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Forecasting of Production Order Lead Time in Sme's

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1. Introduction

More and more companies on the global market are today capable of manufacturing individual or small-series orders at comparable prices and quality. The main difference between these companies is the expected production order development-time and the observance of delivery deadlines.

Before making a bid, the sales department must establish what operations will have to be carried out for a particular order, the time needed for performing these operations, and what delivery time is required.

Currently, operation-time data are usually obtained from experienced company employees (however, a problem arises if they leave the company, because SMEs do not usually have systems for knowledge capture—the “knowledge” with which they are dealing is more “oral tradition”, knowledge obtained by experience), while the customer specifies the delivery time. However, estimates on lead times, and thus delivery times, based on personal experience can be rather misleading. Bids may consequently be based on wrong decisions, or even worse; because of an incorrectly specified delivery time the company may not receive the order, because the delivery time (if not specified by the customer) may be too long and therefore uncompetitive in comparison with other bids. Another type of a problem arises if the specified delivery time is too short and cannot be met.

The development of information and communication technologies (ICT) makes it easier for a company to improve and maintain its competitive advantages on the market (Leem C.S., Suh J.W., 2005), because it is very easy to access the data. A company striving to be competitive on the global market needs a suitable enterprise resource planning (ERP) system. There are several ERP systems available (Scherer E., 2005) and each company must select the optimal system for its needs (Starbek M., Grum J., 2000).

This chapter presents how the data stored in the ERP system can be used for the calculation of lead times of operational and assembly orders and indirectly, for forecasting production order lead times, depending on the confidence interval.

Naturally, if the company does not have an ERP system, it is possible to manually obtain the data required for forecasting lead times. The disadvantage of such a method is that the manual procedure is rather time-consuming in order to build an applicable database.

The chapter presents a review of the literature and some achievements and guidelines related to lead times of orders and delivery times. A procedure for forecasting production

order lead times is presented and described, as well as the results of the application of this procedure in a tool shop.

The result of the proposed procedure for forecasting production order lead times is an empirical distribution of possible lead times for a production order. On the basis of this distribution, it is possible to forecast the probable lead time of a production order as a function of the confidence interval.

Using the proposed procedure, the sales department can make a delivery time forecast for the customer of the planned production order.

Conclusions, findings and guidelines for further activities are presented at the end of the chapter.

2. Literature review

Considerable research has been done on the possibilities of determining production lead times. In 1979, Weeks (Weeks, 1979) researched the impact of forecasted lead times based on various statistical measurements in individual production of variable volume and structure. He tested the following three hypotheses:

Delivery time rules based on estimates of individual job lead-time conditions have a better effect on workshop congestion than widely reported total work content rules when employed with delivery time oriented dispatching rules.

Delivery time oriented dispatching rule investigated performed better than the shortest-imminent-processing-time dispatching rule in terms of meeting delivery times.

Delivery time performance tends to worsen as workshop structure becomes more elaborated and complex.

Weeks concluded that this was just the beginnings of research on forecasting delivery lead times with one of several possible statistical tools and that there were many unanswered questions and much research would have to be done in this field.

(Vig & Dooley, 1991) used two new dynamic rules for defining delivery time in existing delivery-time forecast models. They discovered that data on orders that had been completed recently could be very useful for forecasts in the future. Their study confirmed the conclusions of other research: the characteristics of a particular order and the type of production are very important for the forecast of lead time.

(Enns, 1994) stated that short lead times and high supply reliability were required for job shop customers.

Lawrence S.R. (1994) presented a methodology for negotiating due dates between the customer and the producer in a complex production environment.

Nyhuis P., Vogel M. (2006) presented a methodology for tracking and accurate logistic control of a one-piece material-flow process.

Denkena B., Lorenzen L.-E., Batino A. (2006) studied the possibilities of increasing production flexibility and efficiency and proposed a new production-planning model: integration of centralized labour and decentralized decision-making.

Several studies (Buzacott J.A. & Mandelbaum M., 1985; Chen Y.J et al., 2005; Wang Z. et al., 2004; Krause F.L. & Altmann C., 1991) have shown that the flexibility of enterprise resource planning can be improved only if alternative technology solutions are used during repeated planning of manufacturing operations. However, the aforementioned studies do not deal with the basic question of how to obtain quality input data for successful production planning.

Because of the ever more dynamic market, Wiendahl H.-P., Dammann M., 2006, presented the concept of a method for measuring dynamic influences and tools that can help companies to choose the right response to these dynamic influences. He used Begemann's (Begemann C., 2006) approach for capacity control, targeted at completion time, and Lödding's (Lödding H., 2005) model of production control. However, according to Wiendahl, the whole concept is still in its initial phase and needs detailed overview and research.

In our research, we did not find any lead time forecasting approach as described in this paper, so we assume this is a new approach that uses known theory on lead times and adds a new method for forecasting production order lead times.

Tatsiopoulos I.P. & Kingsman B.G., 1983, presented a comparison of two alternative approaches for determining planned values for manufacturing lead times for use in production planning and control systems. One approach was to treat manufacturing lead times as probabilistic and the second was to emphasise the control of manufacturing lead times. The conclusion of their paper was that new tools would have to be developed for planning, and theories for determining lead times would have to be improved.

Kingsman B.G., et al., 1989, described a developed methodology for controlling manufacturing lead times in make-to-order companies.

Kingsman B.G. (2000) presented modelling of input-output workload control for dynamic capacity planning in production planning systems, and ended with the conclusion that the arrival of orders in produce-to-order companies cannot be forecast in advance, and that managing lead times is a better approach than using forecast lead times. These conclusions encouraged us to try to find a better way of forecasting production order lead times.

Ooijen & Bertrand, 2001, wrote that, from the economic point of view, it is necessary to process orders within the deadline and, at the same time, it is necessary to take into account the acceptance of the delivery date from the customer's point of view and consider the reality of the deadline when making a bid.

Over the past decade, a lot of advanced methods and generic algorithms for scheduling production processes (Lestan, et al., 2009; Tasic et al., 2007; Kušar et al., 2004) and scheduling systems have been developed in industry and academia, but there are still unsolved general problems.

Studies on common cycle lot-size scheduling for a multi-product and multi-stage arborescent flow-shop environment was done (Ashjari & Fatemi Ghom, 2001; Fatemi Ghomi & Torabi, 2001) and solution methods to determine simultaneous production cycle time and production schedule were given.

Öztürk et al., 2006, found that it is not enough to forecast short delivery times—the forecasted delivery times has to be accurate. The main problem is that most of the lead time consists of queue and transport, while a relatively small part of it consists of the actual processing—which is why it is so difficult to forecast lead times. They tried to forecast lead times by using data mining; they used a regression tree approach and linear regression for forecast.

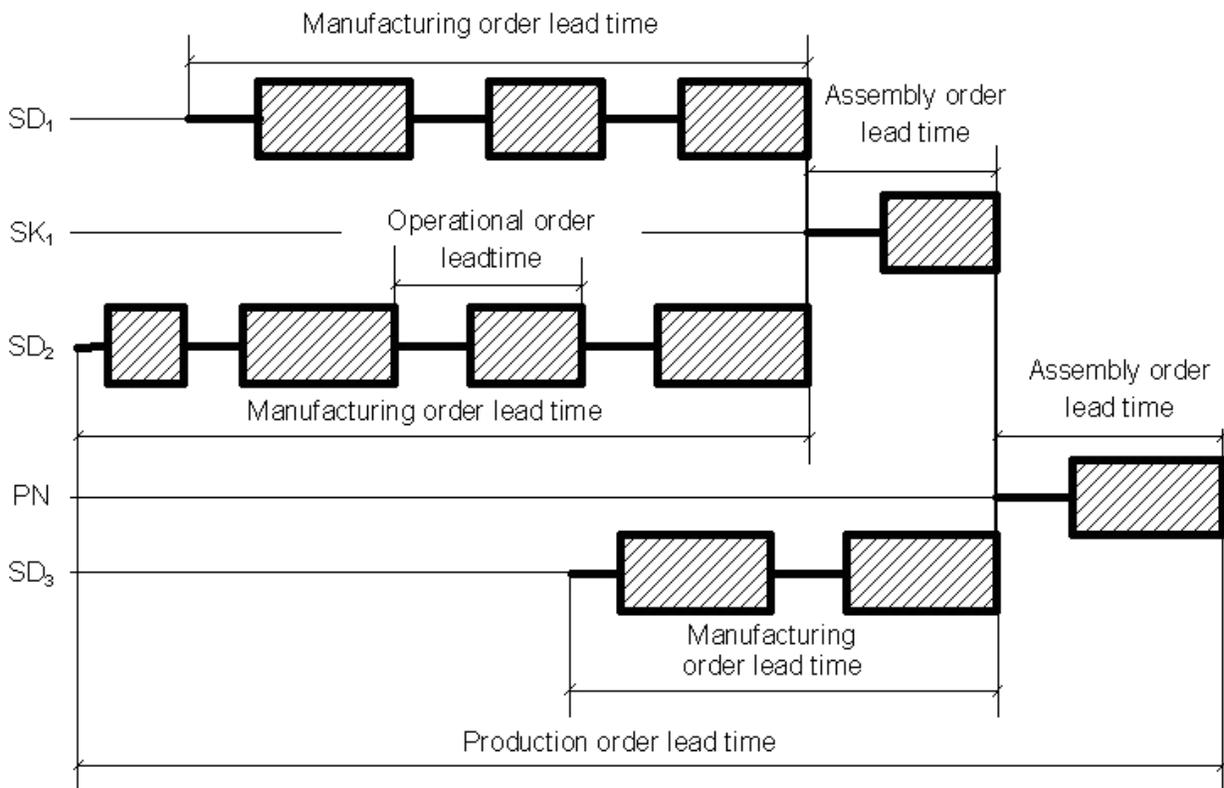
In our research, we did not find any lead time forecast approach as described in this chapter, so we assume that this is a new approach that uses known theory on lead times and adds a new method for forecasting production order lead times.

