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# Project logistics: integrating the procurement and construction processes

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**The paper presents a stochastic model to plan the delivery of material to a building site, in view of ensuring the continuity of the construction process. The model assesses the amount of material that should be available at the site at a given time to guarantee the desired level of protection against changes in delivery dates and the rate of progress. The model may be used in early project planning, when detailed analysis based on network techniques is not yet available, and represents a basic tool for the aggregate management of the procurement, expediting and transport activities involving materials delivery to sites.** 

Keywords: project logistics, procurement, construction

## Introduction

An engineering and contracting project may be represented as a sequence of macro-phases (engineering, procurement, construction, etc.).

Project planning is a sequence of ever more detailed stages, passing from an overall project plan to more precise specifications for each macro-phase. The overall project plan indicates the milestones representing the frame of reference for the subsequent development of detailed schedules. In general, the project scheduling process is based on a backwards approach: the deadlines for construction activities influence delivery and procurement, which in turn affect the engineering schedule. From a logistics point of view, project control may be described as a 'push' process, aiming to comply with scheduling deadlines as defined by the overall and detailed project plans.

The management of the interface between two successive phases is critical in guaranteeing the integration of the overall project.

This relationship may be analysed either at aggregate or at detailed level. The former is typical of the early planning stage, the latter occurs when the project is more advanced. At an aggregate level, the project life-cycle may be represented by a sequence of 'S' curves describing the expected progress of each phase as a function of time (see *Figure 1*). The relationship between any two successive phases may be described by comparing the corresponding progress curves and highlighting the following two parameters (see *Figure 1*):

- the difference in progress, SM, between the two curves at a given date;
- the lead time, ST, ensuring that the downstream curve equals the progress of the upstream curve.

At a detailed level, the lead time ensuring that each activity in the upstream phase anticipates the subsequent activities in the downstream phase can be evaluated more accurately when the network model of the project becomes available.

This paper focuses on the integration at aggregate level of the procurement and the construction phases. The problem arises from the obvious fact that the beginning of a construction activity in a given area of the building site requires the availability of the necessary materials. Orders for these should have taken account of procurement and transport lead times and all possible sources of uncertainty in the construction schedule. On the one hand, a safety stock must be available to prevent the interruption of the construction process at the site, while, as in work-in-progress in manufacturing processes, the size of this safety stock must be so evaluated as to limit the financial exposure and the costs involved in the storage and hand-

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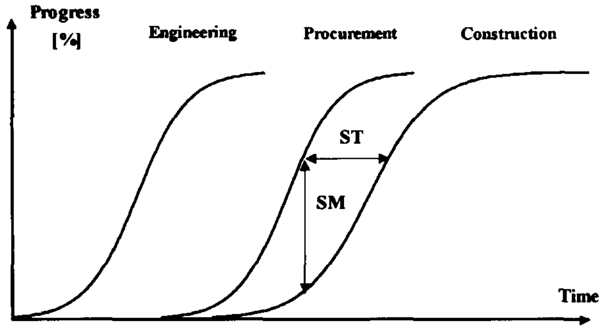


**Figure 1** Expected progress for Engineering, Procurement and Construction during the project life-cycle. *SM* indicates the safety stock of materials and *ST* the safety lead time

ling of materials. The problem may thus be formulated as: how much material should be available at the site at a given time in order to guarantee a desired level of protection against interruptions due to the shortage of materials?

A 'required availability' progress curve must be obtained which represents the fundamental reference for the scheduling of deliveries to the site. For each planning period, the 'actual availability' level ensured by the delivery process should never be less than the 'required availability' level. The relationship between the construction, the 'required availability' and the 'actual availability' or delivery progress curves (where the stepwise pattern reflects the sequence of deliveries) is shown in *Figure 2*.

The problem of the requirements that the delivery progress curve should meet in order to comply with a given construction progress curve has not yet received sufficient attention. The practical approach used by some engineering and contracting companies is based on a constant safety lead time which is applied to the whole duration of the construction phase. According to this approach, materials should be delivered to the site in advance of the starting date of the corresponding construction activity. In other words, the construction progress curve is anticipated by a constant safety lead time. This approach has two main shortcomings:

- it does not take into account the different stages of the construction process, in that it considers every planning period in the same way;
- it does not take explicit account of the uncertainty factors that influence the delivery and the construction processes, causing delivery delays and variability in productivity.

This paper aims to bridge the gap in both the literature and practice. It presents a stochastic model which evaluates the safety stock and the corresponding safety lead time required for the delivery of materials to the site in each planning period, taking account of variability in delivery dates and the rate of progress of construction. The model is a basic tool for the aggregate management of the procurement, expediting and transport functions. At the very beginning of the project, when information is scarce and detailed analysis based on network techniques is not yet available, an aggregate approach is the only way to deal with the problem of integrating the procurement and construction phases. It should be emphasized that the aggregate requirements which the delivery plan should meet must include the uncertainty factors within the project environment and, given the long lead times for materials procurement and delivery to the site, must be evaluated at the early planning stage. This is particularly true for critical materials which influence the starting dates of activities on the critical path.

