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# Technical and industrial issues of Advanced Planning and Scheduling (APS) systems

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ABSTRACT

The basic functionality of planning and scheduling in Advanced Planning and Scheduling (APS) systems, especially constraint-based planning and optimization, is analyzed and discussed by use of theory and examples including how objectives, decision-variables and penalty factors are handled.

The paper concludes that the planning functionality is radically improved compared to MRP and ERP, but stresses how essential it is for a good outcome that the user is familiar with the core APS functionality to enable a careful setup of the many (conflicting) planning parameters.

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## 1. Introduction

During the last thirty years, manufacturing planning and control systems have been gradually developed towards closed loop systems entitled Manufacturing Resource Planning (MRP II), which integrate both materials and capacity requirements. Latest, Enterprise Resource Planning (ERP) and Advanced Planning and Scheduling (APS) systems have improved the integration of materials and capacity planning. APS has by far outperformed the planning and scheduling functionality of the ERP-system and has become an impressive and important tool within planning and control. A strong feature in APS is the ability to "simulate" different planning scenarios before plan release.

APS is a relatively new approach for planning and meeting customer demand using finite material availability and plant resource capacity. APS takes into account constraints at enterprise level as well as at plant level. Materials and capacity issues are considered simultaneously, and manufacturing, distribution, and transportation issues are integrated. The APS planning engine is based on an optimization algorithm and a constraint-based planning algorithm. This enables companies to optimize plans according to financial and other strategic objectives of the enterprise and to create plans which satisfy multiple objective goals.

Unlike traditional ERP systems, APS seeks to find feasible, near optimal plans while potential bottlenecks are considered explicitly [1]. Many ERP and APS systems make it possible to include suppliers and customers in the planning procedure and thereby optimize a whole supply chain on a real-time basis [2–4]. Unfortunately, no common (accepted) definition of APS systems exists, and several systems on the market do not fulfil the description above.

Advanced planning systems utilize complex mathematical algorithms to forecast demand, to plan and schedule production within specified constraints, and to derive optimal sourcing and product-mix solutions. APS systems introduced the benefits of constraint-based planning and optimization to the business world. In spite of the supply chain functionality, most APS implementations are limited to a single organization or a single manufacturing site.

APS aim at automating and computerizing the planning processes by use of simulation and optimization. Still, the decision-making is done by planners with insight in the particular supply chain and know how on the system constraints but likewise important: a feeling for feasibility of created plans. Thus, APS aim to bridge the gap between the supply chain complexity and the day-to-day operative decisions. This require, however, that planners are able to model and setup decision rules for the planning and optimization.

The literature reports on some successful implementations of decision support systems in either special supply chain planning situations or optimization models for the entire chain. Gupta et al. [5], for example, describe a decision support system which helps

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Pfizer to plan their distribution network. Brown et al. [6] present a large-scale linear programming optimization model used at Kellogg Company to support production and distribution of decision making on both operational and tactical levels.

A study from an APS implementation in the Vita Group serving the packaging industry show an increase in delivery accuracy from 79% to 96–99% while reducing lead time from 5 to 7 days to zero and reducing the planning resources by 30% [7]. The results are primarily achieved by increasing visibility of customer and production orders. The impacts of new orders are seen in real time, and existing orders (1000 per month) are automatically rescheduled.

Early adopters of APS report significant reductions in cycle time, resource and inventory load and up to 300% return of investment [8–10]. However, according to a study by Funk [11] only 20% of the APS installations investigated are successful (based on a threshold of achieving 70% of projected gain to become a success). Studies show that there are several problems involved in using planning software such as high complexity, lack of training and knowledge among managers and personnel, low-data accuracy, and lack of support from the software vendor [12]. This makes it quite difficult to forecast the return of an investment for any system implementation.

## 2. From MRP to APS

With the exception of the early reorder point systems of the 1960s, Material Requirements Planning (MRP) was the first generation of systematic materials planning systems. MRP was built around a Bill of Materials Processor and the advantage was the ability to explode the components required to build the finished items and to summarize and time the need for individual components across the total volume of orders. In the early and mid-1970s almost all major computer manufacturers and (future) major MRP-vendors such as SAP, Lawson, J.D. Edwards and BaaN launched their first MRP software packages to take advantage of the growing industrial interest in MRP-systems based on declining computation costs and rising inventory costs [13,14].

