Material Requirements Planning Performance Improvement due to Safety Stock Relaxation

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***Abstract*—Material Requirement Planning (MRP) is a broadly applied production planning method. One problem reported by practitioners and identified in research is that capacity constraints are not included in the planning algorithm. In this paper, the implementation of a simple capacity balancing function into the MRP run by allowing to temporarily relax the safety stock is investigated. Since such a safety stock relaxation method can be implemented in different ways, three specific implementations are developed and tested in a simulation study. For a simple production system structure with uncertainties in processing and customer demand, the performance improvement of the different safety stock relaxation methods is tested when a rolling horizon MRP planning is applied. A detailed analysis of planning parameter effects is presented and a broad set of scenarios provides further insights in the performance of the developed methods. In general, all three methods reveal a significant potential of improvement in comparison to MRP. Managerial insights are that too low production lot sizes and too low safety stocks should be avoided and the interaction between these two planning parameters cannot be neglected. Furthermore, very high and very low production system utilization reduce the improvement potential.**

Keywords – Material Requirements Planning; Rolling Horizon Planning; Discrete Event Simulation; Sensitivity Analysis; Safety Stock Relaxation.

I. INTRODUCTION

Material Requirement Planning (MRP) is widely applied for production planning due to its well comprehensible algorithm for scheduling production orders to satisfy material requirements. However, one problem in MRP application is that capacity constraints are ignored in the planning algorithm. In this paper, different methods for temporary safety stock relaxation within the MRP run to enable a capacity balancing are investigated. Note that this paper is an extension of [1] where preliminary results have been presented. Specifically, [1] is extended by a more thorough safety stock relaxation method presentation, a specific algorithmic explanation of its integration into MRP, a broad numerical study design and the specific formulation of managerial insights based on the numerical results.

MRP is studied a lot in literature, see [2] for its basic development, [3] for a detailed discussion, and [4] for parameter optimization. Specifically the problem of neglecting the limited capacity has often been addressed in literature [5][6][7]. Literature shows that neglecting capacity constraints leads to the generation of usually infeasible production plans by MRP, which require additional planning effort at the production control level [8][9][10]. 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 [11]. One possibility is to react on capacity problems after the MRP run [8][9][12], 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 [13][14]. Another approach is the formulation of an optimization problem with capacity constraints instead of the MRP run [15][16], or the including of a solution heuristic into the MRP algorithm [11]. 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 [11], [17], [18], [19], or [20].

In [19], 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 concept developed in [19] is Material and Capacity Requirements Planning (MCRP), however, only a conceptual framework is provided, but details on the implementations are missing. In [21] the concept of MCRP is further detailed and some first insights on the overall performance of the MCRP algorithm are presented. However, details on the performance of different safety stock relaxation methods are still to be investigated.

The above introduced literature shows that the implementation of capacity limits into MRP is a relevant field of research. Practical requirements often imply that such solution heuristics should be easy to implement, to enable a further real world implementation of the specific methods. Therefore, the implementation of simple safety stock relaxation methods into the MRP run for enabling capacity balancing already within the planning algorithm provide a significant contribution. In this paper, three safety stock relaxation methods for capacity load balancing are developed, based on the conceptual framework of [19]. Related to these methods, the following research questions are addressed:

- What is the performance improvement potential of the different safety stock relaxation methods in comparison to MRP?
- What is the influence of the planning parameters lot size and safety stock on the performance of the developed safety stock relaxation methods and how do these parameters interact?
- How do tardiness costs, production system utilization and setup effects influence the performance of the developed methods?
- What safety stock relaxation method has the highest improvement potential and can be applied for further research and in practical applications?

To answer these research questions, Section II provides the algorithmic extension of MRP and a detailed explanation of the different safety stock relaxation methods. For evaluating the performance of these methods, a simulation study is performed. The respective production system setup and the evaluated scenarios are introduced in Section III. To identify the general performance improvement potential of safety stock relaxation in comparison to MRP, the numerical results of a basic scenario are presented in Section III as well. The detailed planning parameter influence is evaluated in Section IV, where again the basic scenario is focused. The influence of different tardiness costs, production system utilization and setup effects are then evaluated in Section V with a broad numerical simulation study. Furthermore, the different methods performance is compared in this section in detail. In Section VI, concluding remarks summarize the main results and outline future research.

II. SAFETY STOCK RELAXATION

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, [3] and [2]) and is only used for unplanned occurrences. In the approach introduced in [19], 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.

In Fig. 1 the MRP algorithm with the extension of the safety stock relaxation is presented. The MRP algorithm starts at Low Level Code 0 (LLC), which usually includes the sales parts, with the step *netting* for each material. The inputs are the gross requirements of LLC0 from customer orders or master production scheduling, the scheduled receipts from production orders currently processed, and the current inventory. After netting, the step *lot sizing* is applied, followed by the step *capacitating*.