It should be further noted that the model does not aim to define a detailed delivery plan-in terms of delivery lots and delivery dates-but it does aim to define the requirements that the delivery plan should meet in order to ensure the continuity of the construction process. These requirements can be met by different delivery frequencies and delivery lot sizes.

The remainder of the paper is divided into three sections. In the first, we describe the problem of integrating the procurement and construction processes when faced with the scarce information available in the early stage of the project life-cycle. In the second, we develop the stochastic model. Finally, in section three, we present a numeric example comparing the proposed model with a deterministic approach based on a constant safety lead time.

*Integration of procurement and construction*

Integration of the procurement and construction processes at a detailed planning and control level requires a comparison of the materials delivery schedule and the corresponding construction schedule.[1-7,12] A possible report created for this purpose should list all construction activities with the corresponding deliveries and verify that the schedules are fully compatible. The starting dates of the construction activities should depend on the time constraints deriving from the actual delivery dates. In this way, it is possible to identify the activities that will be held up by delays in materials deliveries. Obviously, the most critical delays are those involving activities on the critical path.

At an aggregate level, i.e. during the early planning stage, when detailed information about construction activities is not yet available, the procurement and construction phases can be integrated by comparing the two progress curves. It should be noted that the

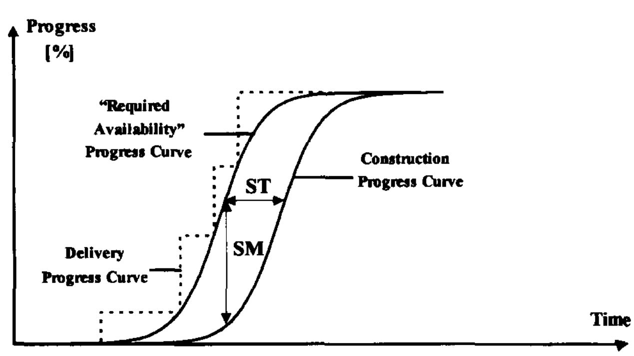


**Figure 2** Relationship between Construction, 'Required Availability' and Delivery Progress Curves

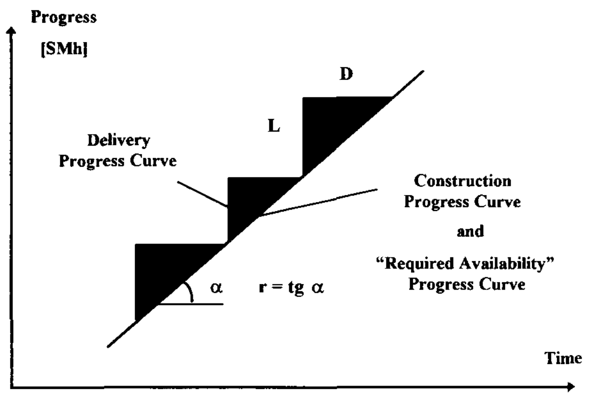


**Figure 3** Stock of materials at the site assuming Delivery synchronised with Construction. *L* indicates the lot size, *D* the lot depletion time and *r* the construction progress rate

construction progress curve must be defined at the very beginning of the project with the overall plan and take account of the main project milestones. From this construction progress curve, a delivery progress curve can be derived, which acts as a reference for the detailed expediting and transport plans.

The relationship between procurement and construction may be analysed by expressing both progress values in the same unit of measure. To this end, the cumulative amount of material progressively delivered to the site will be evaluated in terms of equivalent standard man hours of construction (SMh). Thus, each delivery of materials will be translated into an equivalent amount of SMh, using standard rates which convert physical units into standard man hours. Once materials have been installed, the equivalent amount of SMh will be 'earned'.

Consider the following 'ideal' assumptions concerning a construction work package (WP):

- the construction progress rate is definite;
- materials are delivered to the site in compliance with the construction sequence;
- materials are delivered to the site in compliance with the established delivery dates;
- materials delivered to the site are immediately available for construction.

If these assumptions hold, there is no need for a safety lead time for the deliveries to the site, since every aspect of the problem is known definitely.

The materials stock awaiting use at the site is defined by the shaded area in *Figure 3*, where:

- L = size of a generic lot of materials delivered to the site (expressed as SMh);
- r = construction progress rate (SMh 'earned' per time unit);
- D = L/r = time required for lot depletion.

Since it is impossible to synchronize materials delivery with construction scheduling fully, a safety stock of materials should be provided at the site, in order to ensure the continuity of the construction process. This corresponds to the determination of the above-mentioned 'required availability' progress curve, which anticipates the construction progress curve with a given safety lead time and provides a reference for delivery planning.

The problem then is to evaluate the safety lead time (ST) with which materials should be delivered in advance of the time they are scheduled for use (see *Figure 2*), or, alternatively, calculate the size of the material safety stock (SM). Both parameters, ST and SM, should be defined as a function of time.

