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► **To cite this version:**

Hermann Lödding, Steffen Lohmann. INCAP - Applying short-term flexibility to control inventories. International Journal of Production Research, 2011, pp.1. 10.1080/00207543.2010.544336. hal-00710924

**HAL Id: hal-00710924**

**<https://hal.science/hal-00710924>**

Submitted on 22 Jun 2012

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**INCAP – Applying short-term flexibility to control inventories**

Journal:	<i>International Journal of Production Research</i>
Manuscript ID:	TPRS-2009-IJPR-1081.R1
Manuscript Type:	Original Manuscript
Date Submitted by the Author:	30-Aug-2010
Complete List of Authors:	Lödding, Hermann; Technische Universität Hamburg-Harburg, Institut für Produktionsmanagement und -technik Lohmann, Steffen
Keywords:	PRODUCTION CONTROL, INVENTORY MANAGEMENT
Keywords (user):	

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Manuscripts

## INCAP – Applying short-term flexibility to control inventories

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*(Received 24 November 2009; final version received xx Month 20xx)*

Inventory Based Capacity Control (INCAP) is a very simple method that allows inventory levels to be effectively controlled by using short-term capacity flexibility in make-to-stock settings. Moreover, INCAP can be used for finished goods inventories as well as for semi-finished goods inventories. The basic idea is to define upper and lower inventory limits and to adjust capacities if the inventory level reaches either limit. Should the inventory fall below the lower limit, capacity is increased to prevent stock-outs. Similarly, in order to avoid excess inventories the capacity is decreased should the inventory rise above the upper limit. INCAP is thus able to control inventory levels within a defined inventory range. In order to do so, it applies short term measures like over-time or extra shifts to increase capacities and cancels work hours or shifts to decrease capacities. Simulation experiments based on data from the automotive industry show that INCAP is able to improve the performance of a manufacturing system in that it significantly reduces the inventory levels necessary for guaranteeing a satisfactory service level. Overall, INCAP is found to be a straightforward but powerful method, able to cope both with uncertainties in production output as well as with varying demand.

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2  
3 However, some restrictions do apply: INCAP depends not only on a minimum level of  
4 short-term capacity flexibility, but also in the standard set-up presented here it is limited  
5 to make-to-stock environments with similar products.  
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10  
11 Keywords: capacity control, inventory management, make-to-stock  
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## 14 15 16 **1 Introduction**

17  
18 With the ongoing discussion regarding the virtues of short-term capacity flexibilities  
19 the focus is slowly turning from production planning processes to short-term control  
20 issues. Both practical evidence as well as theoretical reasoning shows that capacity  
21 control has a critical impact on attaining logistical targets. Since existing policies do  
22 not explicitly address a make-to-stock environment we would like to introduce and  
23 evaluate INCAP here as a simple but effective capacity control capable of controlling  
24 inventory levels by means of the capacity flexibility. In order to structure this  
25 discussion clearly § 2 provides a brief review of related publications, while § 3  
26 addresses the basics of capacity control and its integration in the framework of  
27 manufacturing control. Following that in § 4, INCAP is described in detail including  
28 the procedural rules as well as the variables involved. The results obtained from  
29 simulation experiments are then reported in § 5. Based on this and a qualitative  
30 discussion, the advantages and limits of INCAP are discussed in depth. Finally,  
31 recommendations for setting upper and lower limits centred on the existing capacity  
32 flexibility and fluctuations in the inventory input and output are provided in § 6.  
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## 54 55 56 **2 Related Publications**

57  
58 INCAP is a method that relies on flexible capacities to control inventories. Flexible  
59 capacities have been investigated in research for many years. Although, the focus is  
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3 still on capacity planning and less on capacity control, we will briefly cover the  
4  
5 research in both production planning and manufacturing control.  
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### 10 *Production Planning*

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12 Of all the focuses in production planning research, two areas are related to our  
13  
14 discussion here: capacity management and inventory management.  
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19 Typical research questions in capacity management are: What type, size, and timing  
20  
21 of investment in machines and production equipment is optimal (see e.g. Van  
22  
23 Miegheem 2003 for a review of literature)? What is the optimal flexibility and size of  
24  
25 the work force (e.g. Wu et al. 2005, Alp and Tan 2008)? What are the long, medium,  
26  
27 and short term capacity requirements (See Vollmann et al. 2005 or Hopp and  
28  
29 Spearman 2008 for an introduction to this well-developed topic)? These questions can  
30  
31 be discussed under varying conditions as deterministic or stochastic demand i.e.,  
32  
33 stable or unstable production processes.  
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40  
41 Typical questions in inventory management include: Which are the optimal lot sizes?  
42  
43 What are appropriate order generation policies? And in general, what are optimal  
44  
45 production plans when it comes to deterministic or stochastic demand? Integrated  
46  
47 Capacity and Inventory Planning combines both tasks and yields better performance  
48  
49 with flexible capacities and stochastic demand than isolated approaches (Tan and Alp  
50  
51 2009, Jodlbauer and Altendorfer 2009). This research is of interest for this paper, as it  
52  
53 applies to the same make-to-stock environment as INCAP and also makes use of  
54  
55 flexible capacities. However, it is situated in production planning, while INCAP is a  
56  
57 manufacturing control method.  
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6 Generally speaking the main goal of production planning can be described as finding  
7  
8 an optimal or at least a good plan for capacities, capacity flexibility, lot sizes,  
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10 production quantities and sequences. Here the research question then turns to how  
11  
12 optimal, simple heuristics such as Kanban or Basestock policies are. For the purpose  
13  
14 of our discussion it is important to note that optimality is often measured in costs,  
15  
16 such as inventory holding costs, stock-out costs and costs for over-time or other  
17  
18 measures of capacity flexibility, like hiring and firing costs.  
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24 We will now turn our attention to manufacturing control. The underlying premise of  
25  
26 our discussion will be that production planning has been carried out carefully and  
27  
28 suitable plan values exist for parameters such as capacities, production outputs and  
29  
30 inventories.  
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### 34 35 36 *Manufacturing control* 37