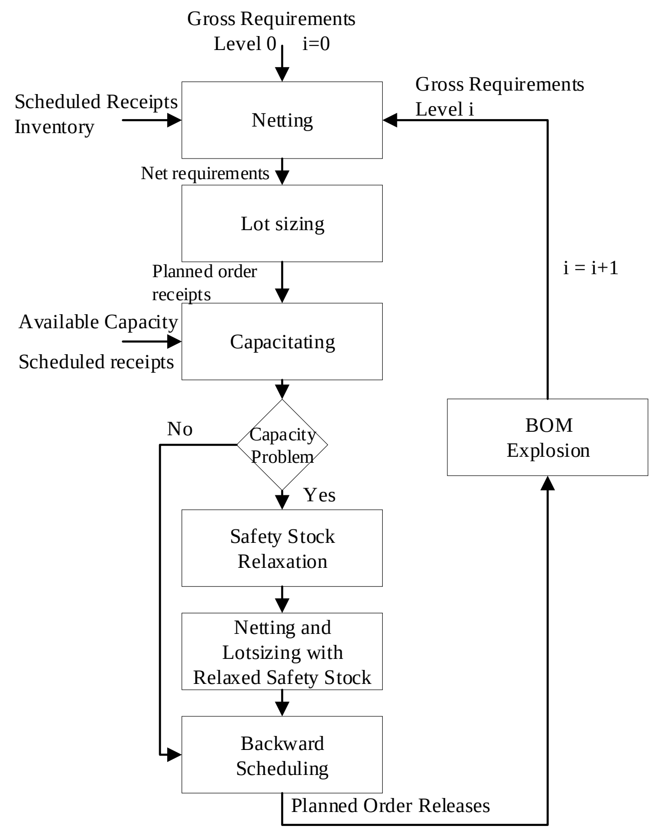

Figure 1. MRP Algorithm with Safety Stock Relaxation.

The capacitating step is fundamental for applying the safety stock relaxation because capacity constraint violations are determined by comparing *cumulated capacity available* with *cumulated capacity needed*. For each period within the MRP run, the capacity needed is calculated based on scheduled receipts and planned order receipts applying the corresponding processing and setup times for all materials and all machines at the current LLC. The available capacity is given by the work schedule applied for each machine. Whenever the *cumulated capacity needed* is higher than the *cumulated capacity available* within one planning period, a safety stock relaxation is applied. Note that the steps *capacitating* and *safety stock relaxation* are not part of the traditional MRP run. After *safety stock relaxation*, the steps *netting* and *lot sizing* are again performed with the relaxed safety stocks. These lower safety stocks lead to lower net requirements and, therefore, influence the resulting production lot sizes. The next steps are *backward scheduling* and *bill of material* (*BOM) explosion*. The steps *backward scheduling* and *BOM explosion* are also executed if no capacity problem has been detected. In the following subsections, the different methods for safety stock relaxation are introduced.

Fig. 2 shows an example for the *capacitating* step, where a capacity problem is detected in period 5. Note that this calculation is applied for each machine within the production system. In this example the available capacity for each planning period, i.e., periods applied in the MRP run, is constant. This could be 8 hours capacity available for each day. The *cumulated capacity needed* includes all capacity demands from currently processed orders and new production lots resulting from the MRP step *lot sizing*. The capacity needed is scheduled at the planned end date of the order in this calculation. Whenever the *cumulated capacity needed* is higher than the *cumulated capacity available* a capacity problem occurs. In the example in Fig. 2, such a problem occurs in period 5. This capacity problem is the basis for the different safety stock relaxation methods discussed in the following subsections.

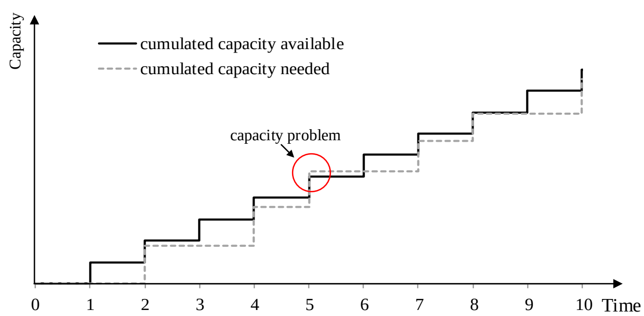

Figure 2. Cumulated capacitiy available vs. capacity needed.

A. *Safety Stock Relaxation Method 1*

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 in the numerical study, the lot sizing rule FOP (Fixed Order Period) is applied, which summarizes net requirements of multiple periods, so there is not a planned order receipt for each material in every period. The safety stock is reduced to the level needed, so that the capacity problem is solved in the respective period; i.e., *cumulated capacity needed* after safety stock relaxation is equal or smaller than the *cumulated capacity available*.