Later on, the MRP systems were enhanced to handle capacity requirements planning and were termed "Closed Loop MRP" as they provided information feedback that led to the capability of plan adjustments and regeneration. The acronym MRP II was invented by Ollie Wright in the early 1980s, to distinguish these from the early MRP-systems [13]. Later, the MRP II acronym was renamed "Manufacturing Resource Planning" to fully cover the new functionality. In 1990 Gartner Group invented the term Enterprise Resource Planning [15] as the software tools had gradually integrated other application areas such as forecasting, long term planning and critical resource planning.

In line with the acceptance of MRP/ERP being the main information system in companies, other systems such as Computer Aided Design, Shop Floor Planning, Data Collection, Product (Sales Order) Configuration, etc. have been integrated with the major MRP/ERP systems.

Around year 2000 the major ERP vendors started to integrate APS. SAP and Oracle were among the first to include such a functionality in their business suites. The optimisation is in both cases based on Ilog's "engine" but customised and implemented differently. APS does not substitute but supplement existing ERP systems. The ERP system handles the basic activities and transactions, as e.g. customer orders, accounting, etc. whereas the APS system handles the daily activities for analysis and decision support.

In parallel to the ERP vendors, new competitors have emerged in the Supply Chain Planning (SCP) area such as I2 to support the need for more intelligent plans covering one or more partners in the supply chain. According to Green [16] the distinction between ERP and SCP is somewhat blurry as ERP generally covers the full range of manufacturing, sales and accounting while SCP tends to be more oriented towards specific logistics functions such as forecasting, production, transportation, delivery and distribution. Green further states that ERP vendors have no intention of being edged out by SCM.

## 3. Supply chain planning

The growing interest in APS systems for e.g. supply chain planning is according to Shapiro [17] the result of two overlapping motivations among industrial managers:

- The need for models and business processes to support fact-based decision making in designing and operating their supply chains
- The need to integrate decisions across supply chain functions, geographically dispersed facilities and time

Fact-based decision-making refers to the development, validation and application of data-driven models to analyse supply chain planning problems. Due to advances in IT, fact-based decision-making has become possible and necessary. It is possible because enterprise databases finally exist in many companies, although improvements in their flexibility and functionality are still investigated. Firms which fail to exploit their enterprise databases by creating and using models will face serious competitive disadvantages. New business processes are needed to fully explore and exploit insights provided by models. The essence of fact-based Supply Chain Management is integrated planning, which has three important dimensions:

- functional integration involving decisions about purchasing, manufacturing and distribution activities within the company and between the company and its suppliers and customers,
- geographical integration of these functions across physical facilities located in one or several continents,
- integration of strategic, tactical and operational supply chain decisions primarily concerning resource acquisition, resource allocation and business execution.

Models imbedded in easy-to-use modelling systems are critically needed to support integrated decision-making. These systems employ descriptive models and optimisation models. Descriptive models, such as those forecasting future demand or computing direct and indirect manufacturing costs, are used to create supply chain decision databases, which act as input to optimisation models. Optimisation models allow managers to explore the space of decision options and constraints to identify effective plans.

According to the IMTR initiative [18] the linkage between process simulation systems and process planning systems is limited, so there is little ability to do automated analyses to optimize efficiency or production for profitability, or to provide real-time updates based on current production operations status or changes in requirements. This is much in line with our findings within planning and execution, as very few companies rely entirely on production plans from their MRP/ERP/APS system. Manual adjustments are needed, either caused by missing functionality of the systems used or missing accuracy of the data used (bill of materials, routings, processes, equipment capabilities, etc.). Collecting and maintaining data are, together with the high investment costs, the major deficiencies in scheduling systems today.

The effectiveness of Mixed-Integer Linear Programming (MILP) methods depends on the size of the linear-programming sub-problems and, more importantly, on the gap between the objectives for the best feasible solution (optimum) and the objective function value obtained from the initial Linear Programming (LP) sub-problem, the integrality gap. A number of more sophisticated algorithms exist which focus on these aspects and use different ways of generating LP sub-problems, like Branch and Cut [19,20] and Branch and Price [21]. These algorithms make use of valid inequalities (cuts) to yield small integrality gaps for sub-problems and to improve the performance of the solution algorithms.

