Sensitivity Analysis of Simulation Study Results on Safety Stock Relaxation in Material Requirement Planning

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***Abstract*—In Material Requirement Planning, the lack of capacity constraints can lead to production plans, which cannot be fulfilled on time. One countermeasure for coping with capacity problems is a temporary relaxation of safety stock, which can be implemented in different ways. In this paper, three variants for relaxing safety stock are presented and compared in a simulation study for a simple manufacturing structure. All three methods reveal a significant potential of improvement in comparison to MRP. In a sensitivity analysis, the influence of two MRP planning parameters, i.e., safety stock and production lot size, on the overall costs and the relationship between these two parameters are examined.**

Keywords-Discrete Event Simulation; Sensitivity Analysis; Material Requirements Planning; Safety Stock Relaxation.

I. INTRODUCTION

In production planning, Material Requirement Planning (MRP) [1] is widely applied due to its well comprehensible algorithm for scheduling production orders to satisfy material requirements by external demand. However, there are some weak points of MRP like the assumption of infinite machine capacity and constant production lead times [2] [3]. Neglecting capacity constraints leads to the generation of usually infeasible production plans by MRP, which require additional planning effort at the production control level [4] - [6].

In the last decades, several approaches have been developed to deal with the drawbacks of MRP. Especially for the integration of capacity constraints, there exist a set of different solution approaches [7]. One possibility is to react on capacity problems after the MRP run [4] [5] [8], although it is hard to solve these problems, which are generated at the higher MRP level. Some authors start before the MRP run and try to avoid capacity violations already at the Master Production Schedule (MPS) level [9] [10]. Another approach is the formulation of an optimization problem with capacity constraints instead of the MRP run [11] [12]. In addition to the high computational effort for solving real world planning problems, the theoretical formulations limit the practical application of these approaches. The integration of a solution heuristic into the well-known MRP algorithm for tackling the capacity constraints is another possibility, which is more likely to be accepted for practical implementations. Different approaches can be found in [7], [13]- [16].

In [16], capacity planning is integrated into MRP by providing simple algorithmic measures, like the temporary relaxation of safety stock, load dependent dynamic planned lead times and lot size adaption heuristics. The basic concepts of Material and Capacity Requirements Planning (MCRP) are provided, but details on the implementations are missing. First insights on the performance of the MCRP algorithm are presented in [17] with a simulation study of a simplified production system structure, with eight final products and three Bill Of Material (BOM) levels.

In this paper, two variations of the safety stock relaxation for capacity load balancing, introduced in [16], are defined (Section II) and their performance is compared to the initial implementation and traditional MRP in a simulation study (Section III). To derive a better understanding of the proposed methods for safety stock relaxation, a sensitivity analysis of two MRP planning parameters on the performance of the production system is conducted and the interrelationship of these parameters is investigated in Section IV in detail. In Section V, concluding remarks summarize the main results and outline future research.

II. SAFETY STOCK RELAXATION

A. Production System

The modeled production system structure applied in this paper is motivated by different automotive suppliers' production systems and similar to the production system presented in [18]. However, it is a very streamlined version (low number of products, simple BOM structure, only one machine per low level code) to not disturb the simulation experiment results unnecessarily, which are generated later on. Figure 1 shows the resources, bill of material and work schedule applied.

The studied production system is a pure Make-to-Order (MTO) system. Eight final products (low level code, i.e., LLC, 0) are delivered to a set of different customers stating their orders with a random customer required lead time in advance of the respective due date. These final products consist of 1 piece of a semi-processed material on LLC 1 and 2, whereby the raw materials on LLC 3 are assumed to be always available. One machine is available for each processing step and the transformation from one low-level code to the next always includes one processing step. The lot sizing policy is Fixed Order Periods (FOP) for all materials (see [19] for details). The different scenario parameterizations concerning processing times, setup times, demand behavior and customer required lead time are introduced in Section III.