Fig. 2 showed a capacity problem in period 5 of c=1.7 hours. If we assume that the processing time for a material, which has a planned order receipt in period 5 is p=2.55 minutes at the respective machine, the safety stock would be relaxed by r=40 pcs, i.e., $r=c/(p/60)$ (1.7 / (2.55/60)), for this material. Please note that the safety stock is relaxed for all periods of the current FOP lot size. To illustrate the specific safety stock relaxation methods, a numerical example is generated in which the capacity demand from Fig. 2 is generated by only two materials, which both apply the lot sizing policy FOP 3. Note that this assumption only applies for the simple illustrative example here but not for the numerical study presented later. The key results of the MRP run for this example are presented in Table I, where the period with the capacity problem is shaded in grey. Note that the *net requirements* include a current inventory and no projected inventory on hand is reported here to keep the example simple. The result in Table I shows that the safety stock relaxation leads to lower *planned order receipts after relaxation*, i.e., a lower production lot size for the respective lot and, therefore, lower cumulated capacity needed. The following production lot, i.e., the *planned order receipts* in period 8, include the *net requirements* and the amount needed to refill the safety stock.

TABLE I. MRP RUN FOR SAFETY STOCK RELAXATION METHOD 1

Period	1	2	3	4	5	6	7	8	9	10
Gross Requirements	100	90	78	129	72	87	100	30	84	80
Scheduled Receipts	300	0	0	0	0	0	0	0	0	0
Net Requirements	0	75	78	129	72	87	100	30	84	80
Safety Stock before relaxation	285	285	285	285	285	285	285	285	285	285
Planned Order Receipts before relaxation	0	282	0	0	259	0	0	194	0	0
Safety Stock after relaxation	285	285	285	285	**245**	**245**	**245**	285	285	285
Planned Order Receipts after relaxation	0	282	0	0	**219**	0	0	**234**	0	0

To account for uncertainties, a minimum safety stock level can be considered as lower bound for the relaxation. 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.

B. *Safety Stock Relaxation Method 2*

Safety stock relaxation method 2 extends the set of materials for which the safety stock relaxation can be applied. 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 FOP) 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. Table II shows the results for the safety stock relaxation of the second material, which leads to the capacity demand from Fig. 2. This material has the same processing time and a *planned order receipt* in period 4. Note that this example assumes that the safety stock of the material from Table I has not been relaxed. Again, the *net requirements* calculation is skipped for simplicity reasons.

TABLE II. MRP RUN FOR SAFETY STOCK RELAXATION METHOD 2

Period	1	2	3	4	5	6	7	8	9	10
Gross Requirements	91	92	112	93	95	120	43	86	91	92
Scheduled Receipts	0	230	0	0	0	0	0	0	0	0
Net Requirements	0	0	0	67	95	120	43	86	91	92
Safety Stock before relaxation	285	285	285	285	285	285	285	285	285	285
Planned Order Receipts before relaxation	0	0	0	282	0	0	220	0	0	92
Safety Stock after relaxation	285	285	285	**245**	**245**	**245**	285	285	285	285
Planned Order Receipts after relaxation	0	0	0	**242**	0	0	260	0	0	92

The results in Table II show that in this case the safety stocks for periods 4 to 6 are relaxed and that the following production lot, i.e., the *planned order receipts* in period 7, include the *net requirements* and the amount needed to refill the safety stock. Note that this relaxation solves the capacity problem of this simple example since the lower capacity demand in period 4 reduces also the cumulative capacity needed in period 5.

C. 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. However, in a rolling horizon planning, methods 1 and 2 do not store the relaxed safety stock numbers for the next MRP run. In a pure deterministic setting this would lead to a situation where the safety stock relaxation decision has to be taken in each MRP run until the capacity problem has passed. In comparison to methods 1 and 2, the relaxed safety stock numbers are stored in method 3 for the MRP run performed in the next period. 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. Note that in a stochastic setting where demands and shop floor behavior incur uncertainties, this method may lose some flexibility to react on short term influences. The MRP run from Table II, in which the safety stock was relaxed from period 4 to 6, is repeated one period later in Table III. Note that period 3 in Table III corresponds to period 4 in Table II, and the period with the capacity problem shifted to period 4.

TABLE III. MRP RUN FOR SAFETY STOCK RELAXATION METHOD 3

Period	1	2	3	4	5	6	7	8	9	10
Gross Requirements	92	112	93	95	120	43	86	91	92	83
Scheduled Receipts	230	0	0	0	0	0	0	0	0	0
Net Requirements	0	0	67	95	120	43	86	91	92	83
Safety Stock before relaxation	285	285	**245**	**245**	**245**	285	285	285	285	285
Planned Order Receipts before relaxation	0	0	**242**	0	0	260	0	0	175	0

The relaxed safety stock from the previous period is already stated in the *safety stock before relaxation* and if a further capacity problem occurs further safety stocks could be relaxed.

To test the behavior of these three safety stock relaxation methods in stochastic environments with rolling horizon planning, a simulation study is performed.

III. SIMULATION STUDY

In this section the modeled production system for the simulation study and the different scenarios are described, followed by the planning parameters investigated. For a basic setting, the performance of the different safety stock relaxation methods is compared to standard MRP. The generic simulation framework SimGen based on AnyLogic©, also used in [22] and [23], is applied for the simulation study. This framework allows to implement production planning simulation models efficiently. For details, see also [24].

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 [22]. 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. Fig. 3 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 (LLC0) 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 LLC1 and LLC2, whereby the raw materials on LLC3 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 FOP for all materials (see [3] for details).