One way of reducing the number of sub-problems to investigate is to truncate the search effort. For example, the user may either set a certain time limit for the search, (which unfortunately is the approach that some APS vendors have selected) or indicate that the search has to stop once a specific number of feasible integer solutions has been found. However, the problem with truncation is that it is not known in advance at which point in time a feasible or good solution will be found. Most of all, the user has no idea how near the solution is from optimum. At the same time the solution has a high dependence on the search strategy.

Another option is to limit the computational effort of branch-and-bound by stopping the search for an improved solution once it is certain that there is no feasible integer solution which is at least $\delta$% better than the current best solution (the $\delta$-value is specified in advance). This allows calculation of an aspiration level in the course of branch-and-bound, simply by multiplying the objective function value of the current best solution by $(1 + \delta\%)$. The question remains whether a feasible integer solution exists with an objective function value no less than the aspiration level known from the maximum upper bound of all unfathomed sub-problems. If the maximum is less than our aspiration level, the search is stopped. The same procedure is used for the minimization problem. In this way it is possible to control how close the solution is to meet the optimality and the time.

## 4. Constraint-based programming

Constraint-based programming is used for both constraint-based planning and optimisation. The difference is that in constraint-based planning no plan optimisation objectives or criteria are considered; only constraints. This option produces a feasible but not necessarily *optimal* plan. The optimized plan on the other side is based on a cost or profit perspective, which leads to an optimal plan seen from a financial perspective but not necessarily an optimal plan seen from a manufacturing or a customer point of view.

The search strategies used are related to those used when solving mixed integer programming (MIP) problems via branch-and-bound procedures. In general, constraint-based programming combines the power of sophisticated algorithms with the flexibility and modelling capabilities of expert systems. A constraint-based programming tool provides functionality for declaring decision variables, for stating constraints and for solving the resulting problems. The strength of the approach is that it allows a clean separation between the statement of the problem (the variables and the constraints) and the resolution of the problem (the algorithms). Constraint-based systems scale well into large problem spaces and yield results quickly. The time used to generate a plan for a whole supply chain has been reduced significantly using constraint-based programming.

In most mixed integer programming problems, constraints represent limitations or requirements, which must be met. Therefore, the solution to a mixed integer programming problem does not allow a constraint to be violated. However, in any planning problem, a distinction is needed between constraints that cannot be overruled ("hard") and constraints which may be overruled if necessary ("soft"). In order to handle hard and soft constraints, APS systems use goal programming formulation in the constraint-based programming.

As an example, if the demand domain is considered a hard constraint and the supply domain is considered a soft constraint, customer due dates are enforced while materials and capacity availability may be overruled. If instead the supply domain is considered a hard constraint, the capacity limits are enforced whereas the customer due dates may be overruled.

Another important feature of the constraint-based programming is the ability to use rules. Rules are used as explicit decisions made by the planner and used when more options exist in the plan generation. Rules are ranked by use of priorities of given topics such as demands, customers and items. Rules play an important role in constraint-based planning by avoiding the traditional (time-consuming) re-planning and re-scheduling after plan generation.

It is sometimes difficult to specify a single objective for a given planning scenario. For example, a company may wish to maximise the amount of capacity used while minimising on-hand inventory. When multiple objectives exist, and they are in conflict with one another, an approach is needed to model and evaluate the trade-off among the conflicting objectives. The key to support this is once again the goal programming formulation with multiple objectives in which each of the objectives has a *target* or goal. The objective is to minimize deviations from pre-specified goals. The specific goal itself is a soft constraint and this enables more "*political*" goals or constraints such as inventory service level or inventory turns. For example, a production manager might wish to come as close as possible to a 95% capacity utilisation or a distribution manager might seek to minimise the amount of inventory held, while also minimising the number of back orders.

Objective weights in general do not show the precise relative importance of each objective in planning decisions. The cost magnitude of the objective should also be considered, and it is the product of the weight and the cost magnitude of the objective which reflect the relative importance of each objective in the planning decisions. Multiple conflicting objectives are handled by weighting the different objectives according to their *importance*, and by combining them into a single objective through a normalisation process. This approach relies on the subjective judgment of the decision-maker to determine the relative importance of each of the objectives.

