety lead time and safety stock on the delivery performance with unreliable ADI, in the form of product type changes, quantity changes and sequence changes is studied. These demand changes are modelled as the likelihood that a product plan change will be required at a plan evaluation moment where 0.1 represents a chance of 10%. The plan evaluation moment is set to 12 hours to approximate current practice for the company, which suggests that plans were changed up to two times a day. Changes in product type (series II) are modelled by randomly picking an order within the plan of which the demanded product type is modified, randomly picking from all product types with equal chance. Quantity changes (series III) are modelled as an order of which the production volume is modified. Based on the empirical analysis of the order changes we restrict the order quantity changes to at most ±20 units (uniform distribution), where we kept the modified order within the regular order size band (10 – 50 units). If an order change would violate these limits, the order quantity is set equal to the lower or the upper bound. Sequence changes (series IV) are modelled as two randomly selected orders whose positions in the production plan are switched.

In the fifth and the sixth series of experiments, the effects of safety lead time and safety stock on delivery performance with a combination of the different ADI unreliabilities *and* supply variability are studied. In these series, only one level of the various demand changes is evaluated at the same time (i.e. all demand uncertainties have a probability of 0.1). Series V shows the effects of the various combinations of the different ADI unreliabilities and supply variability on the desirable levels of safety lead time and safety stock. Experiment VI is added because we expect the number of stock keeping units (SKUs) to have a major influence on the effectiveness of safety lead time and safety stock.

The series of experimental outcomes are evaluated in terms of delivery performance and inventory levels. Delivery performance is measured as the fraction of orders that meet the packaging due date according to the production plan. Inventory levels are measured since there is a strong focus on cost reductions in the case company and because their physical storage capacity is limited. Inventory levels are measured every 24 hours, revealing differences in the average level of inventory when adopting safety stock or safety lead time approaches.

The software package that is used to carry out the simulation experiments is Tecnomatix Plant Simulation 7.6 ™. A total of 100 runs were carried out for each experiment. The system can be described as a non terminating production system (operations run 24 hours a day - seven days a week). Therefore a warm up period was used to arrive at the steady state. The length of the warm-up period is determined using the Welch procedure (Law and Kelton 2000) based on the observations of the can throughput times. Given the outcomes of the procedure, the warm-up period and run length are set at 150 and 1500 days respectively.

5. Results

In this section, we present the results for each series of experiments in the form of two figures: one showing delivery performance, and one depicting inventory levels. For all the experiments we found that the confidence interval half width is at most 0.8% for the delivery performance and 2.1% for the inventory levels respectively, given $\alpha=0.05$. Differences between stock policies have been tested for statistical validity using a paired-t approach with a 95% confidence interval (see Law and Kelton, 2000). The tests pointed out that differences greater than 0.3% for delivery performance and 2.1% for inventory levels should be considered significant.

5.1 Comparing safety stock and safety lead time with various levels of supply variability (Series I)

Figure 2 shows that greater supply variability leads to lower delivery performance. Safety lead times lead to better delivery performance than equivalent levels of safety stock. As one adds more and more safety stock, or increases safety lead time, the benefit diminishes. Figure 3 shows that utilising a safety lead time results in lower inventory levels than holding equivalent levels of safety stocks. Increasing supply variability leads to a linear increase in inventory level but at a slow rate.

----INSERT FIGURES 2 and 3 AROUND HERE-----

5.2 Comparing safety stock and safety lead time in the event of product type changes (Series II)

Figure 4 shows that increasing unreliability in required product type leads to decreased delivery performance. Increases in safety lead time or safety stock reduce the effect of ADI unreliability in product type on delivery. The differences in delivery performance for the various safety stock levels are small compared to those for the equivalent range of safety lead times. In general, safety stock is more effective in managing this uncertainty, where only 24 units of ST achieves a comparable result to 9 units of SS at the highest level of uncertainty (0.4). Figure 5 shows that average inventory rises when unreliability in terms of product type increases. The effect of increasing ADI unreliability on the average inventory is greatest when pursuing a safety lead time solution. A safety lead time approach results in lower inventory levels when product type uncertainty is low, whereas a safety stock approach results in lower inventory levels when product type uncertainty is high.