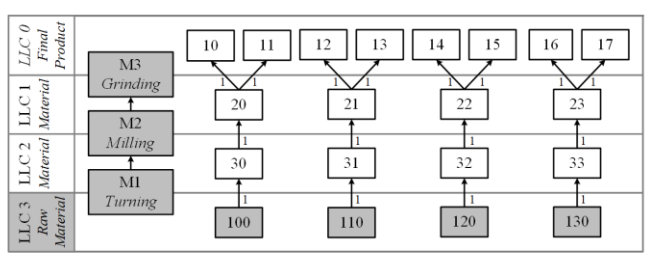

Figure 3. Production System.

B. Scenario Definition

To evaluate the performance of the safety stock relaxation methods in comparison to MRP, three different utilization levels are evaluated. This is necessary in order to study the effectiveness of the proposed methods, since for low work load, in comparison to the available capacity, methods for capacity balancing are getting pointless. The utilization factors evaluated in this study are 90%, 95% and 98%. The time that is spent for setup in comparison to the total capacity needed can also have an influence on the performance of the different safety stock relaxation methods. Therefore, two different percentages of setup activities (5% and 10%) and two different setup scenarios are investigated. In the standard setup scenario, called *always setup*, setup times occur for every order. In the second setup scenario, named *setup at material change*, setup times only occur if the next product produced is not the same as the previously produced. The different utilization scenarios are generated by varying customer demands. Starting with customer demands (log-normally distributed with a coefficient of variation of 1), which result in a shop load of 100% without setup, the utilization scenario is generated by multiplying the monthly demand with the utilization factor minus a predefined percentage of setup activities (5% and 10%). 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 time (CRL) 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 below 100% 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 for the basic scenario. In the sensitivity analysis, tardiness costs of 9 and 99 CU per piece and day are investigated as well. 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 CRL, each iteration is evaluated with 10 replications.

C. Planning Parameters

Applied lot sizing rules, safety stock levels and planned lead times are important planning parameters for MRP [3]. 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 B. 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 IV shows the specified values for all planning parameters with respect to the different utilization factors.

TABLE IV. PARAMETER SETTINGS WITH RESPECT TO DIFFERENT UTILIZATION FACTORS

	Utilization Factor		
Parameter	90%	95%	98%
FOP periods	{1,2,3,4,5,6,8,10}	{4,5,6,8,10,12,14,16}	{4,6,8,10,12,14,16}
Safety stock factor	{0,1,2,4,6,8}	{0,1,2,4,6,8,16}	{0,1,2,4,6,8,16}
Planned lead time factor	{0,0.5,1,1.5,2}	{0,0.5,1,1.5,2,2.7}	{0,0.5,1,1.5,2,2.7,3.4}
Minimum safety stock factor	{0, 0.25, 0.5, 0.75}	{0, 0.25, 0.5, 0.75}	{0, 0.25, 0.5, 0.75}

D. Improvement potential and best parameters for basic scenario

The basic scenario is defined as the setting with 95% utilization, always setup and tardiness costs of 19 CU. However, since the percentage setup leads to different production systems both 5% and 10% setup are included into this basic scenario. The optimized planning parameters are found by identifying the parameter combination that leads to minimum overall costs for each method of safety stock relaxation and for MRP. Table V shows the results for this basic scenario with 5% and 10% setup. For both settings, 5% and 10% setup, all methods for safety stock relaxation reduce the overall costs significantly.

For 5% setup, method 3 delivers the best result and leads to a cost improvement of 25% in comparison to MRP. In this 5% setup setting, 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.

TABLE V. OPTIMAL SETTINGS FOR UTILIZATION 95%

Setup		MRP	Method 1	Method 2	Method 3
5%	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
10%	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 cost minimum solution for 5% setup, the introduced minimum safety stock factor is only applied for method 3.

In the setting with 10% setup, method 1 leads to the best result. The selected parameters show that methods 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 do not 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.

To understand the influence of the planning parameters on the inventory, tardiness and overall cost more in detail, the following section discusses respective effects.

IV. PLANNING PARAMETER EFFECTS FOR BASIC SCENARIO

In this section, the influence of the two MRP parameters FOP periods and safety stock factor is investigated in detail to create a comprehensive understanding of how the three introduced safety stock relaxation methods behave in comparison to MRP. The influence on the performance, as well as the interrelationship of these parameters, is analyzed. Note that this analysis is performed for the basic scenario with 95% utilization, always setup and tardiness costs of 19 CU. The effects of the other parameters are discussed in the scenario analysis in Section V.

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 in this basic scenario, which are examined separately. For each specified value of the number of FOP periods (see Table IV), we select the combination of the other planning parameters, which results in minimal overall costs. Additionally we show the amount of inventory and tardiness costs and the minimum cost from MRP in Fig. 4.