However, it is important to notice that multiple objectives must have the same order of magnitude. According to Jeffrey and James [22] *"If the coefficients vary a great amount over the different objectives, then one or more of the objectives will have to be scaled by dividing through by a constant. Otherwise, an objective that has much larger coefficients than other objectives will have an excessive amount of importance in the combined objectives"*.

To illustrate this, suppose that we would like to maximize two objectives:

$$(1)\, 2x_1 + x_2 \; (2)\, 210x_1 + 320x_2$$

having objective 1 three times as important as objective 2

The normalisation gives the following weights:

$$3/(3+1) = 0.75 \text{ for objective 1 and } 1/(3+1) = 0.25 \text{ for objective 2.}$$

The combined objective is then:

$$0.75 * (2x_1 + x_2) + 0.25 * (210x_1 + 320x_2) = 54x_1 + 80.75x_2$$

Notice that the coefficients are relatively large, and $x_2$'s coefficient is much larger than of $X_1$, even though $X_1$'s coefficient is twice that of $X_2$'s in our most important objective. If all

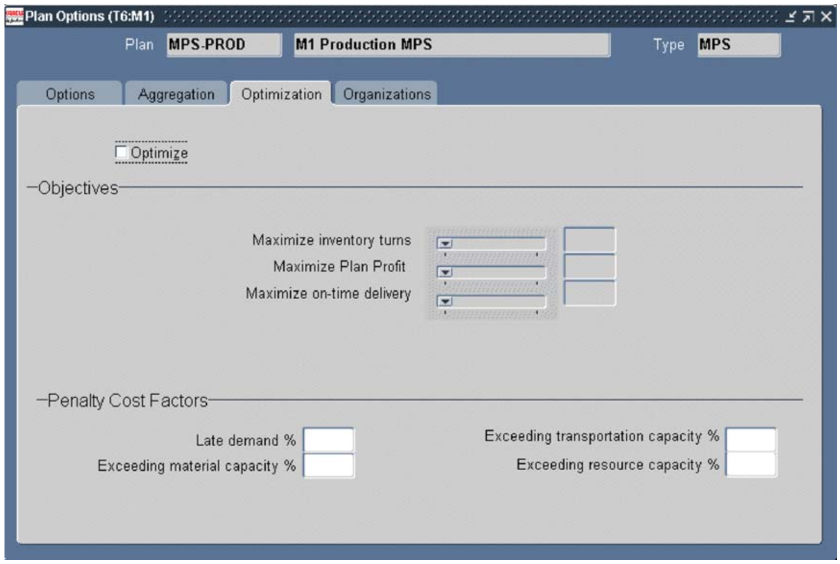


**Fig. 1.** Plan options used to generate an optimal plan [illustration from Oracle's APS system].

coefficients are scaled to reach values in between 0 and 1 the combined objective is then:

$$0.75 * (x_1 + 1/2x_2) + 0.25 * (21/32x_1 + x_2) = 1656x_1 + 1.5x_2$$

Now objective 1 has three times the influence of objective 2 in determining the coefficients of the combined objective, which is what the decision-maker would expect based on the specified weighted objectives.

Exactly how APS handles the normalization process has not been possible to evaluate, but it is very important for the quality of the optimization. At the same time, knowledge about both the production condition/structure and cost structure is vital as optimization is based on relative parameters.

## 5. Optimization

Optimized plans are generated based on plan objectives and constraints. The rules used as explicit decisions in constraint-based planning are substituted with decision variables and penalty factors which again are used to evaluate the trade-off between soft constraints and decision variables. As the optimization is based on cost or profit, the soft constraints may be overruled if this reduces the total costs. The pre-defined rules used in constraint-based planning, e.g. demand priority and supplier allocation ranks, could be overruled to reach the best profit. If a rank 2 supplier results in lower cost than a rank 1 supplier, orders will be allocated to the rank 2 supplier. However all decisions cannot be based on costs and profit. Many reasons can exist for a supplier to have a higher rank based on a total business point of view (e.g. better quality or better delivery performance). The total costs may be lower even though the costs of the part are higher, but unfortunately this is not possible to model. Another point worth mentioning is the use of penalties for late delivery, resource overload and material shortage.

### 5.1. Objective function, decision variables and penalty factors

In the objective function there are three parameters to weight: *inventory turns*, *plan profit* and *on-time delivery*, see Fig. 1. To optimize a total plan, one single mutual (financial) measure is needed. This could be either costs or profit depending on the parameter settings. If "plan profit" is weighted differently from zero the optimisation is based on profit. Elsewhere the optimisation is based on costs.