----INSERT FIGURES 4 and 5 AROUND HERE-----

5.3 Comparing safety stock and safety lead time in the event of quantity changes (Series III)

Figure 6 shows rather small differences (the scale is the same in all the figures reflecting ADI unreliabilities) in delivery performance between safety stock and safety lead time approaches in the event of quantity changes compared to the differences seen for the other ADI uncertainties (as shown in Figures 4 and 8). In both approaches even high levels of quantity uncertainty have little impact on the delivery performance. Figure 7 shows that inventory levels rise if the uncertainty in demanded quantities increases. This increase is more marked when adopting a safety lead time approach. Nevertheless, adopting a safety lead time results in lower average inventory levels than if one had opted for an equivalent level of safety stock, even at high levels of quantity uncertainty.

----INSERT FIGURES 6 and 7 AROUND HERE-----

5.4 Comparing safety stock and safety lead time in the event of sequence changes (Series IV)

Figure 8 shows that increasing uncertainty in product sequencing reduces delivery performance, and that holding more safety stocks improves delivery performance in such a situation. The use of safety stocks results in a better delivery performance than if one had opted for safety lead times with moderate or high safety settings (SS6 vs. ST16, SS9 vs. ST24), but lower delivery performance for low safety settings (SS3 vs. ST8). A large increase in delivery performance can be observed when going from SS3 to SS6 that can be related to the set-up time. With the values used in the simulation, the set-up period of two hours can be effectively buffered by a safety stock level of four or more units (four units is equivalent to 4 x 32 minutes of production time). A safety stock level of three units (SS3) cannot buffer an additional set-up, should one be required to adapt to a last-minute change in order sequence. Clearly, the larger simulated stocks (SS6 and SS9) can buffer such a loss of production time. Figure 8 further shows that the gain in delivery performance when going from 8ST to 16ST is small compared to the difference when further extending lead time from 16ST to 24ST. This effect is discussed in Section 6.2. Figure 9 shows that inventory levels rise slightly when ADI unreliability increases, and that safety lead times result in lower average inventory levels than equivalent levels of safety stock.

----INSERT FIGURES 8 and 9 AROUND HERE-----

5.5 Comparing safety stock and safety lead time in the event of a combination of supply variability and different ADI unreliabilities (Series V)

Figure 10 shows that increasing demand uncertainty reduces delivery performance, while increasing safety stock or safety lead time improves delivery performance. The decrease in delivery performance as demand uncertainty increases is greater if one opts for a safety lead time approach. Nevertheless, the use of a safety lead time results, in all the situations considered, in a better delivery performance. Figure 11 shows that average inventory levels increase when the ADI unreliability increases. The inventory increase is larger if one opts for safety lead times rather than equivalent safety stocks. Figure 11 shows a crossover point in inventory levels for comparable levels of safety lead time and safety stock around an unreliability level of 0.1. Beyond this point, safety stocks result in lower average inventory levels than safety lead times.

----INSERT FIGURES 10 and 11 AROUND HERE-----

5.6 Comparing safety stock and safety lead time in the event of a combination of supply variability and various sources of ADI unreliability with different quantities of SKUs (Series VI)

Figure 12 shows that a single product situation results in identical delivery performances for safety stock and safety lead time approaches. In a multiple product situation (3, 5, 10 SKUs), delivery performance is better when following a safety lead time approach than when holding a comparable level of safety stock. This difference in delivery performance, between safety lead time and safety stocks, increases as the number of SKUs increases. Figure 12 further shows that delivery performance worsens as the level of demand uncertainty increases. The decrease in performance is larger if a safety lead time approach is pursued. Figure 13 shows that the average inventory level, in a single product situation, is lower if a safety lead time approach is applied whereas, in general, in multiple product situations, inventory levels are lower if a safety stock policy is adopted. In multiple product situations, safety lead times only result in lower inventory levels at low levels of ADI unreliability. In multiple product environments, the crossover point for average inventory levels, given comparable levels of safety stock and safety lead time, depends on the number of SKUs. Increasing the number of SKUs will shift this crossover point to lower levels of uncertainty, leading to higher average inventory levels when a safety lead time approach is used compared to a safety stock approach.