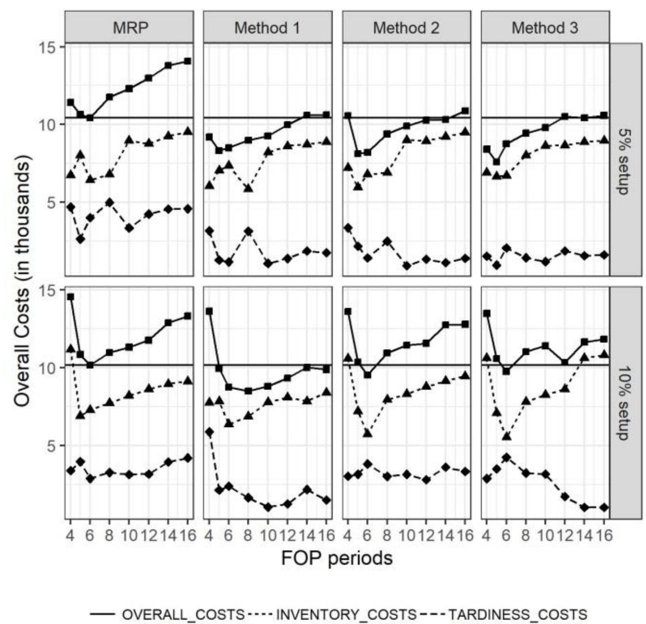

Figure 4. Influence of FOP periods on costs.

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 significantly higher overall costs in the 10% setup setting, whereas a higher number leads to a moderate increase in costs. The reason is that lower lot sizes lead to significantly higher setup times and, therefore, higher overall utilization in the 10% setup case in comparison to the 5% setup case. 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 [7].

A detailed comparison of the optimal costs for safety stock relaxation methods with MRP shows that for the 5% setup setting, all safety stock relaxation methods lead to lower overall costs for a broad range of FOP lot sizes. This means that for lower setup times the negative effects of too high lot sizes can be mitigated by the safety stock relaxation methods. For 10% setup, only the safety stock relaxation method 1 leads to lower costs for a broad range of FOP lot sizes. This means that methods 2 and 3, which allow more frequent safety stock relaxation occurrences, are no more able to benefit from the capacity balancing if lot sizes become higher. This result fosters the finding from the previous section that these higher number of safety stock relaxation occurrences leads to some additional small production lots that reduce the overall performance.

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 5. Note that the potential to apply safety stock relaxation for capacity balancing is linked to the amount of safety stock available. This subsection, therefore, identifies how much safety stock is needed for relaxation and how well additional safety stock is used by the methods.

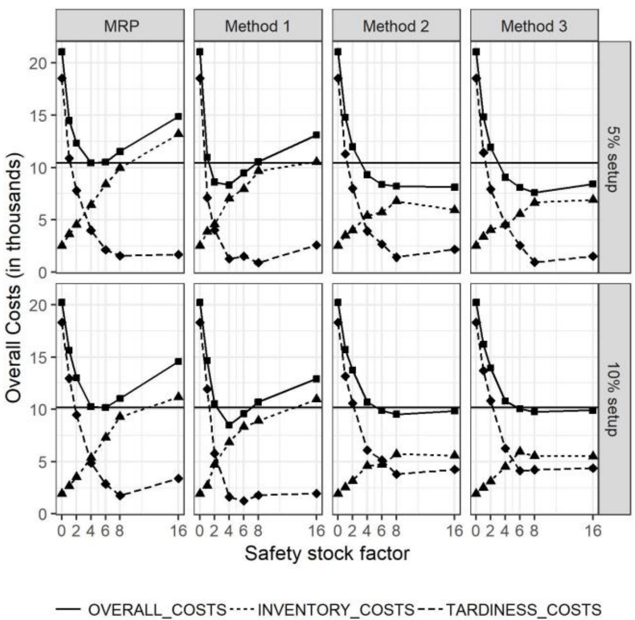

Figure 5. Influence of safety stock factor on costs.

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. Looking at the safety stock configurations for the relaxation methods that lead to lower costs than the optimal MRP setting shows that, contrary to the FOP influence, here methods 2 and 3 have a broader range of better parameters.

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 Fig. 6. This means, that for a fixed number of FOP periods, all other parameters are varied in the predefined grid (see Table IV) and the safety stock factor, which leads to the minimal overall costs is selected. Again, the 5% setup and 10% setup settings are shown for the basic scenario. The optimal parameter settings presented in Table V 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 Fig. 4). 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.

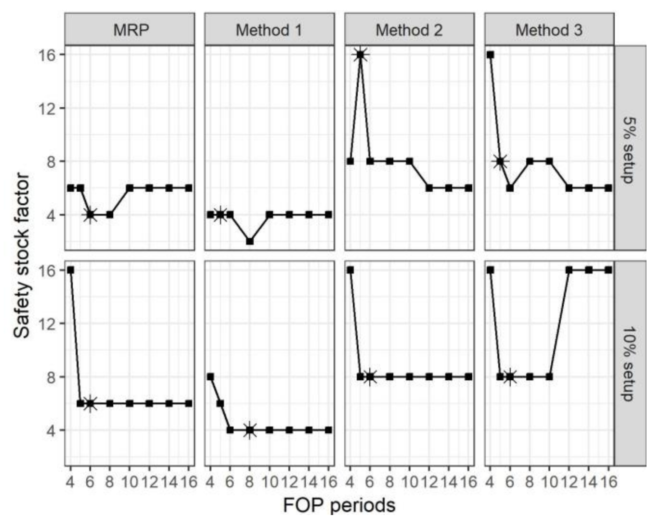

Figure 6. Influence of FOP periods on safety stock factor.

