Material and Capacity Requirements Planning with dynamic lead times.

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Material and Capacity Requirements Planning with dynamic lead times

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Traditional MRP does not consider the finite capacity of machines and assumes fixed lead times. This paper develops an approach (MCRP) to integrating capacity planning into material requirements planning. To get a capacity feasible production plan different measures for capacity adjustment such as alternative routeings, safety stock, lot splitting and lot summarization are discussed. Additionally, lead times are no longer assumed to be fixed. They are calculated dynamically with respect to machine capacity utilisation. A detailed example is presented to illustrate how the MCRP approach works successfully.

Keywords: MRP, Material Requirements Planning, capacity planning, dynamic lead times

1. Introduction

Conventional enterprise resource planning (ERP) material planning methods are based on material requirements planning (MRP), a production planning system developed by Orlicky (1975). The MRP steps for each level in the bill of material (BOM), beginning with the end items, are netting, lot sizing, offsetting and the BOM explosion (see Figure 1). Two of the most important weak points of MRP are the assumptions of infinite machine capacity and of production lead times which are constant or depend on lot size, processing and setup time. In practice, lead times depend on many factors such as machine utilization, lot size, inventory and dispatching rules and are thus variable. Kanet (1986) shows that using fixed lead times results in over-planning of inventory at every level.

Ignoring finite machine capacity leads to capacity infeasible schedules which have to be revised by the user. Although the capacity requirements planning (CRP)

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function in some MRP II packages provides some assistance (see Harl 1983, Nagendra et al. 1994), this is a very time consuming procedure. Another alternative is the implementation of a shop floor control (SFC) system. But SFC systems are not able to solve problems that have been created at the higher MRP planning level (Bakke and Hellberg 1993, Taal and Wortmann 1997). Ram et al. (2006) try to deal with unexpected shortages by using a flexible BOM instead of traditional methods like safety stocks and safety lead times. Chen et al. provide a capacity requirements planning system for twin Fabs of wafer fabrication. They adjust capacity to the actual equipment loading but there is no capacity threshold.

Choi and Seo (2009) use capacity-filtering algorithms for flexible flow lines to convert an infinite-capacity loading-profile to a finite-capacity loading-profile. This rather theoretical approach needs some adjustments (additional constraints, integration of dispatching rules, etc.) to deal with real-life problems. A finite-capacity procedure for a Belgian steel company has been developed by Vanhoucke and Debels (2009) in which a multi-objective function consisting of five different cost functions is minimized under consideration of very company specific constraints.

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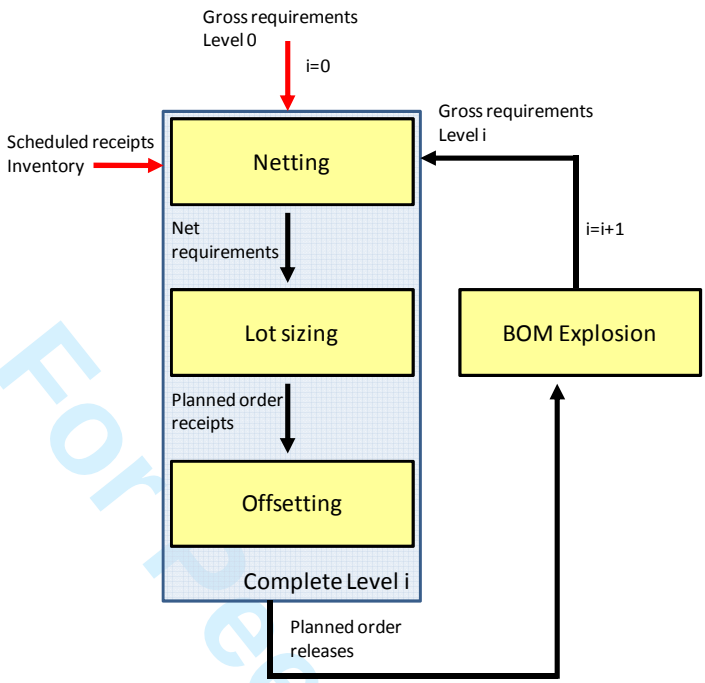

Figure 1. Traditional Material Requirements Planning

It is desirable to prevent capacity problems at the MRP calculation stage using an integrated approach of MRP and capacity planning. There are some research works that address this problem. Billington and Thomas (1983, 1986) formulated linear programming (LP) and mixed integer programming (MIP) models for capacity-constrained MRP systems. Tardif (1995) developed an LP model for multiple products with the same routeing (MRP-C).

Sum and Hill (1993) present a method that determines the release and due dates of production orders while taking capacity constraints into account. Their algorithm splits or combines production orders to minimize setup and inventory cost. Taal and Wortmann (1997) focus on solving capacity problems using different scheduling techniques like alternative routeing, splitting lot sizes, using safety stocks and backward shift of late orders.

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Pandey et al. (2000) point out that complex algorithms are often not easily understood by the planner and so they have developed a less mathematically complicated system for finite capacity MRP (FCMRP), which is executed in two stages. First, capacity-based production schedules are generated and then, in a second step, the algorithm produces an appropriate material requirements plan to satisfy the schedules obtained from the first stage. The model is restricted to lot for lot as the only possible lot sizing rule and there is a single resource for each part type.

Wuttipornpun and Yenradee (2004) study a FCMRP system where they use a variable lead time for MRP depending on the lot size, processing and setup time. After scheduling jobs they reduce capacity problems by using alternative machines if possible and adjusting the timing of jobs (starting the jobs earlier or delaying them). Limitations of this model are: Bottleneck machines produce only one part, lot-for-lot is the only lot sizing rule which is allowed and there is no overlap of production batches. A further development of this approach is TOC-MRP (Wuttipornpun and Yenradee 2007). With similar limitations the TOC philosophy is adopted in FCMRP which results in a better performance compared to FCMRP.

Commercially available FCMRP software uses two different approaches for including finite capacity: pre/post-MRP analysis and finite capacity scheduling (Nagendra and Das 2001). Neither of them resolves the capacity problem during the MRP run itself. Additionally computational effort increases substantially and so Lee et al. (2009) proposed parallelising the MRP process and using a computational grid which can exploit idle computer capacity.

Kanet and Stößlein (2010) describe 'Capacitated ERP' (CERP) – a variation of MRP that takes resource capacity into account before exploding requirements to

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lower level components. The model is limited to one-stage production, single-level BOM, single resource and no backorders.

The main approaches of MRP and capacity planning are summarized in Table 1. As you can see, considering finite capacity in Material Requirements Planning is an old issue in production research but one which has not yet been solved satisfactorily. Theoretical scheduling algorithms cause high calculating times for real word problems and are not easy for planners to understand. MRP-CRP, MRP-SFC and FCMRP approaches are also very time-consuming and attempt to solve the capacity problem after an MRP run. Research contributions which try to integrate capacity constraints into MRP are often limited to simple production environments.

Table 1. Main approaches of MRP and finite capacity planning

Approach	References	Limitations
Traditional MRP	Orlicky (1975)	fixed lead times, infinite capacity
MRP- CRP	Harl (1983)	identification of capacity problems after an MRP run, considerable participation of planner is necessary
MRP-SFC	Taal and Wortmann (1997)	capacity problems are not solved on MRP level
FCMRP	Pandey et al. (2000)	capacity problems are not solved on MRP level, lot sizing: only lot-for-lot, single resource for each part type
	Wuttipornpun and Yenradee (2004)	capacity problems are not solved on MRP level, lot sizing: only lot-for-lot, bottleneck machine: one part type
Finite capacity scheduling algorithms	Choi and Seo (2009)	flexible flow line, theoretical approach, constraints for real-life problems are missing
	Vanhoucke and Debels (2009)	company specific constraints
MRP and integrated capacity planning	Billington and Thomas (1983)	mathematical programming formulation of the problem, high computational effort for real-life problems
	Tardif (1995)	same routeing for all products
	Sum and Hill (1993)	capacity-sensitive lot sizing with complex algorithms (not easy for planners to understand, high computational effort for real-life problems)
	Taal and Wortmann (1997)	fixed lead times
	Kanet and Stößlein (2010)	one-stage production, single-level BOM, single resource, no backorders

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This paper aims to modify traditional MRP in two directions:

(1) by integrating capacity planning in the MRP run at each level in the BOM.