Besides the objectives a number of decision variables can be used to achieve the business goals wanted. Multiple objective criteria are used to evaluate plans for an unlimited number of decision variables. The decision variables are almost the same as the rules used in Constraint-based Planning but here alternative and substitute conditions are considered. The decision variables (all time-phased) are:

- Production supplier sources.
- Choice of routings and resources.
- Production and purchasing quantities.
- Choice of transportation carrier mode.
- Choice of bill-of-materials and items.
- Safety stock levels.

The optimization seeks the best combination of the decisions. The optimized plan suggests which items to produce, how many to order, and when to order them. It also suggests the source (in-house or supplier), bill of materials, routings, resources, transportation methods, and the level of safety stock inventory to maintain; all in relation to cost and profit. The optimization satisfies weighted objectives and takes into consideration the penalty factors[1] related to these decision variables.

The following penalty (cost) factors are used explicitly in relation to decision variables: Late demand, exceeding material, exceeding inventory capacity, exceeding resource capacity and exceeding transportation resource capacity. For each factor, percentages are used to indicate how important it is that those outcomes do not occur in the plan. The optimization process drives penalties out of the solution, tending to drive the most costly penalty factors out first. A high degree of accuracy in setting penalty factors is not as important as the relationship between penalty factors [23]. When the system makes decisions to avoid late demand, it will place higher priority on keeping large sales orders on time. When the penalty for late demand is higher than the penalty for exceeding resource capacity, the solution will tend to plan overtime work in order to avoid late delivery. In general, all penalty factors work this way. An issue worth discussing in relation to this is how a company estimates the costs of a late

[1] The term "factor" indicates that the number you enter is multiplied by something else. For example, the late demand penalty factor is a percentage multiplied by line item value.

delivery to a customer? It may result in a lost order or a lost customer and injure the company's reputation or it may have no consequence at all.

As the optimisation is entirely based on cost or profit in contrast to the planning considerations, more or less re-planning must be expected before an optimized plan is ready for use.

### 5.2. Implicit objectives

Implicit objectives can be characterized as default or foundational objectives which the optimization solver always attempts to honour. In addition to the objectives defined above, which can be selected/weighted or deselected by the planner, an implicit (hidden) objective is taken into consideration no matter what the planner select. The implicit objective is maximized by minimizing the penalty costs for:

- *Late or unmet demand.*
- *Supplier, resource or transport capacity violation.*
- *Safety stock violation.*
- *Unused supply.*
- *Alternate sources, resources, bill-of-materials or routings.*
- *Substituted items.*

Implicit objectives are overridden if necessary when the primary objectives are specified. For example, to obtain the primary objective, *on-time delivery*, it could become necessary to substitute *resources, bills, routings, or items*. Other substitutes and alternates may also be recommended for cost saving reasons.

Some costs are contained in more than one objective. For example, an inventory-carrying cost is part of both the plan profit and inventory turn objectives, which in general make the optimization a little blurry. In this paper these twofold objectives are defined as dependent objectives. Another subtle case of dependent objectives is penalty cost for late demand, which appears both in the on-time delivery objective and in the implicit objectives.

## 6. Scenarios of the optimization approach

The goal of managing a manufacturing operation is to maximise the financial performance of the entire system. In Oracle's APS application, different scenarios can be evaluated based on combinations of e.g. *hard* and *soft constraints*, penalty factors and weights of the objectives. The outcome of the scenarios is presented in terms of *key performance indicators* (KPIs), exception messages and pegging information. A graphical interface illustrates the KPIs for all scenarios. In Fig. 2 four default KPIs are shown: (1) Planned utilization, (2) On-time delivery, (3) Inventory turns and (4) Profit margin percent. Other KPIs can be added subject to demand and purpose.

