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MODELLING OF A ROLLING - MILL LINE

Summary. The paper present a problem of Flexible Rolling Line (FRL with the probabilistic input) control. In the case of FRL decision variables for rolling process and roll replacement are distinguished which determine the sequences and product range for certain charge and the choice of unit in which roll replacement is required.

1. Introduction

The feature of the Flexible Rolling Line (FRL) is sequential manufacturing the products of various range of goods on the same line. A proper tools is needed for each assortment and particular line unit. The production of different range of goods is related to the necessity of tool replacement. It is assumed that the tools are multifunctional, i.e. they can be used for manufacturing various assortments. The tool replacement causes FRL shut-downs, which decreases its effectiveness. To accomplish such a manufacturing process, replacements of tools and working programmes of the FRL are necessary. The problem of the control is that sequence and quantity of produced goods and procedure of tool renewal are determined - for maximization of the line effectiveness.

FRL control aims at maximization of making use of the line. The main limitations result from availability and usual wear and tear of tools. Additionally, it is assumed that the flow of objects delivered to the line and their uptake is not determined and the control should be performed at an actual time.

With the problem probabilistic FRL (FRL with the probabilistic input) control the FRL is assumed to be fed with random lots of charge at random moments of time. Various assortments are conveyed from FRL to the buffer stores having limited capacity, from which material is taken out at random moments and random lots [1,2,3]. Buffer stores are placed at the entry and exit of the FRL. In the buffer store, the charge reserves are restocked by a charge mass flow at a constant time. The FRL products are conveyed by portions to the further units. These units should be operated continuously. Buffer stores for proper products are provided before them to ensure that the units are operated continuously. The product of one type can be located in each buffer store. The absence of product causes specified production losses. Concurrent production of different assortments on the FRL necessitates tool replacement and the line down-time. In this case, the control of FRL aims at minimization of losses resulting from lack of goods in the buffer stores.

In a situation of random charge supply onto FRL and random uptake of goods from buffer stores the schedule generation of manufacturing process is not possible. In practice, decisions made to establish FRL schedule resolve themselves to the use of heuristic rules.

The paper present a problem of FRL with probabilistic input control. In the case of FRL decision variables for rolling process and roll replacement are distinguished which determine the sequences and product range for certain charge and the choice of unit in which roll replacement is required.

2. Basic definitions and assumptions

We shall assume the following denotations:

m - number of charge types ($m=1,...,M$),
n - number of product types ($n=1,...,N$),
i - number of assemblies of FRL ($i=1,...,I$),
j - maximum number of passes on roll assembly ($j=0,1,...J_i$),
k - decision stage number ($k=1,...,K$).

In order to introduce a matrix notation we shall assume that

$$J = \max_{1 \le i \le I} J_i \qquad (1)$$

We shall assume that the amount of products which can be obtained on FRL is the number of passes of the last assembly, i.e.:

$$N = J_i \qquad (2)$$

2.1 Relation between charge and product

Let us assume that a FRL is given in which N types of products can be obtained from M types of charge (Fig.1).

A relation exists between the charge types and products, and expressed by matrix:

$$R = [\ r_{m,n}\ ] \qquad m=1,...,M\ ;\ n=1,...,N \qquad (3)$$

The elements of this matrix are determined as follows:

Fig.1. Flexible Rolling Line (FRL) - Charge-product relation
(m - charge type number, M - number of types of charge, n - product type number, N - number of types of products)

$$r_{m,n} = \begin{cases} 1, \text{ if product of n-th type can be obtained from charge m-th type} \\ 0, \text{ in a contrary case} \end{cases} \qquad (3a)$$

The charge is substitutive if the following condition is satisfied:

$$\forall_{1 \le n \le N} \quad \sum_{m=1}^{m=M} r_{m,n} > 1 \tag{4}$$

The charge is not substitutive if the following condition is met:

$$\forall_{1 \le n \le N} \quad \sum_{m=1}^{m=M} r_{m,n} = 1 \tag{5}$$

In practice, when M > N then the charge is substitutive. In case when M ≤ N, the charge may not be substitutive.

