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METHOD OF CALCULATING THE LENGTH OF MANUFACTURING CYCLE FOR PRODUCTS IN WOOD INDUSTRY ENTERPRISES

Abstract: The paper discusses principles of establishing the duration of manufacturing cycle for a batch of parts using the computational method. A classification of manufacturing cycle components appropriate for this method is presented, as developed based on the classifications proposed in literature on the subject. The paper gives characteristics of the cycle components, for which the time periods are established. Formulas used to determine the length of manufacturing cycle are presented. Individual types of formulas are applicable depending on the availability of data and demand for a specific degree of result accuracy. Formulas are presented for the engineering period of a cycle taking into consideration serial, parallel and mixed serial-parallel production for a batch of parts.

Key words: woodworking industry, the duration of manufacturing cycle, a batch of manufactured parts, run of a manufactured batch

INTRODUCTION

Time is the primary measure of the execution of manufacturing process (Liwowski, Kozłowski 2007). Time is used to determine the amount of time required or consumed for the performance of a manufacturing task by employees (labour consumption) and a given workstation (workstation requirement). Duration of a manufacturing process is measured in relation to its one run, i.e. a single cycle. In general terms the time (duration, length, length of time) of a manufacturing cycle for a product[34] refers to the period contained between the starting point and the moment of completion of a single run of manufacturing process for a single product or a group (batch or series) of products. In relation to parts comprising the final product the cycle time begins at the moment of collection of materials from input warehouses or warehouses located between successive technological stages of manufacturing process, while it ends at the time worked parts are released to the completion warehouses. For final products the cycle time begins when the materials are collected for production from input warehouses and ends with the release of manufactured products to the final production warehouse.

The object of work, in relation to which cycle time is established may be: a single element, subassembly, assembly or a final product, or a group (batch) of parts or a group (series) of final products. Typically the length of a cycle is established for a batch of manufactured elements – as a simple cycle, or a batch of manufactured complex parts – as a complex cycle. The duration of a cycle is measured in such units as seconds, minutes, hours, shifts, calendar days or workdays, less frequently in calendar units (1-, 3- or 5-day). Time units are selected based on the length of a cycle and the accuracy required of its determination.

Methods used to establish the duration of a manufacturing cycle of a product may be divided into two groups. One comprises aggregate methods. These methods are used to determine the length of a cycle as a whole, disregarding its structural components. Aggregate methods are used first of all when the organisation of production in an enterprise is of a low standard, which is manifested by a lack of time standards.

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[34] In this study the term "product" is applied in a general sense and refers to arbitrary objects of work. However, in situations requiring a greater precision the term "product" is replaced or supplemented accordingly with specific descriptors, e.g. part, final product.

The other group comprises analytical methods and includes a computational and a graphic method. Both methods use components of the cycle structure and their lengths. The computational method is applied primarily to determine the duration of the manufacturing cycle for a single simple product or a batch of manufacturing parts. In contrast, the graphic method is used mainly to determine cycle time for a complex product or a series of complex final products (Pasternak 2005).

The aim of this paper is to present principles used to establish the duration of the manufacturing cycle of a product when applying the computational method. Manufacturing processes in wood industry enterprises are typically well-organised. This is manifested e.g. in the establishment of time standards in production planning and its calculation. These standards are sources of data, on the basis of which time periods of manufacturing cycles are determined using the computational method, particularly for technological periods. For this reason this method may successfully be used in medium and large wood industry enterprises.

THE STRUCTURE OF MANUFACTURING CYCLE OF A PRODUCT

The structure of manufacturing cycle of a product (the structure of a manufacturing cycle) is composed of manufacturing operations, natural processes and intervals between these components. Within these three main components we may distinguish more specific components. Literature on the subject presents various variants of two basic classification systems of manufacturing cycle components, which may be used to establish cycle time applying the computational method.

The first method of grouping cycle structure components is to distinguish two types of periods (Lis 1984, Pasternak 2005, Durlik 2007). During the first period products are subjected to actions, which cause changes in their properties or preserve these properties. Such types of times for actions and operations were included in the working period (active period). In turn, the second period is composed of intervals, in which products are inactive. These cycle components and their times are included in the interval period (inactive period, waiting period).

