Structural analysis and formalization of continuous flow technologies in timber harvesting

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Abstract. Currently, cross-cutting continuous flow lines with longitudinal or transverse feeding of tree-length are used in the forest industry. The currently used equipment requires improvement or replacement due to the rapid development of automation and increased quality requirements for roundwood assortments. We propose a method for modelling technological movements performed when bucking tree-lengths, using lines with a longitudinal feed as an example; the method is based on matrix transformations of coordinates. The modelling process is preceded by a structural analysis. We suggest that such analysis should be carried out for each structural unit of the bucking line due to the specificity of the subject of labour and equipment created with the special properties of the object of labour (tree-lengths, whole trees) in mind. This will allow us to demonstrate the influence of the properties of the object of labour (tree-lengths, whole trees) on the technological process model.

1. Introduction
Bucking of tree-length is a technological operation that can be performed on logging sites in a mechanized way or often by machine, in combination with delimbing by harvesters, and on landings of logging and wood processing enterprises, both in a mechanized way and by machine. Thus, bucking is an obligatory technological operation of logging, which provides the necessary dimensional and quality characteristics of round timber defining the quality of final products; in addition, the yield of industrial wood depends on the methods of cross-cutting, which determines the degree of utilization of raw timber.

The development of a new generation of production lines, in particular with a longitudinal feed, is impossible without understanding the current level of technological development. The specificity of the object of labour (tree-lengths, whole trees) requires the creation of new modelling methods that will allow us to take into account the functional capabilities of the mechanisms which have been tested under production conditions [1, 2]. When modelling continuous flow production lines, the formalization of the process of movement through matrix coordinate transformations (MCT) allows us to simulate the bucking process in a continuous mode taking into account deterministic factors and stochastic disturbances that cannot be accounted for at the design stage without experimental data.

2. Materials and methods
The object of our study is continuous flow lines with a longitudinal feed of tree-length; such lines provide the bucking of tree-length into assortments followed by sorting by purpose, diameter, species, and length.
For the purposes of our research we adopted the method of modelling technological processes using matrix coordinate transformations developed in SibGU named after M F Reshetnev [1, 3, 4].

3. Justification of the structural analysis method

Let us consider a workflow of a cutting line of the type LO-15C (Figure 1).

Disassembling and feeding into the zone of the hydraulic manipulator (GM) 4 a pack of tree-length 1 is carried out on the platform of the RRU (unloading device) 2, by the branches of the RRU system 3.

GM 4 delivers a tree-length to the feeding conveyor 5, which moves the tree-length for butt removal and subsequent bucking (circular saw 6) on the receiving table 7. The cut off assortment is dropped on the receiving conveyor 8.

For a formalized representation of the technological process by the method of matrix coordinate transformations (MCT), we introduce a floating coordinate system that corresponds to each new tree-length to be processed.

$\mathbf{A}_1$ is the operation of disassembling of a tree-length bundle (moving three to four tree-lengths to the zone of operation of a twin type LO-13C hydraulic manipulator at a distance $l_1$); $\mathbf{A}_2$ is the operation of feeding a single tree-length to the feeding conveyor (movement $l_2$); $\mathbf{A}_3$ is the operation of feeding a tree-length for butt removal (movement $l_3$); $\mathbf{A}_4$ is the operation of cross-cutting of the butt end of a tree-length with a circular saw (reciprocating movement: $+l_4$ - working turn; $-l_4$ - reverse stroke); $\mathbf{A}_5$ is the operation of feeding a tree-length for the measurement of the ordered assortment (movement $l_5$); $\mathbf{A}_6$ is dropping the assortment ($l_6$ is the distance of the movement of the dropper); $\mathbf{A}_7$ is the movement of the assortment at a distance $l_7$ by the receiving conveyor to the measurement area and transfer to the sorting conveyor; $\mathbf{A}_8$ is the movement of the assortment by cross-arms of the sorting conveyor ($l_8$, $+l_4$, $-l_4$), $l_8$ are movements that are variable in nature and depend on the diameter of a tree-length and the length of the required assortments).

This structure consists of sequentially performed operations based on movements. Movements can be performed in two modes:
a) coordinate systems $O_i X_i Y_i Z_i$ ($i = 1, 2, \ldots, n$, where $n$ is the number of movements when performing technological operations to obtain the final product), each of which is associated with a separate object of labour; the line belongs to the continuous flow. That is, tree-lengths (processing object) are fed continuously, and on each mechanism there is a tree-length with its own coordinate system.

b) coordinate systems $O_i X_i Y_i Z_i$ are assigned to the same object of labour, which is sequentially moved by the mechanisms of the technological flow; the line belongs to cyclic action flows.