3. How to FORECAST a production order lead time

When dealing generally with "an order", it is necessary to distinguish between (Wiendahl H.P., 1995):

- operational order,
- manufacturing order,
- assembly order,
- production order.

The types of orders given above and their corresponding lead times are shown in Figure 1.



Legend:

- PN – production order
- SK_x – x-th component
- SD_x – x-th part

Fig. 1. Types of orders and their corresponding lead times (Wiendahl H.P., 1995)

When designing a procedure for forecasting production order lead times, it will be assumed that the company wishing to forecast the lead times of orders uses an ERP/ PPC system, the database of which contains data on past operational and assembly orders.

The ERP/ PPC system will be the basis for forecasting production order lead times.

4. Method for FORECASTING production order lead times

An overview of known procedures in the literature for determining realistic lead times of operations (Wiendahl H.P., 1995; Nyhuis P., Wiendahl H.P., 1999) and the experience obtained during many tests of practical implementation of these procedures, led us to the conclusion that it would be possible to forecast lead times of planned orders on the basis of actual operational and assembly order lead times achieved in the past. These forecasts (on the basis of ERP-system data or on the basis of manually acquired past data) are accurate enough for individual production because manufacturing processes on individual machines

are taken into account. By using these data it is thus possible to forecast lead times even for fairly complex products with several machining operations and individual order features. Based on our research we concluded that the procedure for forecasting lead times for future production orders should consist of the steps shown in Figure 2.

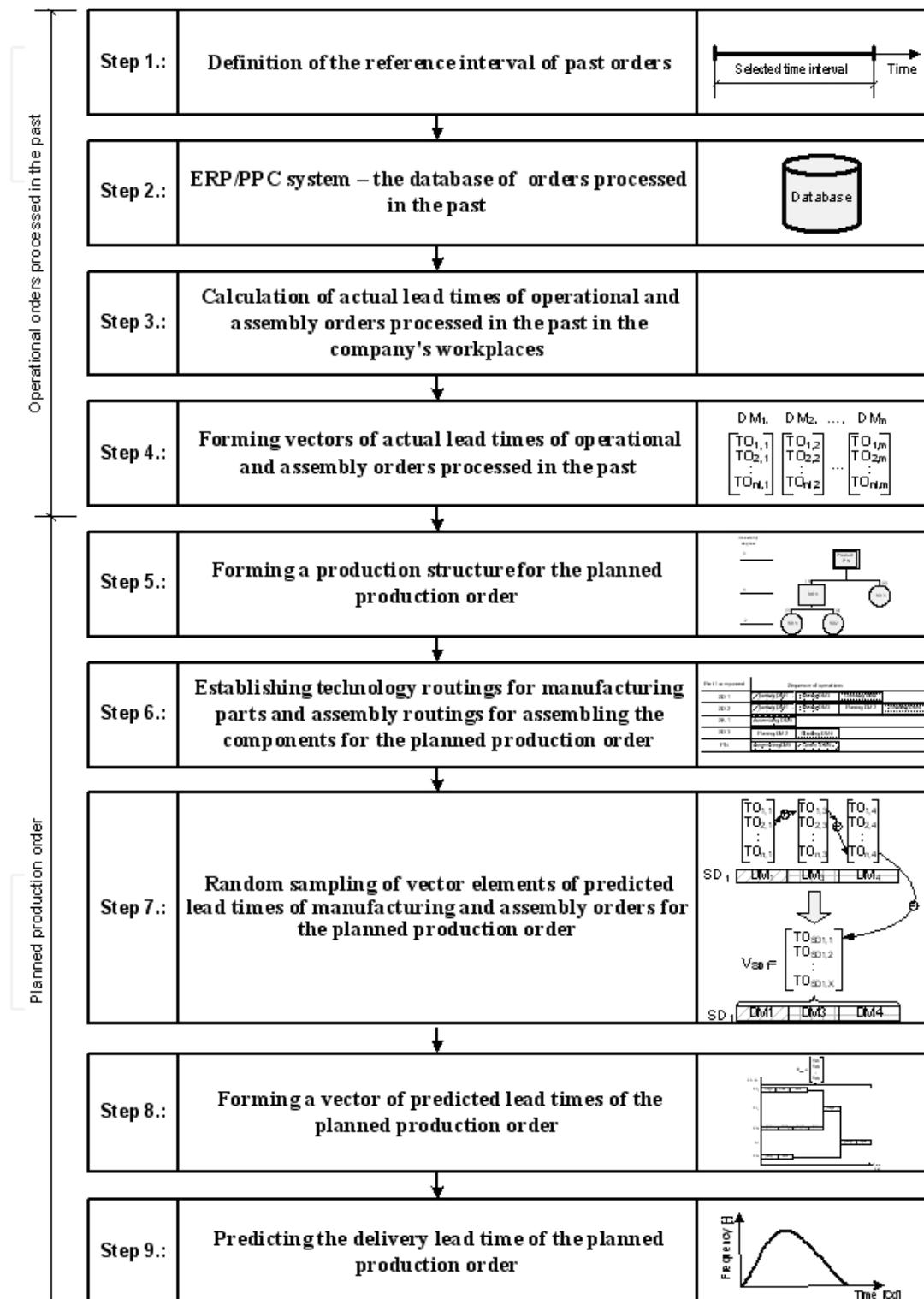


Fig. 2. Procedure for predicting planned production order lead times

Step 1. Definition of the reference interval of past orders

At the beginning of lead time forecasting it is necessary to define the interval for data acquisition of past operational and assembly orders. This interval can be a month, a quarter, a year or several years.

Step 2. ERP/PPC system—the database of orders processed in the past

As mentioned, a company wishing to forecast lead times must have an ERP/ PPC system as a basis for all further steps, because this is the database of orders processed in the past. The ERP/ PPC system should provide data on (Figure 3):

- operational or assembly order codes,
- type and sequence of operations in manufacturing and assembly orders,
- IDs of workplaces at which operational or assembly orders have been processed,
- actual execution times of operational or assembly orders,
- date of completing a particular operational or assembly order in the previous workplace,
- date of completing a particular operational or assembly order in the observed workplace.

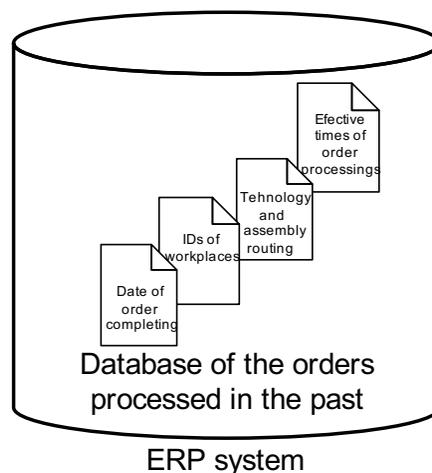


Fig. 3. ERP/ PPC system database

Step 3. Calculation of actual lead times of operational and assembly orders processed in the past in the company's workplaces

The lead time of the i -th operational order N_i ($1 \leq i \leq n$), processed in the j -th workplace DM_j ($1 \leq j \leq m$) is defined as the interval calculated from the time when the i -th operational order was completed in the previous, i.e. $(j-1)$ -th workplace, until the time when the i -th operational order is completed in the observed, i.e. j -th workplace (Wiendahl H.P., 1995), as presented in Figure 4.