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 Fig. 7. In six of the eight cases, the number of FOP periods show a concave shape with respect to the safety stock factor. Only for methods 2 and 3 in the 10% settings 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 V).

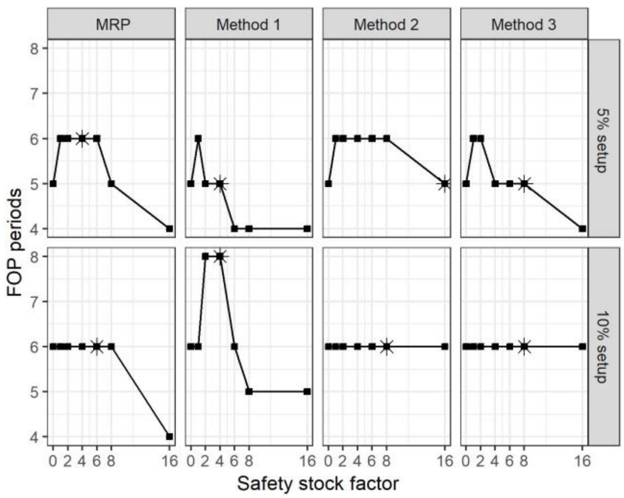

Figure 7. Influence of safety stock factor on FOP periods.

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 Fig. 5). 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.

The in depth discussion of the functionality of the different safety stock relaxation methods and the effects of different planning parameters on the performance of these methods indicates that these methods are promising for further research and practical application.

V. SAFETY STOCK RELAXATION COST PERFORMANCE FOR DIFFERENT SCENARIOS

After the in depth discussion of the functionality of the different safety stock relaxation methods in the last section, this section provides an analysis of the cost performance for a broader range of scenarios. Since three different methods for safety stock relaxation are presented in this paper, the current section shows which of them perform best in different cases and can be suggested for practical application and further research.

A. Tardiness Cost Effects

Since production systems face customers, which have different tardiness perceptions, this subsection investigates the methods performance for tardiness costs of 9 and 99 CU/day in comparison to 19 CU/day in the basic scenario. These values are selected, because based on simple inventory models and in combination with inventory costs of 1 CU/day, they correspond to a service level target of 90%, 95% and 99%. Table VI shows the results for tardiness cost of 9 CU/day and an intuitive result is that overall costs for all methods are lower than in the basic scenario. For 5% setup, the cost reduction potentials are similar to the basic scenario, however, method 1 and method 3 lead to nearly the same cost reduction potential. In this case the result for method 1 is interesting since it needs only very few safety stock. For 10% setup, the cost reduction potential is in this scenario significantly lower than in the basic scenario, specifically method 1 performs worse since here a 5.3% cost reduction can be realized in comparison to 16.4% in the basic scenario. In general the results for tardiness costs of 9 CU/day show a lower cost improvement potential with safety stock relaxation. Note that the 10% setting is the only one in the broader numerical study in which method 2 shows the best performance.

TABLE VI. OPTIMAL SETTINGS FOR UTILIZATION 95% WITH TARDINESS COSTS 9

Setup		MRP	Method 1	Method 2	Method 3
5%	Minimum overall costs	8,225.7	6,476.1	6,970.3	6,497.5
	Relative Improvement	0.0%	-21.3%	-15.3%	-21.0%
	FOP periods	6	5	5	5
	Safety stock factor	2	2	16	8
	Planned lead time factor	1.5	1.5	1.5	1.5
	Minimum safety stock factor	0	0	0	0
10%	Minimum overall costs	7,684.5	7,277.1	7,175.4	7,482.5
	Relative Improvement	0.0%	-5.3%	-6.6%	-2.6%
	FOP periods	6	6	6	6
	Safety stock factor	4	6	6	4
	Planned lead time factor	1	1	1	1
	Minimum safety stock factor	0	0.5	0.5	0.75

For higher tardiness costs, i.e., more impatient customers, Table VII shows the results and in general, a much higher cost reduction potential is observed. For 5% setup, method 3 performs best and for 10% setup method 1, which is consistent with the results of the basic scenario. However, method 2 shows a lower performance than in the basic scenario. A further interesting finding is that higher safety stocks are applied by most of the methods. This result is in line with simple analytical planning parameter optimization models without safety stock relaxation opportunity, which also show an increase in safety stock if tardiness costs increase [4]. The minimum safety stock factor is not significantly higher than in the basic scenario meaning that all safety stock is available for capacity balancing. Summarizing the general results for tardiness costs shows that higher tardiness costs lead to a better performance of safety stock relaxation. For practical application, this means that capacity balancing is more important if customers are more impatient or service level sensitive.