38 When an enterprise incorporates production planning, it is the general aim of  
39  
40 manufacturing control to implement the developed production plan, even if there are  
41  
42 disturbances (Wiendahl 1995). Typical disturbances include deviations in the actual  
43  
44 demand compared to the forecasted and differences in the production output  
45  
46 compared to the planned.  
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51  
52 For manufacturing control, optimality is not as much of a focus as one would expect  
53  
54 since it is assumed that the production plan is good. Instead, the ruling principle is  
55  
56 simplicity. Since manufacturing control takes effect on the shop floor, successfully  
57  
58 implementing it is a matter of people understanding and supporting the control policy.  
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6 As is also reflected in existing publications, manufacturing control encompasses three  
7  
8 specific tasks: order release, sequencing, and capacity control.  
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12 The *order release* determines when the processing of a known order can begin on the  
13  
14 shop-floor (Wiendahl 1995). The simplest rule is to release the order at the planned  
15  
16 start date. However, sometimes coupling the release of orders to the output of the  
17  
18 manufacturing area in order to regulate the WIP level is preferred. Among the well-  
19  
20 known methods for accomplishing this are CONWIP (Hopp and Spearman 2008),  
21  
22 Workload Control (Jendralski 1978; Bertrand and Wortmann 1981) and Polca (Suri  
23  
24 1998).  
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31  
32 *Sequencing* exists both in planning and in manufacturing control. While planning  
33  
34 ascertains the planned sequence, manufacturing control determines the actual  
35  
36 sequence. The obvious and simplest rule for manufacturing control is to process the  
37  
38 orders in the planned sequence. At times in make-to-stock environments though, it  
39  
40 can be beneficial to speed up variants for which the actual demand exceeds the  
41  
42 forecast before the next planning run is executed (Schönsleben 1995).  
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49 Finally, *capacity control* makes use of short-term flexibility such as over-time or  
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51 hiring temporary labour in order to set the actual capacity. In our research we were  
52  
53 able to identify no more than five strategies for controlling capacities. Since INCAP is  
54  
55 a capacity control method, we will describe the strategies that already exist for this in  
56  
57 more detail:  
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4 • *Backlog control*: This concept has been used for many decades, with Toyota  
5 perhaps being the most prominent example. The idea here is to increase capacity if  
6 a backlog occurs and to decrease capacity if the cumulated output is ahead of the  
7 plan. Petermann (1995) and Wiendahl and Breithaupt (2000) explore the theory of  
8 backlog control.  
9
- 10  
11 • *Plan-oriented capacity control (Lödding 2008)*: This concept also has a dominant  
12 practical background. The basic idea is to react to a disturbance in capacity thus  
13 preventing backlogs or overproduction. A simple example would be to announce  
14 over-time or extra shifts if the actual capacity is lower than planned, e.g. because  
15 one of the operators is absent.  
16
- 17  
18 • *Due-date-oriented capacity control (Begemann 2005)*: Begemann extended the  
19 use of capacity flexibility from a pure resource view to the expected lateness of  
20 single orders. He forecasts the expected completion dates of orders at a  
21 workstation based on the planned sequence and work content and adjusts the  
22 capacity if that helps to prevent an order from being late or at least reduces its  
23 lateness. He finds that this technique improves on-time-delivery.  
24
- 25  
26 • *Performance maximizing capacity control (Lödding 2008)*: If demand is higher  
27 than (maximum) capacity, companies are likely to run the factories at maximum  
28 capacity. As the capacities of the workstations differ, it is efficient to limit the use  
29 of maximum capacity to the backlog work station. Workstations preceding the  
30 bottleneck should then be operated at a level sufficient for supplying the  
31 bottleneck workstation with enough orders to fully utilize its capacity; whereas  
32 workstations that follow the bottleneck should be operated at same tact as the  
33 bottleneck. The same applies when there is more than one bottleneck workstation.  
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Those familiar with Goldratt and Cox (1984) will probably recognize that this technique applies their considerations to capacity control.

- *Workload-dependent capacity control*: Mincsovic and Dellaert (2009) investigate a workload-dependent capacity control for make/engineer-to-order-settings; a similar method can be traced back to Tijms and van der Schouten (1978). The workload-dependent capacity planning policy is defined by two switching points: one 'down' and one 'up' for each pair of neighboring capacity levels. Switching points are specific workload values, for which a job arrival or departure can trigger a switch in capacity. If the system is at an up switching point, and a job arrives, then the policy switches from the lower to the higher capacity. If the system is at a down switching point, and a job departs, the capacity is switched to the lower capacity. With this policy, the WIP and throughput times are regulated, allowing for a higher due-date reliability. Unlike INCAP this strategy is designed for make or engineer-to-order companies and not for make-to-stock.

### 3 Fundamentals of Capacity Control and Inventory Management

In order to further explore the theoretical background of INCAP, we would now like to discuss two fundamental aspects in more detail: Storage Operating Curves (§ 3.1) and the capacity control within the framework of manufacturing control (§ 3.2)

#### 3.1 Storage Operating Curves

The basic idea of INCAP is to control the inventory by adjusting the short-term capacity. This is due to the importance of the inventory in a make-to-stock production, best shown in Storage Operating Curves (see Figure 1; Nyhuis and Wiendahl 2009). Storage Operating Curves depict the service level as function of the mean inventory of a variant. At very low mean inventory levels the service level is

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3 also low, because of variances in production and demand it is unlikely that the  
4 customer can get the desired product directly from stock. At higher inventories the  
5  
6 customer can get the desired product directly from stock. At higher inventories the  
7  
8 service level increases up to a point where all customer demands can be fulfilled on-  
9  
10 time in the expected quantity (service level = 100%). Nyhuis and Wiendahl define  
11  
12 this inventory level as the practical minimal stock level.  
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17 [please Insert Figure 1 here]  
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21 Figure 1: Storage Operating Curve (Lutz, Lödding and Wiendahl 2003)  
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26 Though Storage Operating Curves are calculated for a single variant, the basic  
27  
28 conclusions are also true for the total inventory as the sum of the variant specific  
29  
30 inventories. One important merit of INCAP is that it helps companies position  
31  
32 themselves within a defined range of the Storage Operating Curve and have the ability  
33  
34 to maintain their inventory at the specified level.  
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38 However, companies should also aim to improve the curve's progression. In  
39  
40 the context of manufacturing control the main levers for this are the *reliability of the*  
41  
42 *supply* and the *reaction to demand fluctuations*.  
43  
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45 Increasing the reliability of the supply (on-time delivery), which is influenced  
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47 by the backlog and the sequence deviation at the supplying workstation, will improve  
48  
49 the Storage Operating Curve's progression. It should be noted here that although  
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51 INCAP reacts to backlogs because the inventory falls when the production is behind  
52  
53 schedule, INCAP will not react to sequence deviations between the variants: It only  
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55 measures the total inventory and neglects its distribution amongst the different  
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57 variants. Both of these aspects are also applicable to the backlog control.  
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3 Speeding up reaction times to demand fluctuations will also improve the  
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5 progression of the Storage Operating Curves. In that INCAP reacts to demand  
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7 fluctuations because the inventory level falls if the demand exceeds the expected level  
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9 and rises in the adverse case, INCAP proves to be advantageous over the backlog  
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11 control in this respect.  
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### 14 15 16 **3.2 The Role of Capacity Control in a Make-to-Stock Environment** 17

