A note on production bottlenecks

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Simme Douwe P. Flapper

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Graduate School of Industrial Engineering and Management Science
Eindhoven University of Technology
P.O.Box 513, Paviljoen F6
NL-5600 MB Eindhoven
The Netherlands
Phone: +31.40.472230
Fax: +31.40.464596

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Graduate School of Industrial Engineering and Management Science
Eindhoven University of Technology
P.O.Box 513, Paviljoen F6
5600 MB Eindhoven, The Netherlands

ABSTRACT

In production two types of bottlenecks can be distinguished: bottleneck operations and bottleneck resources.
In this paper both types of bottlenecks are systematically examined with respect to their origins, their relationships, their commonalities and differences as well as the consequences of the latter with respect to the possibilities to eliminate partly their undesired effects. Subjects for further research on bottlenecks are indicated.

INTRODUCTION

In literature on goods flow and shop floor control much attention has been, and still is, paid to bottleneck resources, especially with respect to the question how to cope with them. See e.g. (Bechte, 1988), (Bertrand et al., 1990), (Goldratt, 1991), (Umble and Srikanth, 1990), (Weeda, 1991), (Wiendahl, 1991).
Thereby it is often assumed that what is meant by a bottleneck as well as how to estimate a bottleneck is clear.

In the first part of this paper a critical review of two of the presently most often used definitions of a bottleneck resource is presented including an overview of problems related to these definitions.

Usually production bottleneck resources are considered within the context of maximizing throughput, i.e. the quantity of products or services produced within a given period of time.
It isn't always the limited availability of one or a number of resources which restricts the throughput most however.
Throughput time may as well be a bottleneck, whereas it may be that the duration of a given operation can't be influenced by a higher availability of resources.
The relations between these time-based bottlenecks and the above mentioned bottleneck resources form the subject dealt with in the second part of this paper.

A GENERAL VIEW ON BOTTLENECKS

Organisations are usually founded to earn money (profit center) or to realise certain services (non-profit center).
In accordance with both these points of view a bottleneck can be defined as "everything that restricts an organisation in realising her goal(s)".

In order to realise the goal(s) of the owners of the organisation, there have to exist demands for the products or services produced by the organisation.
So a shortage of customer orders may be a bottleneck.

In case a shortage of customer orders can be discarded, the following definition of a bottleneck applies

"a bottleneck denotes everything that prevents an organisation from transforming customer orders directly into contributions to her goals"

where the latter may concern a contribution to the profits in case of a profit center and products in case of a non-profit center.

Within the context of this paper we shall restrict ourselves to the total time required for transforming an actual customer order into an actual delivery to the customer; i.e. to the left-hand side of the following figure.

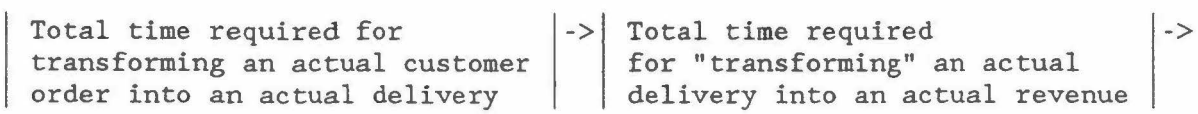


FIGURE 1 : TOTAL TIME REQUIRED FOR THE TRANSFORMATION OF A CUSTOMER ORDER INTO AN INCOMING CASH FLOW

Note that the operation and inventory expenses as well as the "throughput" are related to the total lead time indicated in Fig. 1. See for a discussion on this point e.g. (Wouters, 1991).

In this way we arrive at the following definition of a production bottleneck

"a production bottleneck denotes everything that results in a time-delay between the demand for a product or service and the delivery of that product or service".

Supplying products or services involves transformations in time, place, structure and form of all kinds of data and materials by means of all kinds of processing facilities like machines, operators, tools, transport and communication media. The execution of these transformations always takes time. Therefore the best an organisation can do is trying to restrict these time delays "as much as possible" or to forecome as much as possible "unnecessary" time delays.
By "as much as possible" and "unnecessary" we mean within the boundaries placed by financial and technological restrictions (which also can be viewed as bottlenecks) on the organisation. In this paper no detailed attention will be paid to these two very important bottlenecks.