After defining the construction progress curve, the 'required availability' progress curve may be defined using the values of parameters ST and SM to obtain a basic reference for the delivery progress curve with a typical stepwise trend (see *Figure 2*).

Assuming that the materials delivery sequence is consistent with the construction sequence and that the materials delivered to the site are immediately available for construction, the values of SM and ST at a given planning period depend on the variability of delivery dates with respect to scheduled dates and the variability of the rate of construction progress (variability of labour productivity and operating conditions at the site, etc.). The values of SM and ST will also depend on the level of protection necessary to offset the risk of work interruption due to material shortages.

Such an approach may be applied to the whole construction process or to single WPs. In the third section of the paper, a practical example relating to a typical bulk materials WP (e.g. pipeline installation) is illustrated.

### *The 'stochastic' model*

The proposed approach involves the following basic steps:

1. divide the planning horizon, i.e. the duration of the construction process, into planning periods with duration $t_u$, e.g. months or weeks (see *Figure 4*); the index $i$ will refer to the generic planning period (e.g. March 1997) with $i = 1,\ldots,n$;
2. assess the expected progress rate of the construction process for each planning period ($r_i = SMh_i$);
3. decide the level of stockout protection which safety stocks should guarantee ($LS_i$);
4. determine the value of the materials safety stock ($SM_i$) which in each period ensures the continuity of the construction process at the required level of stockout protection and consequently determine the safety lead time ($ST_i$).

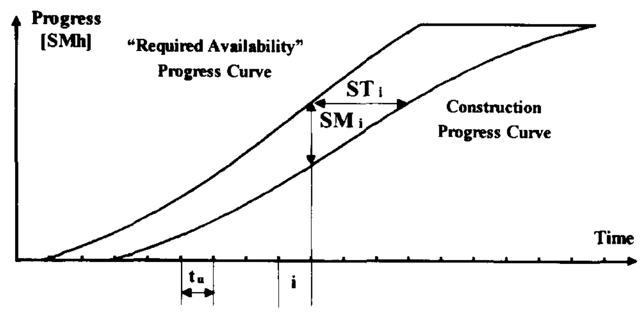


**Figure 4** Planning horizon, safety stock of materials ($SM_i$) and safety lead time ($ST_i$) in the $i$-th planning period

The need to consider discrete planning periods stems from the availability of discrete expected progress data relating to the construction process. In particular, the length of the planning period ($t_u$) is related to the level of detail with which the quantity of materials to be installed in each period is known. This inherent level of aggregation is a typical feature of the overall project planning in this preliminary phase of the study.

Considering a generic construction WP, the expected level of progress at a given period may be expressed in terms of *SMh* 'earned' from start-up to the period considered. Let $p_i$ be the expected productivity value in period $i$ with:

$$p_i = \frac{SMh_i}{EMh_i} \tag{1}$$

where:

- $SMh_i$ indicates the standard man hours to be 'earned' in the $i$-th period;
- $EMh_i$ (Expected Man Hours) indicates the actual hours to be spent in the $i$-th period, as a function of the human resources available, period by period, and of the related working hours.

The parameter $p_i$ mainly takes account of the characteristics of the labour force and the expected working conditions at the site.

Let productivity be modeled as a normally distributed random variable whose mean value and standard deviation in the $i$-th period are represented by $p_i$ and $\sigma_{p_i}$. These values may be assessed with reference to historical data, as well as by forecasting the working conditions of the construction process period by period.

For the remainder of the paper, $EMh_i$ will be a deterministic parameter, the function of the resources expected to be allocated to the *WP* in the $i$-th period. This assumption would be critical in a detailed approach, because the control of the construction process (e.g. expediting actions) might require a resource re-allocation. However, taking $EMh_i$ as a deterministic parameter is not a critical assumption when dealing with preliminary planning rather than control.

According to the previous assumptions, the progress rate in the $i$-th period is also assumed to be a normally distributed random variable, whose mean value and standard deviation are linked to the time profile of the work effort ($EMh_i$) by the mean productivity value, $p_i$, and the standard deviation $\sigma_{p_i}$:

$$r_i = SMh_i = p_i \cdot EMh_i \tag{2}$$

$$\sigma_{r_i} = \sigma_{p_i} \cdot EMh_i = \frac{\sigma_{p_i}}{p_i} \cdot r_i \tag{3}$$

For all materials, purchase orders should have been issued before the construction process starts. The procurement process is subsequently managed according to a 'push' approach, so as to deliver materials to the site in compliance with the deadlines established by the expected construction schedule. *consequentally*, the safety stock of materials, $SM_i$, which should be available at the end of the $i$-th period must be sufficient to cover all variabilities from start-up of the construction process to the end of the $i$-th period.