18  
19 As mentioned previously, the three core functions of manufacturing control are order  
20  
21 release, capacity control and sequencing (Lödding 2008) of these, capacity control  
22  
23 and sequencing are particularly important for our discussion of a make-to-stock  
24  
25 environment. Figure 2 shows their influence on the logistics objectives.  
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30 [Please insert figure 2 here]  
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35 Figure 2: Manufacturing control Model in a Make-to-Stock Environment  
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#### 38 39 40 **3.2.1 Capacity Control** 41

42  
43 The capacity control sets the capacity and thereby the production output at a defined  
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45 level. The production output equals the input to the inventory (i.e. the more a  
46  
47 workstation produces, the more items will enter the inventory). The output of the  
48  
49 inventory is determined by the customer demand. Thus, the resulting inventory level  
50  
51 equals the difference between the cumulated input and cumulated output. The  
52  
53 inventory level in turn determines the service level as described by the Storage  
54  
55 Operating Curves. The inventory itself is depicted twice to emphasize its double role  
56  
57 as a control variable and as a target criterion.  
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### 3.2.2 Sequencing

The manufacturing control task ‘sequencing’ determines the *actual* sequence, in which a workstation processes the orders in the waiting queue (note that this is different from the sequencing used to determine the *planned* sequence as part of the planning function). A suitable sequence will enhance a well balanced variant mix in the inventory, while a unsuitable sequence will lead to a situation, in which there is too much inventory of some variants and too little inventory of others. This aspect is depicted by the deviation of the actual sequence from the optimal sequence or more pragmatically – since the determination of the optimal sequence can be difficult – from a planned sequence, e.g. given by the sequence in which the Kanbans arrive at the workstation.

While sequencing is not in the scope of this research, it is important to note that any capacity control has to be complemented by a well working sequencing function.

## 4 Description of INCAP

INCAP is an acronym for Inventory Based Capacity Control. Two rules define how INCAP works:

Rule 1: Adjust the capacity if either the lower or upper inventory levels are reached (or exceeded). If the current inventory is equal to or below the lower limit increase the capacity; if the current inventory is equal to or above the upper limit decrease the capacity.

Rule 2: Determine the extent and duration of the capacity adjustment according to the deviation of the planned inventory and implement appropriate capacity measures.

The aim of the first rule is two-fold. On the one hand, it strives to ensure that the company is able to deliver by maintaining sufficient inventory. Since a decreased inventory may be due to either an increased demand or a reduced output from manufacturing, the rule addresses both of these. On the other hand it is aimed at preventing excessive inventory levels – most of the times caused by reduced demand, though at least theoretically due to an increased manufacturing output.

While the first rule determines when a capacity adjustment is triggered, companies have to decide on the extent and duration of the adjustment (Rule 2). The difference between the planned and the actual inventory gives a good estimation of the required adjustment. One has to separately account for capacity adjustments made in the past but which are effective in the future.

$$\Delta CAP \cdot T_{application} = (Inv_{Plan} - Inv_{actual}) \cdot \frac{t_{unit}}{60} \quad (1)$$

$\Delta CAP$ : capacity adjustment [h/day],

$T_{application}$ : application time [days],

$Inv_{plan}$ : planned inventory [pc],

$Inv_{actual}$ : actual inventory [pc],

$t_{unit}$ : unit time [min/pc].

Be aware that this equation measures the inventory across all variants. Therefore it implies that the unit time per piece is constant across the variants. It also neglects the influence of set-ups i.e. assumes that they are a part of the unit time. In most big scale serial productions, this simplification is tolerable. However, if the unit time varies considerably from variant to variant, Equation (1) has to be calculated for each variant and then summed. Note that  $T_{application}$  is constant for each variant. The right hand side of Equation (1) can be interpreted as the backlog compared to the planned state

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3 defined by the planned inventory. Thus, INCAP can be considered a special form of a  
4  
5 backlog control with a planned output directly linked to the demand.  
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8 If several independent measures for adjusting capacities are available, two  
9  
10 strategies can be distinguished to decide which measures to apply: The *pragmatic*  
11  
12 *approach* is to let the shop floor management decide. Since sometimes other aspects  
13  
14 have to be taken into consideration (e.g. public holidays) this may be a better solution  
15  
16 than it first appears to be. However, even with this policy it will be useful to  
17  
18 document the standard procedure in a decision table. The *algorithmic approach* uses  
19  
20 defined criteria to decide which measure(s) to apply, for example, the reaction time of  
21  
22 the measure or impact of the measure on the output. Note however, it is better to  
23  
24 provide one effective measure with little to no reaction time than to optimise the use  
25  
26 of several different measures with long reaction times. This is because both the  
27  
28 resulting backlog from stochastic output as well as the resulting demand fluctuations  
29  
30 increase over-time. Therefore, less capacity flexibility is needed if the reaction time is  
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32 short.  
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38 Figure 4 shows the principle of INCAP. In the example, the inventory level  
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40 falls below the lower inventory limit at  $T_0$  (Figure 3a), so that the company increases  
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42 capacity. This capacity increase takes effect at  $T_1$  after the reaction time and remains  
43  
44 effective until  $T_2$  (Figure 3b). With the increased capacity the inventory level rises to a  
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46 level that is within the inventory limits. As comparison, the grey line shows the  
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48 inventory level that would occur when the capacity is not adjusted.  
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55 [please insert figure 3 here]  
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## 5 Evaluation of INCAP

Our validation of INCAP here starts with a theoretic assessment (§ 5.1) before describing the set-up and results of simulation experiments (§ 5.2).