TABLE VII. OPTIMAL SETTINGS FOR UTILIZATION 95% WITH TARDINESS COSTS 99

Setup		MRP	Method 1	Method 2	Method 3
5%	Minimum overall costs	17,262.1	12,381.5	12,612.4	11,607.9
	Relative Improvement	0.0%	-28.3%	-26.9%	-32.8%
	FOP periods	6	5	12	5
	Safety stock factor	8	6	8	8
	Planned lead time factor	1.5	2	2.7	1.5
	Minimum safety stock factor	0	0.25	0	0.25
10%	Minimum overall costs	17,771.2	12,436.8	16,706.9	15,290.3
	Relative Improvement	0.0%	-30.0%	-6.0%	-14.0%
	FOP periods	5	10	6	16
	Safety stock factor	16	6	16	16
	Planned lead time factor	0.5	2	1	2.7
	Minimum safety stock factor	0	0	0.5	0

B. Utilization Effects

The comparison between 5% setup and 10% setup in the basic scenario already provides the insight that overall system utilization has a big impact on the performance of safety stock relaxation methods. In this subsection the influence of lower overall utilization, i.e., 90%, and higher overall utilization, i.e., 98%, is studied.

The results for lower utilization are shown in Table VIII and a general intuitive finding is that lower utilization leads to lower overall costs for all methods including MRP. For the 5% setup case, no safety stock is optimal for MRP and methods 1 and 2, i.e., these methods do not lead to a performance improvement. Method 3 leads to a performance improvement of 3.9%, which is far less than in the basic scenario. For 10% setup, method 3 leads to a cost reduction potential of 10.1%, which is higher than in the basic scenario. An interesting finding here is that for 10% setup method 1 and method 2 lead to higher costs than MRP. This means that for low utilization, the additional disturbances, which are caused by capacity balancing and relaxing safety stocks, have a higher negative influence on the overall performance than the positive effect of avoiding capacity shortages. The good performance of method 3 shows that especially in such lower utilization cases it is important to memorize the safety stock decisions to avoid additional disturbances. In general the result for 90% utilization shows that low production system utilization has only few needs for capacity balancing and only low improvement potential.

TABLE VIII. OPTIMAL SETTINGS FOR UTILIZATION 90%

Setup		MRP	Method 1	Method 2	Method 3
5%	Minimum overall costs	4,310.1	4,310.1	4,310.1	4,143.2
	Relative Improvement	0.0%	0.0%	0.0%	-3.9%
	FOP periods	3	3	3	3
	Safety stock factor	0	0	0	1
	Planned lead time factor	1.5	1.5	1.5	1.5
	Minimum safety stock factor	0	0	0	0
10%	Minimum overall costs	5,307.3	5,405.0	5,398.0	4,769.0
	Relative Improvement	0.0%	1.8%	1.7%	-10.1%
	FOP periods	6	6	6	4
	Safety stock factor	1	2	1	4
	Planned lead time factor	1.5	1.5	1.5	1.5
	Minimum safety stock factor	0	0	0	0

For high utilization cases, Table IX shows that capacity balancing has only a lower improvement potential and that all safety stock relaxation methods lead to similar results. High safety stocks are needed by all methods including MRP and a high minimum safety stock factors is needed for the different methods. The high utilization leads to a system that is near to instability, i.e., a lot of planning parameter combinations lead to a theoretical utilization above 100% and, therefore, to an instable system. An interesting finding is that all methods (including MRP) lead to optimal lot sizes, which are below the maximum lot size of FOP 16. Based on the production system and customer demand uncertainties, higher lot sizes imply that sometimes short term demands occur for which additional production lots have to be issued. Hence, one explanation for this medium optimal lot size in this case is that this medium lot size provides a trade-off between too many setup operations based on low lot sizes and too many setup operations based on short term demands or safety stock refill orders.

In general, the results concerning utilization show that the best performance for capacity balancing can be gained for medium to high system utilizations. If the system utilization is too low, capacity balancing is not needed and if the system utilization is too high, there is only very few room for balancing the capacity, i.e., it is difficult for safety stock relaxation methods to refill the relaxed safety stock.

TABLE IX. OPTIMAL SETTINGS FOR UTILIZATION 98%

Setup		MRP	Method 1	Method 2	Method 3
5%	Minimum overall costs	17,096.2	15,904.4	15,915.0	15,975.5
	Relative Improvement	0.0%	-7.0%	-6.9%	-6.6%
	FOP periods	6	6	6	6
	Safety stock factor	16	16	16	16
	Planned lead time factor	0	0.5	1	1
	Minimum safety stock factor	0	0.75	0.75	0.75
10%	Minimum overall costs	15,538.6	14,316.1	14,365.0	14,319.6
	Relative Improvement	0.0%	-7.9%	-7.6%	-7.8%
	FOP periods	8	6	6	6
	Safety stock factor	8	16	16	16
	Planned lead time factor	1	0.5	0.5	0.5
	Minimum safety stock factor	-	0.75	0.75	0.75