In order to arrive at a more operational definition of a production bottleneck, we have to know how customer orders are transformed into deliveries of desired products or services. This will be briefly discussed in general terms in the following section.

CUSTOMER ORDERS, ACTIVITIES NETWORKS AND CRITICAL PATHS

In general customer orders and products are related as follows

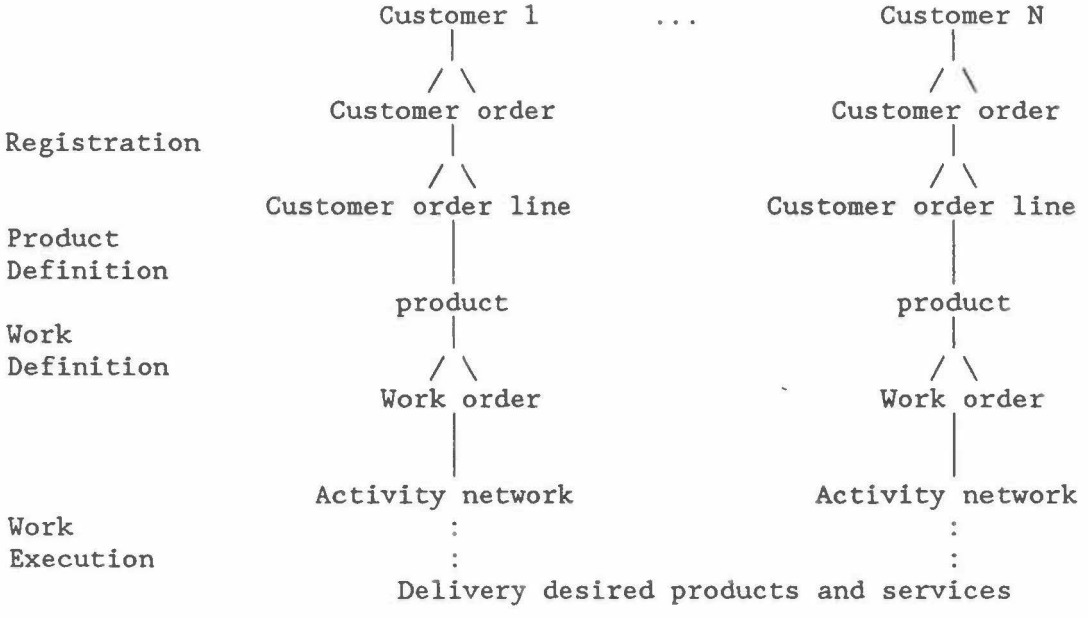


FIGURE 2 : FROM CUSTOMER ORDERS TO DELIVERIES OF PRODUCTS OR SERVICES

where the customer may be the company herself, which applies e.g. to companies producing make-to-stock or assemble-to-order wise, whereas a customer order may denote the actual delivery of given quantities of products or services as well as a quotation.

Every customer order line is characterised by a quantity q and a delivery time t. One may expect that both the quantity and the time aspect of customer orders should be reflected in the definition of a bottleneck.

With each customer order corresponds a network of activities related to the receipt of a customer order upto the delivery of the required quantity of the product or service to the customer. Restricting ourselves to the left-hand side of Fig.1, the network includes (aggregate) activities like customer order acception and registration, product definition, work definition, work execution inclusive the procurement of materials and the distribution of the products, as denoted in the left hand side of Fig.2.

The minimum total time required for the production and delivery of a given set of products corresponds to the sum of the lead times of the activities (operations) together making up the so called critical (time) path in the corresponding (aggregate) network. See e.g. (Battersby, 1970) and (Lockyer and Gordon, 1991).
Based upon the duration of the critical path, delivery times are estimated. So when controlling the progress of the activities in the production network notably attention should be paid to the activities together making up the critical path of the set of customer orders.
It seems justified to call the operations in the set of operations making up the critical path of a network the time-bottlenecks of the network, because each of the latter operations directly influences when the execution of all other activities "actually" contributes to the realisation of the goals of the owners of the organisation.

In order to estimate the critical path in a network, first the durations of all activities making up the network have to be estimated.