### 5.1 Theoretic assessment

While backlog control by definition reacts only to deviation in the output, INCAP also takes into account demand fluctuations. For the purposes of our evaluation we classified the production output for a given period in three categories: behind schedule, on schedule and ahead of schedule. Likewise we categorized the demand in the same period as: behind expectation, as expected and above expectations. A matrix with nine fields was thus described (see Figure 4).

[Please insert figure 4 here]

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Figure 4: Inventory Deviation using Backlog Control

If demand is as expected (Fields VI, V, VI) INCAP and backlog control show the same reactions and therefore the same results: If the output falls behind schedule (Field IV), the capacity is increased; if the output is ahead of schedule (Field VI) capacity is decreased. The inventory level meets the planned level in all three cases, since both the production output as well as the demand achieve the planned values. If demand is lower than expected (Fields I, II, III), backlog control still adjusts the capacity according to the backlog, but does not consider demand. If output is behind schedule (Field I), backlog control increases capacity. Since demand is lower this leads to higher inventories. If output is ahead of schedule (Field III), capacity is decreased to a level where output would be on schedule. Since demand is lower this

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3 still leads to higher inventory levels. INCAP considers the changed demand rate and  
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5 in this case (Field III) decreases capacity more strongly than backlog control, such  
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7 that the inventory remains constant. Even if output is on schedule (Field II) INCAP  
8  
9 decreases capacity so that the inventory remains constant. If output is behind schedule  
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11 (Field I), INCAP does not increase the capacity; the lower output thus meets the lower  
12  
13 demand and inventory remains constant.  
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15

16  
17 If demand is higher than expected (Fields VII, VIII, IX), the effects are the same, only  
18  
19 in the other direction. This results in lower inventories with backlog control and  
20  
21 constant inventories with INCAP. Backlog control adjusts the output in all fields to  
22  
23 being on schedule. Since demand is higher, this leads to lower inventory levels.  
24  
25

26  
27 INCAP on the other hand does not decrease capacity if output is ahead of schedule  
28  
29 (Field IX), increases capacity if output is on schedule (Field VIII) and increases  
30  
31 capacity even higher if output is behind schedule (Field VII). With the higher  
32  
33 demand, this results in constant inventory and a satisfactory service level.  
34  
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36  
37 *Summary:* INCAP is superior to a backlog control in all but the cases in which the  
38  
39 demand is as expected.  
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## 42 43 44 **5.2 Evaluation by Simulation**

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46 Our discussion about the evaluation of INCAP using simulations will first discuss the  
47  
48 simulation set-up (§ 5.2.1) and present the simulation results for INCAP (§ 5.2.2)  
49  
50 before finally comparing INCAP with backlog control (§ 5.2.3)  
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### 53 54 *5.2.1 Simulation Setup*

55  
56 Both the production output and the demand rate are based on real data from a large  
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58 scale serial production in which one sub-assembly line feeds several assembly lines  
59  
60 with a component, decoupled by a supermarket. Orders are generated by a classical



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3 one-card-Kanban. To exclude the influence of sequencing, we limited the scope to  
4  
5 one variant. For multiple simulation runs we used multiple random values based on  
6  
7 the same output or input distributions. The simulation included the production of  
8  
9 scrap, however for the sake of simplicity we will not go deeper into this issue in our  
10  
11 study. To exclude the influence of production planning (tactical level) the average  
12  
13 demand and output distributions are normalized and their means set equal.  
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15

16  
17 Standard capacity for the simulation experiments is twelve shifts of 8 hours  
18  
19 each per week (six days with two shifts). Here, we distinguish three levels of capacity  
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21 flexibility: none, medium flexibility (+/- 2 shifts at the next weekend), and high  
22  
23 flexibility (+/- 2 hours at the end of each shift). Both the production output and the  
24  
25 demand rate are subject to considerable fluctuations with different variation  
26  
27 coefficients (0; 0.15; 0.3) for the output and demand.  
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### 35 5.2.2 Simulations Results for INCAP

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37 To see whether or not INCAP meets expectations we first evaluate INCAP without  
38  
39 comparing it to a backlog control. In order to do so we apply the following criteria:  
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#### 44 (1) Inventory fluctuations

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46 The distribution of the inventory deviation (= difference of planned inventory to  
47  
48 actual inventory) with INCAP when there is high flexibility is much narrower than  
49  
50 without using a capacity control (see Figure 5). The standard variation of inventory  
51  
52 deviation after 12 shifts is 244 (compared to 1661 without capacity control). The  
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54 distribution with INCAP is negatively skewed, because the production output cannot  
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56 exceed the capacity. Without capacity control, deviations of each shift add up to a  
57  
58 normal distribution.  
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6 [Please Insert figure 5 here]  
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10 Figure 5: Distribution of Inventory Deviation after Twelve Shifts  
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## 13 14 15 (2) Storage Operating Curves

16  
17 When alternating the mean inventory in the simulation runs by increasing or  
18  
19 decreasing the number of Kanbans (and adjusting the inventory limits of INCAP) for  
20  
21 a given inventory, the service level with INCAP is always higher than without  
22  
23 capacity control (see Figure 6). Similarly, the service level with high capacity  
24  
25 flexibility is always higher than with medium capacity flexibility. The differences are  
26  
27 considerable. For example, with a mean inventory level of 2000 pieces a service level  
28  
29 of 99.2% is reached with INCAP and a high capacity flexibility. This figure goes  
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31 down to 81.8% with medium capacity flexibility and to 46.3% with no capacity  
32  
33 flexibility.  
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41 [Please insert figure 6 here]  
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45 Figure 6: Storage Operating Curves with INCAP  
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### 51 *5.2.3 Comparing INCAP and Backlog Control*