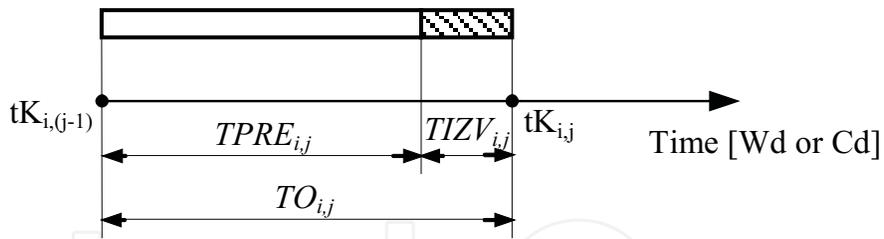
The lead time of an operational or assembly order is therefore:

$$TO_{i,j} = tK_{i,j} - tK_{i,(j-1)} \quad (1)$$

$TO_{i,j}$ – lead time of the i -th operational order in the j -th workplace

$tK_{i,j}$ – completion time of the i -th operational order in the j -th workplace

$tK_{i,(j-1)}$ – completion time of the i -th operational order in the previous $(j-1)$ -th workplace



Legend:

- $TPRE_{ij}$ – crossing time of the i -th operational order in the j -th workplace
- $TIZV_{ij}$ – execution time of the i -th operational order in the j -th workplace
- TO_{ij} – lead time of the i -th operational order in the j -th workplace
- tK_{ij} – completion time of the i -th operational order in the j -th workplace
- $tK_{i,(j-1)}$ – completion time of the i -th operational order in the previous $(j-1)$ -th workplace
- Wd – work day
- Cd – calendar day

Fig. 4. Lead time of operational order (Wiendahl H.P., 1995)

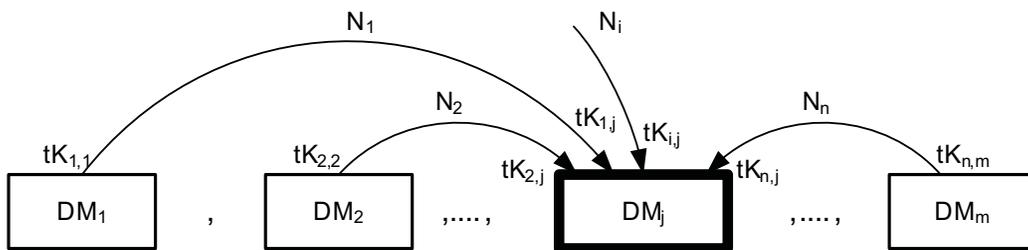


Fig. 5. Flow of operational orders through DM_j workplace

On the basis of the ERP/ PPC system output data, it is possible to calculate (for any j -th workplace DM_j) the actual lead times of previously processed operational orders, i.e. orders that have been processed in the j -th workplace in the observed time interval (Figure 5). The actual lead times of operational orders processed in the j -th workplace in the selected time interval are therefore:

$$\begin{aligned}
 TO_{1,j} &= tK_{1,j} - tK_{1,(j-1)} \\
 TO_{2,j} &= tK_{2,j} - tK_{2,(j-1)} \\
 &\vdots \\
 &\vdots \\
 &\vdots \\
 TO_{i,j} &= tK_{i,j} - tK_{i,(j-1)} \\
 &\vdots \\
 &\vdots \\
 &\vdots \\
 TO_{nj,j} &= tK_{nj,j} - tK_{nj,(j-1)}
 \end{aligned}
 \tag{2}$$

Step 4. Forming vectors of actual lead times of operational and assembly orders processed in the past

It is necessary to form vectors of actual lead times of orders processed in the past in the company's workplaces (Table 1).

Workplace	SELECTED INTERVAL from ... to ... [Wd]					
	DM 1	DM 2	...	DM j	...	DM m
Vectors of actual lead times of orders	$TO_{1,1}$	$TO_{1,2}$		$TO_{1,j}$		$TO_{1,m}$
	$TO_{2,1}$	$TO_{2,2}$		$TO_{2,j}$		$TO_{2,m}$

	$TO_{n_j,1}$	$TO_{n_j,2}$		$TO_{n_j,j}$		$TO_{n_j,m}$

Legend:

TO_{ij} – lead time of the i -th operational order in the j -th workplace

DM_j – j -th workplace

Wd – work day

Table 1. Vectors of actual lead times of operational and assembly orders processed in the past

Vectors of actual lead times of orders processed in the past will be the basic data for forecasting lead times of the planned new production orders.

Step 5. Forming a production structure for the planned production order

It is necessary to make a graphic presentation of the production order structure for the planned production order (Figure 6).

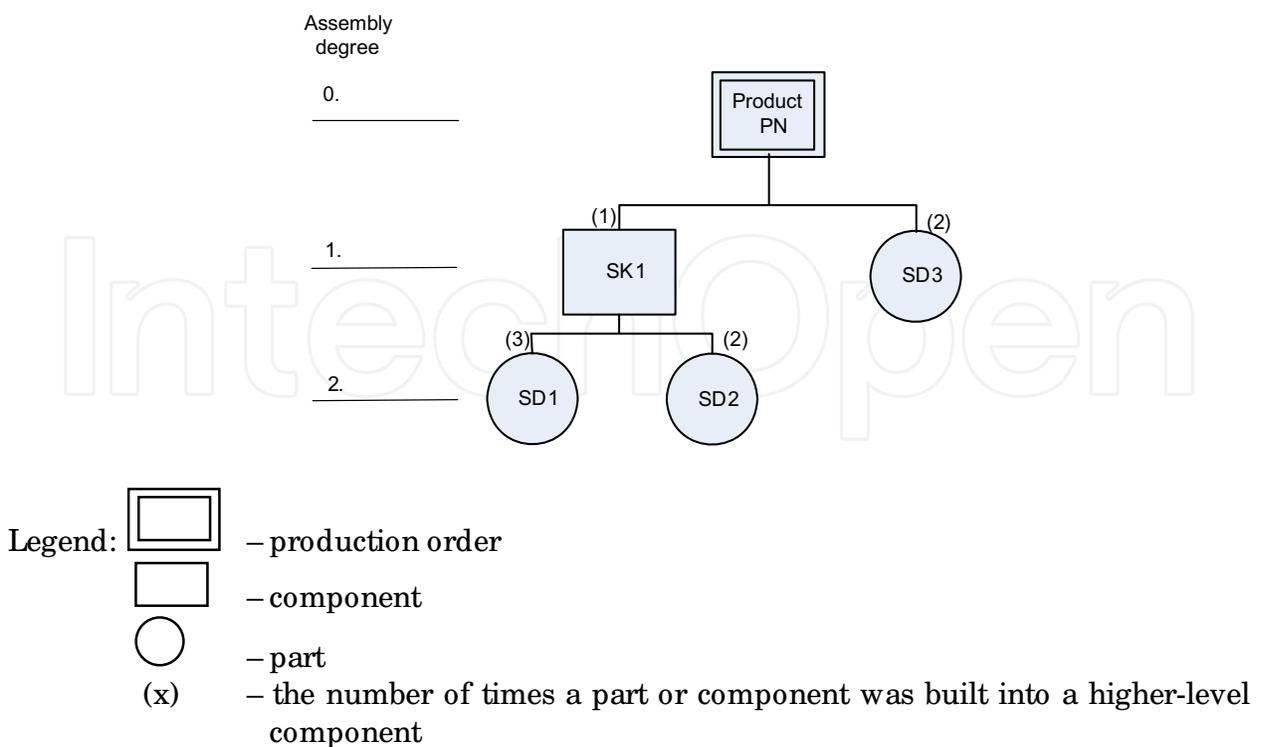


Fig. 6. Production structure of the planned production order

Step 6. Establishing technology routings for manufacturing parts and assembly routings for assembling the components for the planned production order

Figure 7 gives an overview of technology and assembly routings for manufacturing parts and assembling components of the planned production order.

Part / component	Sequence of operations		
SD 1	Turning DM1	Milling DM3	Grinding DM4
SD 2	Turning DM1	Milling DM3	Planning DM2
SK 1	Assembling DM5		
SD 3	Planning DM2	Grinding DM4	
PN	Assembling DM5	Control DM6	

Fig. 7. Technology and assembly routings for manufacturing parts and assembly of components of the PN production order

Step 7. Random sampling of vector elements of forecast lead times of manufacturing and assembly orders for the planned production order

On the basis of the production structure (defined in step 5) for the planned production order, and on the basis of technology and assembly routings for manufacturing parts and assembling components (defined in step 6), software (SPSS, Matlab, etc.) can be used to form vectors of forecast lead times of manufacturing and assembly orders for the planned production order (Figure 8).

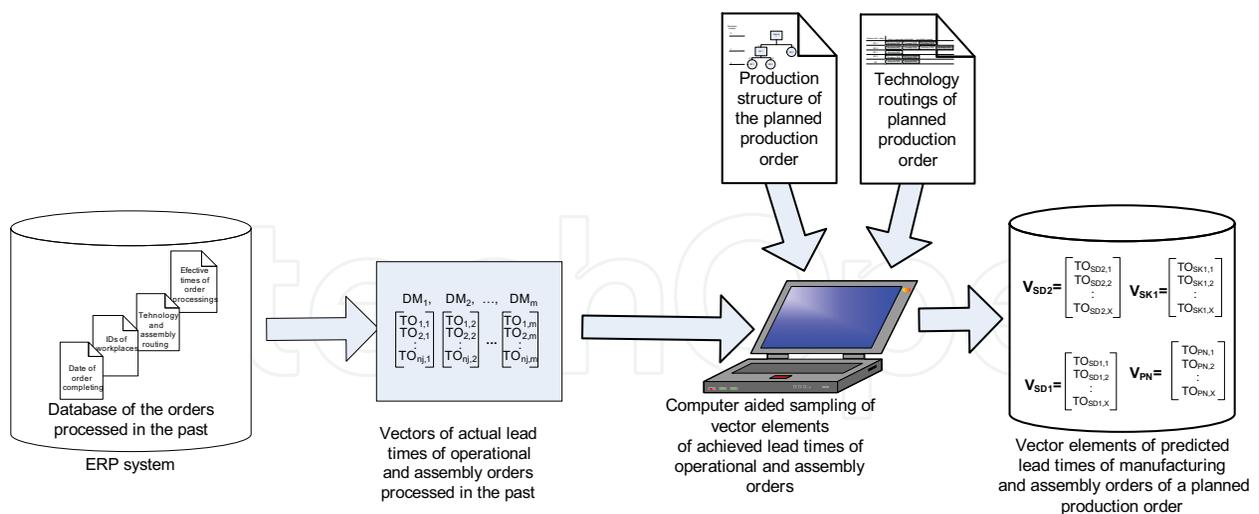


Fig. 8. Principle of vector element sampling of predicted lead times for manufacturing and assembly orders of a planned production order