The time that is required for dealing with an activity is made up of time spent waiting before the activity can be executed and the time required for executing the activity. The former time can be further sub divided into waiting time due to

-the characteristics of the available processing resources
 -technical restrictions concerning the execution of the process like
  -a minimum processing batch size (batch completion waiting time)
  -set up time
 -maintenance requirements

-the time-phased availability of required resources
 -repair after a breakdown of a machine, tool, transport medium
 -absence of operators, due to illness, holidays etc.
 -delayed, incomplete or wrong supply of required materials, (semi-)finished products, information

-other customer orders requiring partly the same resources during the same period of time, including orders originating from rework on or repair of products

-rules in the organisation concerning the execution of the activity like
 -a minimum economical processing batch size (batch completion waiting time)
 -the logistic control procedures used (scheduling rules, sequencing rules, lot sizes, overlap, operation and order splitting)

(Internal) transport is dealt with as a separate activity. Batch completion times resulting from the way transport is executed are thereby considered as waiting time for the transport activity.

The processing and set up times are determined by the resources and the work method used. The latter two may be fixed or varying, depending on the set of customer orders that (partly) are to be dealt with during the same period of time as the set of customer orders under consideration.

The waiting time due to the time-phased resource requirements of other orders for (partly) the same sets of resources as the set of customer orders under consideration, depends on the setup and processing times required for dealing with these, how many units of the resources are required, as well as on the way the control is organised within the organisation, e.g. how (much) the resources involved are loaded with work.

So whether an operation forms a time-bottleneck operation with respect to the delivery of certain quantities of certain products within a given period of time may not only depend on the required quantities or products but also on the time-phased resource requirements of all the other deliveries that interfere with this delivery as well as the time-phased availability of the resources required for the operation.

From the above it is clear that the duration of a time-bottleneck operation can be reduced by either reducing the processing time or the waiting time. Both times are related to resources, so it seems logical to relate bottlenecks to resources.
In the following section two of the presently most often used definitions of a production bottleneck resource will be discussed.

PRODUCTION BOTTLENECK RESOURCES

RATE-BASED PRODUCTION BOTTLENECKS.

According to the APICS dictionary (APICS, 1991) a bottleneck is "a facility, function, department, etc. , that impedes production - for example a machine or work center where jobs arrive at a faster rate than they can be completed". Thereby production concerns the requisition of raw materials to the delivery of finished products, whereas a product is defined as any commodity produced for sale. A commodity may indicate as well a material as a non-material product (service).

The two most important words in the above definition are "impedes" and "rate", the latter denoting either the number of products produced, the quantity of material processed per unit of time, or the number of clients served within a unit of time. In Fig.3 the essential quantities with respect to the above definition of bottleneck are depicted

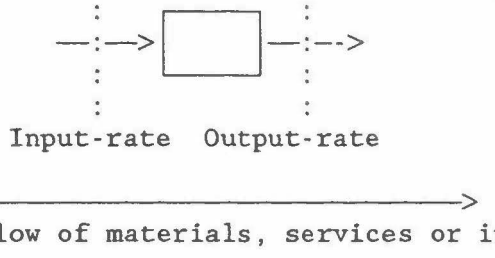


FIGURE 3 : FLOWS OF INPUTS INTO AND OUTPUTS FROM A PROCESS (OPERATION)

where the box in the middle of Fig.3 denotes the facility, function, department etc. under consideration, whereas the two vertical : lines denotes the places where the input and the output rate are measured.

At first sight the above definition of a bottleneck seems appealing and self-evident.
A closer look gives rise to a number of remarks however.

Remark 1.

The above definition is a "circumscribing" definition; i.e. what is meant is indicated via an example.

Remark 2.

The APICS definition is rate based. So the duration of an operation, including the time products have to wait before the operation can be executed for them, plays only indirectly a role, whereas according to e.g. Fig.1 it are these times themselves that matter.

Remark 3.

It isn't explained how the rates should be defined.
Should the rate be determined per product or unit quantity of some material, per production order, given quantities of a number of products to be dealt with within a given period of time?
How to deal with technologically predescribed processing lot sizes that are

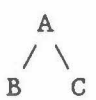
different for different operations?
How are waiting times and set up times included in the calculation of the rates in the former case?
Estimating a rate, requires a decision on the time scale to be used as well.

Remark 4.

The APICS' definition is a goods-flow-stream-upwards definition of a bottleneck. Whether or not "something" is a bottleneck is determined by its processing rate relative to the rate of the immediately preceding activities!