52  
53 The simulation experiments illustrate the advantage of INCAP over backlog control  
54  
55 (see Figure 7). For any mean inventory level, INCAP yields a higher service level  
56  
57 than a backlog control. This is not surprising since the backlog control cannot react to  
58  
59 demand fluctuations and is not overruled by a planning instance in the simulation  
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3 environment. Nevertheless, the backlog control still results in higher service levels for  
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5 any mean inventory than those obtained without capacity flexibility. In other words, it  
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7 is much better to use backlog control, than nothing at all.  
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12 [Please insert figure 7 here]  
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17 Figure 7: Storage Operating Curves with Backlog Control  
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21 Here we would like to insert a side note with regards to the evaluation approach. A  
22  
23 classic approach would be to assess the costs associated with the control policies, in  
24  
25 consideration of inventory holding costs, labour costs (normal/over-time), stock-out  
26  
27 costs, and possibly other types of costs. Nevertheless, we consciously refrain from  
28  
29 this and rather plot a service level characteristic since, based on our experience, this is  
30  
31 easier to read and understand than cost comparisons: The course is independent of the  
32  
33 somewhat arbitrary cost setting and it more clearly illustrates the trade-off between  
34  
35 the service level and the mean inventory. Moreover, it allows alternative control  
36  
37 policies to be easily compared for different inventory levels.  
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42 However, the over-time is not included in the service level characteristic. We  
43  
44 therefore checked the over-time for the different simulation runs. For a given service  
45  
46 level, INCAP always used less extra hours than backlog control.  
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## 50 51 **6 Setting the Upper and Lower Inventory Limit** 52

53  
54 The inventory tolerance is defined as the difference between the upper and lower  
55  
56 inventory limit. In order to control the actual inventory close to the planned inventory  
57  
58 level, a low inventory tolerance is advantageous. However, this is likely to cause the  
59  
60 capacity control to intervene frequently leading to a nervous control pattern. In

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3 contrast, INCAP will intervene less frequently with a bigger inventory tolerance, but  
4  
5 will not be able to control the inventory level as close to the planned level as with a  
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7 narrow tolerance.  
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10 Apart from these general thoughts, companies should consider the following  
11  
12 aspects:  
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14

#### 15 16 *Minimum Effect of the Capacity Measures* 17

18 It obviously does not make any sense to trigger a capacity measure if it will cause the  
19  
20 inventory level to violate the opposing inventory limit (or less harmful: to exceed the  
21  
22 planned inventory level in the direction of the opposing limit). Such effects can occur  
23  
24 if the capacity measure has a strong effect (like additional shifts). Therefore,  
25  
26 companies should consider the impact of the capacity measures when setting the  
27  
28 inventory levels. As a rule, the difference between the inventory limit and the planned  
29  
30 inventory level should be greater than the effect of the corresponding capacity  
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32 measure.  
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#### 38 39 *Stability of the Manufacturing Output* 40

41 Large fluctuations in the manufacturing output lead to large fluctuations in the  
42  
43 inventory level. To avoid a nervous control pattern, companies should dimension the  
44  
45 inventory tolerance a bit more generously (and work on the stabilization of the  
46  
47 manufacturing output). Conversely, a stable manufacturing output allows for a lower  
48  
49 inventory tolerance.  
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#### 53 54 *Constancy of the demand* 55

56 Large fluctuations in the demand lead to large fluctuations in the inventory level. To  
57  
58 avoid a nervous control pattern, companies should dimension the inventory tolerance  
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3 a bit broader (and work on the levelling of the demand). Conversely, a levelled  
4 demand allows for a lower inventory tolerance.  
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7  
8 Taking these aspects into account, the inventory limits need to be specifically set  
9 depending on the individual application in which INCAP is used. A general approach  
10 can be taken if the maximum, minimum and planned inventory levels are  
11 predetermined, e.g. if the maximum inventory is limited by available space on the  
12 shop floor. Since maximum or minimum inventory should never be reached,  
13 inventory limits have to be set on the one hand so that capacity measures are triggered  
14 on-time (well before maximum inventory) in order to have the desired effect. On the  
15 other hand, they have to be set so that they are not triggered too early (close to  
16 planned inventory) in order to avoid frequent intervention.  
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29 For easy-to-use practical purposes, inventory levels can be set at or around 60% of the  
30 difference between the maximum and planned inventory for the upper inventory limit.  
31 Accordingly, the lower inventory limit can be set at or around 60% of the difference  
32 between planned and minimum inventory level. These values were also used for the  
33 simulations shown above.  
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40 To evaluate sensitivity, we varied the upper inventory limit between 40-80% of the  
41 difference between the planned and maximum inventory. There was little effect on the  
42 service level characteristic: Service level differences were between 0.5% (for high  
43 service levels) and 1.4% (for medium service levels) for highly flexible capacities.  
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50 The inventory limit also has a minimal impact in cases where the capacity has  
51 medium flexibility. It can thus be concluded that INCAP reacts robustly to variations  
52 in the inventory limit.  
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## 7 Summary

INCAP is a highly effective and efficient capacity control for make-to-stock-environments, able to promote the delivery readiness even under the difficult conditions of high fluctuations in demand and production output. Its simple algorithm is easy to understand and implement. The most important factor that influences the effectiveness is a company's flexibility to adjust capacity on short notice.

## 7 References

- Alp, O. and Tan, T., 2008. Tactical capacity management under capacity flexibility. *IIE Transactions*, 40, 221–237.
- Begemann, C., 2005. *Terminorientierte Kapazitätssteuerung*. Thesis (Dr.-Ing.). Leibniz Universität Hannover (in German).
- Bertrand, J. W. M. and Wortmann, J. C., 1981. *Production control and information systems for component-manufacturing shops*. Vol. 1 of Studies in Production and Engineering Economics, Amsterdam: Elsevier.
- Goldratt, E. and Cox, J., 1984. *The goal. A process of ongoing improvement*. Great Barrington/Massachusetts: North River Press.
- Hopp, W. J. and Spearman, M. L., 2008. *Factory Physics*. Chicago et al.: Irwin.
- Jendralski, J., 1978. *Kapazitätsterminierung zur Bestandsregelung in der Werkstattfertigung*. Thesis (Dr.-Ing.), TU Hannover (in German).
- Jodlbauer, H. and Altendorfer, K., 2010. Trade-off between capacity invested and inventory needed. *European Journal of Operational Research*, (203), 118–133.
- Lödning, H., 2008. *Verfahren der Fertigungssteuerung. Grundlagen, Beschreibung, Konfiguration*. Berlin et al: Springer (in German).