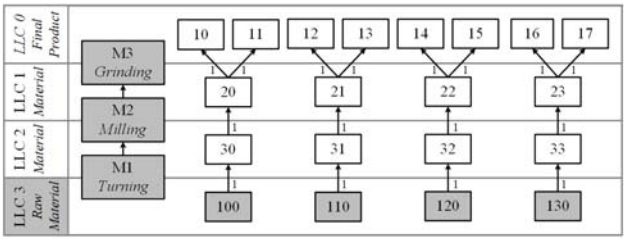

Figure 1. Production System.

B. Safety Stock Relaxation Method 1

A safety stock within MRP is applied to reduce the negative effects of uncertainties in customer demand and production processes. From a planning perspective the safety stock is never undershot in the original MRP algorithm (see netting in MRP algorithm, [19] and [1]) and is only used for unplanned occurrences. In the approach introduced in [16], safety stock is already applied in the planning algorithm for capacity load balancing, i.e., available safety stocks are used to temporary reduce the capacity needed. This leads to a shift in capacity consumption since this safety stock has to be refilled in later periods, which leads to a higher capacity consumption there. The basic idea behind that measure is that capacity shortages are only temporary and, therefore, some idle capacity is available further in the future, i.e., capacity load is balanced.

The integration into MRP looks as follows: The MRP algorithm starts with the steps netting and lot sizing for all materials at the respective LLC. After these two steps for all machines at the respective LLC the cumulated capacity needed is calculated. If the cumulated capacity is higher than the available capacity within one planning period, a safety stock relaxation is performed. These three steps (netting, lot sizing and capacitating) are conducted identically for all safety stock relaxation methods evaluated.

In safety stock relaxation method 1, the safety stock for a specific material can only be reduced if there is a planned order receipt in the period of the capacity problem. (Note, that the applied lot sizing rule FOP summarizes net requirements of multiple periods, so there isn't a planned order receipt for each material in every period.) The safety stock is only reduced to the level needed, that the capacity problem in the period of the capacity problem is solved (cumulated capacity needed is equal or smaller than the available capacity). The safety stock is reduced to the end of the coverage of the current FOP lot size. Additionally, a minimum safety stock level can be considered as lower bound. For the application of the safety stock relaxation method, the materials are ordered according to their capacity consumption per piece at the respective machine. The method starts with the material, which has the highest capacity consumption per piece and is performed for further materials until the capacity problem is solved.

The following steps are again performed for all safety stock relaxation methods in the same way. The MRP steps netting and lot sizing are recalculated including the relaxed safety stocks. The MRP algorithm ends with the steps backward scheduling and BOM explosion for all materials at the respective LLC.

C. Safety Stock Relaxation Method 2

Safety stock relaxation method 2 starts similar as method 1 with the MRP steps netting and lot sizing and the calculation of the cumulated capacity needed until a capacity problem is detected. In method 1 the safety stock relaxation can only be performed, if there is a planned order receipt in the period of the capacity problem. In method 2, this restriction is removed. A safety stock relaxation can also be performed, if there is a planned order receipt that covers net requirements (due to lot sizing policy FPO) in the period of the capacity problem. This allows that the safety stock for planned order receipts with end dates before the period of the capacity problem can be relaxed. The consequence is that the amount of materials, for which a safety stock relaxation can be performed, is extended. Safety stock relaxation method 2 ends with recalculation of netting, lot sizing, backward scheduling and BOM explosion.

D. Safety Stock Relaxation Method 3

Safety stock relaxation method 3 is an extension to method 2 and uses the same logic for the safety stock relaxation. In comparison to method 2, the relaxed safety stock numbers are stored for the next MRP run, usually for the next day. The next MRP run is calculated with the predefined relaxed safety stocks.

Method 3 has the effect that when a safety stock relaxation for a planned order receipt is made, it is never revised. The only exception is that the safety stock can be further relaxed to the minimum safety stock, if there is a new capacity problem. The safety stock is then refilled with future planned order receipts.

III. Simulation Study

In this section, we outline the design of the simulation study and evaluate the performance of the three different methods for safety stock relaxation, presented in Section II, in comparison to MRP. For the simulation study, the generic simulation framework SimGen based on AnyLogic©, also used in [18], is applied.