If condition is satisfied:

$$\forall_{1 \le m \le M} \quad \sum_{n=1}^{n=N} r_{m,n} = 1 \tag{6}$$

then charge is dedicated.

In case when

$$\forall_{1 \le m \le M} \quad \sum_{n=1}^{n=N} r_{m,n} > 1 \tag{7}$$

the charge is not dedicated.

When M < N the charge is not dedicated. In case when M ≥ N the charge can be dedicated.

Further on, we shall assume that the charge is substitutive and non-dedicated.

2.2 Structure of FRL

Let us assume that FRL is composed of I roll assemblies (units). Each unit can include J_i passes. A train of passes makes a process line.

The process line is the FRL axis along which a conveyor is placed. The units can be shifted in such a way that appropriate passes are located on the FRL axis. The train of these passes forms a technological route of product.

The FRL structure is presented by a matrix:

$$S = [\ s_{i,j}\ ] \qquad i=1,...,I\ ;\ j=1,...,J \tag{8}$$

The elements $s_{i,j}$ are determined as follows:

$$s_{i,j} = \begin{cases} j, \text{ if } \ 1 \le j \le J_i \\ -1, \text{ in a contrary case} \end{cases} \tag{8a}$$

We shall assume that the charge be passed once through a chosen pass of selected rolls to obtain the n-th product. A sequence of the number of these passes forms the technological route (Fig.2).

Technological routes of products are expressed in the matrix form

$$A = [\ \lambda_{i,n}\ ] \qquad i=1,...,I\ ;\ n=1,...,N \tag{9}$$

The elements of this matrix are expressed as follows:

$$\lambda_{i,n} = \begin{cases} j, \text{ if charge must be passed through the j-th pass} \\ \quad \text{of i-th roll to obtain the n-th product} \\ -1, \text{ if the i-th roll is not utilized to manufacture} \\ \quad \text{the n-th product} \end{cases} \tag{9a}$$

From the notation (11) it follows that each technological route is passing by consecutive FRL rolls from the firts to the last one.

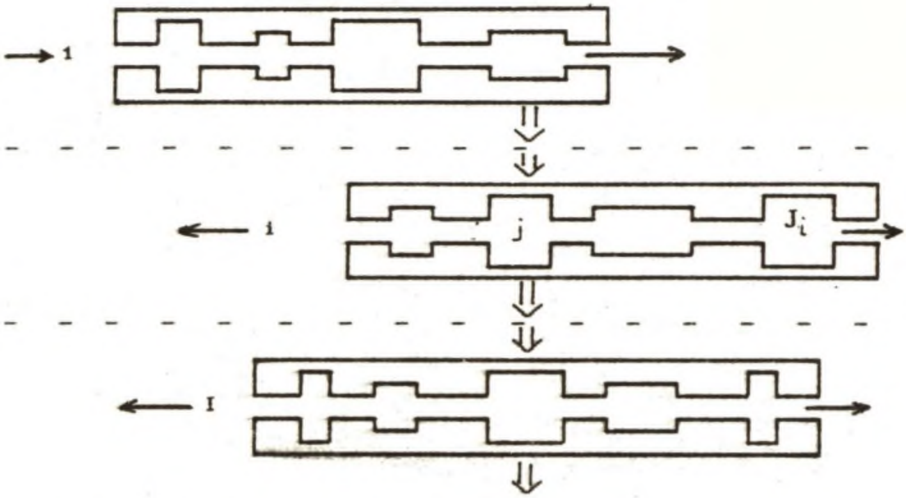

Fig.2. FRL - technological routes
(i - unit number, I - number of units, j - pass number, J_i - number of passes of i-th unit).

Moreover, we allow possibility

$$\underset{n}{\exists} \quad \underset{\nu\neq\mu}{\exists} \quad \underset{i}{\exists} \qquad \lambda_{i,n} = \lambda_{i,\nu} \tag{9b}$$

2.3 Statical charakteristic

From the viewpoint of rolling process controll, statical characteristic of pass is of essential importance. This characteristic determines a distance between roll surfaces in a pass depending on the mass of material rolled.

