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DECISION SUPPORT MODEL FOR PRODUCTION DISTURBANCE ESTIMATION

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A current modeling framework for disturbance in manufacturing systems (MS) is given by concepts like discrete event systems, stochastic fluid models and infinitesimal disturbance analysis. The goal of modeling is to achieve control and structural and functional optimization of MS. Objective functions of these optimization models are focused on quantities which reflect the level of reliability, the level of manufactured products, the quality of products or the impact on the environment of MS with disturbances. These models do not allow a dynamic evaluation of consequences of the disturbances which appears in the operation of MS machines and also do not allow an evaluation of the evolution in time of disturbance consequence indicators. Disturbances in technological lines of MS represent local bottlenecks of production with severe economic consequences in what regards production time losses. Good estimation of disturbances dynamics can be very helpful to both technological line designers, who can optimize their projects and production managers who can minimize their losses. Our model allows a dynamic evaluation of consequences of some disturbance of machine operation in MS, using indicators

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based on time, energy and costs. A MATLAB software package was developed for tests.

Keywords: Technological line, disturbance propagation, mathematical model, dynamics algorithm, control.

1. Introduction

The social and economic importance of manufacturing systems is well known. Considering the importance of these systems, regarding the general efforts to ensure the actual need of society, through innovative technological processes, the International Manufuture Conferences[1],[2], are decisive for establishing European research, development, and implementation strategies dedicated to production systems. Competitiveness of manufacturing companies depends not only on a high productivity of their own production systems, but also on the swiftness of response to market changes, and on consumers' needs. Thus, beside the classical, technological line, and flexible MS, recently, the reconfigurable manufacturing systems[3] have emerged. These systems are designed to respond as quickly and efficiently as possible, to changes that can intervene inside or outside the manufacturing process. In [4] a synthesis of analytical models for Flexible Manufacturing Systems (FMS) is presented and strong and weak points are specified for each model. Specific aspects are described regarding FMS operation, blocking phenomena, transitory behaviors and differences between systems with flexible machines and flexible systems are highlighted.

A Multi-Agent architecture for resolving the reconfiguration capacity of the manufacturing systems is analyzed by Renna[3] through the performance based management of technological lines. By production disturbances we understand phenomena which lead to reduction of quality and or quantity of the manufactured products compared to the programmed level with negative effects on manufacturing costs and/or market share. An example of disturbance effects in manufacturing processes on an important product is given in [5], where a number of the biomechanical problems associated with total hip replacements (THR) are examined. The manufacture perturbations (fabrication tolerance) and impacts of femoral head and acetabular cup upon the failure of function of THR. THR function loss is associated with a combination of several risk factors - use of inappropriate prosthesis materials, geometry and surface finishing treatment. In this case "manufacture perturbations" means errors in the manufacturing process which influences the quality of the product and external disturbance economic effects are not evidenced.

To identify the adequate response to the disturbances which inevitably occur inside and outside the manufacturing processes, the following main directions of research and development have been established[6]: adaptive manufacturing, digital manufacturing, manufacturing based on knowledge and the manufacturing network. These methods are also evoked in European strategies regarding manufacturing processes[1],[2]. A large number of papers on manufacturing systems deal with identifying and demonstrating the advantages of using the planning and control models dedicated to human-machine production systems subjected to internal disturbances[7],[8],[9],[10],[11].

Production control problems in manufacturing systems have been studied, starting with the pioneering work in 1983 by Kimemia & Gershwin[7]. In a typical manufacturing setting, a machine may either occasionally break down, or, in a multi - product environment, it may be temporarily inaccessible to a certain part because it is serving another one[11].

A control model structured on two levels is detailed by Golenko-Ginzburg & Kats[10]. The analyzed MS contains one section and several production units (technological lines, machine groups, machines), having the feature that each unit can manufacture all product types on the companies list. The command of the manufacturing process is done on two levels: on the section's level and on the unit's level, each unit being controlled separately. In these circumstances, the control-command model is conceived in a way that, in the case of disturbances exerted on some of the production units, attributes and resources of other units will be reallocated, in order to complete the overall manufacturing program. In these papers the consequences of disturbances are not modeled as function of FTL characteristics.

For the analysis of disturbances, control and optimization of MS, Yu & Cassandras[11] adopted stochastic fluid models (SFM) in order to capture the main features of production control policies without requiring a detailed discrete - event model for analysis. The authors describe a threshold-based flow control policy in which the objective is to adjust the threshold parameters (hedging points) so as to optimize an objective function combining throughput and overflow rate metrics, without modeling economic consequences of disturbances.

Two efficient control methods of the manufacturing processes are described by Weng & Fujimura[12]. These methods, called stage-based control (SBC) and machine-based control (MBC) are suitable for intelligent manufacturing processes which follow the growth of competitiveness through the integration of high-performance production with the needs of the clients.