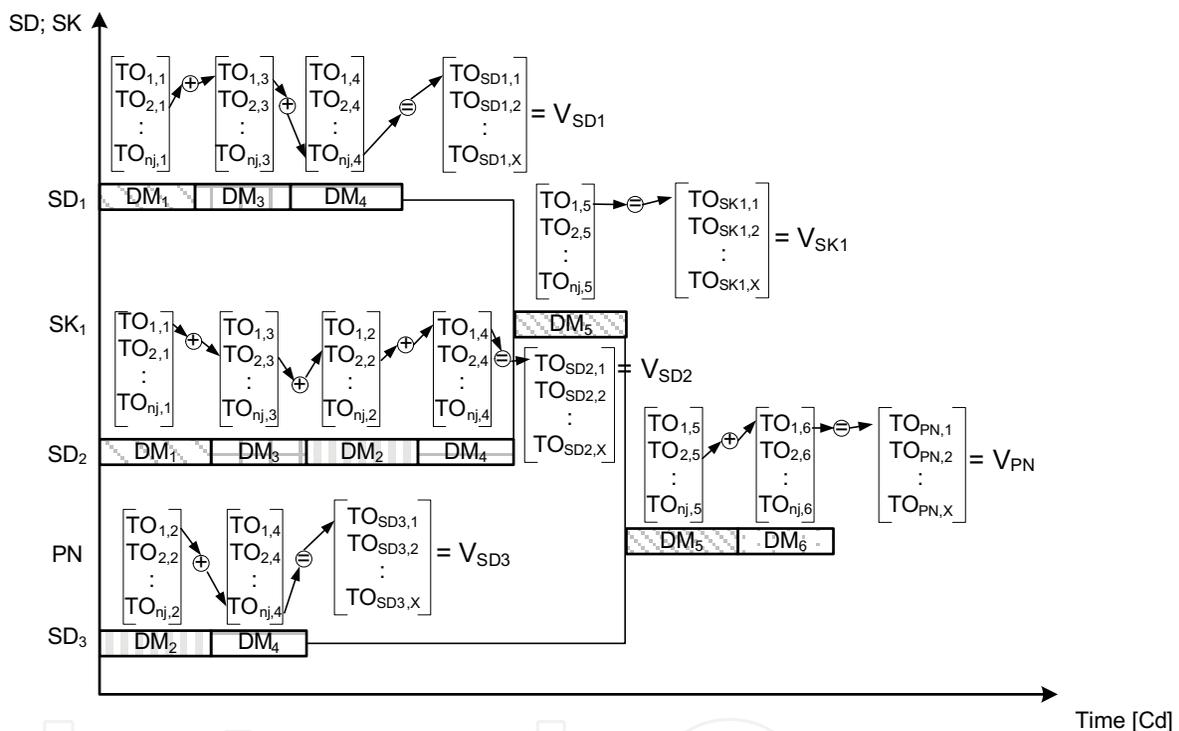
Figure 8 shows the principle of computer-aided sampling of vector elements of forecast lead times for manufacturing and assembly orders for the planned production order.

The results of sampling are vectors of random lead times of parts and components. The number of vector elements of forecast lead times of manufacturing and assembly orders for

the planned production order depends on the number of random samplings performed on a random selection of lead times for manufacturing and assembly orders for the planned production order. Tests have shown that lead times with a small number of random samplings (500 samplings) differ considerably from lead times obtained with a higher number of random samplings (5000 samplings). A large further increase in sampling number (50000 samplings) does not significantly change the results, it merely increases the computing time.

Tests will therefore be required to define the number of random sampling in order to ensure a stable process.

Figure 9 is a Gantt chart presentation of the principle of random sampling of vector elements of forecast lead times of manufacturing and assembly orders for a planned production order.



- Legend: \oplus – the summing symbol
 $TO_{SD1,1}$ – lead time of the SD₁ part, obtained after the first sampling
 $TO_{SK1,1}$ – lead time of the SK₁ component, obtained after the first sampling
 $TO_{PN1,1}$ – lead time of the PN product, obtained after the first sampling
 V_{SD1} – vector of lead times of the SD₁ part, obtained after x samplings

Fig. 9. Gantt chart of random sampling of vector elements of predicted lead times for manufacturing and assembly orders of the planned production order

Step 8. Forming a vector of forecast lead times of the planned production order

In order to define the vector elements of forecast lead times for the planned production order, the Gantt chart of a production order (Figure 9) must be transformed into an activity network diagram for the production order and entered into the lead times (found during sampling in step 7) of parts and components for the planned production order (Figure 10).

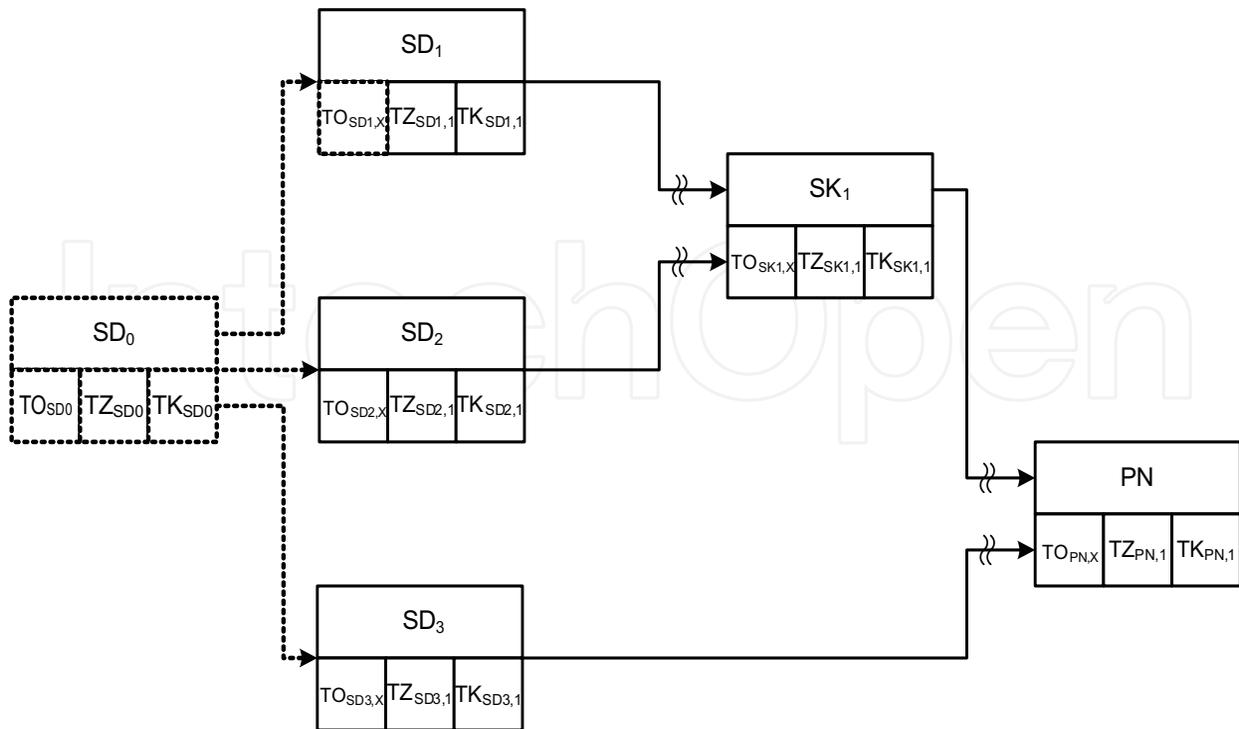


Fig. 10. Activity network diagram of the planned production order

Initial data for the activity network diagram of the production order:

- date of starting the processing of the virtual manufacturing/ assembly order SD_0

$$TZ_{SD_0} = 0 \tag{3}$$

- vector of virtual manufacturing/ assembly order V_{SD_0} :

$$V_{SD_0} = \begin{bmatrix} 0 \\ 0 \\ \dots \\ 0 \end{bmatrix} \tag{4}$$

vectors of the expected lead times of manufacturing/ assembly orders for the planned production order:

$$V_{SD_1}, V_{SD_2}, \dots, V_{SK_1}, V_{PN}$$

For the virtual manufacturing/ assembly order SD_0 , which has no predecessors in the activity network diagram, it is assumed that the date of starting the order processing is

$$TZ_{SD_0} = 0 \tag{5}$$

The date of completing the order processing is

$$TK_{SD_0} = TZ_{SD_0} + TO_{SD_0} = 0 + 0 = 0. \tag{6}$$

For other manufacturing or assembly orders which have one or more predecessors (Figure 11):