----INSERT FIGURES 12 and 13 AROUND HERE-----

5.7 The effect on inventory space

The inventory graphs in Section 5.1-5.6 show the average inventory which is an important measure to determine differences in inventory holding cost between safety stock and safety lead time. However, space needs is also of interest as it limits the inventory level. Therefore the 95 percentile of the inventory level measurements is studied as a measure for the space needs. Studying this point revealed that the storage space needs for safety stock or safety lead time in the series of experiments are 12 to 93 per cent higher than the average inventory level (see Table 3). Specifically for series II, V, and VI we find high inventory space requirements, suggesting that for realistic settings of inventory space, extra care has to be taken in transferring the average inventory results into space requirements. In general, high inventory level fluctuations (as in series II, V, VI, related to respectively type change, multiple uncertainties and multiple uncertainties) can be associated with rapid increases in average inventory levels when the uncertainty levels increase (see the inventory graphs in Section 5.1-5.6).

----INSERT TABLE 3 AROUND HERE-----

6. Discussion

This section is organised in line with the three research issues concerning respectively: the effect of supply variability, the effect of demand uncertainty, and their combined effect.

6.1 The effect of supply variability

The first research issue concerns determining the effect of supply variability. Experiment series I found that increasing levels of supply variability decreases delivery performance. The literature reports similar relationships (e.g. Karaesmen 2003, Kunnumkal and Topaloglu 2008). Incorporating a safety lead time is found to lead to better delivery performance than holding a safety stock when coping with supply variability (see Figure 2). This can be explained by the inherent mix flexibility associated with a safety lead time, since products are not pre-specified as they are with safety stocks.

Utilising a safety lead time achieves a better delivery performance while resulting in lower average inventory levels (see Figure 3). With a safety lead time, inventory levels decrease in advance of a period without any demand (e.g. at the end of a production period or during a machine set-up) and this results in lower average inventory levels than if a safety stock approach is used. The benefits decrease as the system becomes more loaded.

6.2 The effect of demand uncertainty

The second research issue concerned the effect of uncertainty in demand. Experiment series II to IV show that increases in ADI unreliability (in three different forms) decreases delivery performance. This outcome is again in line with earlier findings (e.g. Bourland et al. 1996, Tan et al. 2007). In general, holding a safety stock is found to be more effective than buffering in a safety lead time in coping with ADI unreliability. The greater effectiveness of safety stock can be explained by the consequent ability to have tighter coupling between the supplying company and demanding company. Orders to the supplying company can be released later than in a similar situation relying on a safety lead time, and this makes the system less vulnerable to demand changes. While Liberopoulos et al. (2003) found that safety stock and safety lead time are totally interchangeable in a single product situation, we find that holding a safety stock is more effective in a multiple product setting.

The various types of demand uncertainty affect delivery performance differently. This can be observed in Figures 4, 6 and 8, where the effect of a change in order quantity is relatively small compared to the effect of changing either the product type or the production sequence. This difference can be explained by the magnitude of the change and the set-up implications. Firstly, if a quantity is changed, the magnitude of that change is limited since an order is modified (we used a uniform distribution of ±20 units, see Table 1) compared to a product type or a sequence change where an entire order is changed (a uniform distribution from 10 to 50, see Table 1 order size). Secondly, quantity changes result in fewer set-up changeovers than product type or sequence changes.

The chosen level of safety stock for each product type should be sufficient to cope with at least one additional set-up. In Figure 8, this is illustrated by the large gain in performance by increasing the safety stock from three to six units.