- 1  
2  
3 Lutz, S.; Lödding, H. and Wiendahl, H.-P., 2003. Logistics-oriented Inventory  
4  
5 Analysis, *International Journal of Production Economics*, 85 (2), 217–231.  
6  
7  
8 Nyhuis, P. and Wiendahl, H.-P., 2009. *Fundamentals of Productions Logistics*,  
9  
10 *Theory, Tools and Applications*. Berlin et al.: Springer.  
11  
12 Mincsovics, G. Z. and Dellaert, N. P., 2009. Workload-dependent capacity control in  
13  
14 production-to-order systems. *IIE Transactions*, 41 (10), 853–865.  
15  
16  
17 Petermann, D., 1995. *Modellbasierte Produktionsregelung*. Thesis (Dr.-Ing.). TU  
18  
19 Hannover (in German).  
20  
21  
22 Schonberger, R. J., 1982. *Japanese Manufacturing Techniques. Nine hidden lessons*  
23  
24 *in simplicity*. New York: Free Press.  
25  
26  
27 Schönsleben, P., 1995. Corma: Capacity Oriented Materials Management.  
28  
29 *Proceedings of the APICS World Symposium in Auckland, Australasian Production*  
30  
31 and Inventory Control, 160–164.  
32  
33  
34 Suri, R., 1998. *Quick Response Manufacturing. A companywide approach to reducing*  
35  
36 *lead times*. Portland: Productivity Press.  
37  
38  
39 Tijms, H.C. and van der Schouten, F.A., 1978. Inventory control with two switch-over  
40  
41 levels for a class of M/G/I queuing systems with variable arrival and service rate,  
42  
43 *Stochastic Processes and Their Applications*, 6, 213–222.  
44  
45  
46 Van Mieghem, J.A.V., 2003. Capacity Management, Investment and Hedging:  
47  
48 Review and Recent Developments. *Manufacturing & Service Operations*  
49  
50 *Management*, 5 (4), 269–302.  
51  
52  
53 Vollmann, T.E. et al., 2005. *Manufacturing Planning and Control Systems for Supply*  
54  
55 *Chain Management*, New York et al.: McGraw-Hill.  
56  
57  
58 Wiendahl, H.-P., 1995. *Load-Oriented Manufacturing Control*. Berlin et al.: Springer.  
59  
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3 control theory. *International Journal of Production Economics*, 63 (1), 33–46.

4  
5 Wu, S. D.; Erkoc, M.; Karabuk, S., 2005. Managing Capacity in the High-Tech

6  
7 industry: A review of literature. *The Engineering Economist*, 50, 125–158.

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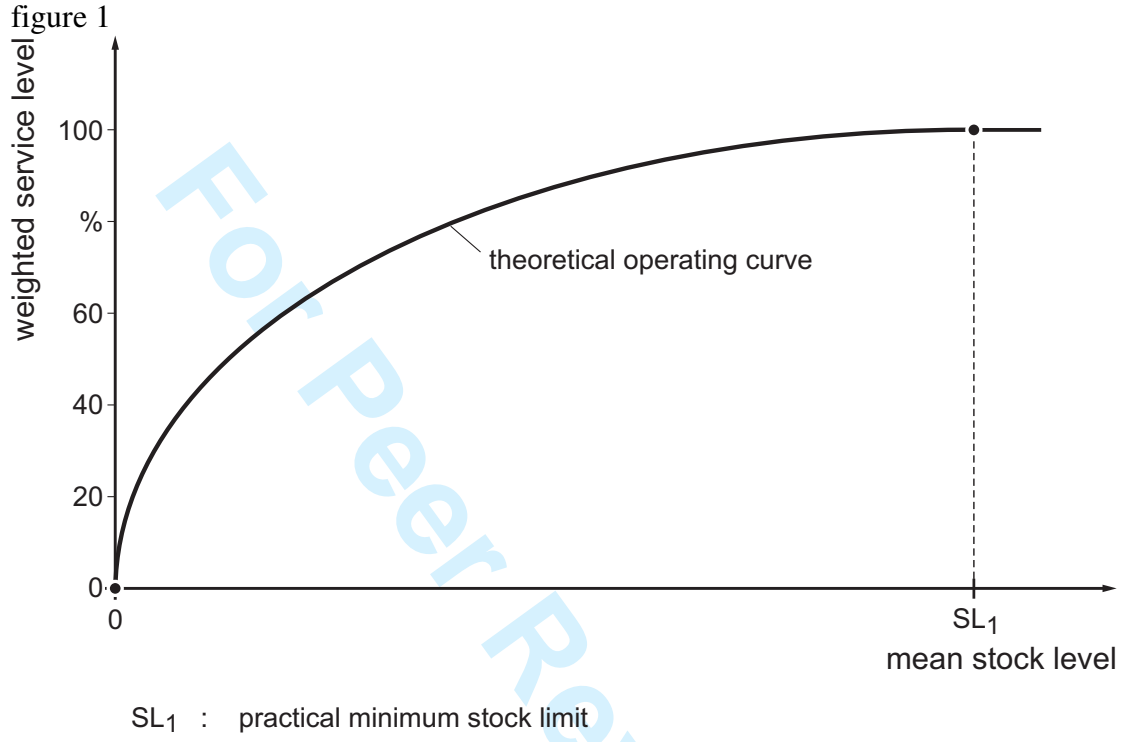