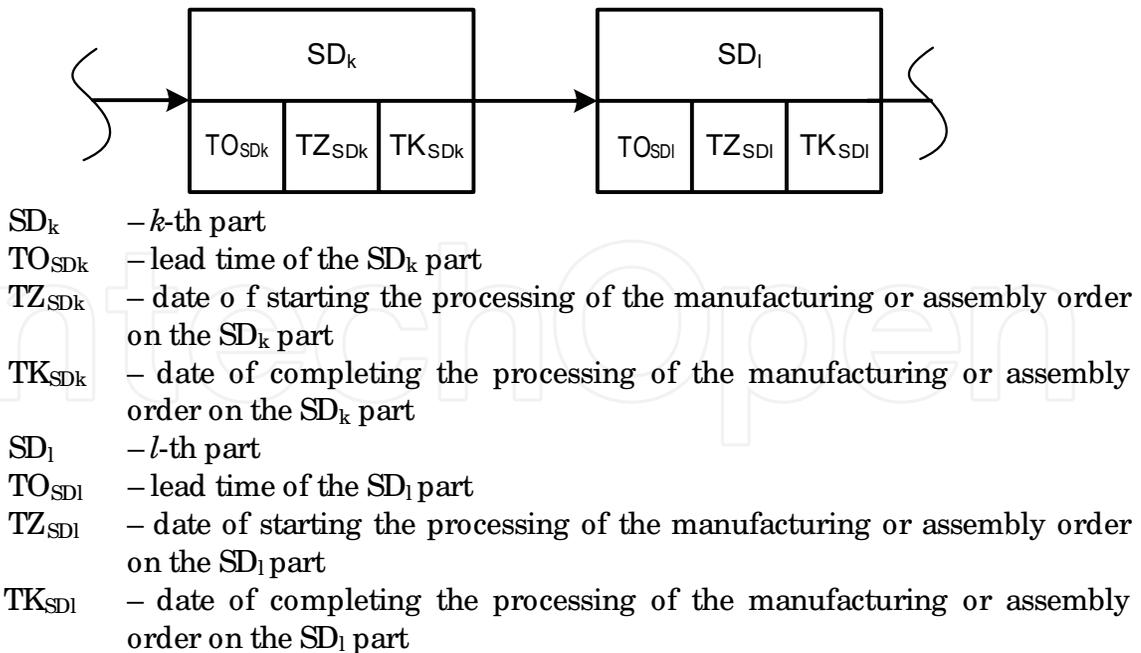


Fig. 11. Basic elements of activity network diagram

The date of starting the processing of the l -th manufacturing or assembly order:

$$TZ_{SD_l} = \max_{k \in PR} \{ TZ_{SD_k} + TO_{SD_{k,x}} \} \quad (7)$$

PR – predecessors of the observed order l

The date of completing the processing of the l -th manufacturing or assembly order:

$$TK_{SD_l} = TZ_{SD_l} + TO_{SD_{l,x}} \quad (8)$$

The date of completing the last assembly order in the activity network diagram is equivalent to the expected lead time of the planned production order TO

$$TK_{PN} = TO \quad (9)$$

Figure 10 shows the calculation for one vector element of the expected lead time of the planned production order. Such a calculation has to be repeated for a selected number of iterations of randomly sampled values from vectors of an individual part or component of a production order, which finally leads to the vector of the forecast lead times of the planned production order and corresponding distribution function of the order lead time.

Step 9: Forecasting the delivery lead time of the planned production order

The result of step 8 of the procedure for forecasting the production-order lead time is the vector of forecast lead times of the planned production order and the corresponding order lead time distribution function.

In real life, however, an exact deadline for product delivery to the customer is required.

The most probable delivery lead time for the planned production order can be estimated by using the median, which means that there is a 50% probability that the actual delivery time will be shorter, and 50% probability that it will be longer than forecast.

A 50% probability is not acceptable in practice, so it is necessary to extend the confidence interval and thus also the forecast production order lead time.

In engineering, a 95% confidence interval is usually used, which means that there is a 95% probability that the production order will be delivered within the forecast lead time.

The maximum order-delivery lead time that can be guaranteed to the customer with a 95% probability, therefore corresponds to the 95th percentile of the empirical distribution of the forecast lead time of the production order (Rice J. A., 1995; The MathWorks, Inc., 2002), as shown in Figure 12.

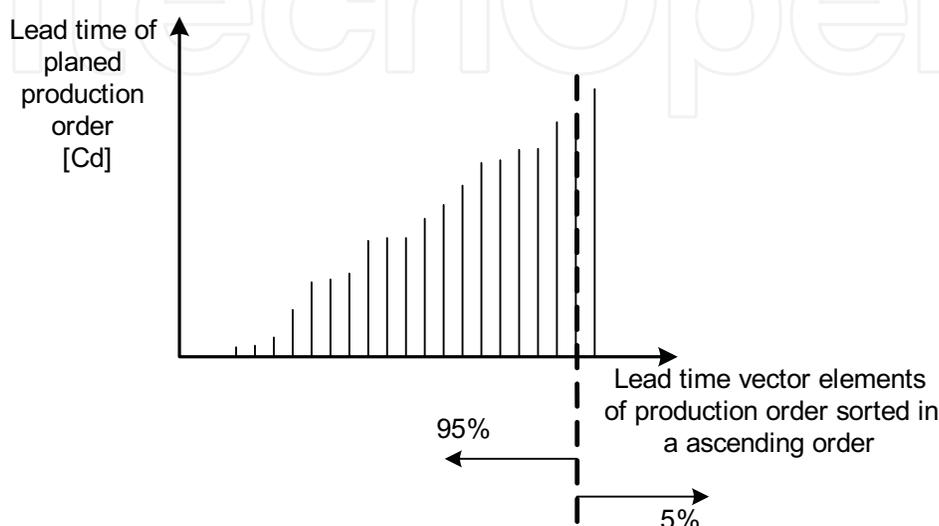


Fig. 12. An example of the 95th percentile

In order to obtain the P -th percentile of lead time vector elements (X), sorted in an ascending order, it is necessary to calculate the percentile rank R (Ferligoj A., 1995):

$$R = \frac{X}{100} \cdot P + \frac{1}{2} \quad (10)$$

R – percentile rank—sequence number of an element in the lead time vector sorted in an ascending order

P – percentile

This value is rounded to the nearest integer and the value from the X set which corresponds to this rank is then selected.

Naturally, the choice of the percentile may depend on the importance of the order and the customer; the more important the customer, or the more important the order, the stronger is the interest of the company in obtaining a particular order; so the company will be ready to accept a higher risk.

After all nine steps of the procedure have been completed, a good forecasting of the production order lead time can be obtained, which is then sent to the customer.

5. Testing the procedure for FORECASTING production order lead time

The procedure for predicting production order lead times was tested in a tool shop company from Slovenia. The company produces tools for transforming and cutting, tools for injection moulding of thermoplastic and duroplastic materials, jet and press machines for

duroplastic materials, press machines for ceramic materials, and automated assembly appliances. The model for forecasting lead times was tested in the tool shop for manufacturing tools, but not for manufacturing devices. A separate database for manufacturing devices would have to be made, because orders for tools are completely different from orders for devices.

The tool shop's speciality is designing and manufacturing high-quality tools for injection moulding of thermoplastic and duroplastic materials. On the basis of its long experience in making tools for its parent company, the tool shop started producing tools and appliances for external customers in the following fields:

- automotive industry,
- household appliances,
- medical technology,
- electrical engineering and electronics,
- illumination.

The tool shop uses the Largo ERP system, developed by the Perftech Company from Bled, Slovenia (Largo, 2007). Due to their production method (tools are made for known customers and each tool is unique) it is very difficult to precisely forecast the duration of tool production, yet this information is essential for making bids and winning orders. In the past, delivery times were guessed or were estimated by experienced company employees. Several times the specified delivery times were too short, which resulted in penalties, sometimes even in cancellation of further cooperation with a particular business partner; and goodwill was also affected. In all industries (but especially the automotive), it is very important that the agreed deadlines are met, because SMEs are usually sub-suppliers or suppliers in a long supply-chain for a large corporation and if one delivery is late, the whole supply chain may be late.

The company management therefore decided to test the suitability of the proposed procedure for forecasting lead times of production orders in a case study of determining the lead time of a production order for a "tool for a linking element of an oil vent # 708145". The final product manufactured with this tool is shown in Figure 13.