In the following four scenarios of the optimisation approach are discussed:

| No | Primary Objective | Hard Constraint |
|---|---|---|
| 1.1 | Max. on-time delivery | Demand due date |
| 1.2 | Max. on-time delivery | Capacity |
| 2.1 | Max. inventory turns | Demand due date |
| 2.2 | Max. inventory turns | Capacity |

1.1. If the primary objective is "maximize on-time delivery" and "demand due date" is a hard constraint, the capacity becomes a soft constraint and the only penalties to be considered are related to the supply (operation, supplier and transportation resources). With this setup the planner assumes that the penalty for late supply (back-orders) is higher than the penalty for exceeding resource capacity (overtime) or producing to stock. Or he simply follows a company policy. If necessary, due to constraints on the supplier side, the optimization algorithm considers the trade-off between the penalty costs of overtime labour against the penalty cost of inventory carrying.

1.2. If the primary objective is "maximize on-time delivery" and "capacity" is a hard constraint (e.g. materials, machines, labour) the demand due-dates become a soft constraint and the only penalties to be considered are therefore related to the late demand.

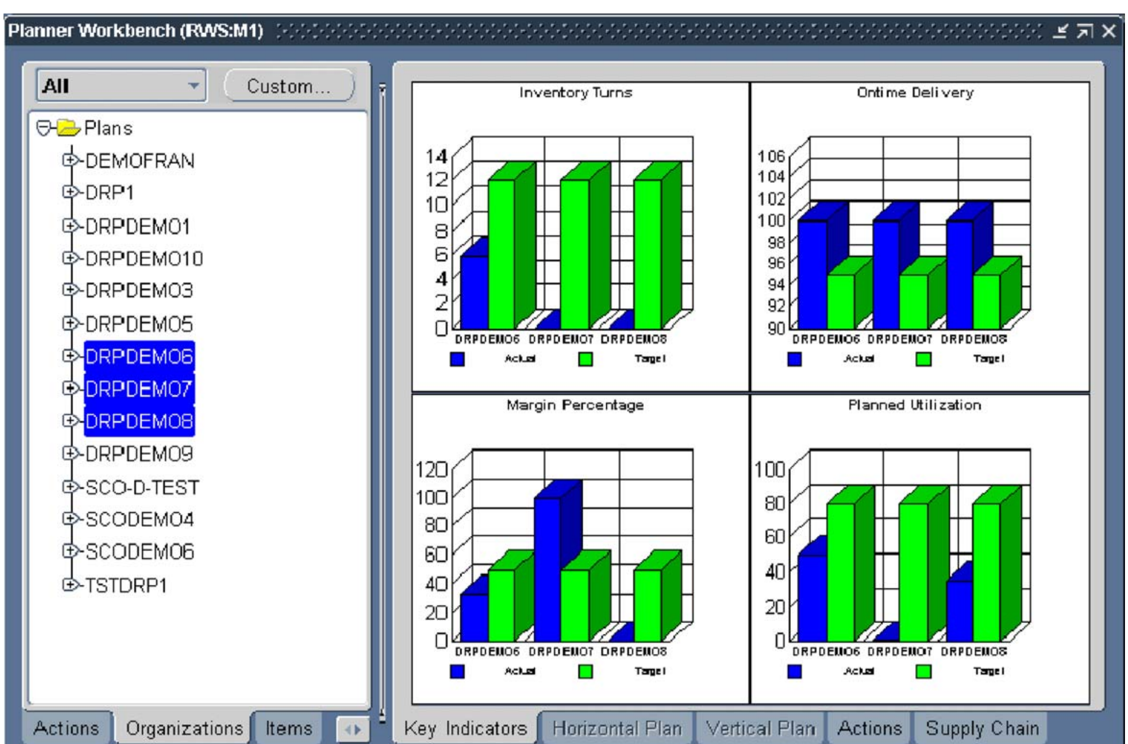


**Fig. 2.** A comparison of 4 default key performance indicators (actual versus target) for 3 different scenarios before plan release [illustration from Oracle's APS system].