The safety stock of materials can therefore be assessed by the following well known relationship which is widely applied in logistics to evaluate the safety stock in cases of demand variability during lead time:[8–11]

$$SM_i = k \cdot \sigma_{c,i} \tag{4}$$

where:

- $\sigma_{c,i}$ is the combined standard deviation of the overall materials requirement from start-up of the construction process to the end of the $i$-th period. It considers both the variability of the progress rates (from period 1 to period $i$) and the variability of delivery dates;
- $k$ is a managerially determined factor reflecting the desired level of stockout protection (*LS*) to be adopted against the risk of interrupting (or slowing down) the construction process due to materials shortages. Factor $k$ is expressed as the number of standard deviations with reference to the normal standard distribution which guarantees a given level of stockout protection (e.g. for $LS = 98\%$, $k = 2.06$).

*Equation (4)* holds until the 'required availability' progress curve equals the total amount of materials required to complete the WP. From that point on, no more material has to be delivered to the site and the concept of material safety stock loses significance (as the level of stockout protection equals 100%). The stock of materials decreases, reaching zero at the end of the construction phase.

Assuming that progress rates are not autocorrelated and are independent of delivery dates, the value of $\sigma_{c,i}$ may be calculated by the following relationship:[8]

$$\sigma_{c,i} = \sqrt{\sigma_{R_i}^2 + r_{i+1}^2 \cdot \sigma_T^2} = \sqrt{\left(\sum_{j=1}^{i} \sigma_{r_j}^2\right) + r_{i+1}^2 \cdot \sigma_T^2} \tag{5}$$

where:

$$R_i = \sum_{j=1}^{i} r_j$$

and

$$\sigma_{R_i} = \sqrt{\sum_{j=1}^{i} \sigma_{r_j}^2}$$

are the mean value and standard deviation of progress in construction at the end of the $i$-th planning period;

- $\sigma_T$ indicates the standard deviation of the delivery dates with respect to the planned dates; the former, in case of delay in materials delivery at the end of the i-th period, must be multiplied in *Equation (5)* by the progress in construction of the successive period $i + 1$.

It should be noted that, given the assumption of a deterministic work effort profile, independence between the construction progress rates means independence between the productivity values. This assumption implies that the effect of possible corrective actions involving construction progress rates is to be taken into account in a subsequent control phase and not in the preliminary planning stage.

A look at relationships (4) and (5) shows that $SM_i$ grows as:

1. the desired level of stockout protection increases;
2. productivity and materials delivery dates become less predictable;
3. the expected construction progress rate in the $(i+1)$th planning period increases;
4. construction process progresses, since $\sigma_{c,i}$ is a function of the sum of the variances in progress rates to the end of the $i$-th period.

According to the definition of construction progress rate (expressions (2) and (3)), and assuming constant values both for expected productivity and standard deviations in each planning period ($p_i = p$ and $\sigma_{p_i} = \sigma_p$ $\forall i$), relationship (5) changes as follows:

$$\sigma_{c,i} = \sqrt{\gamma_p^2 \cdot \left(\sum_{j=1}^{i} r_j^2\right) + r_{i+1}^2 \cdot \sigma_T^2} \tag{6}$$

where $\gamma_p = \sigma_p / p$ is the dispersion index of productivity.

The 'required availability' ($A_i$) is finally derived by summing the materials safety stock and the construction progress curve (see *Figure 5*):

$$A_i = R_i + SM_i \tag{7}$$

The delivery progress curve has to be consistent with the minimum requirements outlined in the 'required availability' progress curve (see *Figure 5*). The former usually exhibits a stepwise trend, reflecting subsequent choices in lot sizing involving the detailed delivery schedule.

A safety lead time ($ST_i$) is associated to the safety stock of materials determined above. This is the period necessary to consume the safety stock at a given time, assuming that the construction progress rate is equal to the expected value (see *Figure 6*). For example, if a lot of materials is delivered which increases the available stock over $SM_i$, then this extra stock would be used only after a lead time, $ST_i$, in that $SM_i$ acts as a materials buffer which has to be depleted before extra material can be used.

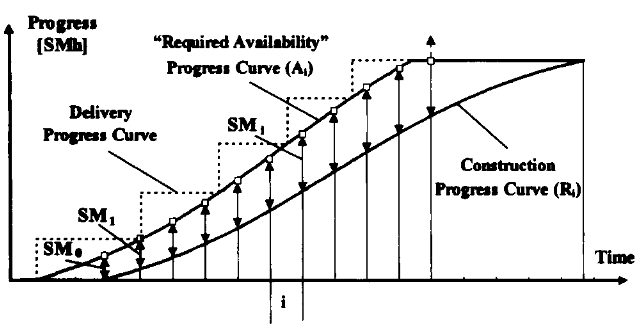


**Figure 5** Derivation of the 'Required Availability' Progress Curve from the Construction Progress Curve (the dotted line represents a possible delivery progress curve)