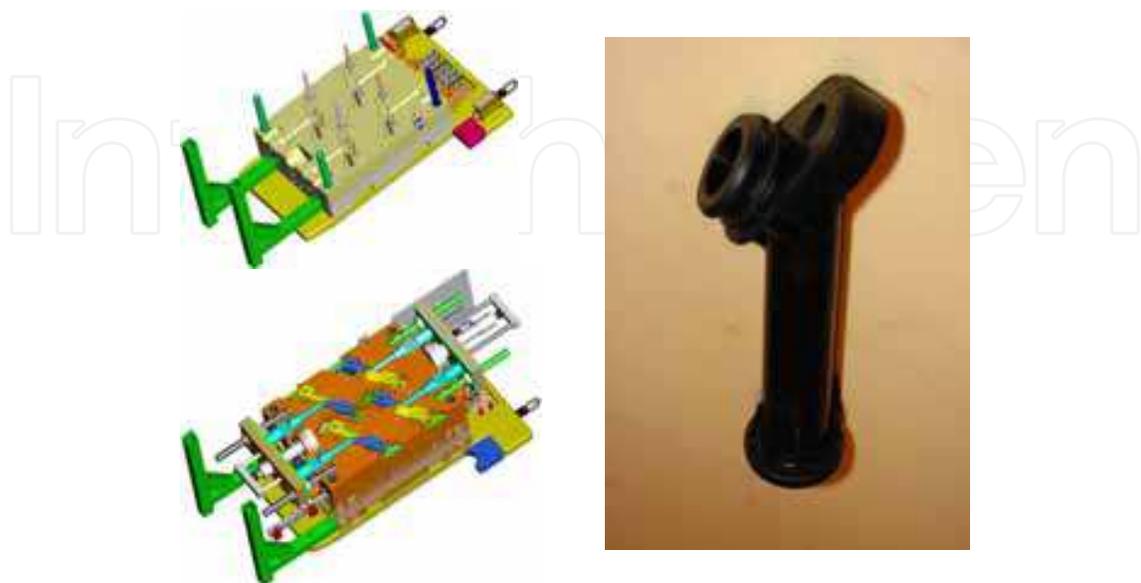


Fig. 13. Picture of tool # 708145 and the linking element of an oil vent made with this tool

Steps of the procedure for forecasting the production order lead time for the "tool for a linking element of an oil vent # 708145":

Step 1. Definition of the reference interval of past orders

In agreement with the tool shop management, it was decided that data from 12 December 2002 to 22 August 2005 would be used for determining the actual lead times of operational orders in the past.

Step 2. ERP/PPC system—the database of orders processed in the past

The data from the Largo ERP system database were first transformed to MS Excel format. The following data were used from the ERP database: order number, arrival date, departure date, manufacturing time, and technology and assembly routings.

The Largo ERP system uses calendar dates and does not take into account the company's workday calendar.

During the time defined in step 1, 22,850 manufacturing orders were processed, with 57,951 operational orders in 35 workplaces (Table 2).

Workplace number	Workplace	Number of orders processed in 3 years
44000	Cooperation—service	21
44141	Design of devices	151
44142	Machine electronics	130
44143	Design of tools	2288
44211	Slitting	1420
44221	Turning	3706
44222	CNC turning	1052
44231	CNC programming	371
44232	CNC Micron milling	2660
44241	CNC programming	668
44242	CNC Picomax 60 milling	4153
44291	Heat treatment	5172
44311	Manual machining	4288
44312	Assembly of tools	812
44313	Assembly of machines and devices	197
44321	Sampling	2
44331	Measurement	885
44332	DEA Omicron measurement	273
	3-year production:	57951

Table 2. Number of operational orders processed in the tool shop workplaces

It can be seen from Table 2 that a widely varying number of operational orders were processed in workplaces during the observed time (minimum 2 orders in workplace 44,321 and maximum 7307 orders in workplace 44,253).

Step 3. Calculation of actual lead times of operational and assembly orders processed in the past in the company's workplaces

Actual lead times of individual operational orders were calculated from the data obtained in steps 1 and 2. The calculation was done in MS Excel, using equation 1.

Figure 14 shows part of the calculation of actual lead times of operational orders in an Excel table.

	B	C	D	E	F	G	H	I	J
	Order Nr	Nr working order	Workplace	Sequence	Workplace name	Production time [Eh]	Arrival date	Departure date	Lead time [Cd]
2	6229	700609	44232	30	CNC Milling Micron	4	22.5.2003	22.5.2003	0
3	6229	700609	44311	20	Manual machining	1.5	15.5.2003	2.6.2003	18
4	6231	700609	44253	10	Rough milling	3.5	13.5.2003	15.5.2003	2
5	6231	700609	44262	30	Plane/profile grinding	2	17.5.2003	30.5.2003	13
6	6231	700609	44242	20	CNC Milling Picomax 60	3	15.5.2003	17.5.2003	2
7	6231	700609	44272	40	Wire erosion	6	30.5.2003	3.6.2003	4
8	6232	700609	44253	10	Rough milling	3	14.5.2003	14.5.2003	0
9	6232	700609	44253	20	Rough milling	3.5	14.5.2003	16.5.2003	2
10	6232	700609	44262	50	Plane/profile grinding	7	19.5.2003	28.5.2003	9
11	6232	700609	44242	30	CNC Milling Picomax 60	9	16.5.2003	17.5.2003	1
12	6232	700609	44242	60	CNC Milling Picomax 60	9	28.5.2003	2.6.2003	5
13	6232	700609	44311	40	Manual machining	3	17.5.2003	19.5.2003	2
14	6233	700609	44253	10	Rough milling	1	16.5.2003	16.5.2003	0
15	6233	700609	44232	20	CNC Milling Micron	2	16.5.2003	19.5.2003	3
16	6233	700609	44311	30	Manual machining	1.5	19.5.2003	2.6.2003	14
17	6234	700609	44253	10	Rough milling	3.75	14.5.2003	15.5.2003	1
18	6234	700609	44262	30	Plane/profile grinding	1.5	19.5.2003	30.5.2003	11
19	6234	700609	44232	20	CNC Milling Micron	4.5	10.5.2003	19.5.2003	4
20	6235	700609	44253	10	Rough milling	9	19.5.2003	19.5.2003	0
21	6235	700609	44232	20	CNC Milling Micron	6	19.5.2003	20.5.2003	1
22	6235	700609	44311	30	Manual machining	2.5	20.5.2003	2.6.2003	13
23	6236	700609	44253	10	Rough milling	4	16.5.2003	16.5.2003	0
24	6236	700609	44232	20	CNC Milling Micron	5	16.5.2003	19.5.2003	3
25	6236	700609	44311	30	Manual machining	2.5	19.5.2003	2.6.2003	14
26	6237	700609	44253	10	Rough milling	2.5	12.5.2003	12.5.2003	0
27	6237	700609	44261	30	Plane grinding	1	17.5.2003	3.6.2003	17
28	6237	700609	44232	20	CNC Milling Micron	3.5	12.5.2003	17.5.2003	5

Fig. 14. Calculation of actual lead times of operational orders processed from 12 December 2002 to 22 August 2005

The results showed that the majority of actual lead times are shorter than or equal to 1 calendar day (Cd). Some extreme cases, e.g. 464 Cd, are exceptions to the rule.

Step 4. Forming vectors of actual lead times of operational and assembly orders processed in the past

The results obtained in step 3 were transformed into vectors of actual lead times; part of the data is shown in Table 3.

Workplace	SELECTED INTERVAL from 12 Dec 2002 till 22 Aug 2005					
	44000	44141	...	44253	...	44332
Vectors of actual lead times of orders	$\begin{bmatrix} 0 \\ 5 \\ \cdot \\ \cdot \\ 2 \end{bmatrix}$	$\begin{bmatrix} 2 \\ 66 \\ \cdot \\ \cdot \\ 9 \end{bmatrix}$...	$\begin{bmatrix} 7 \\ 4 \\ \cdot \\ \cdot \\ 1 \end{bmatrix}$...	$\begin{bmatrix} 2 \\ 10 \\ \cdot \\ \cdot \\ 0 \end{bmatrix}$
Number of vector elements	21	151		7307		273

Table 3. Vectors of actual lead times of operational and assembly orders processed in the past

Step 5. Forming a production structure for the planned production order —tool # 708145

In this step, the known production/ assembly structure of tool # 708145 was used (Figure 15).