Liu et al[13] models and analyzes the throughput of a two-stage MS with multiple independent unreliable working machines (WM) at each stage and one finite-sized buffer between the stages. The machines follow exponential operation, failure, and repair processes. This illustrates the importance of using more than two states to model parallel unreliable WM because of their independent and asynchronous operations in the parallel system. The system balance equations are then formulated based on a set of new notations of vector manipulations, and are transformed into a matrix form fitting the properties of the Quasi-Birth-Death (QBD) process. The Matrix-Analytic (MA) method for solving the generic QBD processes is used to calculate the system state probability and throughput. In this paper the analysis stops at the evaluation of reliability performances, without considering the economic consequences of reliability impediment.

The characterization and evaluation of the performance of a MS is another theme broadly reflected in the literature[14], [15], [16],[17], [18], [19],[23]. Factors affecting the operational performance of MS are related to: their structure, intrinsic performance of the machine, degree of automation, the level of implementation of self-diagnosis techniques, control and reconfiguration.

Colledani & Tolio[15] presents a general theory to analyze the production rate of conforming parts in MS with progressively deteriorating machines and preventive maintenance. Results show that improved system performance can be achieved by a joint analysis and design of these functions, at system level.

A proposed six-step methodology is presented for the restructuring of reduced performance MS by Erozan[16]. The main considered performance indicator is the operational reliability of the MS components, i.e. working machinery, based on which the system's reliability is assessed, also proposing the application of fuzzy modeling for controlling the reliability performance level.

Colledani & Yemane[17] investigates the risk and the potential performance losses due to design and operation decisions derived from neglecting WM reliability uncertainty in the digital manufacturing tools. The proposed method paves the way to the on-line adoption of digital models for MS continuous improvements. The analysis stops at evaluating WM reliability level impact evaluation on operational availability of the MS. To evaluate the performance of a MS, Lin & Chang[18] develops a stochastic-flow network model considering multiple technological lines (TL) in parallel. They construct the MS as a manufacturing network by the proposed graphical/based transformation and decomposition methodologies. In this paper the authors do not express the reliability level in terms of economic performance indicators of the MS. Lofgren & Tillman[19] proposes a method that includes the life-cycle perspective in manufacturing decision making. This method combines discrete-event simulation (DES) - commonly used for the conceptual evaluation of MS - with life-cycle assessment (LCA). This combination captures the dynamic interrelationships between manufacturing processes in order to analyze systemic responses to configuration changes, something that static LCA modeling cannot do. The method evolved when a bearing production line at SKF was being examined to relate manufacturing decision making to environmental consequences. This was done using DES to investigate how parameters normally used to optimize traditional MS performance influence energy use and material losses in MS. The environmental consequences of this material loss and energy use are further computed using LCA methodology. The design of MS in which disturbances occur and there is a need to predict the performances of the MS is a critical task to be addressed throughout the factory life-cycle phases, including the early design, detailed design, ramp-up, reconfiguration, and monitoring. An efficient and effective system design platform may have a relevant impact on the profitability of industrial companies facing these challenges. Colledani el al[20] proposes the integration of heterogeneous software tools supporting factory design activities over a common platform. A virtual factory environment, based on a shared data model providing to all the applications a common language to exchange data, is developed. The above cited works do not reflect realizations in the field of MS disturbances analysis, modeling and applying of control with the purpose of structural and functional optimization of the MS.

Our paper is part of the subjects outlined above, on evaluating the performance of MS when disturbances are being exerted on them. This paper is structured in five parts. After integration, in the first part, of our subject in the general theory of disturbance modeling in a MS with the purpose to find an optimal control of these systems, in the second part we presents the model of propagation and evaluation of disturbance consequences in the technological lines with flexible links (FTL) as parts of the MS. The developed model is dynamic, has FTL characteristics as input parameters and as outputs, technological, reliability and economic characteristics indicators. Based on these indicators, we can enhance the precision of control and optimization of FTL and further, of the MS. In the third part of the paper the software package is presented which had been developed in order to apply the mathematic model presented in part two. The software package had been developed under the MATLAB environment (from Mathworks) and had been used to run computational examples. The simulation results are presented in the fourth part of the paper. Using the 2D and 3D diagrams obtained as a result of the simulation the impact of a certain disturbance on the specific and total costs are highlighted together with parameters as: recovery time, duration of disturbance, position of machine group in FTL on which the disturbance is exerted, quantity of product units in the deposits. The last part sumarize the paper's conclusions

It contributes to the development and to the acquirement of a deeper insight of the subject by modeling and simulation of propagation of disturbances which can occur in certain points of TL as part of MS. It also contributes to the definition and analytical representation of the dynamic evolution of indicators that characterize the availability and economic performances of TL as part of MS.