(2) by using variable lead times

For capacity adjustment, different measures like alternative routeings, safety stocks, adjusting lot sizes and adding capacity are applied in a predefined sequence. Lead times are not predefined fixed parameters. They are calculated dynamically, dependent on lot sizes, inventory and required machine capacity. The presented approach can handle multiple products, multiple resources, multi-stage production and multi-level BOM. There is no restriction concerning the lot sizing rule. As in traditional MRP all lot sizing rules can be used. An advantage of this approach in practice is that it is based on the well-known MRP methodology. Dynamic lead times and finite capacity are integrated at every stage of the MRP run to reduce the shortcomings of MRP.

The paper is organized as follows. The integration of capacity planning is described in Section 2, where each step is explained in detail. Section 3 illustrates the approach with a numerical example. The conclusions are stated in Section 4.

2. Integrating capacity planning into the concept of MRP

In this section the basic ideas of integrating capacity requirements planning as well as capacity adjustment into material requirements planning (MRP) are presented.

In the traditional MRP approach the items in the bill of material (BOM) are sorted in levels according to the rule that items consist only of items from a higher level, whereby end items (that are not part of any other items) are placed at level 0 (low level code). In Figure 2 the steps of Material and Capacity Requirements

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Planning (MCRP) are described. As in traditional MRP the MCRP starts with the gross requirement of end items usually defined by the master production schedule. The level index i is initialized with 0. For all items of level i netting and lot sizing are performed. After completing level i the capacitating for all items and machines of level i is executed. Furthermore, adjusted available capacity and capacity required dynamic lead times for offsetting are determined in the capacitating step. This dynamic lead time takes projected inventory, planned orders, scheduled receipts, released open orders and machine loading into account. After completing the capacitating for level i the offsetting is performed for all end items. The next step is the BOM explosion as in traditional MRP. The gross requirements for the next level $i+1$ are defined by the planned order releases of levels with indices less than or equal to i. Set $i = i+1$ and start the calculation for the next level. The procedure has finished when all levels have been executed. After this overview all steps are described in more detail.

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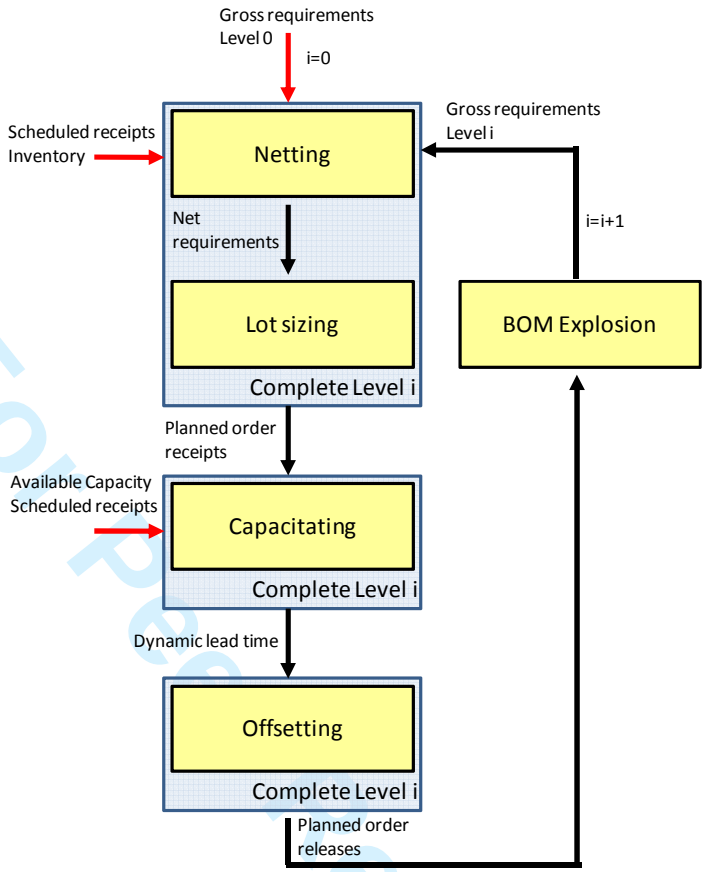

Figure 2. Material and Capacity Requirements Planning (MCRP)

2.1. Netting

In the netting step, the net requirements are determined by taking into account the gross requirements, scheduled receipts and inventory. The gross requirements for the end items are predefined by the master production schedule. The gross requirements for sub items are set by the bill of material explosion during MCRP. Scheduled receipts are converted to planned order receipts and may be released or not released to production. Sub items needed for scheduled receipts are allocated in stock or taken from stock. Netting is performed as in traditional MRP. Net requirements are calculated under consideration of projected inventory, safety stock and gross requirements. A more sophisticated approach can take dynamic planned safety stocks

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into account as Kanet et al. (2010) suggest in their work. Netting is supported by Table 2.

Table 2. MCRP table for one item

Period	1	2	3	4	5	6	7	8	9	…
Gross requirements			from MPS or see BOM explosion							
Scheduled receipts			see convert an order							
Projected inventory			see netting							
Net requirement			see netting							
Planned order receipts			see lot sizing							
Calculated lead time $(l_{j,k})$			see capacity planning							
Planned order releases			see offsetting							

2.2. Lot sizing

To trade off changeover cost against holding cost a lot sizing rule is applied. In this approach all known lot sizing methods for MRP can be applied. If there are no essential changeover costs or if enough excess capacity is available the Lot for Lot strategy is recommended to reduce inventory (see Haddock and Hubicky 1989). In all other cases dynamic rules, for instance Groff (see Groff 1979) or Fixed Order Period (see Hopp and Spearman 2008) should be applied. The results of the lot sizing are the due dates for the planned orders and the batch size of the orders (the two are called planned order receipts). A planned order receipt of 10 items in period 5 means, that it is planned to finish 10 items by the end of period 5. Lot sizing is also supported by Table 2.

2.3. Capacity planning

This step is compared to MRP new and is applied for all items manufactured in-house. Purchased parts, for which subcontracting in the sense of capacity buying is performed, can be treated as parts manufactured in-house, whereby information of the available capacity from the supplier is necessary. All other purchased items are

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treated with predefined planned lead times as in traditional MRP (and no capacity planning is performed). The capacity planning consists of two main steps: capacity adjustment and calculation of the dynamic lead time and the release dates.

2.3.1. Capacity adjustment

The available capacity is based on shift models, working time and number of workers and may be adjusted. Scheduled receipts are determined by the number of items and a due date. The required capacity for scheduled receipts can be calculated under consideration of lot sizes, processing times and set up times and will be referred to as scheduled capacity receipts. In analogy the required capacities of planned order receipts are referred to as planned capacity receipts. The cumulated values are calculated by the sum over the time periods. The cumulated required capacity is defined as the sum of the cumulated scheduled capacity receipts and the cumulated planned capacity receipts. The free cumulated capacity is the difference between the cumulated available capacity and the cumulated required capacity and must be non-negative to ensure capacity feasibility. The calculation is supported by Table 3, the explanation of the capacity envelope follows in the chapter 2.3.2.

Table 3. MCRP table for one capacity group

Period		1	2	3	4	5	6	7	8	9	…
Available capacity											
Scheduled capacity receipts	$(capSR)$										
Planned capacity receipts	$(capPO)$										
Cumulated available capacity	(a_i)										
Cumulated required capacity	(r_i)										
Free cumulated capacity	$(a_i - r_i)$										
Capacity envelope	(e_i)										

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If the planned capacity receipts are higher than the net available capacity this is not necessarily a reason for a capacity infeasible schedule because the scheduled capacity receipts as well as the planned capacity receipts allocate the whole required capacity to the due date (but it may be produced in earlier periods). To achieve capacity feasibility, the cumulated available capacity must be high enough to cover the cumulated required capacity.

If the cumulated required capacity is higher than the cumulated available capacity, there is a capacity problem and no capacity feasible production schedule can be found (see Hübl et al. 2009). The following countermeasures can be considered:

(1) Alternative routeings

(2) Relaxing safety stocks

(3) Applying lot splitting with consecutive processing

(4) Applying lot summarization

(5) Adjusting available capacity by adding capacity (over time, more staff, etc.)