A. Scenario Definition

To evaluate the performance of the safety stock relaxation method in comparison to MRP, a production system with high work load is selected. If there is a low work load in comparison to the available capacity, methods for

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capacity balancing would be pointless. Starting with customer demands (log-normally distributed with a coefficient of variation of 1), which result in a shop load of 100% without setup, a scenario with 95% is generated by multiplying the monthly demand with a utilization factor of 95% minus a predefined percentage of setup activities (5% and 10%). A higher percentage setup leads to more time, which is spent for setup. The resulting demand for, e.g., final product 10 with initial demand of 1,059 pcs/month, a utilization factor of 95% and percentage setup of 5%, is 953 pcs/month.

Applicable Customer Required Lead (CRL) time values are estimated in a preliminary simulation study. Summing up the average production lead times for each processing stage delivers a basic lead time value. The average CRL for our simulation study is determined by multiplying this basic lead time value with a CRL factor of 3. To model stochastic effects in CRL a log-normal distribution with a coefficient of variation of 0.5 is applied. In our simulation model, all customer orders are accepted. Due to an average utilization of 95% in the considered production system, short term overloads can be balanced in future periods or by covering customer orders with safety stocks.

Overall costs, consisting of holding and tardiness costs are selected as performance measure. The holding costs per piece and day are 1 CU for final products, 0.5 CU for semi-processed materials and the tardiness costs for final products are 19 CU per piece and day. In the simulation study, 5 years are simulated, where the first year is considered as the warm-up period and therefore excluded from the analysis. Due to the stochastic effects in demand and customer required lead time, each iteration is evaluated with 10 replications.

B. Planning Parameters

Applied lot sizing rules, safety stock levels and planned lead times are important planning parameters for MRP [19]. In our simulation study, we choose Fixed Order Period (FOP) as lot sizing policy and the number of periods, for which the demand is accumulated into one production lot, as a planning parameter. To examine the influence of different safety stock levels, a safety stock factor is introduced as planning parameter. The actual safety stock is the initial value of safety stock multiplied with the safety stock factor. The fixed planned lead time of MRP is introduced as a factor, which is multiplied by the basic lead time values. These values are generated in the preliminary study, which is already used for setting customer required lead time values (see Section A. Scenario Definition). The initial value for safety stock of a product type is its average demand per day, i.e., a safety stock factor of 4 means that the average demand of 4 days is kept on safety stock.

For the safety stock relaxation methods, defined in Section II, a lower bound for the safety stock is introduced as an additional planning parameter. This minimum safety stock is again implemented as a factor that is multiplied with the applied safety stock. In order to get reasonable planning parameters for the safety stock relaxation methods, as well as for MRP, a grid search procedure is applied. Table I shows the specified values for all planning parameters.

TABLE I. PARAMETER SETTINGS

Parameter	Values
FOP periods	{4,5,6,8,10,12,14,16}
Safety stock factor	{0,1,2,4,6,8,16}
Planned lead time factor	{0,0.5,1,1.5,2,2.7}
Minimum safety stock factor	{0, 0.25, 0.5, 0.75}

C. Results of Safety Stock Relaxation and MRP

Due to different percentages of setup (5%, 10%), two different production scenarios are investigated. For each method of safety stock relaxation and MRP, the parameter combination that leads to minimal overall costs is selected. Table II shows the results for 5% setup. All methods for safety stock relaxation reduce the overall costs significantly, whereby method 3 delivers the best result. The number of FOP periods and the planned lead time factor are similar for all methods, only the safety stock factor is higher for method 2 and 3. In the cost minimum solution, the introduced minimum safety stock factor is only applied for method 3.