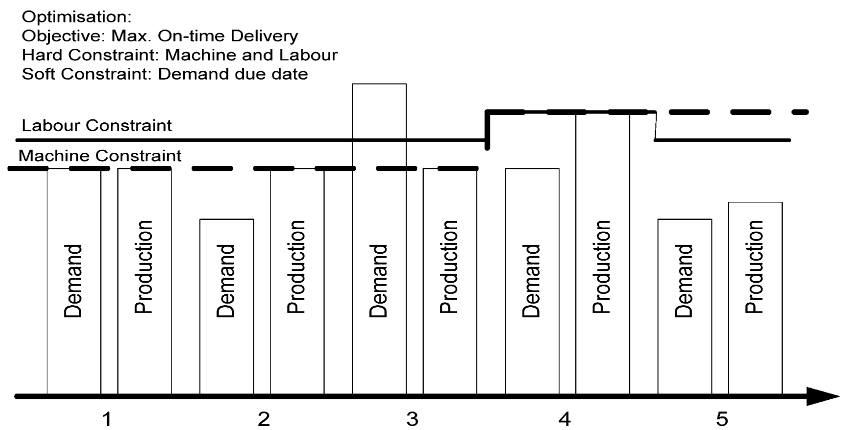


**Fig. 3.** An example of an optimized plan in relation to on-time delivery.

With this setup the planner assumes that the penalty for exceeding material and resource capacity (overtime) is higher than the penalty for late supply (backorders) or build to stock. Therefore, if necessary, due to constrained capacity, the optimization algorithm considers the trade-off between the costs of late demand against the cost of inventory carrying. The weight of the objective affects the outcome. If the weight for example is increased, fewer orders will be late whereas stock will increase.

2.1. If the primary objective is "maximize inventory turns" and "demand due date" is a hard constraint, the capacity becomes a soft constraint and the only penalties to be considered are related to the supply (operation, supplier and transportation resources). With this setup the planner assumes that the penalty for late supply (backorders) is higher than the penalty for exceeding resource capacity (overtime) or build to stock. Therefore if necessary due to constrained supply side, the optimization algorithm considers the trade-off between the penalty costs of overtime labour against the penalty cost of inventory carrying. If the weight of "maximize inventory turns" for example is increased, resource capacity will increase whereas stock will decrease.

2.2. If the primary objective is "maximize inventory turns" and "capacity" is a hard constraint the demand due-dates becomes a soft constraint and the only penalties to be considered are therefore related to the late demand. With this setup the planner assumes that the penalty for exceeding material and resource capacity (overtime) is higher than the penalty for late supply (backorders) or build to stock. Therefore, if necessary due to constrained demand, the optimization algorithm considers the trade-off between the penalty costs of late demand against the penalty cost of inventory carrying. If the weight of "maximize inventory turns" for example is increased, more orders will be late (on-time delivery will suffer) whereas stock will decrease.

Fig. 3 illustrates an example of a plan optimisation in relation to on-time delivery. The aim of the optimisation is to solve the problem in the third period where demand is higher than the available machine and labour resources.

Supply exceeds demand in the second period, as inventory is accumulated for use during the third time period in which demand substantially exceeds supply. Due to limited machine resources, demand cannot be met and an order backlog occurs. Additional machine resources become available in the fourth time period (equal to the labour constraint), and production is now limited by labour as well as machine availability. Demand is less than supply in this period, and some of the backlog is worked off, but not all of it. In the fifth time period, the remainder of the order backlog is worked off as production is neither constrained by labour or machine resources. Avoiding any backlog would be difficult, as it would require increasing machine capacity on a short-term basis. That is unlikely to be feasible. A backlog occurs in the third period because the hard machine constraint makes it impossible to meet the peak demand. In the optimization the cost of labour overtime in the second period is balanced against the cost of carrying the backorder. A "what-if" alternative could be simulated by increasing the work hours at an earlier stage for the labour resource and machines.

## 7. Conclusions

APS is a step in the right direction towards generating more realistic and reliable production plans. But optimisation and its objectives and penalty factors are not yet well supported for production planning from a manufacturing point of view. Currently two different options exist—an optimized plan and a constrained plan. The optimized plan is based on a cost or profit perspective, which does not always lead to an optimal production plan, because some costs are difficult to model in a satisfactory way. Examples of this are the consequences in manufacturing when alternate suppliers are used or the penalty costs of unmet customer due dates. On the other hand, the constraint-based plan is based on business rules and priorities, which for the current release is too simple. When constraint-based planning and optimized planning is not based on the same decisions and assumptions it is difficult for the planner to generate a constraint-based plan and then develop this into an optimized plan subsequently.

A challenge of great importance is the ability to optimize a plan across several partners in the supply chain. APS offers this functionality but it is rarely used as the individual partners belong to a number of supply chains. Each partner needs a plan which covers all their operations and not a plan which only optimizes a subset of their operations. This calls for a more diversified setup and interaction among a number of partners with each their APS-like system.

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