(6) Accepting tardiness respectively by backlog or postponing gross requirement in the master plan

The first measure for decreasing required capacity is choosing alternative routings (see Taal and Wortmann 1997). Production orders, planned on the bottleneck resource in overloaded periods, should be planned on alternative resources if it is possible to unload the bottleneck resource. If the capacity of alternative resources is short, lot splitting with simultaneous processing using alternative resources is suggested.

Measures (2), (3) and (4) require starting the netting and lot sizing with changed parameters on the current level. For the further discussion let T be the latest period at which a capacity problem is given (i. e. cumulated required capacity is higher than the cumulated available capacity).

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Relaxing safety stock is a measure which is also proposed by Taal and Wortmann (1997) but with a lower priority than is used in this approach. It can easily be performed by running the netting and lot sizing with safety stocks equal to zero as long as the net requirements have an influence on the capacity problem. More accurately, all net requirements which are combined to planned order receipts with due dates before or equal to T should be calculated assuming safety stock to be zero. All others should be calculated with the predefined safety stock. This postponement can solve or improve the capacity problem, reduce the inventory and increase the danger of stock outs because of unforeseen events (machine breakdown, scrap, rework, demand fluctuation, etc.).

Lot splitting with consecutive processing is very useful if only short or no set up time is required and net requirements of more than one period are combined to one batch. To execute lot splitting, lot sizing is based on an adjusted rule for all batches which combine net requirements with due dates before T and with due dates after T. All these batches are divided into two lots. The first lot combines all net requirements with due dates earlier than or equal to T and the second the remaining net requirements. The second batch should be planned as late as possible to reduce inventory. Lot splitting can solve or improve the capacity problem, reduce inventory and increase change over costs.

Lot summarization can be useful if there is an essential change over time and the same item is planned in different orders, all with due dates before T. In this case all planned orders with due dates before or equal to T are combined to one new planned order receipt. Lot summarization can solve or improve the capacity problem, increase inventory and reduce changeover costs.

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If the first four mentioned measures do not solve the capacity problem, additional capacity (e.g. over time, more staff, additional shift, etc.) is needed within the allowed and possible capacity boundaries. In general, this measure should solve the capacity problem or the capacity problem has to be accepted, resulting in backlog. Of course additional costs are thereby incurred.

If all measures do not solve the capacity problem, tardiness of at least one job has to be accepted. In order to ensure a consistent procedure a reduction or a postponement of gross requirements in the master plan is recommended whereby it is necessary to start the whole procedure again at level zero. One way to find suitable master plan orders (for reduction or postponement) is to apply pegging (see Hopp and Spearman 2008). The following steps have to be performed: Step 1: Searching the due date T1 of master plan orders which lies the furthermost in the future and is connected with a planned order at the current level whose due date is earlier than or equal to T. Step 2: Select master plan orders with due dates before T1 which are not important (e.g. a stock order, customer acceptance of later delivery date, bad contribution margin and no strategically unimportant order from a C customer, etc.) and in which required capacity at the current level is greater than the missed capacity, and postpone them until after T1 or delete them.

For the capacity adjustment a specific product sequence is defined. Depending on the importance of different managerial goals, one of the following proposed criteria can be chosen to build up the sequence.

- importance of service level (starting with the item with the least important service level)
- holding cost (starting with the item with the highest holding cost per unit)

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For measures (2) and (3) the sequence should be applied as defined above. For measure (4) the sequence of the service level and the holding cost criteria should be applied in the reversed order.

The described measures for capacity adjustment are applied in the order in which they are listed above and for the products in the predefined sequence. If the capacity problem is solved, then the capacity adjustment procedure has to be stopped. If the measures applied to the current level do not lead to capacity feasibility, the measures can be applied to lower levels. After applying these measures, we assume that the cumulated required capacity is less than the cumulated available capacity. Furthermore, if possible (e.g. at the end of the planning horizon) the available capacity should be reduced.

2.3.2. Calculation of dynamic lead times and release dates

Now the second step in capacity planning is performed. This is the calculation of the dynamic lead times and the release dates. The lead time calculation is based on a predefined product sequence, starting with the item which should be produced as late as possible. This can be a different sequence to the one used for capacity adjustment. In order to build up the sequence one of the following criteria can be used:

- holding cost (starting with the item with the highest holding cost per unit)

  This criterion reduces inventory holding costs.
- set up (starting with the item which should be produced last)

  This criterion reduces changeover costs if set up times depend on the sequence.
- tardiness (starting with the item with the lowest tardiness penalty cost)

  This criterion reduces tardiness for items with the highest penalty costs.

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The predefined sequence should be consistent over all levels supporting a first-in-first-out principle along the routeing.

To prepare the dynamic lead time calculation the capacity envelope is determined (see also Table 3). The capacity envelope is the cumulated capacity usage based on the cumulated required capacity. The envelope is piecewise parallel (vertical translation) to the cumulated available capacity or parallel to the time axis and is the lowest possible envelope above the cumulated required capacity. In Figure 3 the capacity envelope is illustrated as an example.

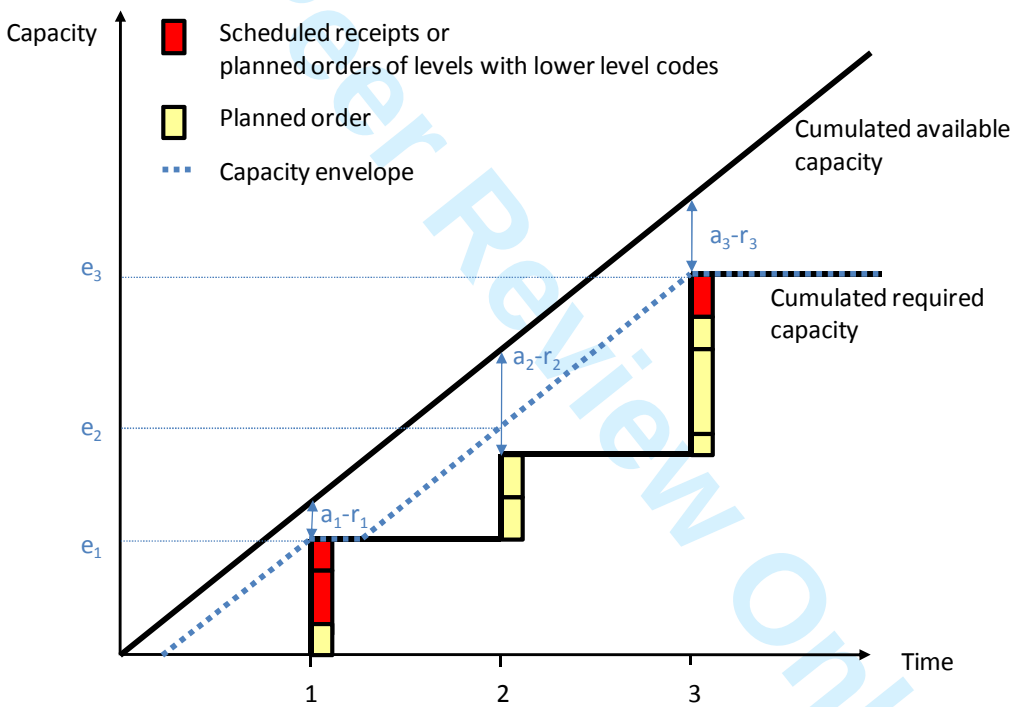

Figure 3. Capacity envelope determination

To get the value e_i of the capacity envelope at period i it is necessary to determine the minimal distance $\min(a_i - r_i, a_{i+1} - r_{i+1}, ..., a_N - r_N)$ from cumulated available capacity to cumulated required capacity in the periods i, i+1, ... n. Subtracting this minimal distance from the cumulated available capacity in period i yields the capacity envelope at period i. Between the times i-1 and i the capacity

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envelope is a piecewise linear function which is constant and equal to the value of the capacity envelope in period i-1 or a linear function of which the slope is the difference $a_i - a_{i-1}$ between the cumulated available capacity values in period i and period i-1. The major value of these two functions determines the value of the capacity envelope. In the following formula the calculation of the envelope is defined.

$$e_i = a_i - \min(a_i - r_i, a_{i+1} - r_{i+1}, \ldots, a_N - r_N) \quad (1)$$

$$e(t) = \max\left(e_{i-1}, e_i + \left(a_i - a_{i-1}\right)\left(t - i\right)\right), \text{ for } t \in \left]i-1, i\right]$$

e_i	$\cdots$	discrete time capacity envelope in period i
$e(t)$	$\cdots$	continuous time capacity envelope with respect to time t
r_i	$\cdots$	cumulated required capacity in period i
a_i	$\cdots$	cumulated available capacity in period i
N	$\cdots$	number of periods in the planning horizon