The disturbances exerted on the system can be of any kind, which leads to the total or partial unavailability of a machine group (MG) in a TL. For example: catastrophic or parametric failure of WM and the unavailability of electric energy of the WM. The consequences of perturbation are estimated on the basis of time- or cost-based indicators, on the level of the TL which contains the WM, subjected to disturbances. It is easy to demonstrate[21,22,24] that whatever the configuration (topology) of the analyzed system, in terms of reliability, it can be reduced to a equivalent serial configuration. This observation is true for the branched TL, any branch being analyzed in relation to the target of the TL regarding the completion of the manufacturing process.

2. Modeling the Propagation and Consequences of Disturbances

Our goal in this paper is to analyze the way the disturbance (caused by the unavailability of some of the WM of a MG) is propagated trough the TL, by evaluating some technical and economic performance indicators. From the point of view of our

approach, there are 3 types of TL[23]:
- rigidly linked TL (RTL) - when the TL has no buffer storages for parts between WMs;
- flexibly linked TL (FTL) - when the TL has buffer storages for parts between WMs;
- combined linked TL (CTL) - when buffer storages for parts are placed only between sections of the TL.

Sections can be defined as parts of the TL comprising a certain number of WMs. A symbolic representation of the three types of TL is presented in Figure 1.

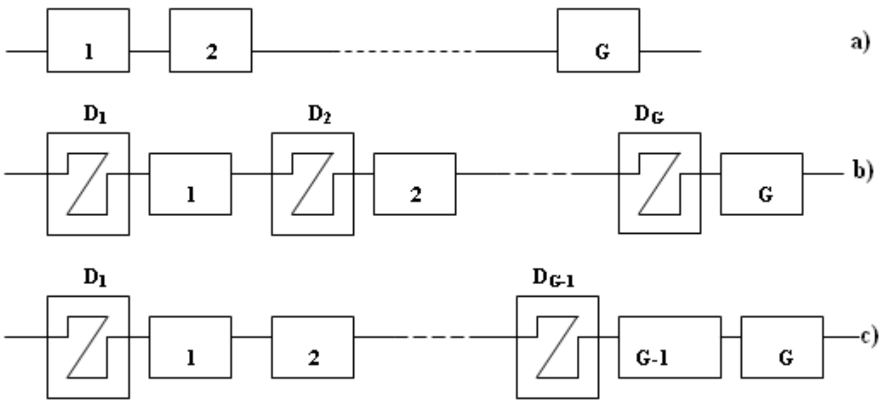

Fig. 1. TL classification and symbolization: a - rigidly linked (RTL) b - flexible linked (FTL); c - combined linked (CTL).

Inputs of the mathematical model are defined as follows:
- line type;
- total number (G) of MG, in pieces;
- total number ($n_{(j)}$) of WMs in group j, in pieces;
- number ($k_{(j)}$) of the backup WM in group j, in pieces;
- productivities ($M_{(h,j)}$) of WMs, in pieces/units of time;
- quantity of product units ($V_{(j)}$) in the deposits ($D_{(j)}$) in the FTL and DSTL CTL, in pieces;
- normal production rate (T) of RTL, in hours or minutes;
- minimum rate (T') under intensified mode of the TL, in hours or minutes;
- total specific damage ($d_{(j)}$) in group j, in energy units/ time units or monetary units/time units (according to the desired indicator).

In the analysis, MG are seen as sliding backup subsystems (Fig. 2[24]), which include, in general, a WM number ($n_{(j)}$) higher than needed for the technological process under nominal production parameters ($n_{(j)} - k_{(j)}$). For the purpose of the analysis it is required to equate in advance, the WM of each MG, when their productivity is not identical in relation to the operations affected.

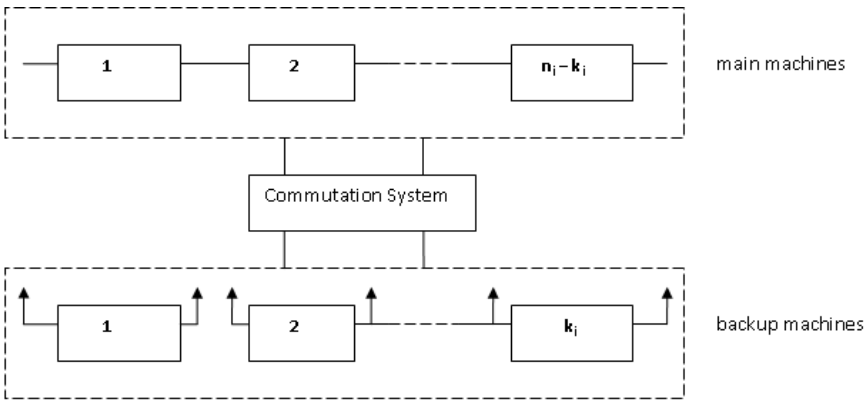

Fig. 2. Symbolic representation of the subsystem "machine group (MG) j".