The length of a safety lead time needs to be chosen with caution. Extending safety lead time, on the one hand, increases the likelihood that changes in the production plan can be accommodated but, on the other hand, it also increases the likelihood that production is already under way when an order modification is received. This effect is illustrated in Figure 8 where safety lead-times of 8 hours and 16 hours result in similar delivery performances. Further experimental runs with a wider range of safety lead times reveal that the marginal effect of additional safety lead time decreases the delivery performance up to around 10 hours of safety lead time (the specific point depending on the model parameters investigated), when it starts to increase again. This results in nearly the same delivery performance with both 8 hours and 16 hours supply lead time. Figure 4 also shows this effect: 8 hour and 16 hour safety lead times result in comparable delivery performances at the 0 and 0.1 demand uncertainty levels.

In the event of demand uncertainties, a safety lead time results in lower average inventory levels at low levels of uncertainty but, at higher uncertainty levels, the required inventory levels increase more rapidly with the safety lead time option (see Figures 5, 7 and 9). This difference between the two options at low levels of uncertainty can be explained by the workload of the system as explained above in Section 6.1. The difference in the rate of inventory growth as uncertainties increase can be explained by the fact that, using safety stocks, orders to the supplying company are released later. This reduces the likelihood that the supplying company has already started producing a wrong type of product.

The various types of demand uncertainty differently influence the average inventory levels. Figures 5, 7 and 9 show that changes to product type have the greatest impact on average inventory levels. This can be explained, firstly, by the limited magnitude of allowed quantity changes (see Section 6.1) and, secondly, by the fact that all production will still be used within the same production period in the event of a sequence change. In comparison, there is greater uncertainty attached to a type change.

6.3 The combination of supply and demand uncertainty

The third research issue concerns the combined effect of demand uncertainty and supply variability. Experiment series V and VI show that increasing levels of ADI unreliability combined with supply variability decreases delivery performance. Within the investigated combinations of variable supply and ADI uncertainty, it is more effective (i.e. better delivery performance) to use safety lead time rather than safety stock in a multiple product situation.

Safety lead time and safety stock achieve almost identical performances when there is only one SKU. This finding is in line with those of Liberopoulos et al. (2003) who showed that safety stock and safety lead time are interchangeable when only demand variability is considered in a single product situation. Increasing the number of SKUs decreases delivery performance. The fall off in performance is lower when the safety lead time approach is selected because this approach provides some mix flexibility whereas a safety stock does not.

Higher levels of ADI unreliability have a greater impact on the delivery performance when the safety lead time approach is selected. This can be explained by the fact that safety lead time is more sensitive to ADI changes than safety stock (comparable to series II to IV) and the fact that the delivery performance with zero demand uncertainty is already lower with the safety stock option (due to the supply variability) which reduces the effect of additional disturbances.

The results further show that inventory levels more rapidly increase when adopting a safety lead time approach as the level of uncertainty or the number of SKUs increases. This rapid increase can be explained by the greater likelihood that the wrong product is produced, combined with the reduced likelihood that this excess stock will be quickly required when there are many different SKUs.

7. Conclusions and future research

Motivated by the industrial case study in the food processing industry, this paper studies the advantages and disadvantages of either safety stock or safety lead time in a multiple product system with a variable supply and unreliability in demand information. The benefit of safety stock is its responsiveness, whereas safety lead time increases flexibility. What was not clear was which buffer strategy is the more effective under specific circumstances.

This study shows that a safety lead time is the more effective strategy for coping with supply variability. Conversely, in most cases, holding a safety stock is to be preferred in coping with uncertainties in demand information. For situations with uncertainties in both supply and demand information, a safety lead time is more effective than an equivalent level of safety stock. The downside of adopting a safety lead time is that it leads to higher inventory levels and to a higher spread in inventory storage needs than with a comparable level of safety stock when demand uncertainty is high. These differences in delivery performance and inventory levels between the use of safety stock and safety lead time become more significant as the number of SKUs increases.

This study has answered some of the questions concerning the use of safety stock and safety lead time in a multiple product situation, but it is also limited by its design. The design of the simulation study is based on a single case study. Although our situation contributes to an integrated approach, including multiple types of uncertainties and realistic parameter settings, modelling other industrial settings will certainly require the addition of other factors such as the pre-emptiveness of jobs, other types of uncertainties, other demand and supply distributions or other dependencies in planning and production. Nevertheless, our study is relevant for a wider audience, as it addresses general types of uncertainty with respect to supply variability, type change, and order size and sequence change. We believe that achieving the optimum trade-off between safety lead time and safety stock is a generic and pervasive problem in many industries and supply chains.