Remark 5.

What do we mean by the rate of the input, if the set of inputs contains not one but a number of different inputs, including data (information), which holds e.g. for assembly like processes?
Consider e.g. the following Bill of Materials structure



If the production rate for part C is twice the rate for B and A, would this mean that the resources involved in the assembly of B and C, as well as in the production of B denote bottleneck resources?

Remark 6.

What do we mean by the rate of the input, if a resource is required for a number of operations on one product (article code)?

Remark 7.

What do we mean by the rate of the input, if a resource is required for one or a number of operations for a number of different products (article codes) if all these operations are (have to be) executed with a different rate?

Remark 8.

The APICS' definition of a bottleneck is based on relative processing rates, where relative refers to the rates of the different operations executed by the organisation herself, her suppliers or contractors. Equal rates does not necessarely means that there are no bottlenecks. The latter is determined by the customers, as stressed by the definition of a bottleneck given in (Umble and Srikanth, 1990): "A resource which production rate is less than the rate asked for by the market!"

Remark 9.

The APICS' definition of a bottleneck is based on relative processing rates.
Equal processing rates does not necessarely means that there are no bottlenecks. That's because equal processing rates doesn't mean that a

product doesn't have to wait a long time before the processes are executed.

The latter aspect is properly taken into account by another often used definition of a bottleneck resource that will be dealt with in the next sub section.

LOAD-BASED PRODUCTION BOTTLENECKS

An(other?) often used criterium for determining whether a resource is or may be a bottleneck during a given period of time is the idle time of that resource during that period. This criterium forms the starting point for the load profiles used in network analysis, see e.g. (Battersby, 1970) and (Lockyer and Gordon, 1991), and (rough-cut) capacity planning as used in e.g. MRP-II, see e.g. (Bertrand et al., 1990) or (Smith, 1989), and in synchronous manufacturing (Umble and Srikanth, 1990).

Also this definition of a bottleneck gives rise to a number of remarks.

Remark 1.

The above definition suggests that it is possible to estimate for each (group of) resource(s) individually whether or nor it is a bottleneck.

Remark 2.

The above definition is based on an absolute criterium: whenever the workload for a (group of) resource(s) exceeds a certain predefined level, the (group of) resource(s) forms a bottleneck.
Note that according to this definition a resource may be a bottleneck resource without being loaded for (more than) 100%!

Remark 3.

How to estimate the above mentioned work load level?

Remark 4.

How are setup times taken into account?
Per production order? Always completely, not at all? Depending on the operation/product combination? Depending on the set of production orders to be dealt with?

Remark 5.

How are forecasts of resource requirements and availabilities included?
How are quotations dealt with?

Remark 6.

For which period of time the workload of a given resource will be considered?
The choice of this period is important because usually it is the (average) load during this predefined period of time that is used to estimate whether a resource is a load-based bottleneck, i.e. whether it is loaded for more than the predefined level.

Remark 7.

How is rework taken into account?

Remark 8.

How are machine breakdowns taken into account?
How is time lost due to problems related to the processes that are executed using the resource accounted for?

BOTTLENECK RESOURCE CLASSIFICATIONS

Independent of which definition of a bottleneck is used, bottleneck resources can be classified in a number of ways. Apart from the first, all classifications are related to the possibilities to cope with them.

Classification 1.

Production bottleneck resources can be defined from a number of different points of view:

-Individual operations
 (which resource determines the duration of a given operation most)
-Individual products or services
-Individual customer orders (set of one or a number of different products
 (article codes) to be delivered simultaneously)
-Set of customer orders to be dealt with during a given period of time
 (a given volume and mix.)
-Varying sets of customer orders to be dealt with in the course of time
 (varying with respect to volume or mix).
 ("Flexibility" point of view. Bottlenecks with respect to changes.)

Classification 2.

Many different types of resources may act as a production bottleneck resource

1) Machines (having either a fixed position or being movable, like transport media)
2) Tools
3) Operators for "direct" production operations
   facility setup/inspection/control
   maintenance, reparations
   Clercks
   Managers
4) (Storage) space
5) Materials
6) Data, information.

Classification 3.

Production bottlenecks may show up

-permanently
-periodically (seasonal)
-unexpectedly (e.g. by the break down of a machine, delayed deliveries

etc.).