In the case of the latter type of classification process components are grouped based on time segments, during which changes in product properties are introduced, caused by technological operations and natural processes as well as segments, in which such changes do not occur, although actions maintaining such changes may be performed in such time segments, e.g. during manipulation operations. Based on such a criterion we distinguish operation and interoperation periods (Wróblewski 1993).

The **operation period** (active period) comprises times of technological operations and natural processes. In their case product properties change. The **interoperation period** (inactive period, waiting period) includes interoperation intervals[35], resulting from the organisation of the manufacturing process and organisation of the workday. Intervals resulting from the organisation of the manufacturing process includes times of manipulation operations (auxiliary operations: control, maintenance, warehousing and transport) as well as storage times of manufactured batches, including waiting time for release of a workstation. In the interoperation period no final changes are made in product properties. Intervals selected for the establishment of the duration of the cycle manufacturing may not overlap with other intervals or the other components of the manufacturing process.

Both types of classification for components of the time of the manufacturing cycle for a product differ in the method of grouping manipulation operations and actions comprising warehousing operations. Applied methods of grouping cycle components have no effect on the obtained final results, i.e. established time. In both cases the results are identical. However, in the computational method a significant role is played by the availability and labour intensity of the

[35] The interoperation interval is defined as a period, which passes between the performance of two successive technological operations or natural processes on a single product or a batch of products, when executing their manufacturing cycle.

identification of data, which need to be used in formulas. In this respect more advantageous conditions are provided by the latter classification of cycle components, using the division of the cycle into the operation and interoperation periods. For this reason in this study this method is indicated as the preferred approach to be applied in the computational method. Figure 1 presents structure components of the time of a manufacturing cycle for a product following the principles of the second classification method. In the next parts of this paper when discussing problems concerning the manufacturing cycle only components identified using the classification presented in Fig. 1 will be used.

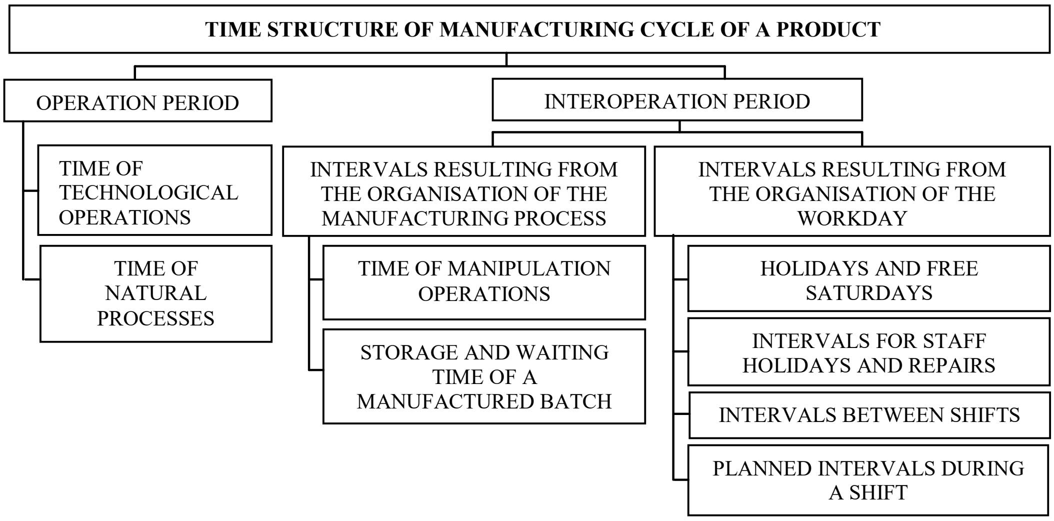

Fig. 1. Time structure of a manufacturing cycle of a product divided into the operation and interoperation periods

Source: own study.