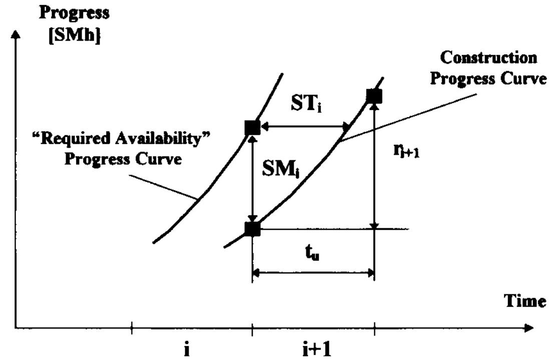


**Figure 6** Relationship between safety lead time ($ST_i$) and safety stock of materials ($SM_i$)

The exact value of the safety lead time in the $i$-th planning period ($ST_i$) can be obtained by dividing the safety stock of materials ($SM_i$) by the construction progress rate. If the construction progress rate follows a regular trend, it is quite fair to adopt the following approximate relationship for $ST_i$, which assumes that the mean construction progress rate during $ST_i$ is equal to the value $r_{i+1}$:

$$ST_i = \frac{SM_i}{r_{i+1}} \cdot t_u \tag{8}$$

where $t_u$ is the length of the planning period.

Relationship (8) holds only till the 'required availability' curve is below its maximum value, i.e. the total amount of material necessary to complete the work package. When all materials have been delivered, the concept of a safety lead time is no longer useful.

$ST_i$ values according to (8) may be increased by the time required to manage materials at the site, e.g. for quality control, handling and warehousing. This can be assumed to be approximately constant.

### *A comparison between the stochastic model and the deterministic approach*

In order to test its effectiveness, the 'stochastic' model is compared to a deterministic approach based on a constant safety lead time. According to the deterministic approach, the 'required availability' progress curve is simply obtained from the construction progress curve by means of a horizontal shift, denoted by $\widetilde{ST}$. The comparison involves the levels of stockout protection provided by the two approaches, at equivalent cost. Consequently, the constant safety lead time should be such that the safety stock profiles generate the same financial effects (see the appendix for a step by step derivation of (9)):

$$\widetilde{ST} = \frac{\sum_{i=0}^{n} SM_i}{\sum_{i=1}^{n} r_i} \cdot t_u \tag{9}$$

According to *Equation (9)*, a constant safety lead time, which in financial terms is equivalent to the $ST_i$

**Table 1 Application of the 'stochastic' model to the example problem**

| | Construction progress rate $r_i$ [SMh] | Construction progress level $R_i$ [SMh] | Material safety stock $SM_i$ [SMh] | Material safety lead time $ST_i$ [months] | Required Availability progress level $A_i$ [SMh] | Stockout Protection level $LS_i$ |
|---|---|---|---|---|---|---|
| 0 | / | / | 1030 | 0.412 | 1030 | 98% |
| 1 | 2500 | 2500 | 3271 | 0.448 | 5771 | 98% |
| 2 | 7300 | 9800 | 5352 | 0.615 | 15152 | 98% |
| 3 | 8700 | 18500 | 8845 | 0.560 | 27345 | 98% |
| 4 | 15800 | 34300 | 13302 | 0.633 | 47602 | 98% |
| 5 | 21000 | 55300 | 17000 | 0.837 | 72300 | 98% |
| 6 | 20300 | 75600 | 19658 | 1.063 | 95258 | 98% |
| 7 | 18500 | 94100 | 21831 | 1.186 | 115931 | 98% |
| 8 | 18400 | 112500 | 10500 | – | 123000 | 100% |
| 9 | 6500 | 119000 | 4000 | – | 123000 | 100% |
| 10 | 3000 | 122000 | 1000 | – | 123000 | 100% |
| 11 | 500 | 122500 | 500 | – | 123000 | 100% |
| 12 | 500 | 123000 | 0 | – | 123000 | – |

series, is simply calculated by dividing the sum of the safety stocks of materials obtained with the 'stochastic' model by the total work content of the work package expressed as SMh.

According to the 'constant safety lead time' model, the safety stock of materials in the $i$-th period ($\widetilde{SM}_i$) can be approximately computed as follows:

$$\widetilde{SM} = \frac{\widetilde{ST} \cdot r_{i+1}}{t_u} \tag{10}$$

It is now possible to determine the safety factors for the desired level of stockout protection which result from the application of the 'constant safety lead time' model. According to *Equation (4)*, the $k$ factors are computed as follows:

$$\tilde{k}_i = \frac{\widetilde{SM}}{\sigma_{c,i}} \tag{11}$$

where $\widetilde{SM}$ are the values obtained from *Equation (10)*.

Finally, the safety factors provided by the 'constant safety lead time' model and by the proposed 'stochastic' model should be compared, in order to highlight the different behaviour with respect to risk protection.

*Example problem*

Let us consider a construction WP concerning a pipeline installation. Bulk materials are usually procured through open orders, allowing the supplier to obtain a progressively more accurate estimate of quantity requirements based on subsequent estimates deriving from material take-offs. Nevertheless, as the supplier needs long lead times to deliver the required materials, it is extremely important to provide a first aggregate reference for the delivery schedule which significantly anticipates the construction scheduled dates.