Practitioners can benefit from our findings. Specifically, we would advise planners in high volume processing/packaging industries who are faced with a combination of supply variability and uncertainties in demand information to opt for a safety lead time approach since this is the more effective. The optimum extent of the safety lead time will depend on the available storage capacity and storage costs. Further, we found that the effects of the various types of demand uncertainty on delivery performance differ, with product type and sequence changes having a greater impact than quantity changes. Therefore, if a planner can influence the kind of demand uncertainty to be faced, delivery performance could be increased. By creating a situation in which demand uncertainty linked to product type is reduced, inventory levels could be cut since changes to product type have a greater impact on inventory levels than production sequence changes or order quantity changes. Our study confirms the experiences of the managers in our case-company with respect to the advantages (higher delivery performance) and disadvantages (high inventories when demand uncertainty is high) of the use of safety lead time to deal with a situation of uncertainty in supply and demand. Their experiences and our results made them decide to test the benefits of a combined approach in partly shifting to safety stock in circumstances where there is advance information concerning potential production schedule changes to mitigate the negative inventory level effects of safety lead time.

Several promising directions for further research remain. In future research one could study combined safety stock and safety lead time policies taking advance information concerning potential production schedule changes into account, like the flexible policy suggested in the previous paragraph. Another direction for further research is to relax specific case study based constraints that we used as this may extend the applicability of the findings. For example, other real life situations might involve different uncertainties, or situations in which rush orders might lead to the halting of an order in progress, which could be modelled as a pre-emption. Another direction for further research relates to the effect of additional safety lead time in a situation with demand uncertainty. This subject was raised in our discussion in Section 6.2 where Figures 4 and 8 revealed that the effect on delivery performance of additional safety lead time is not always positive. Finally, another direction for future research is to relate the delivery performance changes of changing the amount of safety lead time or safety stocks to the associated changes in inventory holding costs. This would explicitly address the trade-off between delivery performance and storage costs and show in which situations additional buffering measures should be taken. Based on the economic benefits of improved delivery performance and the costs of storing more products, one could decide on the appropriate inventory level.

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Table 1. The values of the fixed factors

Fixed factors	Value
Product mix	Equal
Machine setup time	2 hours
Average supply availability	0.80
Initial load of the system	228 units (approx. 80%)
Average unit supply lead time	32 minutes
Order size	Uniform between 10 and 50
Duration of a period	7 days
New schedule generation time	3 days ahead of new period
Plan evaluation interval	12 hours
Order size change	Uniform within ±20.

Table 2. The factors considered in the series of experiments

	Supply variability	Demand uncertainty			Safety lead time	Safety stock	Number of SKUs
		Type change	Quantity change	Sequence change			
Series I	0; ½ ; 1 ; 1½ ; 2 hours				8; 16; 24 hours	3; 6; 9 units	5
Series II		0; 0.1; 0.2; 0.3.; 0.4			8; 16; 24 hours	3; 6; 9 units	5
Series III			0; 0.1; 0.2; 0.3.; 0.4		8; 16; 24 hours	3; 6; 9 units	5
Series IV				0; 0.1; 0.2; 0.3.; 0.4	8; 16; 24 hours	3; 6; 9 units	5
Series V	1 hour *	0; 0.1; 0.2; 0.3.; 0.4	0; 0.1; 0.2; 0.3.; 0.4**	0; 0.1; 0.2; 0.3.; 0.4**	8; 16; 24 hours	3; 6; 9 units	5
Series VI	1 hour *	0; 0.1; 0.2; 0.3.; 0.4	0; 0.1; 0.2; 0.3.; 0.4**	0; 0.1; 0.2; 0.3.; 0.4**	16 hours	Equivalent to 16 hours***	1; 3; 5; 10