As can be seen from Fig.3 the roll surfaces in passes are subject to wear - due to rolling process.

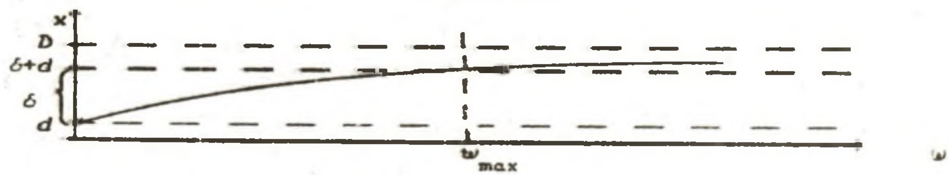

Fig.3. Statical characteristic of pass
(*d* - nominal distance between surfaces of rolls in a pass,
δ - admissible increase in the distance between roll surfaces in a pass,
x - actual distance between roll surfaces in a pass,
w - quantity of charge passed through a pass (in tons or pieces)

The roll surface is wearing more rapidly at a large draft (D/*d*) as compared with a small draft (D/*d*+*δ*) (Fig.4). In case of draft (D/D) the wear of roll surface does not accur. Hence, it is

Fig.4. Wear and tear of roll surfaces
(D - charge thickness, G = $d + \delta$).

supposed that statical characteristic of pass is of convex type. Under practical conditions, such a characteristic can be obtained as a result of identification.

In a general case, the statical characteristic of the i-th roll is a function:

$$x_{i,j} = f_{i,j,m,n}(w) \tag{10}$$

This function can be different for various passes j on different rolls i. Moreover, the course of the function is depending upon the type of charge (e.g. material hardness) and the sort of product (e.g. specified draft).

If the j-th pass of the i-th roll lies on the technological route of N_k products that can be manufactured from each charge, then the number L of all statical characteristic will be:

$$L = M \sum_{k=1}^{k=IJ} N_k \tag{11}$$

which determines the extent of identification problem.

In practice, (for simplicity) linear characteristics of passes are assumed:

$$x_{i,j} = a_{i,j} w + e_{i,j} \tag{12}$$

where: $a_{i,j}$, $e_{i,j}$ - constant coefficients.

In such a case it is possible to determine the distance between rol surfaces on the basic of charge quantity.

Even if linear characteristic is in the form of:

$$x_{i,j} = a_{i,j,n} w + e_{i,j} \tag{12a}$$

and thus

$$x_{i,j} = a_{i,j,m,n} w + e_{i,j} \tag{12b}$$

it is impossible to define the distance between roll surfaces.

From the Fig.5, it follows that rolling in turn w_n and then w_v of charge we shall get the distance x_2 of roll surface. During a reverse order of rolling we obtain the same result. However, when rol ling only the product ν (for $\Delta w = w_n + w_v$) we get the distance of roll surfaces x_s. Therefore the wear of a pass depends on the types of rolled products.

Further on, we shall assume that parameters of passes are given as expressed in matrixes:

- <u>Standart dimensions of passes</u> are given by matrix:

$$D = [\, d_{i,j} \,] \qquad i=1,...,I \; ; \; j=1,...,J \tag{13}$$

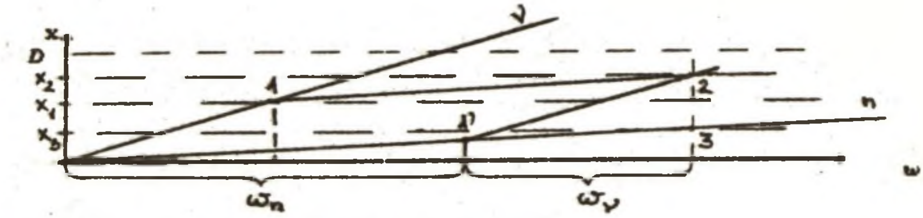

Fig.5. Linear characteristic of passes
(n, ν - product numbers, w_n, w_ν - quantity of products x_2, x_3 - distances between surfaces of passes).

where: $d_{i,j}$ - nominal distance of roll surfaces of the j-th pass on a new i-th roll.