C. Setup Effects

In the scenarios above, each new production order leads to a setup at the respective machine. This setting is chosen since the production system is a simplified setting with a low number of materials in comparison to real world systems. However, the results from Section IV and the two subsections above indicate that methods 2 and 3 might lead for some specific planning parameter combinations to small production lots from refilling the safety stock and less efficient capacity balancing. Therefore, this last investigation allows production lots to be put together and be produced without setup. In detail, a setting where setup occurs only if the material changes is studied. If there are more production orders waiting at a machine, orders with the same material as produced last are preferred as long as no other order has an earlier due date. This implementation mimics the behavior of workers who try to minimize their setup effort at the machine. Note that for this simplified production system structure this leads to less setup operations needed since only few materials are produced at each machine and the respective positive effects might be overestimated.

Table X shows that for all safety stock relaxation methods as well as for MRP, this setting leads to lower overall costs. Furthermore, method 3 has the highest cost reduction potential in this scenario for 5% and 10% setup. This means that being able to add smaller production lots that just refill the safety stock to other ones that already exist, significantly improves the performance of method 3. Looking at the optimal planning parameters, shows that lower safety stocks, lower production lot sizes and slightly higher planned lead times are optimal in comparison to the basic setting. An intuitive result is that the cost improvement potential improves in comparison to the basic scenario for 10% setup since there the setup operations show the highest influence.

TABLE X. OPTIMAL SETTINGS FOR UTILIZATION 95% WITH SETUP MATERIALCHANGE

Setup		MRP	Method 1	Method 2	Method 3
5%	Minimum overall costs	7,755.5	6,832.8	7,019.8	6,305.8
	Relative Improvement	0.0%	-11.9%	-9.5%	-18.7%
	FOP periods	6	4	6	4
	Safety stock factor	2	8	4	8
	Planned lead time factor	2	1.5	2	1.5
	Minimum safety stock factor	-	0	0	0
10%	Minimum overall costs	8,225.1	7,107.9	7,199.2	6,949.9
	Relative Improvement	0.0%	-13.6%	-12.5%	-15.5%
	FOP periods	8	6	6	6
	Safety stock factor	2	8	6	6
	Planned lead time factor	1.5	1.5	1.5	1.5
	Minimum safety stock factor	-	0	0	0.25

D. Overall performance comparison

Overall, 12 scenarios have been tested and the planning parameters for four methods, i.e., MRP and safety stock relaxation methods 1 to 3, have been optimized by search space enumeration. This broad numerical study shows that in all scenarios, the safety stock relaxation for capacity balancing leads to a considerable cost reduction potential. A managerial insight is, therefore, that using safety stock to balance capacity should be considered for improving production planning performance and rather simple heuristics already perform well.

Comparing the different safety stock relaxation methods shows that method 2, i.e., having more safety stock relaxation occurrences but not memorizing them, shows the worst performance and is only in 1 of the 12 scenarios the best option. Interestingly, methods 1 and 3 show in general a similar performance, i.e., method 1 leads in 5 scenarios to the best result and method 3 in 6 scenarios. Also concerning the average improvement potential, method 1 leads to an average cost improvement of 13.2% and method 3 to 13.5%. However, their performance in different scenarios differs significantly. For example, method 1 shows a significantly better performance for 10% setup and the basic scenario as well as for tardiness costs 99 CU/day. However, method 3 shows a significantly better performance at utilization 90%, where method 1 shows even a slight cost increase for 10% setup. From a managerial perspective, this means that both methods perform well but it depends on the specific production system structure, which one might be better to apply. For further research this means that both methods have potential to be further investigated and their sensitivity to planning interactions has to be further studied.

VI. Conclusions

In this article, three methods for temporary relaxing safety stock as an extension to traditional MRP are investigated. 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. For a broad range of numerical scenarios, the relative cost improvement potential of the best respective safety stock relaxation method is between 4% and 33%. Concerning planning parameter effects, 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 inventory costs while decreasing tardiness costs due to capacity balancing. Opposite to this, a safety stock, which is too low, leads to considerably higher overall costs. Also for production lot sizes, too low lot sizes have shown a significantly lower performance than too high lot sizes. With respect to tardiness costs, the results indicate that higher tardiness costs lead to a better performance of safety stock relaxation. Concerning utilization we find that most improvement potential is gained for medium to high utilization. However, a very high utilization leaves only little space for capacity balancing and, therefore, a lower improvement potential is reported.

The performance comparison of the three developed safety stock relaxation methods shows that method 1 and method 3 perform similar while method 2 shows the worst performance. Even though, the performance of method 1 (leading to fewer safety stock relaxation occurrences without memorizing them) and method 3 (implying more relaxation occurrences but memorizing them) are similar, they lead for different system settings to different results. For further research this implies that both methods could be applied and combined with further actions for capacity balancing.

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. The robustness of the solutions, with respect to changes in utilization or machine failure behavior, could also be investigated. Additionally, other methods for capacity load balancing, e.g., lotsize adaption or alternative routings could be implemented and the their performance could be compared to the safety stock relaxation.

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