DETERMINATION OF DURATION OF THE TECHNOLOGICAL CYCLE OF A BATCH OF PARTS

The computational method makes it possible to establish cycle time based on several variants of formulas. They differ in the degree of aggregation of the measures, from which they were constructed. A greater degree of aggregation of the measures used in the formula means that fewer details (components) of cycle structure were included. In this way the calculated cycle time may be characterised by lower accuracy. Selection of a formula appropriate for the needs depends on the labour intensity of collection of data required for the calculations and the expected accuracy of the result. Numerical data used in the computational method are established based on normative (catalogue) values, reading of these values from the manufacturing documentation or as a result of measuring actual times when executing the manufacturing cycle. This measurement may be conducted using the chronometric method, activity study or job sampling[36]. The cost of data collection is lowest when using standard values, while it is highest when measurements are taken.

Using the computational method the length of a manufacturing cycle of a batch of parts (or a cycle of a simple product) may be established based on a general dependence:

[36] Radwańska K., Sobolska-Kutner A.: Próba ustalenia wielkości przerw międzyoperacyjnych w cyklu produkcyjnym wyrobów przemysłu meblarskiego. "Przemysł Drzewny" 1976, nr 9.

$$CCP = COT + CPN + COM + CSP + PDR, \quad (1)$$

where:

CCP – time of the manufacturing cycle of a batch of parts (or time of a cycle of a simple product),
COT – period of technological operations,
CPN – time of natural processes,
COM – time of manipulation (auxiliary) operations,
CSP – storage and waiting times of a manufactured batch,
PDR – intervals resulting from workday organisation.

All time segments of process components, which were applied in formula (1) comprise the serial system (a simple series). This means that times of these components may not overlap with others as a whole or in part.

According to the cycle structure presented in Fig. 1 the first component (COT) found in formula (1) is a period of technological operations. Their determination method depends on the applied type of run of the manufactured batch during the cycle. Technological operations comprise a technological cycle, which time is established for an isolated run of a batch of parts, i.e. not considering the effect on its length by previous batches produced in the same manufacturing unit. It is a model cycle[37]. In such a case cycle time is only dependent on the system of transfer (run) of a manufactured batch between operations and on the number and times of successive operations in the cycle. During the execution of a cycle certain workstations may still be occupied by operations and manufactured batches belonging to the previous cycle. For this reason operations and manufactured batches performed within the current cycle have to wait for the workstation to be released. The duration of a cycle under commercial scale production conditions is longer than the time of the model cycle, calculated for an isolated run of a manufactured batch.

The second component of formula (1) comprises times of natural processes (CPN). Individual natural processes during calculations may be treated analogously as technological operations, considering them as operations of natural processes. They comprise the cycle of operations of natural processes. They are generally found in a serial system. In such a case the component (CPN) is a sum of times of natural processes. In certain cases in manufacturing processes there may be situations, when a part of time of a natural process of a manufactured batch overlaps with the time of the next manufacturing operation. Then this fact is included in the calculations reducing adequately the time of the natural process by the overlapping segment.

Next components of formula (1) comprise the interoperation period. It is a supplementary element, which increases the length of the cycle by including intervals resulting from the organisation of the manufacturing process and organisation of work time. In the calculations only these intervals and idle time are considered, which do not overlap. For example, warehousing operations and public holidays may not be included in the calculations simultaneously if they occur in the same period.

The first group of intervals comprises manipulation (auxiliary) operations. Analogously as technological operations, they comprise a cycle of manipulation operations. Since during their execution no changes are introduced to properties of work objects, manipulation operations are treated as a type of intervals in technological processes. Manipulation operations include transport operations, which need to be clearly distinguished from transport activities. A transport operation takes place only when it is executed by a specified worker, who handles only such an operation. In all the other cases transport activities are classified to handling time (TO), which is included in the

[37] The model form of a cycle is defined in literature on the subject as a model or theoretical cycle.

unit time standard. Based on this standard the duration of operations on a manufactured batch are established.