- admissible dimentions for passes are expressed by matrix:

$$G = [\ g_{i,j}\ ] \qquad i=1,...,I\ ;\ j=1,...,J \tag{14}$$

where: $g_{i,j}$ - actual distance of roll surfaces of the j-th pass on the worn i-th roll.

- tolerance of pass wear is given by matrix:

$$\Delta = [\ \delta_{i,j}\ ] \qquad i=1,...,I\ ;\ j=1,...,J \tag{15}$$

where: $\delta_{i,j}$ - acceptable increase in the distance of roll surfaces on the j-th pass of the i-th roll.

and

$$\delta_{i,j} = |\ g_{i,j} - d_{i,j}\ | \tag{15a}$$

From $g_{i,j}$ and the state $x^k_{i,j}$ it is possible to determine flow capacity of FRL.

FRL flow capacity is expressed by matrix:

$$P = [\ p^k_{i,j}\ (m,n)\ ] \qquad i=1,...,I\ :\ j=1,...,J \tag{16}$$

where: $p^k_{i,j}$ - allowable wear of j-th pass in i-th assembly.

Moreover

$$\underset{1 \le i \le I}{\forall} \quad \underset{1 \le j \le J}{\forall} \qquad p^k_{i,j} = g_{i,j} - x^k_{i,j} \tag{16a}$$

and

$$\underset{1 \le i \le I}{\forall} \quad \underset{1 \le j \le J}{\forall} \qquad 0 \le p^k_{i,j} \le \delta_{i,j} \tag{16b}$$

For non-existing passes we assume:

$$\underset{1 \le i \le I}{\forall} \quad \underset{J < j \le J}{\forall} \qquad p^k_{i,j} = -1 \tag{17}$$

Flow capacity of products technological route is described by matrix:

$$P = [\ p^k_n\ ] \qquad n=1,...,N \tag{18}$$

where: p^k_n - flow capacity of line for the n-th product.

Furthermore

$$p^k_n = \min_{1 \le i \le I} p^k_{i,\lambda_{i,n}} \tag{18a}$$

In case when:

$$\underset{1 \le n \le N}{\forall} \quad p^k_n = 0 \tag{19a}$$

no product can be rolled, the n-th product cannot be rolled (the n-th route ruled out),

$$\underset{n}{\exists} \quad \min_{1 \le i \le I} p^k_{i,\lambda_{i,n}} = 0 \tag{19b}$$

the n-th product cannot be rolled (the n-th route ruled out),

$$\underset{1 \le n \le N}{\forall} \quad \min_{1 \le i \le I} p^k_{i,\lambda_{i,n}} = 0 \tag{19c}$$

FRL is stopped - for replacement of assemblies.

3. The State of FRL

The FRL state can be determined by a distance between roll surfaces in each pass.

Definition 1.: The state of FRL is a matrix:

$$X^k = [\ x^k_{i,j}\ ] \qquad i=1,\dots,I\ ;\ j=1,\dots,J \tag{20}$$

where: $x_{i,j}$ - distance of roll surfaces in the j-th pass of the i-th assembly.

For non-existing passes we shall assume:

$$\underset{1 \le i \le I}{\forall} \quad \underset{J \le j \le J_i}{\forall} \quad x^k_{i,j} = -1 \tag{21a}$$

If i-th assembly is replacement in k-th operation, then we assume that:

$$\underset{1 \le j \le J}{\forall} \quad x^k_{i,j} = d_{i,j} \tag{22}$$

Assembly can be replaced if the following condition is satisfied:

$$\underset{1 \le j \le J}{\exists} \quad x^k_{i,j} = g_{i,j} \tag{22a}$$

Therefore coordinates of FRL state meet the condition:

$$\underset{1 \le i \le I}{\forall} \quad \underset{1 \le j \le J}{\forall} \quad d_{i,j} \le x^k_{i,j} \le g_{i,j} \tag{22b}$$

State of FRL is measurable. In particular, it can be determined after k-th rolling operation or roll renewal. Hence, we shall accept a notation X^k. The state X^0 is an initial condition (as given) whereas X^k provides the end state (unknown).