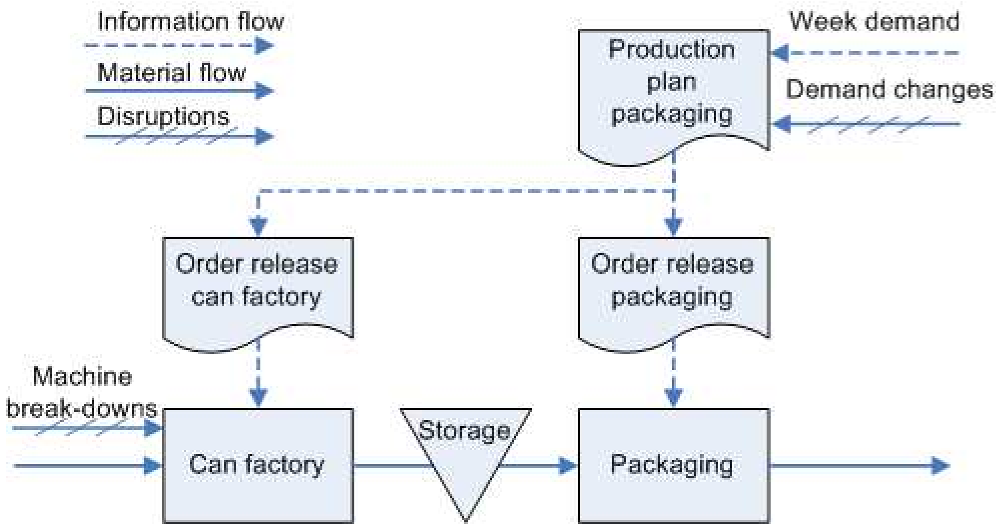
* For presentation reasons we fixed the level of supply variability to 1 hour. Additional experiments show comparable patterns for other levels of supply uncertainty (0:30h, 1:30h and 2:00h).

** Same level as type change uncertainty (i.e. chance 0.1 is evaluated when type change 0.1 is evaluated)

*** The level of safety stock of each unit depends on the number the SKUs; levels equivalent to 16 hours of safety lead time were chosen.

Table 3. Differences between the mean and the 95 percentile storage needs.

	Safety stock			Safety lead time		
	Mean	95 percentile	% difference	Mean	95 percentile	% difference
Series I	31,5	41,1	31%	23,1	38,4	66%
Series II	33,7	52,4	56%	43,1	82,4	91%
Series III	31,0	34,6	12%	25,4	40,1	57%
Series IV	31,0	35,0	13%	23,5	34,9	48%
Series V	38,6	67,1	74%	47,4	91,6	93%
Series VI	38,4	63,8	66%	46,0	86,4	88%



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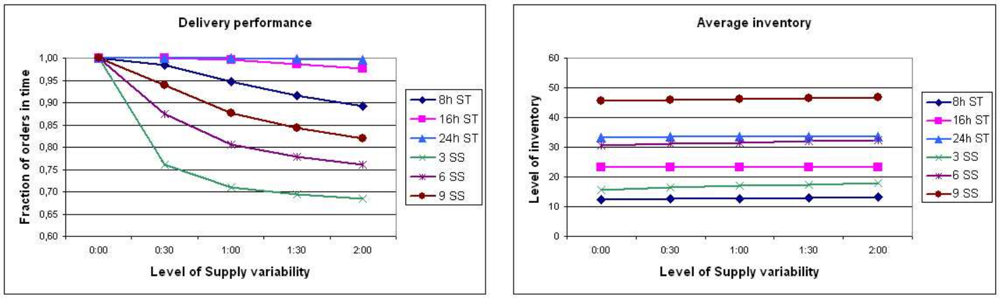

Figures 2 and 3. Delivery performance and average inventory levels for various amounts of safety stock and safety lead time at different levels of supply uncertainty.
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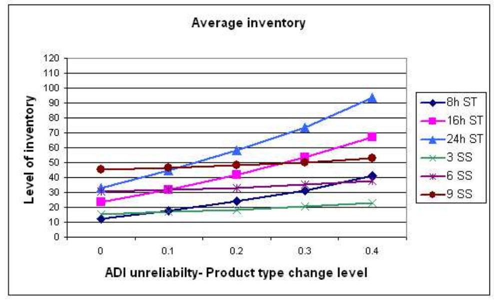