The idea of release date determination is explained in Figure 4. The cumulated required capacity r_j is reduced by the scheduled receipts and planned orders of levels with lower level codes ($capSR_j$) and by the first k-ranked planned orders of the current level based on the criteria explained above ($\sum_{i=1}^{k} capPO_{ji}$). This capacity value $c_{j,k}$ for the k-ranked planned order in period *j* is described by the following formula:

$$c_{j,k} = r_j - capSR_j - \sum_{i=1}^{k} capPO_{ji}, \text{ for j} = N, N-1, \ldots 1 \text{ and } k = 1, \ldots K_j \quad (2)$$

$c_{j,k}$	$\cdots$	cumulated required capacity to period j-1 plus all orders with due date j and not one of the first k-ranked
$capSR_j$	$\cdots$	capacity for the scheduled receipts in period j and planned orders of levels with lower level code
$capPO_{ji}$	$\cdots$	capacity for the planned order with due date j and i-ranked
r_j	$\cdots$	required cumulated capacity to period j
N	$\cdots$	number of periods in the planning horizon
K_j	$\cdots$	number of planned orders with due date j

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Now the capacity value $c_{j,k}$ is intersected with the capacity envelope $e(t)$ for determining the lead time $l_{j,k}$ and the release date $t_{j,k}$ for the k-ranked planned order. The next formula provides detailed information for calculating these two values.

$$l_{j,k} = \frac{e_j - c_{j,k}}{a_j - a_{j-1}} \qquad (3)$$

$$t_{j,k} = j - l_{j,k}$$

$l_{j,k}$ ⋯ calculated lead time of the k-ranked planned order with due date j

$t_{j,k}$ ⋯ release date to the k-ranked planned order with due date j

$c_{j,k}$ ⋯ cumulated required capacity to period j-1 plus all orders with due date j and not one of the first k-ranked

a_j ⋯ cumulated available capacity to period j

e_j ⋯ capacity envelope in period j

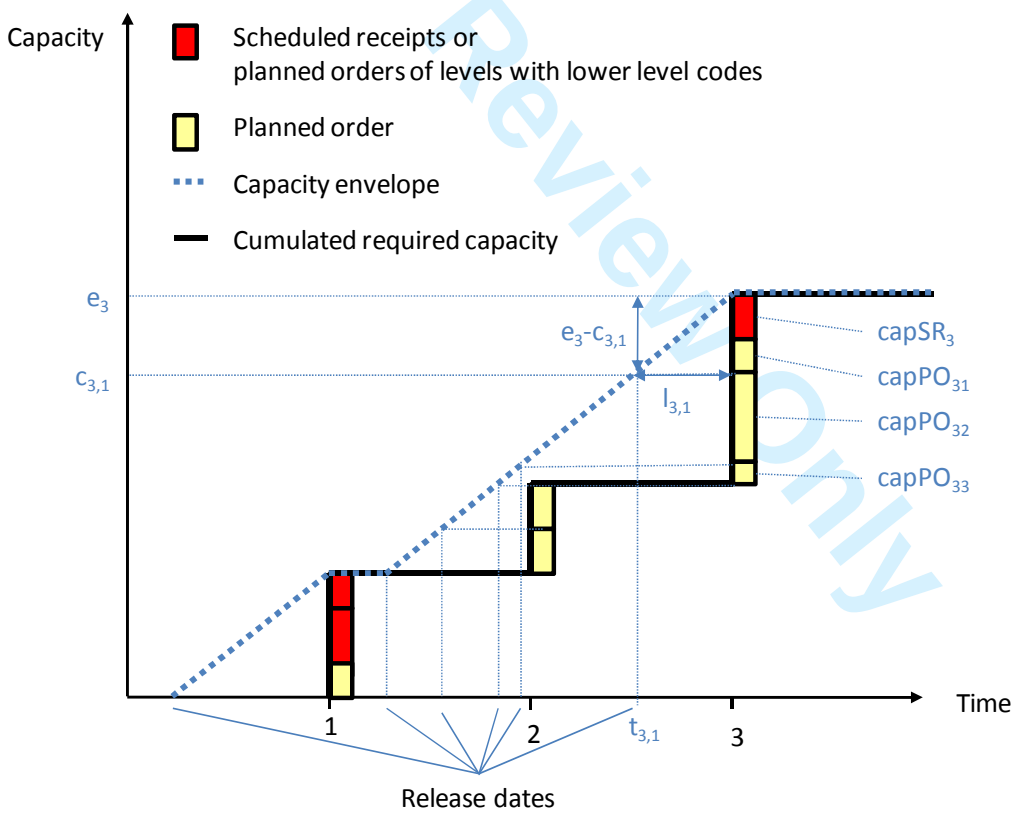

Figure 4. Release date determination

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The determination of the lead time and the release date for the first-ranked order in period 3 is visualized in Figure 4. For the release date calculation in the whole planning horizon it is necessary to start at the furthermost future time period within the planning horizon. If the release date of the first-ranked planned order of the last period in the planning is determined, the capacity value is reduced by the next planned order. This value is intersected with the capacity envelope and so on. If this procedure is completed on the last due date, then the next earlier due date is chosen. The scheduled capacity receipts are subtracted first and then the calculation of the release date is performed with the predefined sequence again until all planned orders are finished. The calculated lead time should be entered in Table 2. The release date for the k-ranked planned order is the latest possible time when the available capacity between the release date and the due date covers the capacity needed to produce the first k-ranked planned orders as well as the scheduled receipts.

2.3.3. Building machine groups

The combination of several machines into one machine group is useful but requires some adjustment of the calculation procedure for the dynamic lead time. If n equivalent machines are combined into one group, the group available capacity is of course the available capacity of the individual machine multiplied by n. But if an order is produced only on one machine and is not split among several machines simultaneously, the order processing time is not equal to required capacity over available group capacity. We have to take into account the number of machines combined into one machine group. Hence the correct calculation of the order processing time is: order processing time is equal to required capacity multiplied by n over available group capacity. Consequently, to determine the dynamic lead time for a machine group the following steps should be performed:

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(1) Group the scheduled receipts and the planned orders in *n* order groups (*n* is the number of equivalent machines)

(2) Calculate the release dates for each order group according to the above formula using required capacity multiplied by *n* instead of required capacity.

To find the order groups, the predefined order sequence (the same as for the lead time calculation) should be taken into account. Furthermore, the required capacity for each group should be approximately the same. The first *n* orders should be taken (starting with the scheduled receipts and then the ranked planned orders) and allocated to the *n* groups. The order groups should be arranged by ascending rank in required capacity. The next *n* orders should be taken, arranged by descending rank and allocated to the group. This should be applied to the next *n* orders and so on until all orders have been allocated.

2.4. Offsetting

In traditional MRP the release date is equal to the due date minus the predefined lead time or, in more advanced systems, equal to a fixed lead time part and the dynamic lead time part taking into account the lot size and processing time. In the MCRP approach the offsetting is based on the dynamic determination of the release date according to Equation (3). Consequently, the planned order release is determined by rounding down the calculated release date. In Table 2 the row "planned order releases" supports this calculation. A planned order release of 10 items in period 5 means that the release of a production order of 10 items is planned just before the beginning of period 5 (at the end of period 4).

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2.5. BOM Explosion

Based on planned order receipts the gross requirements for the next level are calculated by the bill of material explosion. This is done as in traditional MRP. The release date of the planned order receipt (of the lower level item) is equal to the due date of the gross requirements (of the higher level item). In Table 2 all item-related calculations are supported.

2.6. Predefined parameters for the MCRP

To summarize the MCRP approach the predefined parameters for customizing the system are listed in the following table. For a better comparison with MRP the parameters for each step are specified for both procedures.