TABLE II. OPTIMAL SETTINGS (5% SETUP)

	MRP	Method 1	Method 2	Method 3
Minimum overall costs	10426.6	8319.2	8112.1	7595.7
Relative Improvement	-	-18.1%	-20.2%	-25.3%
FOP periods	6	5	5	5
Safety stock factor	4	4	16	8
Planned lead time factor	1.5	2	1.5	1.5
Minimum safety stock factor	-	0	0	0.25

TABLE III. OPTIMAL SETTINGS (10% SETUP)

	MRP	Method 1	Method 2	Method 3
Minimum overall costs	10163.6	8498.1	9528.0	9760.7
Relative Improvement	-	-16.4%	-6.3%	-4.0%
FOP periods	6	8	6	6
Safety stock factor	6	4	8	8
Planned lead time factor	1	1.5	1	1
Minimum safety stock factor	-	0	0.5	0.5

In the scenario with 10% setup (see Table III), safety stock relaxation is also advantageous in comparison to MRP, whereby in this system with higher setup times, method 1 leads to the best result. The selected parameters show that method 2 and 3 demand for a higher safety stock and a minimum amount of this safety stock, which must not be used for relaxation. Again, FOP periods and planned lead time factors don't reveal major differences for the applied methods. An interesting result concerning the comparison of safety stock relaxation methods is that method 1, i.e., having less safety stock relaxation occurrences but recalculating these each MRP run, leads to similar cost reduction potentials independently of the setup times. However, methods 2 and 3, i.e., allowing the safety stock to be reduced more often, do not perform that well if setup times are high. This might be related to the fact that safety stock reduction sometimes implies a new production lot to refill the safety stock after finishing a lot with reduced safety stocks. The negative impact of this unintended behavior is higher if setup times are higher.

IV. SENSITIVITY ANALYSIS

In this section, the influence of the two MRP parameters FOP periods and safety stock factor is investigated in a sensitivity analysis to create a comprehensive understanding of how the three introduced methods behave, also in comparison to MRP. The influence on the performance, as well as the interrelationship of these parameters, is analyzed.

A. *The Influence of FOP Periods on Performance*

The application of four different methods and two different percentages of setup lead to eight different cases, which are examined separately. For each specified value of the number of FOP periods (see Table I), we select the combination of the other planning parameters, which results in minimal overall costs. Additionally we also show the amount of inventory and tardiness costs in Figure 2.

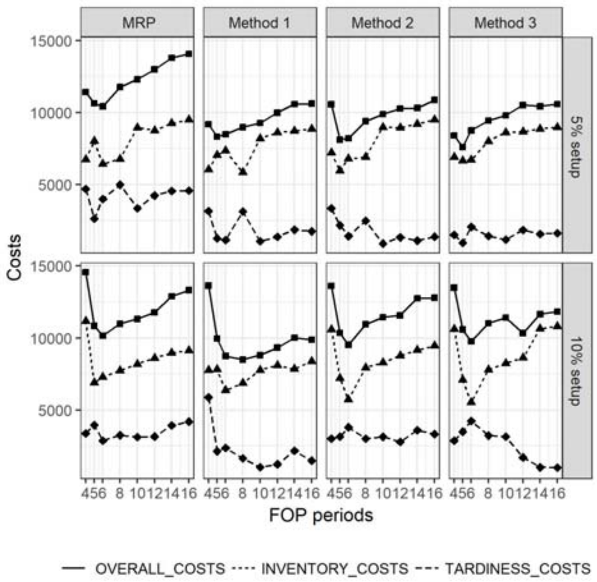

Figure 2. Influence of FOP periods on costs.

All cases show a more or less convex function for overall costs with respect to FOP periods with just a few outliers. As already mentioned in Section III, the optimal value for FOP periods are almost the same for all four methods. A low number of FOP periods leads to significant higher overall costs in the 10% setup scenario, whereas a higher number leads to a moderate increase in costs. For all numbers of FOP periods optimal inventory costs exceed optimal tardiness costs considerably. Apart from some outliers for small number of FOP periods, the inventory costs show a convex behavior with respect to the FOP periods. These results are in line with analytical production system findings without capacity balancing [20].

B. *The Influence of Safety Stock Factor on Performance*

For the safety stock factor, the same analysis as for the FOP periods is performed and the results can be found in Figure 3.