The second group of intervals comprises storage and waiting periods for a manufactured batch for the execution of the next operation in the cycle. Most frequently a batch waits in front of the workstation, since the operation on the previous manufactured batch has not finished. Warehousing operations and intervals connected with storage of work objects need to be adequately distinguished. Warehousing operations take place when work objects are stored in specially designated manufacturing spaces and the movement of stored objects is registered (acceptance and release) by specified workers. If these criteria are not met, we observe storage of objects, typically on the shop floor, waiting for the execution of the next cycle operation. Warehousing operations and storage times for a manufactured batch need to be distinguished to prevent their repeated incorporation in formula (1).

Intervals resulting from workday organisation are the last group of components distinguished in Fig. (1). In formula (1) intervals from that group were included as one measure (PDR), expressing jointly the number of days and shifts off work during a cycle. The measure PDR is expressed in a unit of time, in which the time of the entire manufacturing cycle is expressed.

In certain situations the application of formula (1) may cause problems resulting from a lack of a complete set of data required for calculations, particularly connected with the interoperation period. Then the length of the manufacturing cycle may be established in a simplified manner in relation to formula (1), based on one of the two formulas: (2) or (3). The appropriate formula is selected depending on the type of available data, based on which we may estimate the time of missing components, with accuracy sufficient for the planning and production control processes implemented in the enterprise. In the case when the mean interval per one technological operation is available, the duration of a manufacturing cycle may be established according to the formula:

$$CCP = COT + CPN + k \cdot SCM, \tag{2}$$

where:

k – the number of technological operations included in the cycle,
SCM – mean time of interoperation periods, determined per one technological operation,
– the other denotations as in formula (1).

In manufacturing enterprises data concerning times of technological cycles may be collected from manufacturing documentation. This makes it possible to establish the time of a technological cycle (COT) faster and more accurately than in the case of the other components of the manufacturing cycle. This fact was used in the second, simplified method to determine cycle time. The value of the interval is established based on the technological cycle extension index. Its applications facilitates calculation of the time of a manufacturing cycle using the formula:

$$CCP = COT \cdot (1 + WCT) + CPN, \tag{3}$$

where:

WCT – the technological cycle extension index,
– the other denotations as in formula (1).

Establishment of WCT requires previous measurement of times of manufacturing cycles for a batch of parts under actual manufacturing conditions. Times are measured separately for each product representing a group of technologically similar products. Determined indexes are next applied in relation to the cycles of products belonging to the same groups. This reduces costs of determining times of manufacturing cycles in comparison to a situation, when they are established separately for each type of product. This index is based on the formula:

$$WCT = (CCR - (COT + CPN)) / COT, \quad (4)$$

where:
CCR – time of manufacturing cycle for a batch of parts, measured under actual production conditions,
– the other denotations as in formulas (1 and 3).

Formula (4) specifies the share of the interoperation period in the time of a technological cycle.

The time of the technological cycle (COT) is a significant component in the time of the manufacturing cycle for a batch of parts. It is used as a parameter in formulas (1) – (4). Its length depends on the method (system), which was applied to transfer the batch of parts between workstations (operations). We distinguish three methods to transfer the manufactured batch: serial, parallel and serial-parallel. The duration of the technological cycle, for its model form, is determined based on standardised unit times (NTJ). When necessary they are appropriated adjusted based on the standard time utilisation index (Brzeziński 2013), according to the formula:

$$STJ = NTJ / WNC, \quad (5)$$

where:
STJ – adjusted unit time for a single operation step performed on a single part,
NTJ – standardised unit time of a single operation step performed on a single part,
WNC – the standard execution index for the standard time of the unit time of a single operation step [-].

Based on the adjusted unit time (STJ) we calculate the duration of an operation cycle (a single operation step) for a batch of manufactured parts, according to the formula:

$$CCO = TPZ + (N / (LSR \cdot LCP)) \cdot STJ, \quad (6)$$

where:
CCO – duration of an operation cycle for a batch of manufactured parts
TPZ – changeover or setup time for a production workstation, on which this single operation step is performed,
N – the number of parts in the manufactured batch,
LSR – the number of parallel, interchangeable workstations [38], which simultaneously perform a given single operation step,
LCP – the number of parts in the manufacturing (processing) lot, processed simultaneously during the execution of the single operation step on the workstation,
– the other denotations as in formula (5).