Table 4. Predefined parameters for MCRP and MRP

Step	MCRP	MRP
Netting	safety stock	safety stock
Lot Sizing	lot sizing rule	lot sizing rule
Capacity Planning	allowed countermeasures for capacity problems, allowed available capacity levels, capacity boundary, product sequence for capacity adjustment, product sequence for lead time calculation, processing times, setup times, machine item allocation	lacks in traditional MRP
Offsetting	no predefined parameters (dynamic lead time is calculated)	planned lead time
BOM Explosion	BOM	BOM

2.7. Converting a planned order into a production order

After the MCRP run, planned orders have to be converted into scheduled receipts, sometimes called production orders for in house manufactured items and purchase orders for purchased items. This conversion causes scheduled receipts in the next MCRP run and a reservation of the sub items needed, leading to a reduction of the

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available on hand inventory of the sub items. As in traditional MRP, the conversion should be done at the latest possible time to ensure customer demand oriented production or purchasing orders. Taking this rule into account, the release date of a scheduled receipt is in the past or in period 1.

2.8. Releasing an order

A converted planned order (scheduled receipt) has to be released to production (released scheduled receipt) meaning that the production staff are allowed to start the production process. This release causes a removal of the sub items from the stock and a cancelation of the reservation made at the time of conversion. Similar to traditional MRP the release should be done at the latest possible time and after ensuring the availability of all sub items, tools and resources needed.

For MCRP we suggest that conversion and release should be performed simultaneously at the latest possible time (just before the release date) and after ensuring the availability of all sub items, tools and resources needed.

2.9. Dispatching

After release production can be started. In general there are several released production orders waiting for processing. To prioritize production orders the earliest due date rule is recommended to minimize total tardiness (see Baker 1984), whereby the due date refers to the due date of the corresponding planned order (Modified Due Date MDD). If there is more than one order with the same due date the reverse predefined product sequence (for the lead time calculation) is used additionally. By applying this rule a good adherence to the plan should be achieved.

It is important to note that the task of capacity planning in MCRP is not detailed scheduling in the sense of calculating exact start and completion times. The

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objective is to support material requirements planning by ensuring capacity feasible plans (because of the fact that cumulated available capacity is higher than cumulated required capacity) and lowest possible inventory (because of shortest capacity feasible lead times).

As a result of the planning procedure it may be possible that a production order lies within another production order (release date A ≤ release date B ≤ due date B ≤ due date A) with the same item produced. In this case the summarization of the two orders is recommended.

2.10. Completing the order

After finishing an order the items should be booked to the inventory in real time and the released scheduled receipt has to be deleted in real time. For orders which take a long time it is useful to partly book the items to inventory and to simultaneously reduce the scheduled receipts in order to ensure a realistic cumulated required capacity. Backlog and orders which are late are added to the scheduled receipts in period one.

3. Illustration of the concept

The following example is provided to show how the MCRP approach may be used. In this example two end items A and B are considered. Item A consists of one item X and one item Y. Item B is assembled from one item Y and one item Z. Table 5 delivers necessary input data for all items. The available capacity per period of the two machines M0 and M1 is 420 TU. The predefined product sequence for capacity adjustment and lead time calculation is A, B (for M0) and X, Y, Z (for M1).

Table 5. Input data for all items

Item	A	B	X	Y	Z

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Safety stock	10	10	10	10	10
Lot sizing	FOP 3	FOP 3	FOP 3	FOP 3	FOP 3
Processing time	14	9	7	5	8
Setup time	45	40	30	35	20
Allocated machine	M0	M0	M1	M1	M1
On hand inventory	19	65	50	50	59

In the planning horizon of 10 periods the gross requirements of the MPS and the scheduled receipts are listed in Table 6. With this information projected inventory and net requirements can be computed as in traditional MRP under consideration of the safety stock. For determination of planned order receipts the lot sizing rule fixed order period (FOP 3) is applied.

Table 6. MCRP table for A and B

Item A

Period		1	2	3	4	5	6	7	8	9	10
Gross requirements		10	10	10	20		30	10	10	10	10
Scheduled receipts		20									
Projected inventory	19	29	19	9							
Net requirements				1	20		30	10	10	10	10
Planned order receipts				21			50			20	

Item B

Period		1	2	3	4	5	6	7	8	9	10
Gross requirements		20	20	20	40	20	20	20	20	20	20
Scheduled receipts											
Projected inventory	65	45	25	5							
Net requirements				5	40	20	20	20	20	20	20
Planned order receipts				65			60			40	

By using the MCRP table for machines cumulated available capacity and cumulated required capacity are determined. The difference cumulated available capacity minus cumulated required capacity is equal to the free cumulated capacity. A negative sign indicates a capacity problem in periods 3 and 6. For capacity adjustment the countermeasures “relax safety stock” and “lot splitting” are applied in detail.

Table 7. MCRP table for M0

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Machine M0

Period	1	2	3	4	5	6	7	8	9	10
Available capacity	420	420	420	420	420	420	420	420	420	420
Scheduled capacity receipts	325									
Planned capacity receipts			964			1325			725	
Cumulated available capacity	420	840	1260	1680	2100	2520	2940	3360	3780	4200
Cumulated required capacity	325	325	1289	1289	1289	2614	2614	2614	3339	3339
Free cumulated capacity	95	515	-29	391	811	-94	326	746	441	861
Capacity envelope										

3.1.1. Capacity adjustment by relaxing safety stock

We start relaxing safety stock with item A according to the predefined sequence. The latest period at which the capacity period is at hand is T = 6. As the planned order of item A in period 6 summarizes net requirements until period 8, safety stock should be relaxed until period 8. The calculation of the planned order receipts with relaxed safety stock can be found in Table 8. Relaxing safety stock only for item A does not lead to a capacity feasible production plan, so the same procedure is followed for item B, where safety stock should also be relaxed until period 8. Table 9 shows that now the cumulated required capacity is always less than cumulated available capacity and the capacity envelope can be computed according to Equation (1). Now for the end items A and B the determination of dynamic lead times with Equation (3) can be carried out to get planned order releases. For example the lead time calculation for the planned order receipts of item A in period j = 4 is shown in Equation (4) . The values of the required cumulated capacity, the cumulated available capacity and the capacity envelope are taken from Table 9. There are no scheduled receipts of item A in period 4 and only one planned order of 41 pieces. The capacity of this planned order is received under consideration of the processing and setup time of item A (see Table 5).

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$$c_{4,1} = r_4 - capPO_{41} = 1659 - (14 \times 41 + 45) = 1040 \quad (4)$$

$$l_{4,1} = \frac{e_4 - c_{4,1}}{a_4 - a_3} = \frac{1674 - 1010}{1680 - 1260} = 1.5095$$

Table 8. MCRP table for A and B with relaxed safety stock

Item A

Period		1	2	3	4	5	6	7	8	9	10
Gross requirements		10	10	10	20	0	30	10	10	10	10
Scheduled receipts		20									
Projected inventory	19	29	19	9	-11						
Net requirements					11		30	10	10	20	10
Planned order receipts					41			40			10
Calculated lead time					1.5			1.4			0.4
Planned order releases				41			40				10

Item B

Period		1	2	3	4	5	6	7	8	9	10
Gross requirements		20	20	20	40	20	20	20	20	20	20
Scheduled receipts											
Projected inventory	65	45	25	5	-35						
Net requirements					35	20	20	20	20	30	20
Planned order receipts					75			70			20
Calculated lead time					1.7			1.6			0.5
Planned order releases				75			70				20

Table 9. MCRP table for M0 with relaxed safety stock

Machine M0

Period	1	2	3	4	5	6	7	8	9	10
Available capacity	420	420	420	420	420	420	420	420	420	420
Scheduled capacity receipts	325									
Planned capacity receipts				1334			1275			405
Cumulated available capacity	420	840	1260	1680	2100	2520	2940	3360	3780	4200
Cumulated required capacity	325	325	325	1659	1659	1659	2934	2934	2934	3339
Free cumulated capacity	95	515	935	21	441	861	6	426	846	861
Capacity envelope	414	834	1254	1674	2094	2514	2934	2934	2934	3339

The calculated dynamic lead times and explosion of the bill of material define the gross requirements for the sub items and planned order receipts for X, Y and Z are calculated in Table 10 in the same way as was performed for A and B.