Thus for a random MG (j), containing ($n_{(j)}$) WM with productivities $M_{(1,j)}$, $M_{(2,j)}$ ... $M_{(h,j)}$,...,$M_{(n(G),G)}$, we calculate the equivalent machine's productivity ($M_{e(j)}$) and the correlation coefficient ($C_{(h,j)}$) of each WM with the equivalent machine:

$$M_{e(j)} = \frac{\sum_{h=1}^{n_{(j)}} M_{(h,j)}}{n_{(j)}}; \quad C_{(h,j)} = \frac{M_{(h,j)}}{M_{e(j)}} \tag{1}$$

Availability of a MG $_{(j)}$ is estimated by the value of the momentary availability indicator, defined as:

$$K_{D(j)} = \begin{cases} 1, & \text{for} \quad m_{(j)} \leq k_{(j)} \\ \frac{n_{(j)}-m_{(j)}}{n_{(j)}-k_{(j)}}, & \text{for} \quad m_{(j)} > k_{(j)} \end{cases} \tag{2}$$

where: $m_{(j)} = \sum_{h \in I} C_{(h,j)}$ - number of unavailable equivalent machines WM during the disturbance;

$k_{(j)} = \sum_{h \in RZ} C_{(h,j)}$ - number of backup WM.

When defining and evaluating the indicator $[K_{D(j)}]$ we will consider that as long as the productivity of the backup WM is at least equal with the productivity of the disturbed WM, the MG is not influenced by the disturbance and can work at normal capacity. If the equivalent productivity of the disturbed WM is greater than the productivity of the backup WM, the production of MG decreases under the requested level.

The disturbance that we consider is of the following type: machine group (g) enters - due to external or internal causes (electric energy supply disruption, damage or parametric failure of some WM etc.) - the state of partial or total unavailability characterized by disturbance duration ($T_{p(j)}$) and disturbance intensity ($k_{(j)} < m_{(j)} \leq n_{(j)}; K_{I(j)} = 1 - K_{D(j)}$).

Damage caused at the level MG(j) is determined considering the disturbance intensity and the conditions in which the disturbance occurs (the group "j" can be with or without prevention, and to the other MG, disturbance is applied with prevention):

$$d_{(j)} = K_{I(j)} \cdot d_{M(j)} \tag{3}$$

where, $d_{M(j)} = \{d_{aM(j)}; d_{PM(j)}\}, d_{M(j)}$ - maximum value of the damage specific for group "j", can be without prevention ($d_{aM(j)}$) or with prevention ($d_{PM(j)}$).

For the RTL two significant cases can be drawn (Fig. 3), depending on the specific technological and organizational conditions, namely:

- if the setup of a buffer storage is possible (D_g), than the propagation of disturbance is made in one direction (Figure 3. a), MGs upstream from the disturbed $MG_{(g)}$ are working at normal capacity;

-if it is not possible to set up a buffer storage (D_g), than the disturbance propagation is made in both directions (Figure 3. b), MGs upstream from the disturbed $MG_{(g)}$ are successively disturbed, meaning that their production is reduced to the level of $MG_{(g)}$.

We elaborated the FTL mathematical model, which is more general and from which models for other TL types can be generated.

It is considered that upon the machine group j=g, a disturbance caused by an internal or external cause, is exerted. In case of the FTL, the disturbance propagation

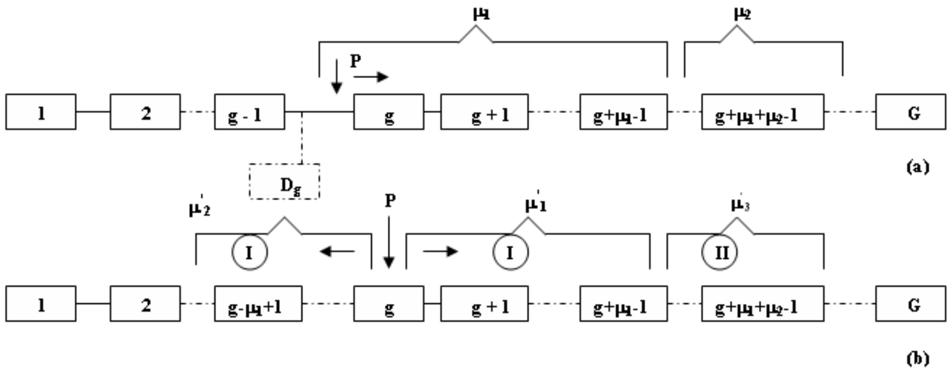

Fig. 3. Disturbance propagation at RTL model. ($\mu_{(i)}, \mu\prime_{(i)}$ - GM number of section "i" affected by the disturbance)

is in one direction (Fig. 4) if it has storages ($D_{(j)}$).