figure 2

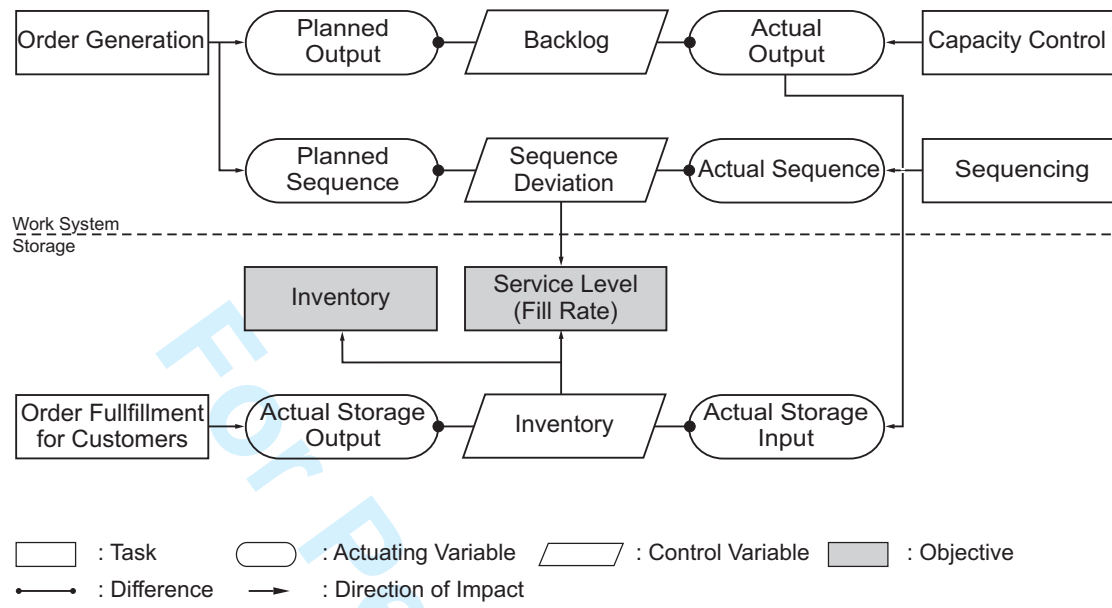
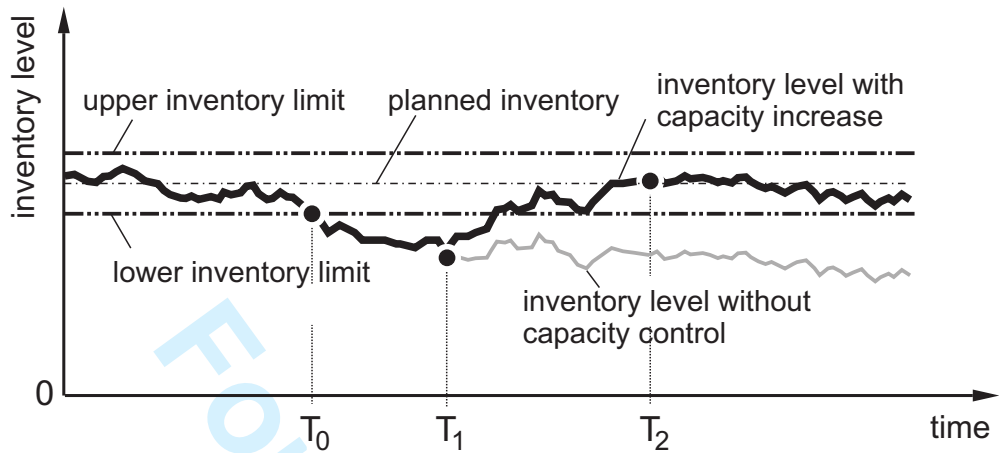
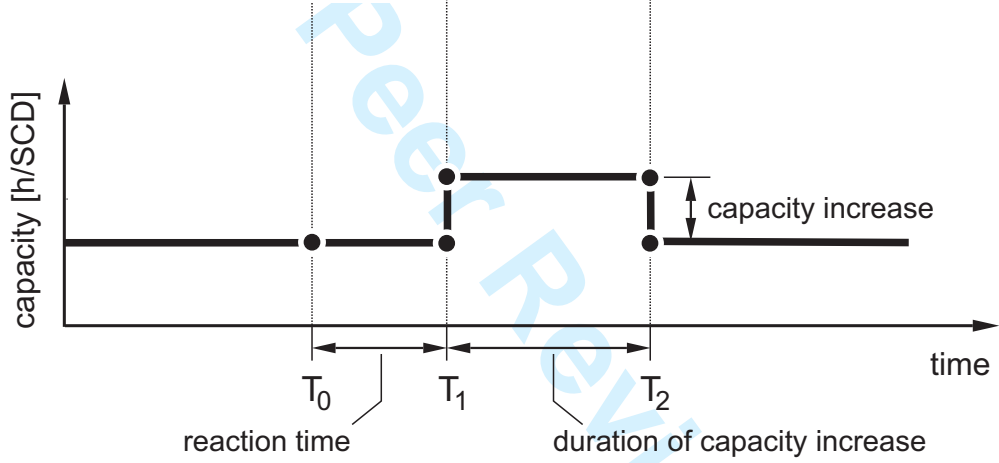