The planned progress curve is described by the values indicated month by month (i.e. $t_u = 1$

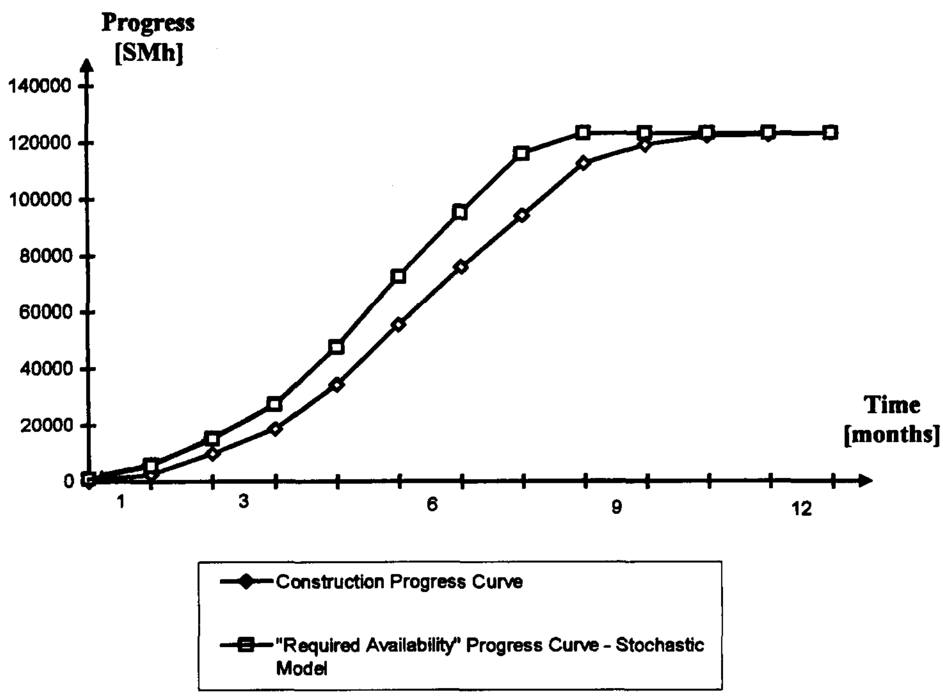


**Figure 7** Example problem: Construction Progress Curve and 'Required Availability' Progress Curve in the 'stochastic' model

**Table 2** Application of the 'constant safety lead time' model to the example problem

| | Material safety stock $\widetilde{SM}_i$ [SMh] | Required Availability progress level $\widetilde{A}_i$ [SMh] | Safety Factors $\widetilde{K}_i$ | Stockout Protection level $LS_i$ |
|---|---|---|---|---|
| 0 | 2160 | 2160 | 4.32 | 99.99% |
| 1 | 6308 | 8808 | 3.97 | 99.99% |
| 2 | 7518 | 17318 | 2.89 | 99.8% |
| 3 | 13653 | 31153 | 3.18 | 99.93% |
| 4 | 18147 | 52447 | 2.81 | 99.75% |
| 5 | 17542 | 72842 | 2.13 | 98.3% |
| 6 | 15986 | 91586 | 1.67 | 95.3% |
| 7 | 15900 | 110000 | 1.50 | 93.3% |
| 8 | 5617 | 118117 | 0.51 | 69.5% |
| 9 | 2592 | 121592 | 0.23 | 59.2% |
| 10 | 432 | 122432 | 0.039 | 51.5% |
| 11 | 432 | 122932 | 0.039 | 51.5% |
| 12 | 0 | 123000 | - | - |

month) in *Table 1* in terms of total SMh to be earned.

For simplicity, the parameters dispersion index of productivity, standard deviation of delivery dates and the $k$ safety factors for the stochastic model have been assumed to be constant within the planning horizon (12 months):

$$\gamma_{p_i} = \gamma_p = \sigma_{p_i}/p_i = 0.25$$

$$\sigma_T = 0.2 \text{ months}$$

$$k = 2.06(LS = 98\%)$$

*Equations (4)* and *(6)* are applied to assess the safety stock of materials required at the end of each planning period. At the end of a fictitious period zero, which corresponds to beginning of the first period, a safety stock of materials, $SM_0$, is to be provided to account for the variability in the delivery date. On the other hand, at the end of the first period, a safety stock of materials, $SM_1$, must account for the variability in both the construction regressionrate in the first period and the delivery date.

For example, let us compute the safety stock of materials for the first two periods:

$$\sigma_{c,0} = \sqrt{\gamma_p^2 \cdot r_0^2 + r_1^2 \cdot \sigma_T^2}$$

$$= \sqrt{(0.25)^2 \cdot (0)^2 + (2500)^2 \cdot (0,2)^2} = 500[SMh]$$

$$SM_0 = k \cdot \sigma_{c,0} = 2.06 \cdot 500 = 1030[SMh]$$

$$\sigma_{c,1} = \sqrt{\gamma_p^2 \cdot (r_1^2) + r_2^2 \cdot \sigma_T^2}$$

$$= \sqrt{(0.25)^2 \cdot ((2500)^2) + (7300)^2 \cdot (0.2)^2}$$

$$= 1588[SMh]$$

$$SM_1 = k \cdot \sigma_{c,1} = 2.06 \cdot 1588 = 3271[SMh]$$

After computing the safety stock values, reported in *Table 1*, the 'required availability' progress curve is easily obtainable.