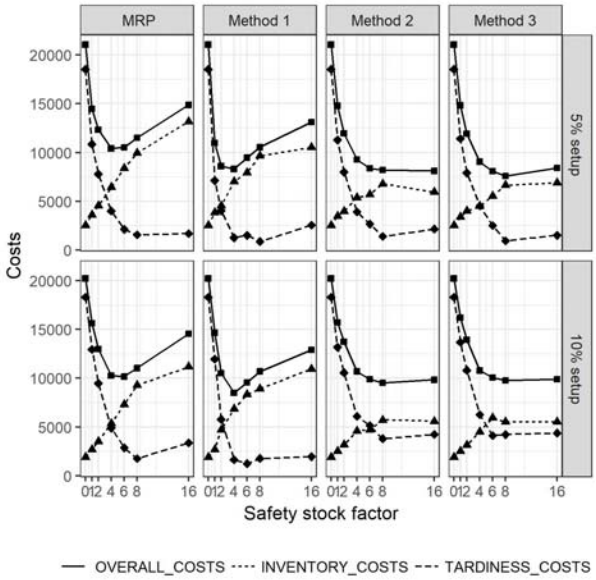

Figure 3. Influence of safety stock factor on costs.

The curves for overall costs show a clear convex shape with respect to safety stock factor, again with significant higher cost values for low safety stock values. For practical applications, this means that it is preferable to choose a higher safety stock when using safety stock relaxation, instead of selecting a safety stock that is too low. Small safety stock factors lead to high tardiness costs in comparison to inventory costs because the ability to balance capacity demands is limited. When safety stock is increased, also inventory costs increase and exceed the tardiness costs. The results show that method 1, with a lower number of safety stock relaxation occurrences, is much more sensitive on defining the right safety stock, similar to MRP. On the contrary, methods 2 and 3, i.e., more safety stock relaxation occurrences without/with memorizing this decision, can also benefit from higher safety stocks. Looking at the inventory costs shows that methods 2 and 3 also have lower inventory costs at higher safety stocks in comparison to method 1 and MRP. This implies that in methods 2 and 3 the average safety stock is lower which is intuitively clear since more safety stock relaxation occurrences are expected with these methods.

C. The Influence of FOP Periods on Safety Stock Factor

To explore the relationship between the parameters FOP periods and safety stock factor, for each value of FOP periods, the optimal safety stock factor is displayed in Figure 4. This means, that for a fixed number of FOP periods, all other parameters are varied in the predefined grid (see Table I) and the safety stock factor which leads to the minimal overall costs is selected. Again, we show all combinations of setup scenarios and methods. The optimal parameter settings presented in Table II and III are marked by a star.

In general, a lower number of FOP periods, i.e., higher overall shop load due to setup times, leads to a higher optimal safety stock factor (apart from one outlier for method 2 at 5% setup). This shows that specifically for high shop congestion, the safety stock relaxation methods demand for more safety stock in order to balance capacity better. The result for method 3 in the 10% setup scenario is interesting and shows a further increase in safety stock for a high number of FOP periods. Note that in this scenario method 3 performs significantly worse than method 1 (see also Figure 2). This implies that memorizing the safety stock reduction decision might in situations with high setup efforts and high lot covering ranges lead to system instabilities, which entail high safety stocks.

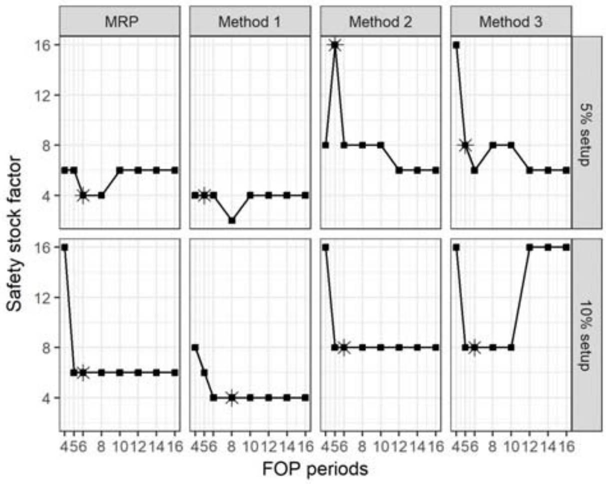

Figure 4. Influence of FOP periods on safety stock factor.