Assuming the linear statical characteristic of pass (14), its flow capacity can be defined for the n-th product originating from the m-th charge. If state of pass $x^k_{i,j}$ is given (from identification), then by (20) we have an equivalent quantity of charge:

$$w = \frac{x^k_{i,j} - e_{i,j}}{a_{i,j,m,n}} \tag{23}$$

Proceeding similarly, we shall determine the maximum charge quantity:

$$w_{max} = \frac{d_{i,j}}{a_{i,j,m,n}} \tag{24}$$

Hence, the flow capacity $p_{i,j,m,n}$ we define as

$$p_{i,j,m,n} = w_{max} - w = \frac{x^k_{i,j} + d_{i,j} - e_{i,j}}{a_{i,j,m,n}} \tag{25}$$

Consequently, the flow capacity of pass $p^k_{i,j,m,n}$ (as opposed to the state $x^k_{i,j}$) is determined for selected product and charge.

Capacity of technological route for n-th product of m-th charge can be expresed as:

$$p^k_{m,n} = \min_{1 \le i \le I} p_{i,j,m,n} \tag{26}$$

For (24) and (25) we assume:

$$j = \lambda_{i,j} \tag{27}$$

If in the state X^k the condition is satisfied:

$$\exists_n \forall_m \ (r_{m,n} = 1) \Rightarrow (p^k_{m,n} = 0) \tag{28}$$

then the FRL cannot manufacture the n-th product.

If in the state X^k the condition is met:

$$\forall_{1 \le n \le N} \ \forall_m \ (r_{m,n} = 1) \Rightarrow (p^k_{m,n} = 0) \tag{29}$$

then the FRL cannot fabricate any product.

In case of (28) it is possible to manufacture products that do not satisfy the condition (28), however in the event of (29) certain FRL rolls must be replaced.

We shall assume that i-th roll can be renewed which meets the conditions:

$$\exists_{1 \le j \le J} \quad x_{i,j} = d_{i,j} + \delta_{i,j} \tag{30}$$

Let us assume that <u>capacities of buffer stores</u> before the units are writen in vector:

$$B = [\ b_n\ ] \qquad n=1,\dots,N \tag{31}$$

where: b_n - capacity of buffer store for n-th product (before unit A_n).

<u>Throughputs of FRL and units</u> for particular products are writen in the matrix:

$$V = [\ v_{n,l}\ ] \qquad n=1,\dots,N \quad ; \ l=1,2 \tag{32}$$

where: $v_{n,1}$ - output of n-th unit (for n-th product),
$v_{n,2}$ - FRL output for n-th product.

The output is meant as the number of tons of material processed in a time unit.

We shall assume that the throughputs satisfy the condition:

$$\forall_{1 \le n \le N} \quad v_{n,1} < v_{n,2} \tag{32a}$$

Specific losses due to shut-downs of units are writen in the vector:

$$H = [\ h_n\ ] \qquad n=1,\dots,N \tag{33}$$

where: h_n - loss of shut-down for n-th units in a time unit.

Let us assume that <u>unitary charge deliveries</u> are writen in vector:

$$D = [\ d_m\ ] \qquad m=1,\dots,M \tag{34}$$

where: d_m - delivery of m-th type charge in a time unit.

We shall assume that capacity of buffer store is not limited for the charge before FRL.

4 <u>Control</u>

The control is that decision is take about production of n-th assortment from m-th charge or replacement of rolls.

<u>Definition 2a</u>: Control of k-th rolling operation is a vector:

$$U^k = [\ u^k_l\ ] \qquad l=1,\dots,M+2 \tag{35}$$

We define the elements of this vector as follows:

u^k_1 - type of product to be manufactured,

u^k_2 - quantity of product,

u^k_{m+2} - quantity of m-th charge (m=1,...,M).