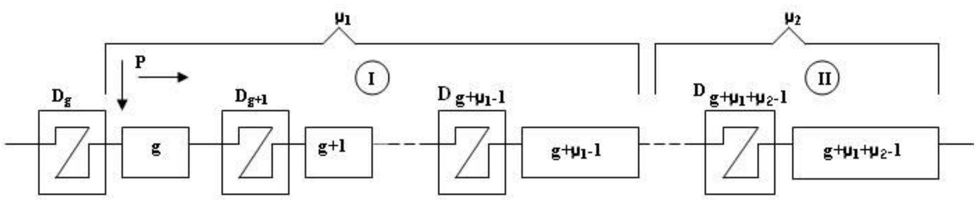

Fig. 4. Perturbation propagation at FTL.

Considering the moment when group g enters state of unavailability(I) as the origin, we can see that in the critical moments ($T_{C(1)}, T_{C(2)}, ...$) this state is transmitted to groups g + 1, g + 2,...

The number MGs of the TL sections that enter gradually in state I will be: $\mu(1), \mu(2), ..., \mu(\beta)$. In Figure 5 the momentary specific damage (MSD) is shown for the first two sections (1, 2) of the TL.

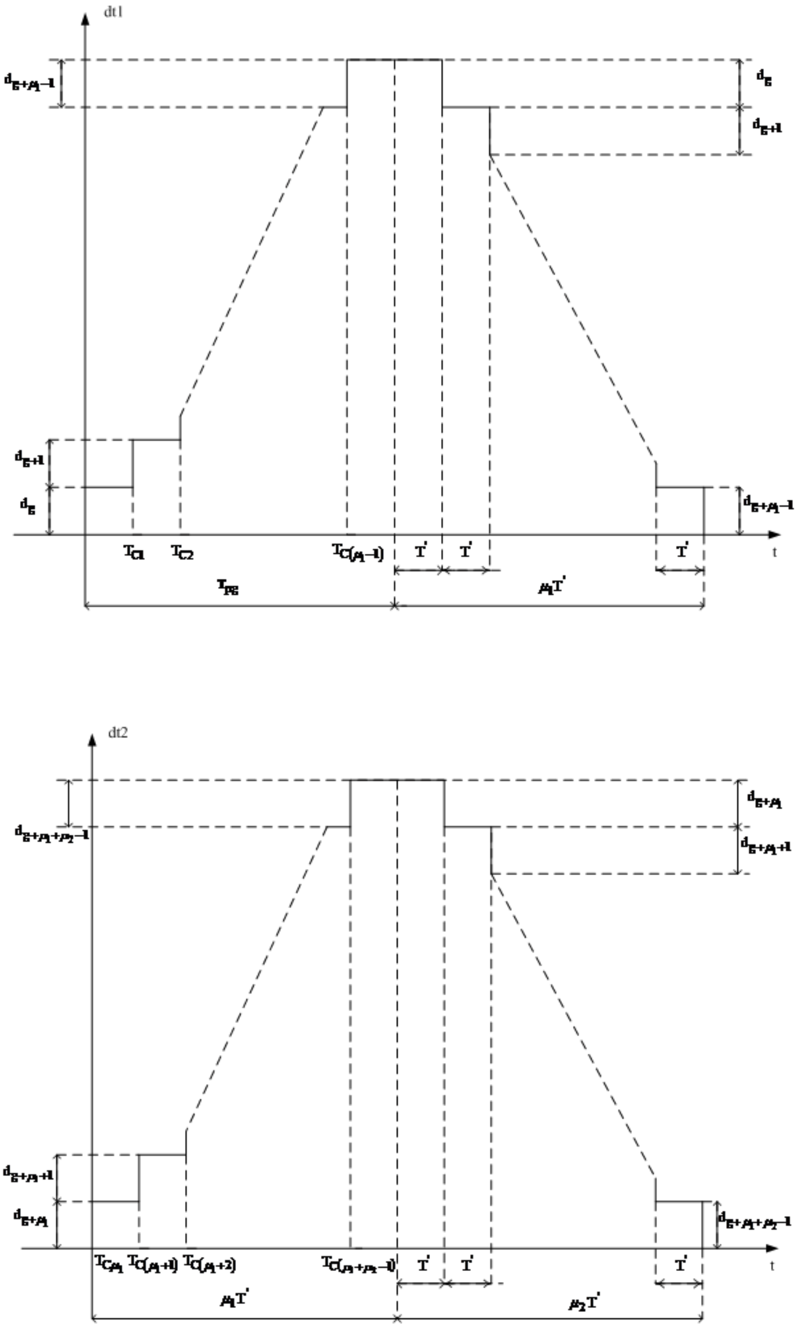

Fig. 5. MSD characteristics for sections 1 and 2 of the TLFL.