figure 3



a) inventory



b) capacity

figure 4

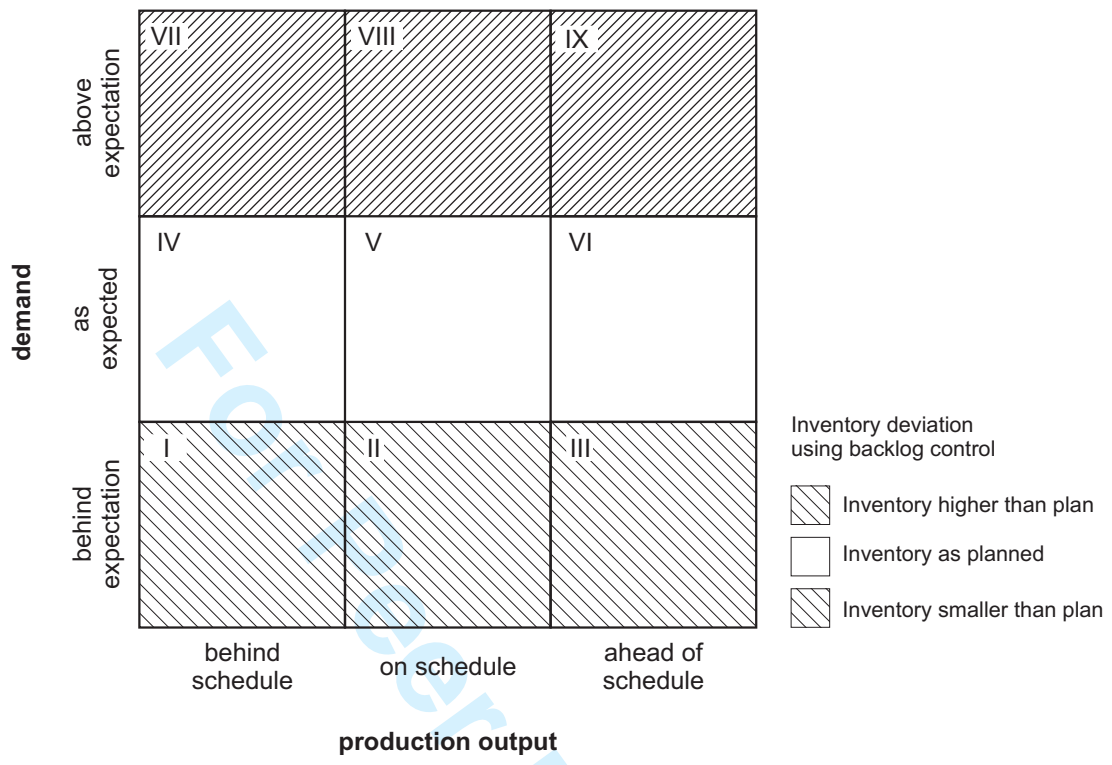
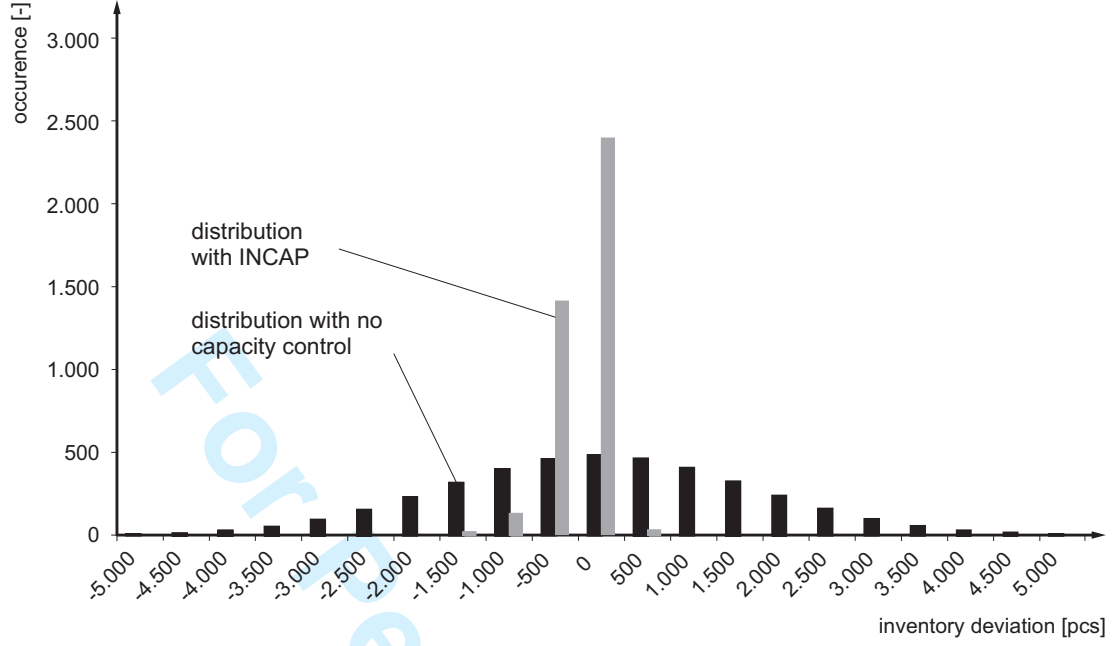
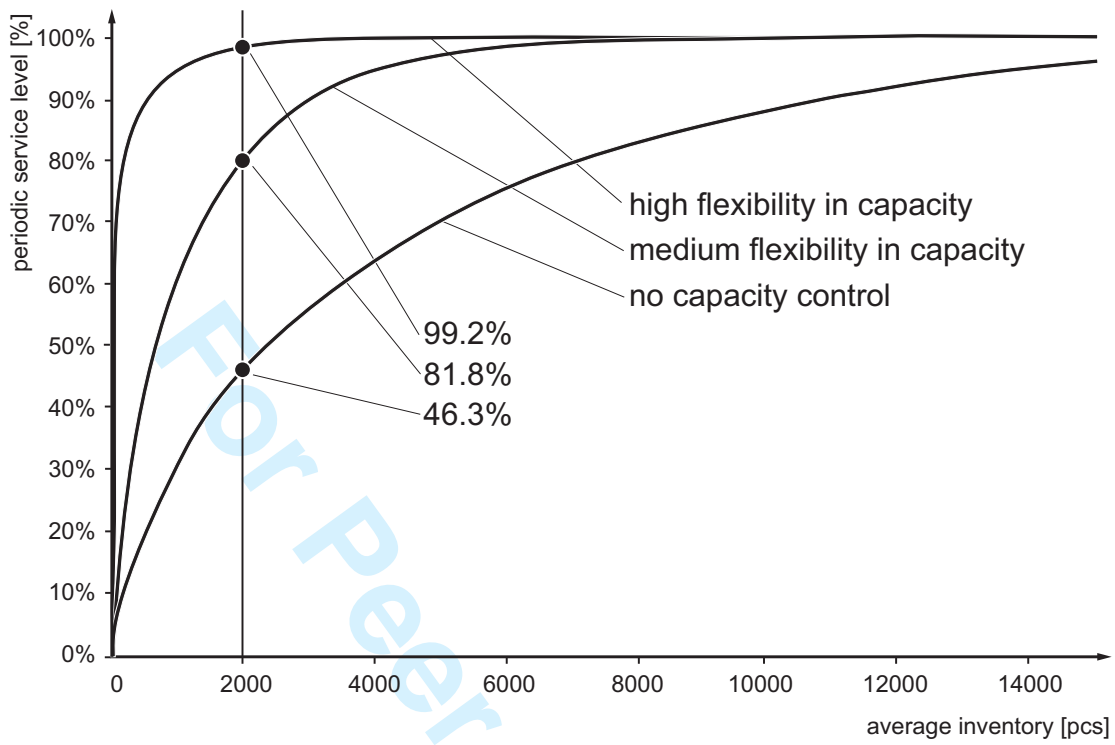


figure 5



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figure 6



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figure 7