Table 10. MCRP table for X, Y, Z

Item X

Period	1	2	3	4	5	6	7	8	9	10

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Gross requirements			41			40				10	
Scheduled receipts											
Projected inventory	50	50	9								
Net requirements			1			40				10	
Planned order receipts			1			40			10		

Item Y

Period		1	2	3	4	5	6	7	8	9	10
Gross requirements			116			110				30	
Scheduled receipts											
Projected inventory	50	50	-66								
Net requirements			76			110				30	
Planned order receipts			76			110			30		

Item Z

Period		1	2	3	4	5	6	7	8	9	10
Gross requirements			75			70				20	
Scheduled receipts											
Projected inventory	59	59	-16								
Net requirements			26			70				20	
Planned order receipts			26			70			20		

Comparing cumulated available and required capacity for M1 in Table 11 indicates a capacity infeasibility in period 5, which can be removed by relaxing safety stock of item X until period 7 (see Table 12 and Table 13). All in all relaxing safety stock of the items A, B and X delivers a capacity feasible production plan.

Table 11. MCRP table for M1

Machine M1

Period	1	2	3	4	5	6	7	8	9	10
Available capacity	420	420	420	420	420	420	420	420	420	420
Scheduled capacity receipts										
Planned capacity receipts		680			1475			465		
Cumulated available capacity	420	840	1260	1680	2100	2520	2940	3360	3780	4200
Cumulated required capacity	0	680	680	680	2155	2155	2155	2620	2620	2620
Free cumulated capacity	420	160	580	1000	-55	365	785	740	1160	1580
Capacity envelope										

Table 12. MCRP table for X with relaxed safety stock

Item X

Period		1	2	3	4	5	6	7	8	9	10
Gross requirements			41			40				10	
Scheduled receipts											
Projected inventory	50	50	9	9	9	-31					
Net requirements						31			10	10	
Planned order receipts						31			20		

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Calculated lead time					0,6			0,4		
Planned order releases					31			20		

Table 13. MCRP table for M1 with relaxed safety stock

Machine M1

Period	1	2	3	4	5	6	7	8	9	10
Available capacity	420	420	420	420	420	420	420	420	420	420
Scheduled capacity receipts										
Planned capacity receipts		643			1412			535		
Cumulated available capacity	420	840	1260	1680	2100	2520	2940	3360	3780	4200
Cumulated required capacity	0	643	643	643	2055	2055	2055	2590	2590	2590
Free cumulated capacity	420	197	617	1037	45	465	885	770	1190	1610
Capacity envelope	375	795	1215	1635	2055	2055	2170	2590	2590	2590

3.1.2. Capacity adjustment by lot splitting

In order to resolve the capacity problem pointed out in Table 7, countermeasure lot splitting can also be successful. Starting again with item A (compare predefined sequence) the lot in period 6 is split into two lots: one is planned in period T = 6 (lot size 30) and the other one is planned after T (lot size 20 in period 7). The MCRP table for M0 shows that after application of this measure a capacity problem still remains in period T = 3. So for item B the lot in period 3 (lot size 65) is split into two lots: one in period 3 (lot size 5) and one in period 4 (lot size 60). All details can be found in Table 14. Filling out the MCRP table for M0 again (see Table 15) shows that the capacity problem was solved and the MCRP run can be executed for the next level.

Table 14. MCRP table for A with lot splitting

Item A

Period		1	2	3	4	5	6	7	8	9	10
Gross requirements		10	10	10	20	0	30	10	10	10	10
Scheduled receipts		20									
Projected inventory	19	29	19	9							
Net requirements				1	20		30	10	10	10	10
Planned order receipts				21			30	20		20	
Calculated lead time				1.7			1.1	0.8		0.8	
Planned order releases			21			30		20		20	

Item B

Period	1	2	3	4	5	6	7	8	9	10
Gross requirements	20	20	20	40	20	20	20	20	20	20

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Scheduled receipts											
Projected inventory	65	45	25	5							
Net requirements				5	40	20	20	20	20	20	20
Planned order receipts				5	60		60			40	
Calculated lead time				1.1	1.9		1.4			1.0	
Planned order releases			5	60		60				40	

Table 15. MCRP table for M0 with lot splitting

Machine M0

Period	1	2	3	4	5	6	7	8	9	10
Available capacity	420	420	420	420	420	420	420	420	420	420
Scheduled capacity receipts	325									
Planned capacity receipts			424	580		1045	325		725	
Cumulated available capacity	420	840	1260	1680	2100	2520	2940	3360	3780	4200
Cumulated required capacity	325	325	749	1329	1329	2374	2699	2699	3424	3424
Free cumulated capacity	95	515	511	351	771	146	241	661	356	776
Capacity envelope	325	694	1114	1534	1954	2374	2699	3004	3424	3424

Table 16 and Table 17 show the MCRP tables for the sub items X, Y, Z and machine M1. In the periods 2 and 3 there is still a capacity infeasibility, which can be removed by applying lot splitting again. There is no planned order receipt of X in the first three periods so lot splitting is applied for item Y first. The lot in period 2 (lot size 136) is divided into two lots: one in period 2 with lot size 46 and the second lot in period 4 (no net requirements in period 3) with lot size 90. However this measure does not supply enough capacity reduction in period 2 and so for sub item Z the lot in period 2 is split too: one lot in period 2 (lot size 16) and one lot in period 4 (lot size 60). Table 18 shows that lot splitting of a total of four lots was successful and the result is a capacity feasible production plan.

Table 16. MCRP table for X, Y and Z

Item X

Period		1	2	3	4	5	6	7	8	9	10
Gross requirements		21			30		20		20		
Scheduled receipts											
Projected inventory	50	29	29	29	-1						
Net requirements					11		20		20		
Planned order receipts					31			20			

Item Y

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Period		1	2	3	4	5	6	7	8	9	10
Gross requirements		86			90		20	40	20		
Scheduled receipts											
Projected inventory	50	-36									
Net requirements		46			90		20	40	20		
Planned order receipts		46			110			60			

Item Z

Period		1	2	3	4	5	6	7	8	9	10
Gross requirements		65			60			40			
Scheduled receipts											
Projected inventory	59	-6									
Net requirements		16			60			40			
Planned order receipts		16			60			40			

Table 17. MCRP table for M1

Machine M1

Period	1	2	3	4	5	6	7	8	9	10
Available capacity	420	420	420	420	420	420	420	420	420	420
Scheduled capacity receipts										
Planned capacity receipts		1343		247	135	340	170	335		
Cumulated available capacity	420	840	1260	1680	2100	2520	2940	3360	3780	4200
Cumulated required capacity		1343	1343	1590	1725	2065	2235	2570	2570	2570
Free cumulated capacity	420	-503	-83	90	375	455	705	790	1210	1630
Capacity envelope										

Table 18. MCRP table for M1 with lot splitting

Machine M1

Period	1	2	3	4	5	6	7	8	9	10
Available Capacity	420	420	420	420	420	420	420	420	420	420
Scheduled capacity receipts										
Planned capacity receipts		413		1232	135	340	170	335		
Cumulated available capacity	420	840	1260	1680	2100	2520	2940	3360	3780	4200
Cumulated required capacity		413	413	1645	1780	2120	2290	2625	2625	2625
Free cumulated capacity	420	427	847	35	320	400	650	735	1155	1575
Capacity envelope	385	805	1225	1645	1780	2120	2290	2625	2625	2625

4. Conclusion

In this paper an approach for coping with the finite capacity of machines in an MRP procedure was developed (MCRP). An additional procedure, capacitating, was inserted between the steps lot-sizing and offsetting to guarantee capacity feasible production plans. To reach this result different measures for capacity adjustment have been proposed and two of them (relaxing safety stock and lot splitting) have been

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successfully applied in a detailed example. Additionally, lead times for offsetting are calculated dynamically to take lot sizes, inventory and the required machine capacity into account.

Some limitations of the proposed approach are the lack of stochastic influences and the lack of a safety lead time which could be advantageous mainly to cope with unreliability in supply (see van Kampen et al. 2010). A safety lead time can be integrated easily by adding this time into the calculation of the dynamic lead time. Furthermore there is no guarantee that the listed countermeasures lead to a capacity feasible production plan. If the application of all countermeasures is not successful, the master production schedule (MPS) has to be changed or otherwise tardiness of some jobs has to be accepted.

On the other hand some managerial goals (e.g. increasing service level, reducing holding costs, changeover costs or tardiness) can be influenced positively by choosing adequate parameters. Integrating capacity planning in an MRP run can supersede or at least reduce a time consuming revision of the schedules by the user.