In our case, the process stops before depreciation the damping of the disturbance, on reaching group G. To establish the calculations for the critical moments $T_{C(i)}$, we resort to the following observations: in time interval $[0, T_{C(1)}]$ $(MG_{(g)})$ accomplishes the production (quantity of products):

$$P_{r(g)} = K_{D(g)} \cdot M_{e(g)} \cdot T_{C(1)} \tag{4}$$

In the same time interval, group "g + 1" could accomplish the production $P_{r(g+1)}$, but has only $P_{d(g+1)}$ units of products (provided by group "g" , in the deposit $D_{(g+1)}$):

$$P_{r(g+1)} = M_{e(g+1)} \cdot T_{C(1)};\ P_{d(g+1)} = V_{(g+1)} + K_{D(g)} \cdot M_{e(g)} \cdot T_{C(1)} \tag{5}$$

The moment when group "g + 1" enters the state of partial unavailability, conditioned by the number of product units made by $(MG_{(g)})$ is not sufficient is obtained as:

$$P_{r(g+1)} = P_{d(g+1)} \Leftrightarrow T_{C(1)} = \frac{V_{(g+1)}}{M_{e(g+1)} - K_{D(g)} \cdot M_{e(g)}} \tag{6}$$

In moment $T_{C(1)}$ the reserves run out in the deposit $D_{(g+1)}$, the two MGs(g and g +1) become with rigid link and a number of the WM $(m_{(g+1)})$ from group g + 1 will enter the state of conditioned unavailability. For determining the number $m_{(g+1)}$ we take into account that the productivities of the rigidly coupled groups g and g + 1, rigidly coupled, are the same:

$$\begin{aligned} &K_{D(g)} \cdot M_{e(g)} = K_{D(g+1)} \cdot M_{e(g+1)} = \tfrac{n_{(g+1)} - m_{(g+1)}}{n_{(g+1)} - k_{(g+1)}} \cdot M_{e(g+1)} \Rightarrow \\ &\Rightarrow m_{(g+1)} = n_{(g+1)} - K_{D(g)} \cdot \left(n_{(g+1)} - k_{(g+1)}\right) \cdot \tfrac{M_{e(g)}}{M_{e(g+1)}} \end{aligned} \tag{7}$$

In order to write relations (4-7) the following rules had been considered which can be applied at the modeling of manufacturing processes [23] of TL:
-Production of a MG is given by the product between productivity [units of product/units of time] and the duration of the process [units of time];
- Production of a MG decreases if the number of available WM decreases, and the decrease is proportional with the decrease of availability indicator;
- MGs in a RTL has an equal operational productivity $K_D \cdot M_e$;
- The general relation (2) has been used to express the availability indicator $K_{D(g+1)}$ of MG_{g+1}.

Similarly relations are established for calculating the critical moments and numbers of machines for the next MG. For the $\mu_{(1)}$ groups of WM of section 1, these relations are:

$$\begin{cases} T_{C(1)} = \frac{V_{(g+1)}}{Me_{(g+1)} - K_{D(g)} \cdot M_{e(g)}} \\ T_{C(2)} = T_{C(1)} + \frac{V_{(g+2)}}{Me_{(g+2)} - K_{D(g+1)} \cdot M_{e(g+1)}} \\ \quad \cdot \\ \quad \cdot \\ \quad \cdot \\ T_{C(\mu(1)-1)} = T_{C(\mu(1)-2)} + \frac{V_{(g+\mu(1)-1)}}{M_{e(g+\mu(1)-1)} - K_{D(g+\mu(1)-2)} \cdot M_{e(g+\mu(1)-2)}} = \\ = \sum_{q=1}^{\mu(1)-1} \frac{V_{(g+q)}}{M_{e(g+q)} - K_{D(g+q-1)} \cdot M_{e(g+q-1)}} \end{cases} \tag{8}$$

$$\begin{cases} m_g \\ m_{(g+1)} = n_{(g+1)} - K_{D(g)} \cdot \left(n_{(g+1)} - k_{(g+1)}\right) \cdot \frac{M_{e(g)}}{M_{e(g+1)}} \\ \quad \cdot \\ \quad \cdot \\ \quad \cdot \\ m_{(g+\mu(1)-1)} = n_{(g+\mu(1)-1)} - K_{D(g+\mu(1)-2)} \cdot \left(n_{(g+\mu(1)-1)} - k_{(g+\mu(1)-1)}\right) \cdot \frac{M_{e(g+\mu(1)-2)}}{M_{e(g+\mu(1)-1)}} \end{cases} \tag{9}$$

Critical moments are those at which product reserves are depleted from existent deposits between MGs of FTL, moments in which MGs are passing from the state of partial unavailability jumps are registered in MSD (Figure 5). It follows that critical moments decisively influence the performances of TL and MS.