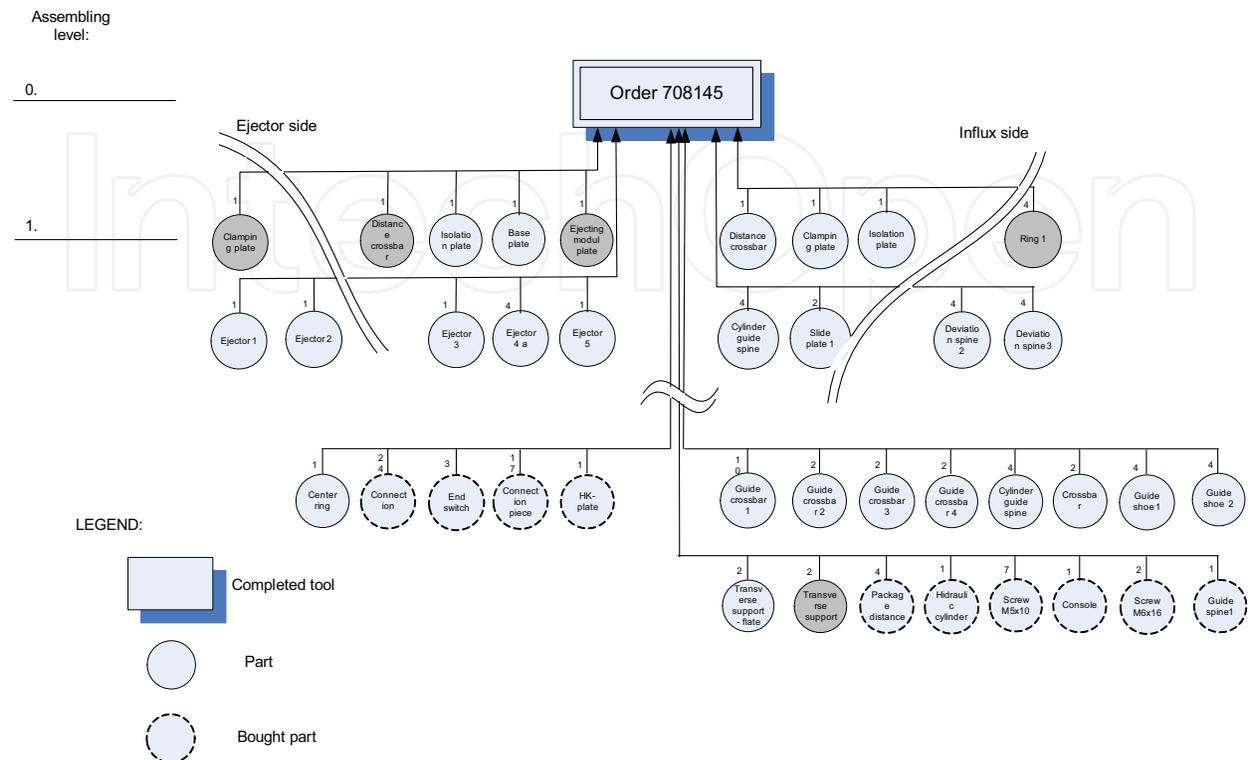


Fig. 15. Part of assembly structure of tool # 708145

As evident from Figure 15, the tool consists of two parts: ejecting and feeding parts. The tool consists of 122 parts (73 parts are manufactured in the tool shop and 49 parts are outsourced). There is just one assembly operation—the final assembly. After assembly, samples are manufactured and measurements are then taken.

Step 6. Establishing technology routings for manufacturing parts and assembly routings for assembling the components for the planned production order

The types and sequence of operations for tool # 708145 were used in this step (Figure 16).

Parts/components	Sequence of operations								
Construction and technology	44143								
Clamping plate	44243	44244	44253	44311					
Distance crossbar	44244	44253	44311						
Ejecting modul plate	44243	44244	44253	44311	44291	44244	44282	44271	44272
Transverse support	44231	44232							
Ring 1	44221								
Order # 708145	44312	44321	44311						

Fig. 16. Some types and sequence of operations required for parts and components of tool # 708145

For tool parts and components manufactured in the tool shop, it was necessary to obtain data on the type and sequence of operations, which ensure quality parts and components of

the tool. 231 operations were carried out on tool # 708145. Some types and the sequence of required operations on some parts and components of tool # 708145 are shown in Figure 16. This tool shop performs prior preparation for manufacturing; for this order it consists of: machine electronics (44142), design of tools (44143) and slitting (44211). The prior preparation itself could not be presented in the assembly structure in Figure 15; it does, however, increase the time for the order processing and must therefore be taken into account in operations.

Step 7. Random sampling of vector elements of forecast lead times of manufacturing and assembly orders for the planned production order —tool # 708145

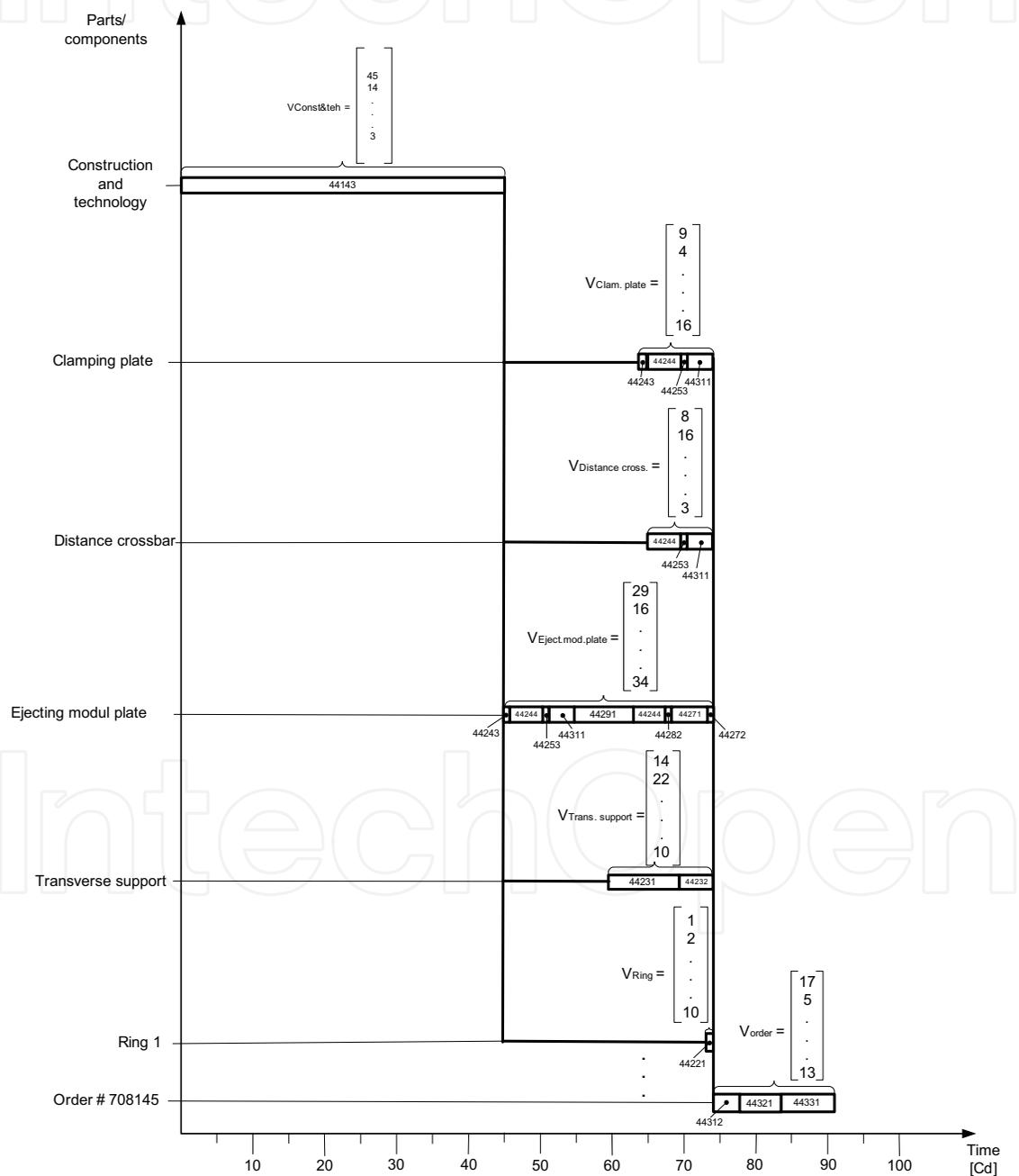


Fig. 17. Random sampling of vector elements of predicted lead times of manufacturing and assembly orders of the planned production order—tool # 708145

On the basis of the defined sequence of operations of parts and components of tool # 708145, Matlab software was used (The MathWorks, Inc., 2002) to form vectors of expected lead times of manufacturing and assembly orders, as described in the theoretical part of this paper.

On the basis of tests with 500, 1000, 5000, 10000, 20000 and 50000 samplings, it was concluded that 10000 samplings were enough for this case. If much fewer than 10000 samplings were used, forecasts between samplings differed considerably, because too few data were used. Using significantly more than 10000 samplings did not improve the result, it only increased the computing time.