Admissible control must fulfil the following conditions:

$$\exists_{m} \ (u_1^k = n) \Rightarrow (p_{m,n}^k > 0) \tag{36}$$

Furthermore

$$u_2^k = \sum_{m=1}^{m=M} u_{m+2}^k \tag{37}$$

and

$$u_{m+2}^k = p_{m,n}^k$$

With the choice u_2^k, i.e. constituents u_{m+2}^k, there is a problem connected with various statical characteristics. For example, one charge μ, which satisfies the condition:

$$\max p_{m,n}^k = p_{\mu,n}^k \tag{38}$$

can be selected, and then to accept:

$$u_{m+2}^k = p_{\mu,n}^k \tag{38a}$$

and for $m \neq \mu$

$$u_{m+2}^k = 0 \tag{38b}$$

In a general case, the problem of charge choice for n-th product can be more complicated .

Definition 2b.: Control of k-th roll replacement is a vector:

$$Y^k = [\ y_i^k\ ] \qquad i=1,\dots,I \tag{39}$$

and at the same time

$$y_i^k = \begin{cases} 1, & \text{if i-th roll is to be renewed in k-th operation} \\ 0, & \text{in opposite case} \end{cases} \tag{39a}$$

Operation of roll replacement takes place when the state X^k fulfils the condition (38). The roll that is being replaced must satisfy the condition (39).

Let us assume that periods of times of roll replacement are given in the vector:

$$T = [\ \tau_i\ ] \qquad i=1,\dots,I \tag{40}$$

where: τ_i - replacement time for i-th roll.

The charge stock after k-th operation is a vector:

$$S^k = [\ s_m^k\ ] \qquad m=1,\dots,M \tag{41}$$

where: s_m^k - reserve of charge of m-th type.

We shall assume that during rolling process the condition must be satisfied:

$$\forall_{1 \le m \le M} \quad u_{m+2}^k \le s_m^{k-1} \tag{42}$$

Stock of products after k-th operation is a vector:

$$\Phi^k = [\ \varphi_n^k\ ] \qquad n=1,\dots,N \tag{43}$$

where: φ_n^k - stock of n-th type product.

Operation time θ^k of rolling FRL charge is expressed by the formula:

$$\theta^k = \frac{u_2^k}{v_{n,1}} \tag{44}$$

at the same time

$$n = u_1^k \tag{45}$$

Let us denote by t^k the moment in which k-th operation is termined ($t^0=0$). Thus, for operation of charge rolling we obtain:

$$t^k = t^{k-1} + \theta^k \tag{46a}$$

and for operation of roll replacement:

$$t^k = t^{k-1} + \tau^k \tag{46b}$$

The time ϑ^k is determined by (44), however, the time τ^k from:

- if rolls are renewed at the same time the replacement time τ^k will be calculated as:

$$\tau^k = \max_{1 \le i \le I} y_i \tau_i \tag{46c}$$

- with consecutive replacement we get:

$$\tau^k = \sum_{i=1}^{i=I} y_i \tau_i \tag{46d}$$

5. Equations of state

Let us assume that FRL initial state X^0, Z^k, V. One should determine the shortest time for execution of orders.

The equations of state take the form:

$$X^k = f\,(X^{k-1}, U^k, Y^k) \tag{47}$$

5.1 Operation of assembly replacement

If the state X^{k-1} fulfils the condition:

$$\forall_{1 \le n \le N} \left[\min_{1 \le i \le I} \left(g_{i,\lambda_{i,n}} - x^{k-1}_{i,\lambda_{i,n}} = 0 \right) \wedge \left(z^{k-1}_{n,m} = 0 \right) \right] \tag{48}$$

then the replacement of assemblies takes place in the k-th operation, i.e.:

$$\exists_i \; y^k_i = 1 \tag{49}$$

and

$$x^k_{i,j} = \begin{cases} d_{i,j}, \text{ for } y^k_i = 1 \\ x^{k-1}_{i,j}, \text{ in opposite case} \end{cases} \tag{49a}$$

$$\forall_{1 \le n \le M} \; z^k_{n,m} = z^{k-1}_{n,m} \tag{49b}$$

Stocks of charge are determined from the formula:

$$s^k_m = s^{k-1}_m + d_m (t^k - t^{k-1}) \qquad m=1,\dots,M \tag{50}$$

The stocks of products are defined according to the formula:

$$\varphi^k_n = \max\left[0,\ \varphi^{k-1}_n - v_{n,2} (t^k - t^{k-1}) \right] \tag{51}$$

Therefore, the following condition must be satisfied lest the stock should be zero:

$$\tau^k < \frac{\phi^k_n}{v_{n,2}} \tag{52}$$

With operation of replacing assemblies the control U is zero vector.