Permanently evaluating the sum:

$$\sum_q \frac{V_{(g+q)}}{M_{e(g+q)} - K_{D(g+q-1)} \cdot M_{e(g+q-1)}}$$

and comparing it with $T_{p(g)}$, the number $\mu_{(1)}$ of the MG is determined as the number of terms of the sum of one of two from the following system of inequalities:

$$\begin{cases} \sum_{q=1}^{\mu(1)-1} \frac{V_{(g+q)}}{M_{e(g+q)} - K_{D(g+q-1)} \cdot M_{e(g+q-1)}} < T_{p(g)} \\ \sum_{q=1}^{\mu(1)} \frac{V_{(g+q)}}{M_{e(g+q)} - K_{D(g+q-1)} \cdot M_{e(g+q-1)}} \geq T_{p(g)} \end{cases} \tag{10}$$

The damage for section 1 ($D_{t(1)}$) is obtained considering the MSD characteristic (Fig. 5).

$$D_{t(1)} = \sum_{q=0}^{\mu(1)-1} \Big(T_{p(g)} - T_{C(q)}\Big) \cdot d_{(g+q)} + T' \sum_{q=0}^{\mu(1)-1} \Big(q+1\Big) \cdot d_{(g+q)} =$$

$$= \sum_{q=0}^{\mu(1)-1} \Big[T_{p(g)} - T_{C(q)} + (q+1)T'\Big] \cdot d_{(g+q)} \qquad (11)$$

We proceed similarly for the next sections. Thus, the number ($\mu_{(2)}$) of MG in the second section of TL represents the sum of the terms in the second inequality of the system (12).

$$\begin{cases} \sum_{q=1}^{\mu(2)-1} \frac{V_{(g+\mu(1)+q)}}{M_{e(g+\mu(1)+q)} - K_{D(g+\mu(1)+q-1)} \cdot M_{e(g+\mu(1)+q-1)}} < \mu_{(1)}T' \\ \sum_{q=1}^{\mu(2)} \frac{V_{(g+\mu(1)+q)}}{M_{e(g+\mu(1)+q)} - K_{D(g+\mu(1)+q-1)} \cdot M_{e(g+\mu(1)+q-1)}} \geq \mu_{(1)}T' \end{cases} \qquad (12)$$

In a similar way, we obtain the following expressions for the critical moments:

$$\begin{cases} T_{C(\mu(1))} = \sum_{q=1}^{\mu(1)} \frac{V_{(g+q)}}{M_{e(g+q)} - K_{D(g+q-1)} \cdot M_{e(g+q-1)}} \\ \quad \vdots \\ T_{C(\mu(1)+\mu(2)-1)} = \sum_{q=1}^{\mu(1)+\mu(2)-1} \frac{V_{(g+q)}}{M_{e(g+q)} - K_{D(g+q-1)} \cdot M_{e(g+q-1)}} \end{cases} \qquad (13)$$

The calculation of the damage for section 2 is obtained considering the MSD characteristic (figure 5) and is given by:

$$D_{t(2)} = \Big(\mu_{(1)} + \mu_{(2)}\Big) \cdot T' \sum_{q=0}^{\mu(2)-1} d_{(g+\mu(1)+q)} -$$

$$- \Bigg\{ \Big[T_{C(\mu(1))} - T_{p(g)}\Big] \sum_{q=0}^{\mu(2)-1} d_{(g+\mu(1)+q)} +$$

$$+ \Big[T_{C(\mu(1)+1)} - T_{C(\mu(1))}\Big] \sum_{q=1}^{\mu(2)-1} d_{(g+\mu(1)+q)} +$$

$$+ \sum_{q=2}^{\mu(2)-2} \Bigg\{ \Big[T_{C(\mu(1)+q)} - T_{C(\mu(1)+q-1)}\Big] \sum_{q=2}^{\mu(2)-2} d_{(g+\mu(1)+q)} \Bigg\} +$$

$$+ T' \sum_{q=1}^{\mu(2)-1} \Big[\Big(\mu_{(2)} - q\Big) d_{(g+\mu(1)+q-1)}\Big] \Bigg\} \qquad (14)$$

Generalizing, we obtain the next relations from which we can determine the number of MGs (μ_i), the damage ($D_{t(i)}$) and the critical time values, referring to any section (i):

$$\begin{cases} \sum\limits_{q=1}^{\mu(i)-1} \dfrac{V_{\left(g+\sum\limits_{p=1}^{i-1}\mu_p+q\right)}}{M_{e\left(g+\sum\limits_{p=1}^{i-1}\mu_p+q\right)}-K_{D\left(g+\sum\limits_{p=1}^{i-1}\mu_p+q-1\right)}\cdot M_{e\left(g+\sum\limits_{p=1}^{i-1}\mu_p+q-1\right)}} < \mu_{(i-1)}T' \\ \sum\limits_{q=1}^{\mu(i)} \dfrac{V_{\left(g+\sum\limits_{p=1}^{i-1}\mu_p+q\right)}}{M_{e\left(g+\sum\limits_{p=1}^{i-1}\mu_p+q\right)}-K_{D\left(g+\sum\limits_{p=1}^{i-1}\mu_p+q-1\right)}\cdot M_{e\left(g+\sum\limits_{p=1}^{i-1}\mu_p+q-1\right)}} \geq \mu_{(i-1)}T' \end{cases} \tag{15}$$

Restriction: $\sum\limits_{i=1}^{\beta}\mu_{(i)} \leq G-g+1$.