What are the differences between and similarities of permanently existing (structural) and temporarily existing (temporal) bottleneck resources and how can these characteristics be used for dealing with them?

"Structural" bottlenecks may among others arise due to

-(long term changes in) the product volume
-(long term changes in) the product mix
(These aspects concern bottlenecks from a flexibility's point of view)
-(new) machines
-(new) processes
-(closing down) of suppliers, transporters
-(long term changes in) the scheduling methods used
-(long term changes in) the sequencing methods used
-(long term changes in) the way the (time-phased) resource requirements related to quotations are taken into account (i.e. what fraction of the requirements of uncertain quotations should be taken into account in "capacity" planning)
-sizes of transformation batches, where transformations may concern time, place, structure and/or form
-accounting method used
(Due to a particular way of cost accounting alternative ways of producing or delivering a given quantity of a given set of products during a given period of time aren't considered, as discussed in e.g. (Muntslag and Ribbers, 1989)
Another point to be mentioned in this context is that according to many cost accounting methods the time required for operations that don't deal with products-in-process when the "value" of these products is low doesn't matter very much because the "costs" for keeping these products in stock isn't high at least if these products don't occupy a lot of space or detoriate quickly.)
-wrong standard times for processing and setting up
-low yield (high scrap) due to operations requiring the bottleneck resource or to preceeding and succeeding operations requiring other (bottleneck) resources
-all possible combinations of the above.

"Temporal" bottlenecks may among others arise due to

-the break down of a machine
-delayed internal or external deliveries
-illness of operators
-(planned) maintenance, but also be the result of
-incidental low yield (high scrap) due to operations requiring the bottleneck resource or to preceeding and succeeding operations requiring other resources.

Classification 4.

Production bottlenecks may lay inside or outside the direct influence of a company.
Examples of the latter might be the production capacities of the suppliers of materials, parts as well as of the companies that take care of parts of the production activities that have to be done by other companies e.g. due

to special equipment (economics of scale) or knowledge, or the external transport by ship or plane.

Classification 5.

Bottleneck resources may also be ranked according to the number of (different) operations in which they are (or have to be) involved and the number of products for which the bottleneck resource are required.
It may be that a given bottleneck resource may be required several times for the production of a given product. For a discussion of the consequences of this for a simple linear production network see e.g. (Weeda, 1991a).

Classification 6.

Another sub division of bottlenecks might be based upon the place where a bottleneck resource is required in a logistic network.
Bottleneck resources may be required for gateway operations, finishing operations or for operations to be dealt with somewhere in between the former.
For the influence of the position of the bottleneck resource concerning the throughput in a production network see e.g. (Goldratt and Cox, 1983), (Fry, 1987) and (Weeda, 1991).

Classification 7.

In principle there exist many possibilities for (temporarely) overcoming the negative effect(s) of production bottleneck resources. Herewith one may distinguish between short, medium and long-term possibilities, see also (Smith, 1989), pp. 303-304, and (Wight and Landvater, 1983), p. 03.

Short term.

-Overtime
-Subcontracting
-Alternative routings
 Within this context it seems important to distinguish between "single machine", (generalised) flow shop and job shop like situations
-Reallocation work force

Medium term.

-Make or buy
-Subcontracting
-Work force (extra shifts)

Long term.

-Land
-Facilities
-Equipment
-Work force.

Apart from the above resource based measures, one may as well consider organisational measures like changing scheduling rules, sequencing rules, lot sizes, allowing overlap, operation and order splitting.
Also one may decide to process/produce a number of copies of a number of

different products (article codes) simultaneously, where simultaneously means the usage of the same set of resources at the same time. See e.g. (Kimball, 1987).

It is useful to classify bottleneck resources according to the above mentioned classes of measures because this gives insight into the possibilities to releave a bottleneck.

Classification 8.

The "available" time of resources is "completely" filled due to set up, loading, processing, repair, maintenance and waiting activities.
The processing time is the most important time, because usually the number of products produced is directly related to this time, and therefore to the goal(s) of a company. See the definition of a bottleneck in the introduction of this paper.
It is therefore important to have insight into whether or not it is possible to reduce the time consumed by the other activities.
Within this context a figure like the following is useful.