In real world implementation most firms integrate traditional MRP in their ERP. Because of the weaknesses of MRP (no capacity planning and fixed lead times) the planners have to adapt the plans subsequently to ensure feasibility – this job list adaption is in general a difficult and time consuming task. The suggested approach has advantage over traditional MRP as well as MRP-CRP (Harl, 1983), MRP-SFC (Taal and Wortmann, 1997) and FCMRP (Pandey et al., 2000). The capacity planning is performed during the MRP-Run between lot sizing and offsetting, a load depending lead time is calculated and therefore in more cases than in traditional MRP capacity feasible planes are determined. Another further available development of MRP is finite capacity scheduling algorithm (for instance Billington and Thomas,

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1983; Sum and Hill, 1993; Cho and Seo, 2009) offered in Advanced Planning Systems like Detailed Scheduling in SAP/APO. General scheduling algorithms are not often used in industrial environments because of lack of understanding, missing constraints for real-life problems, deviation of the deterministic model for the stochastic real world and the long calculation times needed.

For further research material capacity requirement planning with dynamic lead times should be implemented in simulation software to test more complex scenarios and to compare the performance of MCRP with traditional MRP.

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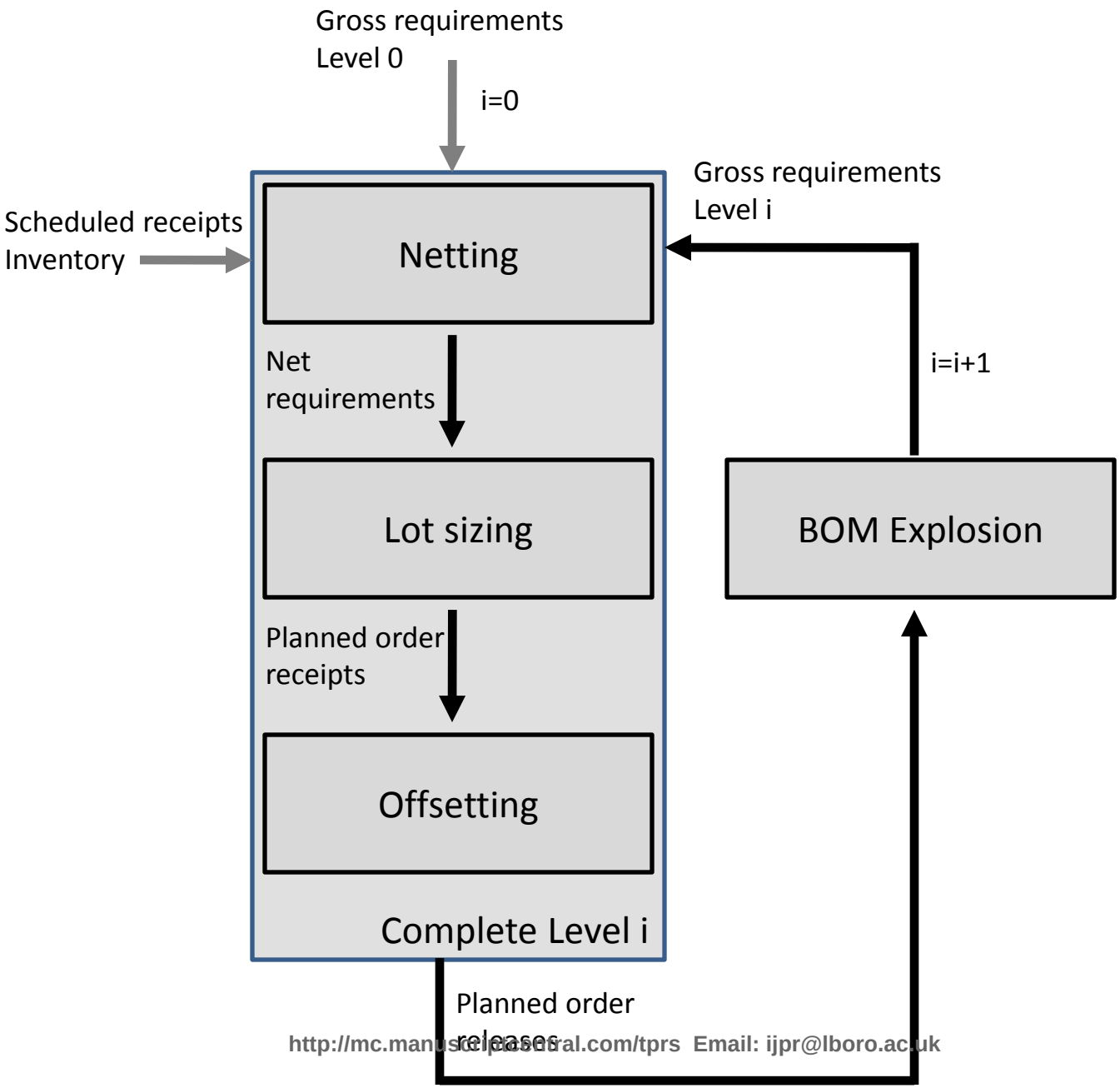
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Complete Level i
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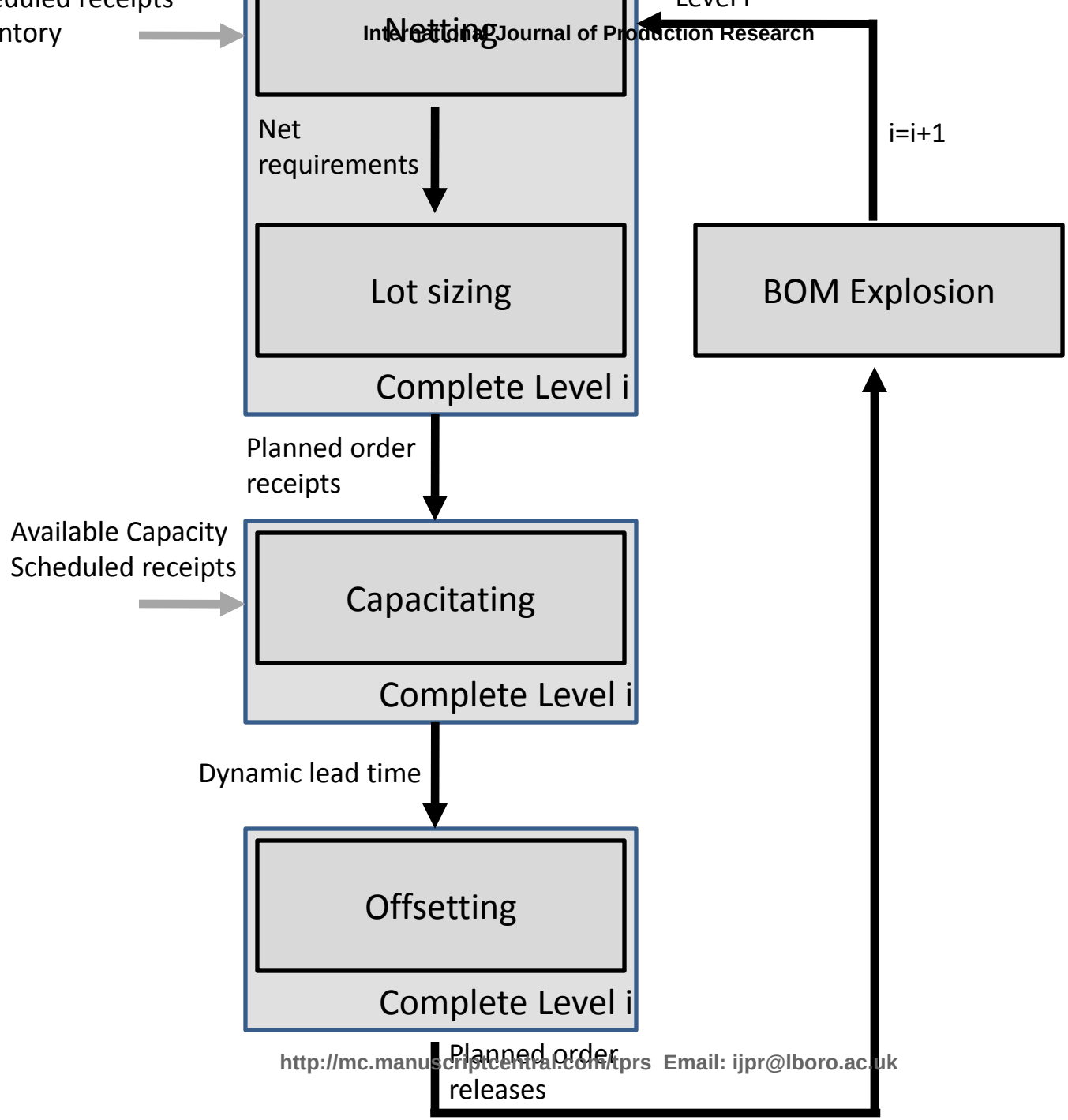
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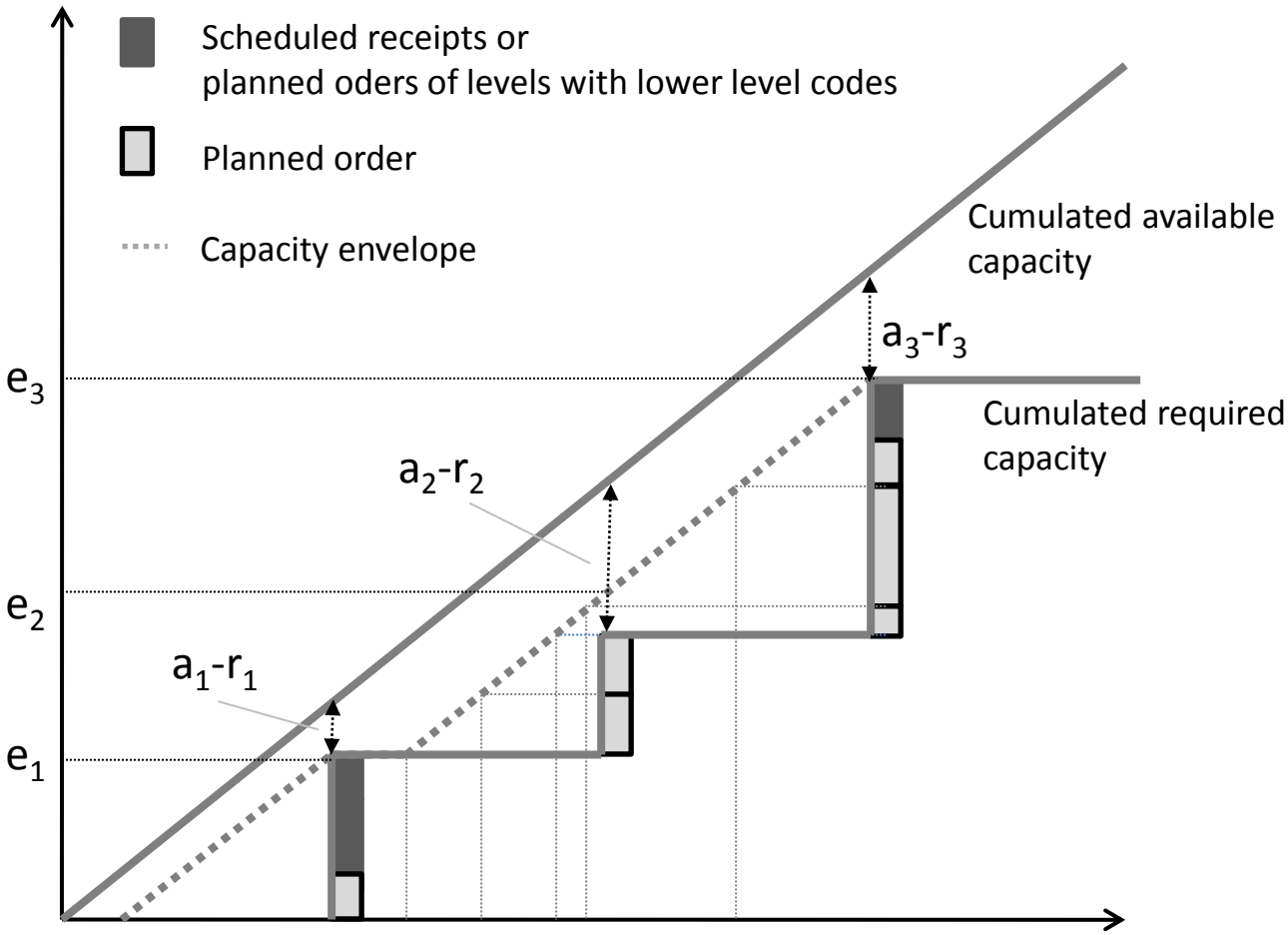
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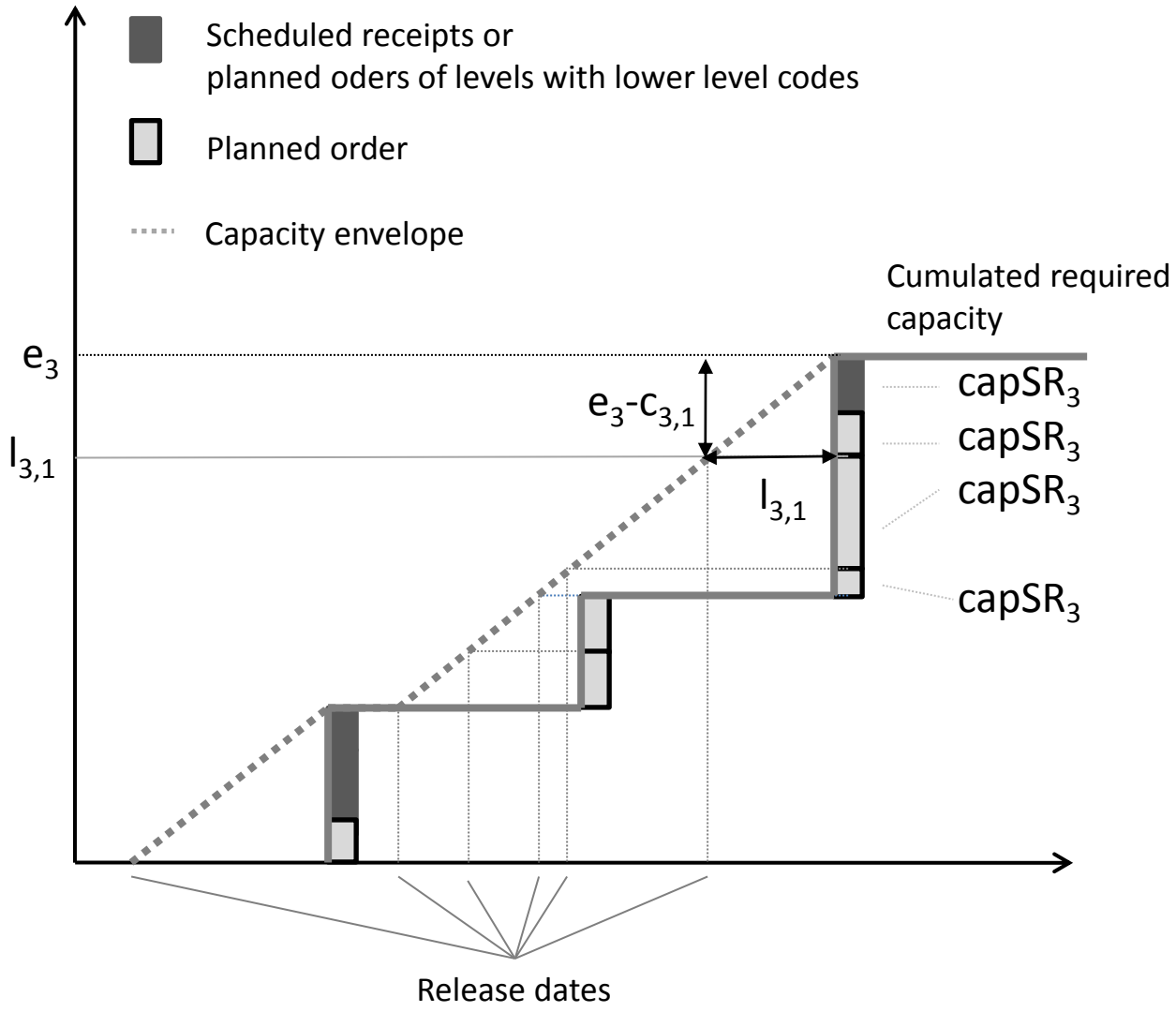
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Release dates