Figures 4 and 5. Delivery performance and inventory levels for various amounts of safety stock and safety lead time at different levels of product type changes.
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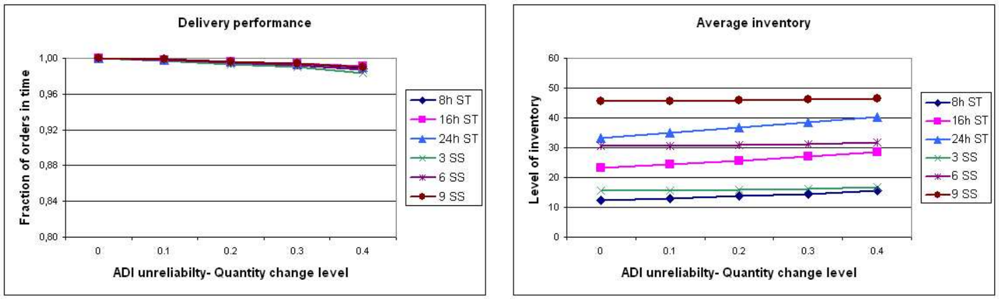

Figures 6 and 7. Delivery performance and inventory levels for various amounts of safety stock and safety lead time at different levels of quantity changes.
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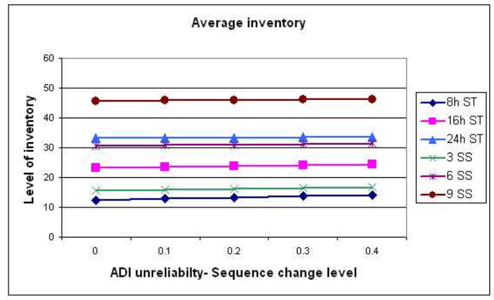

Figures 8 and 9. Delivery performance and inventory levels for various amounts of safety stock and safety lead time at different levels of sequence changes
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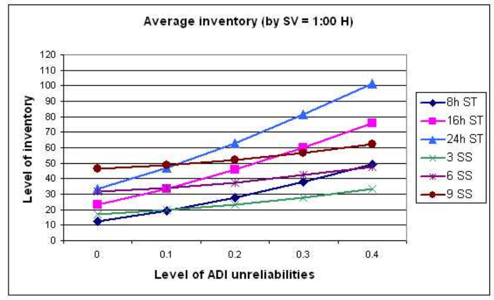

Figures 10 and 11 Delivery performance and inventory levels for various amounts of safety stock and safety lead time at different combinations of ADI unreliability and a constant level of supply variability.
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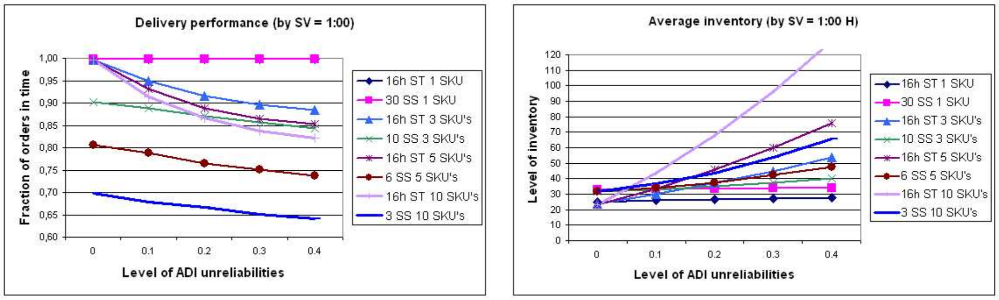

Figures 12 and 13. Delivery performance and inventory levels for various amounts of safety stock and safety lead time with different combinations of ADI unreliability, a constant level of supply variability and various numbers of SKUs.
302x90mm (96 x 96 DPI)