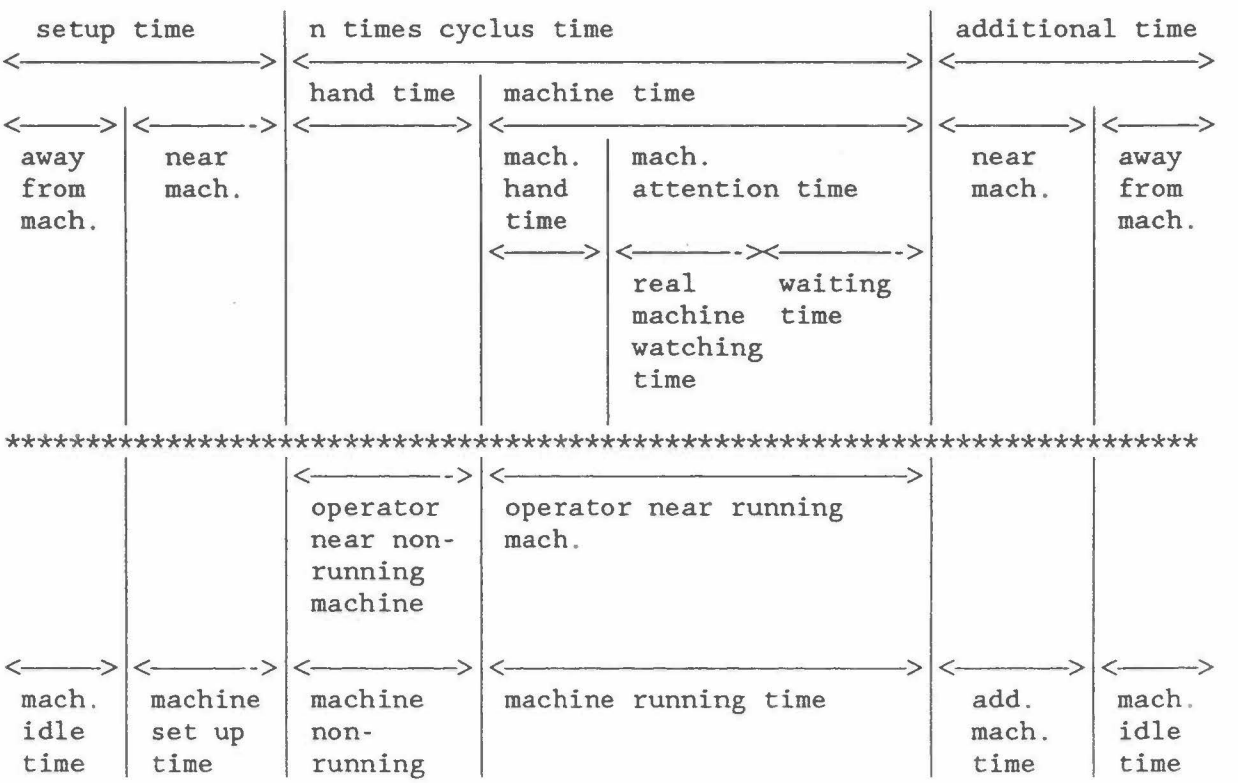


FIGURE 4 : OPERATOR AND MACHINE REQUIREMENTS FOR OPERATIONS REQUIRING ONE OPERATOR AND ONE MACHINE

The part above the line composed of asterisks indicates the "load" of the machine, whereas the part underneath this line shows the operator time requirements.
Based upon the above figure, one arrives e.g. at a sub division of bottleneck processing resources into resources that have or haven't to be setup (always or depending on product, operation).
In case a processing resource requires no setup or the set up times are

independent of the activity to be executed, it isn't possible to reduce this part of the time requirements of the machine by e.g. another way of scheduling/sequencing activities.
For other useful figures in this context see e.g. (Fuse, 1987).

TIME-BASED BOTTLENECKS.

Apart from all the above stated remarks with respect to the two definitions of a bottleneck considered upto here, there is one other remark:
Both definitions suggest that only resources may be bottlenecks!
That this doesn't necessarily hold is clear from considering e.g. the fermentation of wine or cheese, where it is the duration of the process itself that forms a bottleneck in transforming customer orders into deliveries of quantities of products or services.
Other examples concern the cooling of rolls of steel after they have been rolled as well and the drying of cardboard sheets after text has been printed on them.
These time-based bottlenecks differ from resource-based bottlenecks in two aspects.