Circles $A_i$ ($i = 1, 2, \ldots, n$, where $n$ is the number of movements when performing technological operations as part of the production line) are the vertices of the graph. To indicate the direction of the connection between the vertices of the graph, the corresponding edge is marked by an arrow (arc) and is denoted by $a_i$ ($i = 1, 2, \ldots, n$, where $n$ is the number of movements during technological operations) [1].

The bucking by a circular saw is highlighted as an isolated vertex [1] $A_4$, since this operation does not participate in changes in the coordinates of the tree-length, but is a component of the graph [1]. That is, the saw blade of the cutting unit moves perpendicular to the longitudinal axis of the tree-length.

To formalize the structure, (Figure 2), we use matrix coordinate transformations [3]. We assign the $O_i X_i Y_i Z_i$ coordinate systems to all the tree-lengths involved in the process; we will conditionally place the systems in the centre of the butt section under the following conditions:

- a tree-length does not rotate around the longitudinal axis when moving;
- the longitudinal axis does not change orientation relative to the original coordinates.

The tree-length is moved by a mechanism at a distance $l_i$.

![Figure 2](image.png)

**Figure 2.** Technological process of a continuous flow bucking line in the form of a directed graph, combined with the coordinate systems of the objects of labour.

When modelling complex systems [4], 4x4 matrices (square orthogonal) are usually used. Which are transition matrices [5, 6]. In the abbreviated matrix notation [7, 8], the structure in Figure 2 is written as follows (1):

$$M_n = B_1(\vec{k}_1 l_1)B_2(\vec{k}_2 l_2)B_3(\vec{l}_3 l_3)B_4(\vec{k}_4 l_4)B_5(\vec{k}_5 l_5)B_6(\vec{l}_6 l_6)$$

where: $B_i$ are the shift matrices ($i = 1, 2, 3 \ldots N$); $N$ is the number of units involved in the process; $M_n$ is the cycle of movements of the tree-length(s) (1), in which six mechanisms are involved.
In the mathematical sense, $M$, a resultant matrix from the multiplication of 4x4 matrices that make up the structural Formula (1) which in the physical sense defines a vector with coordinates in the $OX_0Y_0Z_0$ system [3, 4].

Conventionally, we denote matrices in expression (1) $B_i$ without indicating the orientation along the coordinate axes, i.e.\( (2) \)

$$B_6 = B_1 \cdot B_2 \cdot B_3 \cdot B_4 \cdot (-B_4) \cdot B_5 \cdot B_6 \cdot B_7 \cdot B_8$$

In expression (1), multiplication $B_4\vec{k}l_4 \cdot B_4(-\vec{k}l_4)$ is the movement of the saw blade (working and idling), i.e. it does not affect the coordinates of a tree-length [4, 9], since opposite matrices multiply.

One of the features of the technological process of production lines with a longitudinal feed of tree-lengths is the need to feed a tree-length to the length of the assortment several times, which violates the continuity of the bucking process. Using expression (2), we write down the technological process of bucking of a single tree-length on a line with a longitudinal feed in the form of a matrix (3) without taking into account operations $A_7$ and $A_9$ (Figure 2) to reduce entries in the matrix (3):

$$\begin{vmatrix}
B_1B_2B_4(-B_4)B_5B_6 & B_2B_4(-B_4)B_5 & B_2B_4(-B_4)B_5 \\
B_1B_2B_4(-B_4)B_5 & B_1B_2B_4(-B_4)B_5 & B_1B_2B_4(-B_4)B_5
\end{vmatrix}$$

where: $B_1$ is feeding a tree-length to conveyor 5; $B_2$ is feeding a tree-length to the receiving table 7; $B_4(-B_4)$ is working and idling of saw 6; $B_5$ is removal of the assortment.

Expression (3) is called the technological matrix, which describes the process of bucking a single tree-length with cutting out four assortments. In fact, matrix (3) is not computational, since it is not synthesized according to mathematical canons. Matrix (3) describes the algorithm for performing operations and is a rough model of the technological process:
- in the first row of matrix (3) there is a model for obtaining a single log with a length $l_5$ from a tree-length $n$.
- in the second row of matrix (3) there is a model for obtaining the second log with the length $l_5$ from a tree-length $n$.
- in the third row of matrix (3) there is a model for obtaining the third log with the length $l_5$ from a tree-length $n$.
- in the fourth row of matrix (3) there is a model for obtaining the first log with the length $l_5$ from a tree-length $n + 1$; $n$ is the sequence number of the tree-length received for processing.

Structural analysis of the mechanisms that make up the production line is necessary to create a refined model of the process of bucking wood raw materials on production lines with a longitudinal movement of tree-lengths.