In the case of machine or machine-manual workstations, which require time-consuming changeovers the amounts of TPZ are standardised and included in formula (6). On manual workstations, if setup operations are relatively short, the TPZ length is not established separately and technical and organisational handling operations of the workstation are included in NTJ.

[38] Interchangeable workstations are workstations, on which the performance of the same operation does not change its workstation requirement. #

A single operation step is performed in a job splitting mode if LSR > 1. **Job splitting** means that a single operation step is performed simultaneously on two or more identical or technologically interchangeable workstations. Then parts comprising the batch are assigned to parallel workstations in the number proportional to their efficiency. In the case when LSR = 1, the single operation step is performed on one workstation. Such a situation is found for most technological operations.

A single operation step is executed simultaneously on several parts constituting a **manufacturing** (processing) **lot** if LCP > 1. This is observed e.g. during operations of veneering panels in multi-platen presses. Then several panels are veneered simultaneously in one operation. Otherwise, when LCP = 1, a single operation step is performed on a single part.

In terms of organisation the serial system is the simplest system of transferring a batch of parts between operations within a cycle. In this run the times of successive operations do not overlap (except for changeover times of workstations), thus the serial run is characterised by the longest cycle time. The length of the technologic cycle, during which the serial run of a batch of parts takes place, is specified by the formula:

$$CCT = CCS = TPZ_1 + (N \cdot \sum_{i=1}^{k} STJ_i)/(\mathrm{LSR} \cdot \mathrm{LCP}), \qquad (7)$$

where:

CCS – time of a technological cycle for a batch of parts in a model serial run,
TPZ_1 – changeover time or setup time of the first operation in the cycle,
N – the number of parts in the manufactured batch, constant during the cycle,
k – the number of technological operations included in the cycle, i = 1,...,k,
– the other denotations as in formulas (5-6).

If TPZ_1 is not found in the first operation of the cycle, formula (7) is reduced to the second component. Changeover times for the workstation for the other operations in the cycle are covered each time by the times of operations performed on preceding workstations. For this reason they do not affect cycle time and are not included in formula (7). Also the time of transport operations connected with the transfer of the manufactured batch from a previous workstation to the next are not found as separate values in formula (7). The time of transport activities is included in unit time and considered in its standard or is included in the time of transport operations.

The technological cycle of a batch of parts in the form of a parallel run is executed most frequently on manufacturing lines. The parallel run is characterised by the greatest overlapping of times of successive operations. For a parallel run the time of a technological cycle for a batch of parts is specified by the formula:

$$CCT = CCR = TPZ + [(N-1) \cdot STJ_{\max} + \sum_{i=1}^{k} STJ_i]/(\mathrm{LSR} \cdot \mathrm{LCP}), \qquad (8)$$

where:

CCR – time of a technological cycle for a batch of parts in a model parallel run,
TPZ – changeover time for a manufacturing line, on which this cycle is performed,
STJ_{max} = max $\{STJ_i\}$ – the longest adjusted unit time among all operations in the cycle,
– the other denotations as in formulas (5-7).

Changeover time (TPZ) for a manufacturing line is the sum of changeover times for all workstations in the line if workstation changeover is performed successively. When simultaneous changeover is performed on several workstations (e.g. by a team of workers), then the TPZ time is respectively shorter and constitutes a sum of non-overlapping segments of changeover times at individual workstations of the line.

The parallel run may be asynchronous or synchronous. If for the i-th single operation step $STJ_i \neq STJ_{i+1}$ (excluding i≠k), the process is asynchronous. Then individual single operation steps are executed non-continuously (there are microintervals), except for operations with the longest time. Formula (8) refers to the asynchronous run. If for each i-th single operation step in the cycle $STJ_i = STJ_{i+1} = STJ$, then the process is synchronous. In such a case in formula (10) values of $STJ_{max} = STJ$ and $STJ_i = STJ$. After substituting these values and transformations, formula (8) is reduced to the form:

$$CCT = CTR = TPZ + [(N-1) \cdot STJ + k \cdot STJ] / (LSR \cdot LCP), \quad (9)$$

where:

$STJ = STJ_i$ – adjusted unit time of a single operation step for the parallel synchronous run,

– the other denotations as in formulas (5 and 8).