5.2 Operation of charge rolling

If the state X^{k-1} satisfies the condition:

$$\forall_{1 \le n \le N} \left[\min_{1 \le i \le I} \left(g_{i,\lambda_{i,n}} - x^{k-1}_{i,\lambda_{i,n}} > 0 \right) \wedge \left(z^{k-1}_{n,m} > 0 \right) \right] \tag{53}$$

and

$$\forall_{1 \le i \le I} \; y^k_i = 0 \tag{54}$$

and the n-th product is realized, then by U^k we obtain:

$$x^k_{i,j} = \begin{cases} x^k_{i,j} + u^k_2, \text{ dla } (u^k_1 = n) \wedge (j = \lambda_{i,n}) \\ x^{k-1}_{i,j}, \text{ in opposite case} \end{cases} \quad (54a)$$

$$z^k_{i,j} = \begin{cases} z^{k-1}_{\nu,j} + u^k_2, \text{ for } (\nu = u^k_1 \\ z^{k,}_{i,j}, \text{ in opposite case} \end{cases} \quad (54b)$$

Furthermore

$$t^k = t^{k-1} + \frac{u^k_2}{v_{n,1}} \quad (55)$$

The charge stocks are determined from the formula:

$$s^k_m = s^{k-1}_m - u^k_{m+2} + d_m (t^k - t^{k-1}) \quad (56)$$

The product stocks are determined according to formula:

$$\varphi^k_n = \begin{cases} \varphi^{k-1}_n + u^k_2 - v_{n,2}(t^k - t^{k-1}), \quad \text{dla } n = u^k_1 \\ \max [\ 0,\ \varphi^{k-1}_n - v_{n,2}(t^k - t^{k-1})],\ \text{dla } n \neq u^k \end{cases} \quad (57)$$

And so, the following condition must be met lest the n-th buffer store should be overfilled:

$$\theta^k \leq \frac{b_n - \varphi^{k-1}_n}{v_{n,1} - v_{n,2}} \quad (58)$$

which results from (57) for $n = u^k_1$.

6. Conclusion

In the paper, the equation of state of rolling process on FRL are derived. On the basis of the equation it is possible to analyse FRL control under deterministic or probabilistic conditions. At the same time, deliveries of charge into the FRL and uptaking products by further units are disturbed.

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MODELLIEREN EINER WALZENSTRASSEN - ANLAGE

Zusammenfassung

In der vorliegenden Bearbeitung wurde das Problem der Steuerung einer Elastischen Walzenstrassen - Anlage (EWA) mit einem probabi - listische Eingang dargestellt. Für die EWA werden die Entscheidungs-variablen des Walz - Prozessen und des Auswechselns der Walzen hervorgehoben, welche für die Sequenzen und die Grösse des Produkt-sortimentes für einen bestimmten Einsatz, sowie für die Wahl des Agregates, in welchem die Walzen ausgewechselt werden sollen, ausschlaggebend sind.

MODELOWANIE LINII WALCOWNICZEJ

Streszczenie

W referacie przedstawiono problem sterowania Elastyczną Linią Walcowniczą (ELW) z wejściem probabilistycznym. Dla ELW wyróżnia się zmienne decyzyjne procesu walcowania oraz wymiany walców, określające sekwencje i wielkość asortymentu produktu dla określonego wsadu oraz wybór agregatu, w którym należy wymienić walce.

Wpłynęło do redakcji w styczniu 1992 r. Recenzent: Ewald Macha