Probabilistic factors affecting the process, first of all, depend on the variety of parameters of the object of labour. These factors should be taken into account using the experience of practical applications of a mechanism in question.

The analysis of the unloading and hauling device with the bundle of tree-lengths 1 and rope systems 3 demonstrated:
- the main vector of movement is perpendicular to the feed conveyor 5;
- a twisted tree-length or a bundle of tree-lengths 1 can be adjusted by turning the corner $\theta$ with the help of cable systems 3. The angle $\theta$ is the angle between the direction of the main vector and the longitudinal axis of a tree-length $\leq \theta < \frac{\pi}{4}$. 

The operation of separation, taking into account additional factors, will be written as follows (4):

$$B_4(k l_1)B_{\text{rot}}(f \pm \theta)$$

where: $B_{\text{rot}}$ is the rotation (rotation) matrix around the coordinate axis $y$; $\vec{f}$ is the unit vector of the $y$ axis; $\theta$ is the rotation angle of the tree-length coordinate system.

The dual hydraulic manipulator of type LO-13C (Figure 1) consists of two sections, each of which has two degrees of freedom. When taking a tree-length (tree trunk), the sections provide the tree-length (trunk) with four degrees of freedom:
- movement in a vertical plane;
- movement in a horizontal plane;
- rotation around the vertical axis $y$;
- rotation around the horizontal axis $z$.

The main vector for the execution of the technological operation is perpendicular to the longitudinal axis of the feeding conveyor 5 (Figure 1).

The operation of feeding the tree-length, taking into account additional auxiliary movements, will be written down as:

$$B_2(k l_2)B_{\text{rot}}(l l_3)B_4(l \theta)B_{\text{rot}}(k \theta)B(k l_2)B(f l_1)$$

The structural formula (5) is of a general type, that is, it takes into account all virtual movements. It is up to the experimenter to decide which of those movements will be implemented in modelling.

The feeding longitudinal two-chain conveyor 5 (Figure 1) can work with different distances $l_k$ depending on the method of harvesting (by mechanized harvesters or motor-manual harvesting). The spreading of rot along the stem will also affect the length of the butt to be cut off.

Thus, the main vector when feeding the length of the assortment $l_i$: output for the butt to be cut off $l_k$.

The generalized structural formula for the feed conveyor:

$$B(l l_i)B(l l_k)$$

The receiving, measuring and dropping device (receiving table) has the main vector of movement of the object of labour perpendicular to the sorting conveyor, the length of the movement is stable and equal to the movement of the lever plus the distance of the fall of the assortment on the sorting conveyor.

It should be noted that the structural analysis of individual mechanisms should take into account not only the design factors, but also all the factors that entail time losses inside the cycle. At this stage of modelling, it is impossible to predict the time loss, since the latter manifests itself in the modelling process and is taken into account when, for example, a tree-length brakes, or when a bent tree-length needs to be removed.

Thus, the main vector of movement of the object of labour on the receiving table 7 (Figure 1) remains without additions, but takes into account the time to return to its original position:

$$B_5(k l_5)B_5(k (-l_5))$$

Tree-length cutting is performed by a circular saw bucking installation 6 (Figure 1). Installation 6 does not move the object of labour, but acts on it, while spending time for working and return strokes:

$$B_4(k l_4)B_4(k (-l_4))$$

The receiving conveyor 8 (Figure 1) has a main vector along the $x$ axis with additional time losses also detected during operation or modelling:

$$B_6(l l_7)$$
4. Conclusions

1. Analysis of the structure of a production line (Figure 1) is carried out in the following sequence:
   - coordinate systems are created for successive movements of the object of labour (tree-lengths);
   - the movements of tree-lengths and mechanisms acting on the tree-lengths without changing their coordinates are plotted;
   - the formalization of an ordered sequence of technological operations is carried out using the 4x4 (1) transition matrices in the abbreviated record of the shift and rotation matrices;
   - with the help of transition matrices that make up the structural formula (1), a technological matrix (3) is constructed, which describes the algorithm for the bucking of a single tree-length.

2. The next step in the modelling of the production line for bucking is the structural analysis of individual mechanisms and installations, also with the help of transitional 4x4 square matrices. At this stage, possible movements of the object of labour, which may arise due to the changing parameters of the raw material, are identified (3).

3. When implementing the tree-length bucking algorithm in an experiment when modelling a bucking process of a series of n tree-lengths, additional deviations in the execution of technological operations on the main vectors are taken into account in the model structure by the formulas (4-9). Thus, the internal cyclic losses are taken into account, which affect the performance of the lines and the rhythm of the production line in general.

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