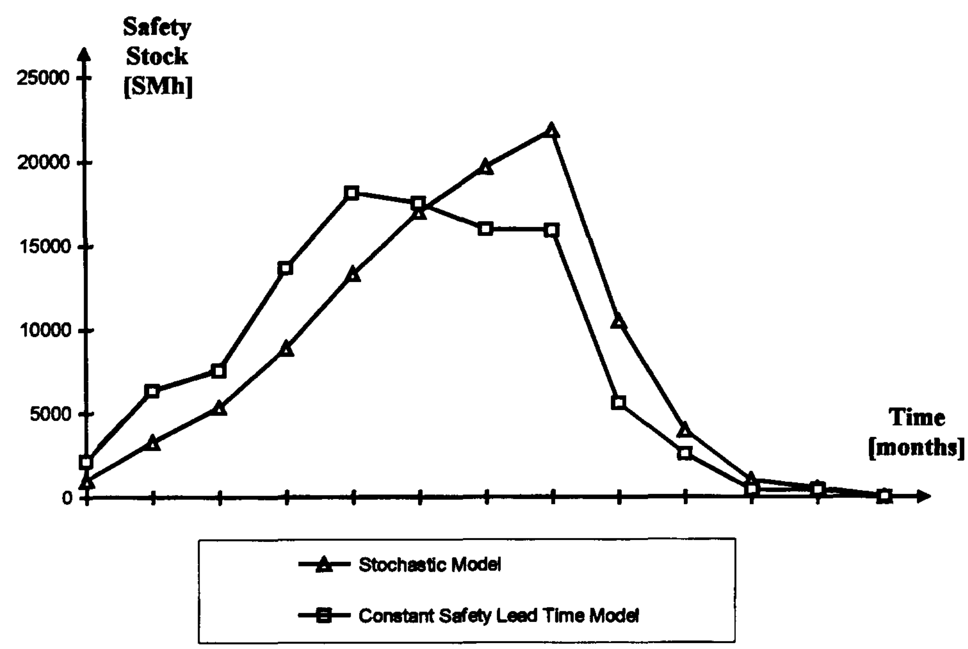


**Figure 8** Example problem: safety stock profile for the 'stochastic' and 'constant safety lead time' models

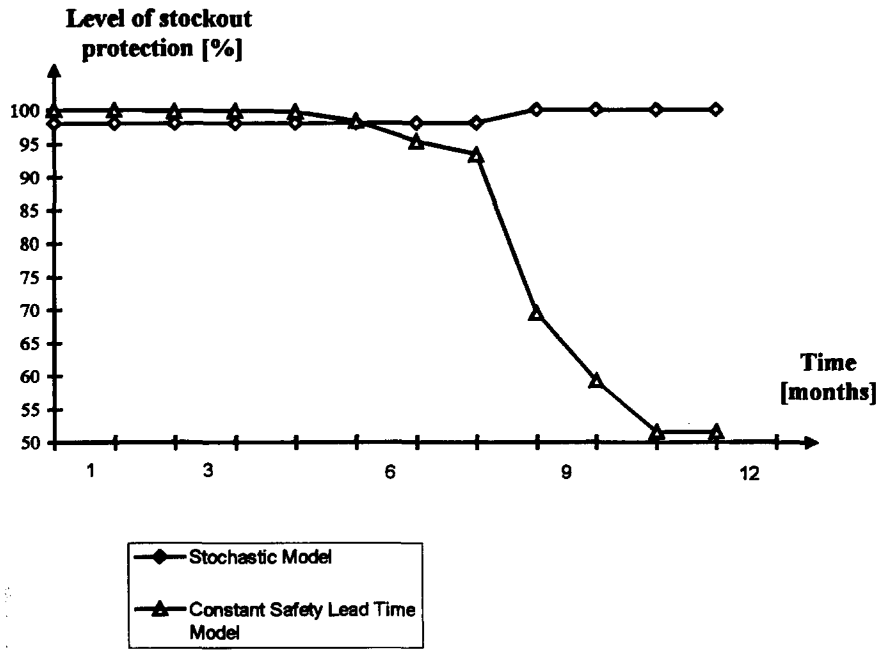


**Figure 9** Example problem: level of stockout protection for the 'stochastic' and 'constant safety lead time' models

For instance, at the beginning of the *WP*, $A_0$ (required availability) equals $SM_0$:

$$A_0 = SM_0 = 1030[SMh]$$

and $A_1$ is computed as the sum of the first period progress rate ($r_1$) and the safety stock of materials at the end of the first period ($SM_1$):

$$A_1 = R_1 + SM_1 = r_1 + SM_1 = 2500 + 3271 = 5771[SMh]$$

The computation, continued recursively following the logic of the previous examples, gives the results shown in *Table 1* and illustrated in *Figure 7*.