In the serial-parallel run a manufacturing batch is divided into transport batches, which are transferred from operation to operation (from workstation to workstation). We have partial coverage of times of successive single operation steps. The length of a technological cycle for a batch of parts for a model serial-parallel run is determined by the formula:

$$CCT = CCK = TPZ_1 + [N \cdot \sum_{i=1}^{k} STJ_i - (N-P) \cdot \sum_{i=i_{\min}}^{k-1} STJ_{i_{\min}}] / (\mathrm{LSR} \cdot \mathrm{LCP}) \quad (10)$$

where:

CCK – duration of a technological cycle for a batch of parts in a model serial-parallel run,

i_{min} = i: STJ = min{STJ_i, STJ_{i+1}} – adjusted unit time for a single operation step shorter in each pair of successive single operation steps in the cycle. Index i_{min} denotes the number of the shorter single operation step selected from each pair. In the case when for a pair of single operation steps $STJ_i = STJ_{i+1}$, then we assume the number of the single operation step with a higher index value,

k – the number of pairs of single operation steps,

P – the number of parts in the transport batch; for N = const and P = const,

– the other denotations as in formulas (5-8).

In the presented form formula (10) is applied if changeover time of a workstation is found in the first operation of the cycle. Otherwise component TPZ_1 is disregarded. Changeover times of workstations during the execution of the other operations in the cycle are covered by times of operations on preceding workstations and they are not considered in formula (10).

Formula (10) is applied when the number of parts in a manufactured batch (N) and in all transport batches (P) transferred between two successive single operation steps is identical throughout the entire cycle. If this condition is not maintained, formula (10) takes the form:

$$CCT = CCK = TPZ_1 + [\sum_{i=1}^{k} (N_i \cdot STJ_i) - \sum_{i=i_{\min}}^{k-1} (N_{i\min} \cdot STJ_{i_{\min}}) +$$
$$+ \sum_{i=i_{\min}}^{k-1} (P_{i_{\min}} \cdot STJ_{i_{\min}})] / (\mathrm{LSR} \cdot \mathrm{LCP}), \quad (11)$$

where: denotations as in formulas (5) – (10).

The number of parts in a manufactured batch may change e.g. as a result of defects occurring during an operation in the cycle. Also the number of parts in transport batches, into which the manufactured batch is divided, may change between successive operations. This may result e.g. from changes in the capacity of used means of transport. If such situations may be predicted and planned, then formula (11) applies.

A more accurate determination of the time of manufacturing cycle for a batch of parts is possible based on the principles applied in the development of manufacturing schedules. They include intervals resulting from the fact that the manufactured batch waits for the release of a workstation. In such a case we additionally need to determine the order of activated batches of parts. This facilitates a precise determination of the effect on the length of cycles of other batches of parts executed in the same manufacturing cell. However, the calculation process based on these principles is labour-intensive and may be executed efficiently using an appropriate computer programme.

CONCLUSIONS

The calculated time of manufacturing cycle for specific products is the basis for the determination of standard values of this time. They are next used in production planning. It is first of all on their basis that the latest admissible times may be specified for the initiation of execution of orders, for which dates of execution of deliveries were established. Thus obtained dates make it possible to create manufacturing plans and schedules. They are the primary tool in manufacturing process control. The higher the organisational standard of the enterprise, the more precisely and accurately the standardised manufacturing cycles need to be specified, which is facilitated by the computational method.

The length of manufacturing cycle is essential for the financial results of enterprise operations. During the cycle the costs of frozen financial means for work processing are aggregated. The longer the cycle, the greater the costs. Frozen funds are released only after the sales of final products. For this reason corporate management boards are interested in the reduction of manufacturing cycles. This may be attained using e.g. the computational method in the determination of the time of manufacturing cycles and its components. This method may be a useful analytical tool. When it is applied we may rationally identify cycle components, which duration may be shortened at the lowest outlays.

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