D. The Influence of Safety Stock Factor on FOP Periods

In this section we fix the safety stock factor and determine the number of FOP periods, which result in minimal overall costs. The results for all methods and scenarios are displayed in Figure 5. In six of the eight cases, the number of FOP periods show a concave shape with respect to the safety stock factor. Only for method 2 and 3 in the 10% scenarios there seems to be no influence of the safety stock on the optimal value of FOP periods. This is an interesting result since these are exactly the two scenarios where safety stock relaxation only leads to a rather small cost reduction potential (see Table III).

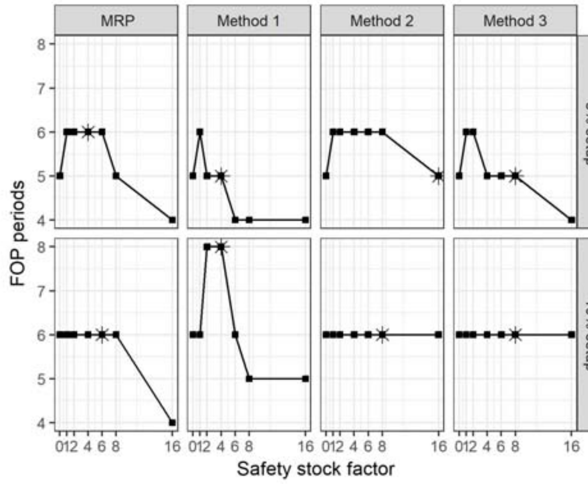

Figure 5. Influence of safety stock factor on FOP periods.

Low safety stock values lead to the situation that flexibility related to the customer demand can only be gained by lower production lot sizes. These situations still lead to high costs because no capacity load balancing is possible (see Figure 3). For medium safety stock levels, a slight increase in lot size leads to a lower overall shop load (and capacity balancing by safety stock relaxation is already possible). This lower overall utilization combined with the capacity balancing leads for most cases also to the lowest overall costs. For very high safety stock factors, high inventory costs and low tardiness costs result, i.e., customer orders can always be fulfilled from the safety stock. Therefore, lower lot sizes (lower lot covering ranges) provide a possibility to slightly decrease the inventory costs.

V. CONCLUSIONS

In this article, three methods for temporary relaxing safety stock as an extension to traditional MRP are investigated. In addition to the safety stock relaxation introduced in [16] two variations are presented and implemented in a simulation model. Since MRP neglects capacity constraints, heuristics for balancing capacity demand can improve the performance of the production system. The results of the simulation study show that all methods for safety stock relaxation lead to significant improvement in overall costs in comparison to MRP. The relative improvement ranges from 4% to 25%.

In a sensitivity analysis, the influence of the planning parameters safety stock factor and FOP periods on the performance of the production system is investigated. The overall costs in dependence of the planning parameters behave similar for method 2 and 3, because they have more common features in their functionality in contrast to method

1. One finding with practical relevance is that a higher safety stock is advantageous when relaxing safety stock, because there is only a small increase in overall costs while increasing safety stock. Opposite to this, a safety stock, which is too low, leads to considerably higher overall costs.

When exploring the interrelationship of the two planning parameters, the results show that especially for high shop loads, due to low number of FOP periods and high percentage of setup, more safety stock is needed for balancing capacity requests. In most of the cases, plotting the optimal number of FOP periods with respect to safety stock shows a concave behavior, whereby medium levels of safety stocks lead to the best solutions for overall costs. Comparing the results of method 1 to the results of methods 2 and 3 shows that method 1 is more sensitive to the safety stock factor whereas methods 2 and 3 perform significantly worse if setup times are high.

Limitations of this study are the selected ranges for the planning parameters for the grid search, which cannot guarantee an optimal solution. Furthermore, the simulation study is applied to a simple manufacturing structure. In further research, the safety stock relaxation methods have to be tested in more complex production structures or real production systems to get better estimates for the improvement potential in real world manufacturing systems.

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