Difference 1.

The occurence of the bottleneck is independent of the number of products that have to undergo the process.

Difference 2.

The effects of this type of bottleneck may be (partly) releaved by processing/producing more in all the foregoing production processes. The latter may require extending the availability of resources involved in these processes ("remote internal solution").

The above may be clearified by considering a "belt" used for transporting materials, (semi-)finished products or data/information.
In order to realise the delivery of a certain quantity within a given period of time, one may either increase the speed of the "belt" or increase the quantity put on the "belt".
Because the first option can't be used when dealing with time-based bottlenecks, only the latter option is left.

COMPARING RATE-, LOAD- AND TIME-BASED BOTTLENECKS

Which relations exist between the above three seemingly different definitions of a bottleneck? Is it possible to combine them into one all including practical definition of a production bottleneck?

In Table I the similarities of and differences between the three above mentioned types(?) of bottlenecks are summarised with respect to a number of important characteristics.

Rate-based bottlenecks seem notably useful if the processing time outweight the waiting time for a process. In that case the concept is useful for deciding which products to produce, i.e. which customer orders to accept.
See e.g. (Umble and Srikanth, 1990) pp. 96-98.
In general the concept rate-based bottleneck resource notably useful when defining production lines for a specific (group of) products, i.e. for

linear networks of production activities.
Although rate-based bottleneck resources are locally estimated, they are introduced for getting insight into what may delay the planned execution of a set of activities most! So they are defined from an integral point of view.
The concept rate-based bottleneck is useful for improving situations permanently.

As a rate is defined by quantity/processing time, it isn't clear whether an unsatisfying rate is due to the quantity, the processing time or to both of them.
Rate-based, as well as load-based, bottleneck resources are based on the idea that the time-delay results from a shortage of resources like machines, operators and tools, not materials or time!

	Rate-based	Load-based	Time-based
Definition	Quantity of materials processed /products produced per unit of time	Part of available quantity of a resource used up during a given period of time	Time required for execution process
Reference	A process	A resource	A process
Aspect	Processing time	More/less resources	Waiting/ processing time
Measurement	Relative to preceding processes	Relative to preset load level	Absolute
Measures	Processing resources involved	Processing resources involved	Preceding processing resources
Control level	Shop Floor Control	Goods Flow / Shop Floor Control	Goods Flow / Shop Floor Control
Application	One product (group)	Several products (product groups)	Product (group) Process

TABLE I : COMPARISON RATE-, LOAD- AND TIME-BASED BOTTLENECKS

The concept of load-based bottleneck resource is clearly in accordance with the definition of a production bottleneck given in the introduction
"A production bottleneck denotes everything that results in a time-delay between the demand for a given quantity of a product or service and the delivery of that quantity.
Always when resources are loaded for more than 100%, this will give rise to very long time-delays. From this point of view load-based bottlenecks may be useful for realising smooth goods flows.

It seems however that load-based bottlenecks have been introduced and are used for estimating delivery times that can be realised in production organisations dealing simultaneously with a number of netwoks, requiring partly the same set of processing resources.

Time-based bottlenecks reveal time-delays that aren't pointed out via one of the other two types of bottlenecks.
They are related to the concept "critical path" used for planning projects.
The concept customer order decoupling point (CODP), stating upto where in the organisation activities are executed specifically for a given customer order, see e.g. (Wouters, 1991), is directly related to the here introduced concept of time-based bottlenecks.
As mentioned before, undoing the undesired effects of time-based bottlenecks almost always involves processing resources used for the execution of the activities preceding the time-bottleneck.

Summarising the above, it seems that each of the here considered definitions of a bottleneck stresses different aspects, all of them should be taken into account when estimating what are the bottleneck resources and processes in a company.

SUMMARY AND CONCLUSIONS

This paper dealt with three different definitions of a bottleneck.
It was shown that each of the three different aspects stressed by each of the here considered definitions of a bottleneck, i.e. (quantity processed)/(required processing time), required processing time and the total requirement for a given resource during a given period of time, should be taken into account when estimating what may be the processes and resources that limit the ability of an organisation to transform customer orders into demanded products.
An overview was given of the problems related to each definition, providing a good starting point for further research on bottlenecks.

ACKNOWLEDGEMENTS

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