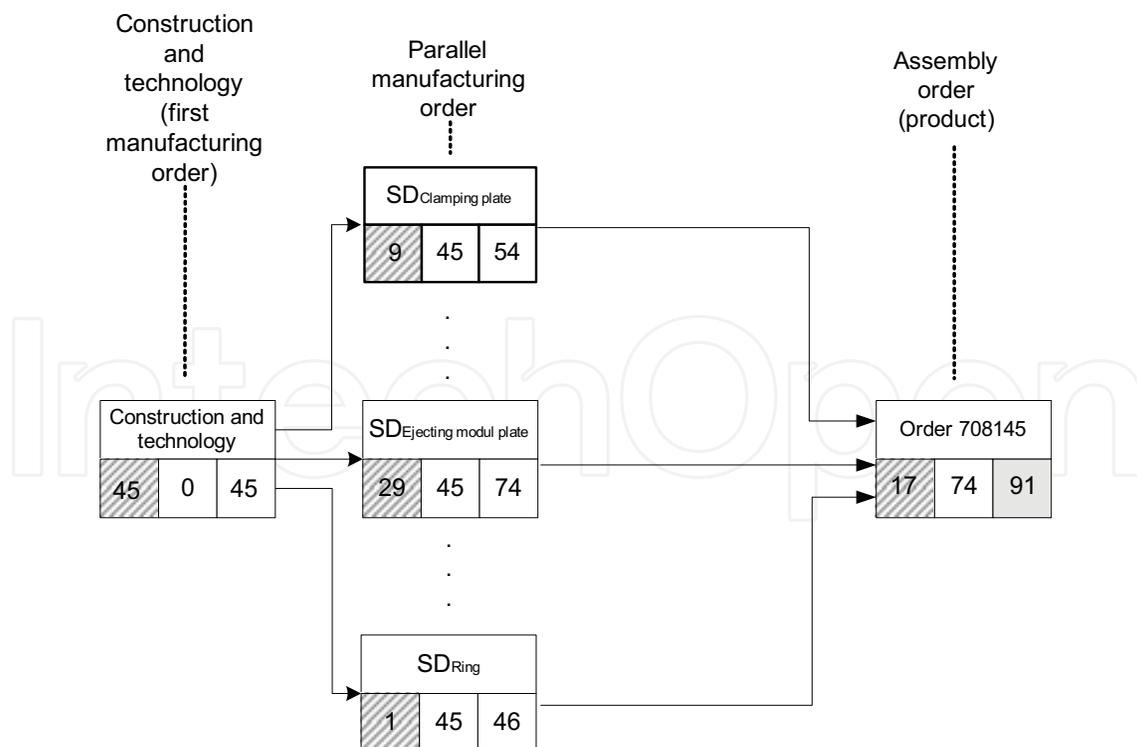
On the basis of these 10000 samplings of lead times of operational orders, the vectors of expected lead times of manufacturing and assembly orders for tool # 708145 were defined (Figure 17).

Step 8. Forming a vector of forecast lead times of the planned production order —tool # 708145

In order to define the vector of expected lead times of the planned production order, 10000 samplings were made.

A sample calculation of lead time for the first sampling is shown in Figure 18. The expected lead time of the planned production order is the sum of the time of the first manufacturing order, maximum time of parallel manufacturing orders (parts) and time for the assembly order (final assembly of the tool).

After having completed 10000 samplings, a vector of expected lead times of the planned production order Vnar for tool # 708145 was obtained. Its lead-time-distribution function is shown in Figure 19.



$$TO = TO_{\text{Const\&teh}} + \max (TO_{\text{parallel manufacturing order}}) + TO_{\text{assembly order}} = 45 + 29 + 17 = 91 \text{ Cd}$$

Fig. 18. Activity network diagram for calculation of lead time for the first sampling of the production order # 708145

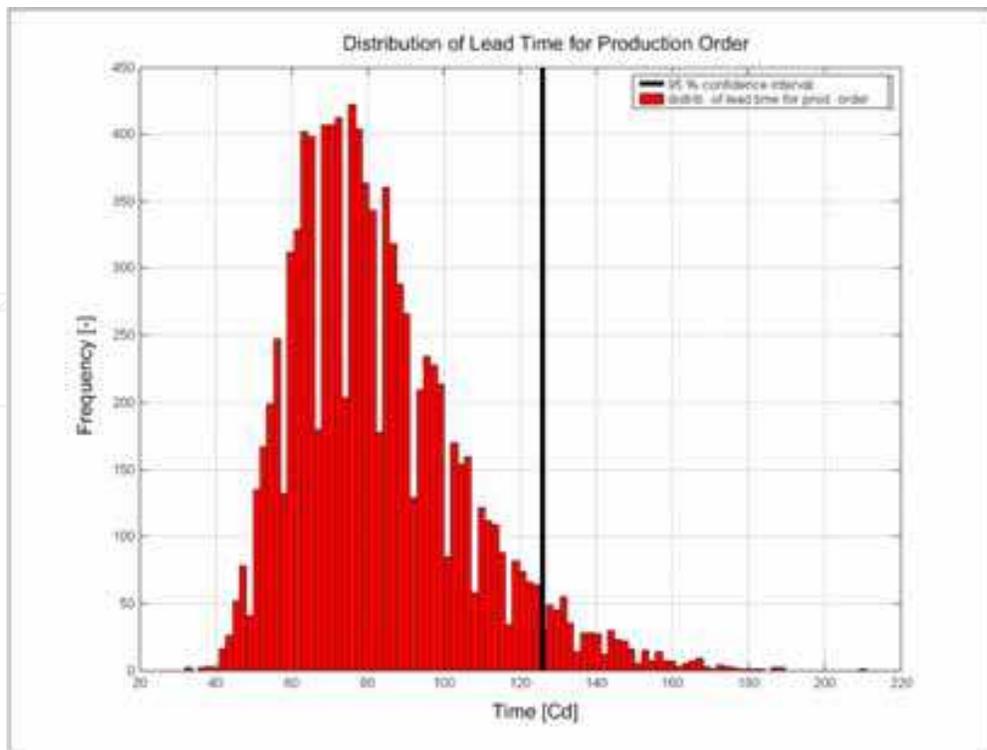


Fig. 19. Lead time distribution of the production order—tool # 708145

Step 9. Forecasting the delivery lead time of the planned production order —tool # 708145

No customer is interested in a lead-time vector of a production order (or its distribution function) as a delivery date, so the median TO_{med} of this vector is used as the first approximate value; for this order it is:

$$TO_{med} = 79 \text{ Cd.}$$

The expected lead time for the production order is therefore equal to the 50th percentile of the V_{nar} vector of the expected lead times of the production order; so there is a 50% probability that the actual delivery time will be within the deadline, and 50% probability that it will not be within the deadline.

However, the median is not a sufficient estimate in engineering; instead, a 95% probability is required, which corresponds to the 95th percentile. For this production order the forecast lead time is: $TO_{95\%} = 126 \text{ Cd.}$

Ninety-five percent is a high enough forecasting probability, so it was suggested to the company that this value be used.

Each company must decide what risk level is acceptable for them when signing a contract with a customer.

As has already been mentioned, the company made bids in the past on the basis of experience and similar past projects. The proposed and signed deadline for tool # 708145 between the tool shop of Eti d.d. company and the customer was 73 Cd. The value of this project was 45,000 €. Penalties for delay were defined as 1% per week up to a maximum of 10% of the order value.

The order was delivered on 103 Cd (the delay of 30 Cd incurred a penalty of 1800 €). However, the penalty may not be the main problem—the main problem is that the tool shop in such a case loses its reputation as a good and reliable supplier—which is an invaluable asset.

Table 4 presents the deadline planned by experienced company employees compared with the actual deadline and forecast deadlines with various probabilities.

	Deadline [Cd]	Deviation from the actual delivery [Cd]	Deviation from the actual delivery [%]
Planned deadline	73	- 30	- 29,1
Actual deadline	103	0	0
Median	79	- 24	- 23,3
60% probability	85	- 18	- 17,5
80% probability	100	- 3	- 2,9
83% probability	103	0	0
90% probability	114	+ 11	+ 10,7
95% probability	126	+ 23	+ 22,3

Table 4. Comparison between the planned-, actual- and various predicted probabilities of order processing lead times

As evident from Table 4, the right forecast for this order was at a probability of 82%. At 95% probability (126 Cd) the forecast would exceed the actual date by 23 Cd.

According to the results obtained with many tests, it can be concluded that the procedure for forecasting lead times yields sufficiently accurate results.

6. Conclusion

Due to ever-fiercer market competition, and because of the transition from a seller's market to a buyer's market, companies must forecast lead times and delivery times with ever greater accuracy. If they give incorrect deadlines, they may not get a request from a particular company the next time, which can lead the company into crisis.

The article proposes a procedure for forecasting production-order lead times on the basis of actual lead times of past operational or assembly orders. Using the proposed procedure, the company can:

forecast the lead time required for delivery of any new order to any customer;

make variations of delivery lead time calculations on the basis of an acceptable risk level by selecting the confidence interval with respect to the size and complexity of an order, and taking into account the company's policy towards its customers. This means that the company can risk more to obtain an important order (narrower confidence interval). The company would thus have to prioritise this order during the manufacturing process, which may cause late delivery of other orders.

The procedure for forecasting lead times was tested several times and is presented in a case study of forecasting lead times for manufacturing a tool for a linking element of an oil vent in a tool shop in Slovenia. The case study was done using data gathered over the last three years in the Largo ERP system database.

Using this procedure, a sales department can make a well-defined bid for the customer in a short time. The sales person does not need many years of experience—(s)he only needs well-defined technology routings, while the company management provides a confidence interval. On the basis of these data, the delivery time for an order can be defined. The main

advantage of this procedure is therefore that companies will not depend so much on estimates made by experienced employees. They will use instead past data, stored in the ERP system or data manually recorded in the past.

On the basis of the tests, it was found that the procedure for forecasting lead times of production orders was well designed and provided very useful data for sales, as well as for production planning and control. Signing a supply contract on the basis of reliable statistical data is completely different from signing a contract on the basis of uncertain, experience-based guesswork.

It is planned that in the future the proposed procedure will be improved by taking into account the sequence of operations required to complete an order, the influence of the number of operations per order, and the influence of the processing time of operations.

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