Without considering the time required for materials handling and quality control at the site, the safety lead times may be approximately calculated by means of *Equation (8)*. For the first two periods, this is:

$$ST_0 = \frac{SM_0}{r_1} \cdot t_u = \frac{1030}{2500} = 0.412[\text{months}]$$

$$ST_1 = \frac{SM_1}{r_2} \cdot t_u = \frac{3271}{7300} = 0.448[\text{months}]$$

All safety lead times are reported in *Table 1*.

As far as the 'constant safety lead time' model is concerned, the lead time must first be calculated by *Equation (9)*, i.e. condition of cost equivalence:

$$\widetilde{ST} = \frac{\sum_{i=0}^{n} SM_i}{\sum_{i=1}^{n} r_i} \cdot t_u = \frac{106289}{123000} = 0.864[\text{months}]$$

The subsequent computation of safety stocks of materials ($\widetilde{SM}_i$) and safety factors ($\tilde{k}_i$) using *Equations (10)* and *(11)* is reported in *Table 2* and illustrated in *Figure 8*.

From an analysis of the results, the following conclusions on the performance of the two models can be drawn:

1. The 'stochastic' model allows for safety stock provision that follows the development of the construction process and accounts for all major variability factors that may affect materials requirements in each period.
2. The 'stochastic' model suggests a safety stock profile (see *Figure 8*) that ensures a constant level of stockout protection for the entire duration of the construction phase. In contrast, the 'constant safety lead time' model tends to provide a large degree of stockout protection in the first periods, but performs less effectively as the construction phase proceeds. The stockout protection in the last periods is excessively low (51.5% in the last two periods) while in the first periods it is excessively high (see *Figure 9*).

### *Conclusion*

The problem of ensuring that sufficient stock of materials is available at a building site to protect the construction process against variability in both delivery dates and the use of materials is crucial to Project Logistics.

The proposed 'stochastic' model calculates the quantity of materials required at a given time to prevent interruption (or a slowing down) of the construction process. Through the evaluation of the 'required availability' for each planning period, the model gives a target reference to plan materials delivery.

It should be noted that the described approach may be applied during early preliminary project planning, when detailed project activities have not yet been outlined and network techniques can therefore not be applied.

Indeed, the prerequisite for the application of the model is the evaluation of the construction progress curve at an aggregate level. This curve may even be based on a limited amount of data, for example the project milestones or historical data from previous experience in similar projects.

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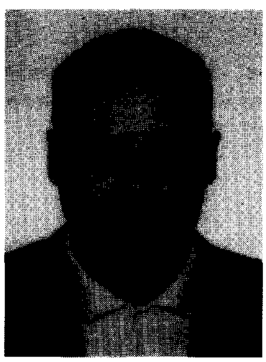


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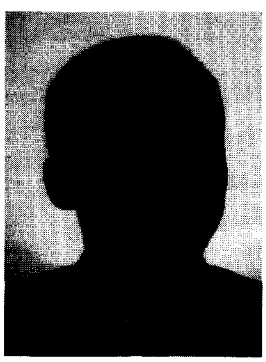


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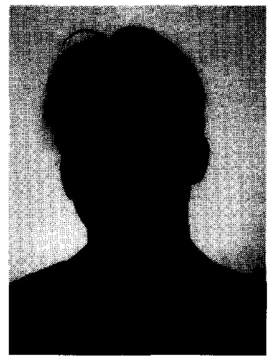

## Appendix

*Computation of the constant safety lead time on the assumption that the safety stock profiles of the deterministic and the stochastic approaches generate the same financial costs*

Financial costs are proportional to the materials stock profile, which is well approximated by the area lying between the 'required availability' curve and the construction progress curve (the actual values depend on the area between the delivery curve and the construction progress curve).

In the stochastic case, this area (say $FA$) may be computed approximately by assuming that the safety stock during each period equals the amount of safety stock at the end of the period:

$$FA \cong \sum_{i=0}^{n}(SM_i \cdot t_u) = t_u \cdot \sum_{i=0}^{n} SM_i \tag{12}$$

Since in the 'constant safety lead time' model the 'required availability' progress curve is a mere shift of the construction progress curve, the above-mentioned area can be computed exactly as:

$$FA = \widetilde{ST} \cdot \sum_{i=1}^{n} r_i \tag{13}$$

The constant safety lead time is obtainable by forcing the condition of cost equivalence for the two safety stock profiles, meaning that $FA$ values, as computed by *Equations (12)* and *(13)*, are equal:

$$t_u \cdot \sum_{i=0}^{n} SM_i = \widetilde{ST} \cdot \sum_{i=1}^{n} r_i \tag{14}$$

$$\widetilde{ST} = \frac{\sum_{i=0}^{n} SM_i}{\sum_{i=1}^{n} r_i} \cdot t_u \tag{15}$$