For i≥3, the afferent damage of section "i" will be calculated from the expression:

$$D_{t(i)} = \sum_{q=1}^{\mu_{(i)}} \left\{ \left[T_{C\left(\sum\limits_{p=1}^{i-1}\mu_{(p)}+q\right)} - T_{C\left(\sum\limits_{p=1}^{i-1}\mu_{(p)}+q-1\right)} \right] \cdot \sum_{\rho=1}^{q} d_{\left(g+\sum\limits_{p=1}^{i-1}\mu_{(p)}+\rho-1\right)} \right\} + \\ +T' \sum_{q=1}^{\mu_{(i)}} q d_{\left(g+\sum\limits_{p=1}^{i-1}\mu_{(p)}+q-1\right)} \tag{16}$$

$$\begin{cases} T_{C\left(\sum\limits_{p=1}^{i-1}\mu_{(p)}\right)} = \sum\limits_{q=1}^{\sum\limits_{p=1}^{i-1}\mu_{(p)}} \dfrac{V_{(g+q)}}{M_{e(g+q)}-K_{D(g+q-1)}\cdot M_{e(g+q-1)}} \\ \vdots \\ T_{C\left(\sum\limits_{p=1}^{i}\mu_{(p)}-1\right)} = \sum\limits_{q=1}^{\sum\limits_{p=1}^{i}\mu_{(p)}-1} \dfrac{V_{(g+q)}}{M_{e(g+q)}-K_{D(g+q-1)}\cdot M_{e(g+q-1)}} \end{cases} \tag{17}$$

The total damage and the technological recovery time for TL is obtained by adding the afferent values of the sections (results in this case from the condition: $\sum\limits_{i=1}^{\beta}\mu_{(i)} = G-g+1$.

$$D_l = \sum_{i=1}^{\beta} D_{t(i)} \tag{18}$$

Recovery time of the technological line:

$$T_{thl} = T' \cdot \sum_{i=1}^{\beta} \mu_{(i)} = T' \cdot (G - g + 1) \tag{19}$$

Time of the technological disturbance of the TL:

$$T_{pl} = T_{p(g)} + T_{thl} \tag{20}$$

3. Disturbance Propagation Numeric Modeling

Based on the presented mathematical model of disturbance propagation in a TL the numeric model had been developed in order to experiment the development of a useful tool for decision making staff. The software has been developed in MATLAB R2012b (8.0.0.783)[25] as it offers a flexible environment. The program can be used to obtain simulated values of disturbance propagation characteristics that can be compared with values obtained in industrial practice, thus validating the accuracy of the mathematical model.

Program modules diagram is presented in Figure 6. T', Tp, g, and d_M values can be specified in edit fields and production system parameters are loaded from saved matrices (M, V, n, k). These matrices are formerly loaded and saved in "mat" file format in the MATLAB command window. The "Help" window provide information about the meaning of the input parameters.

Computations are made results are displayed (as damage values or MSD characteristic diagrams) executing the simulation task.

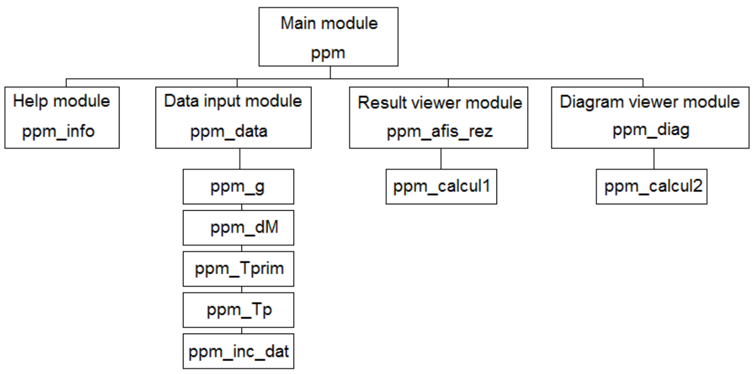

Fig. 6. Program modules diagram.

Flowchart of the algorithm which implements the mathematical model, for TL sections I greater than 3, is given in Figure 7. The flowchart represents the implementation of mathematical expressions given in relations (15)...(17).

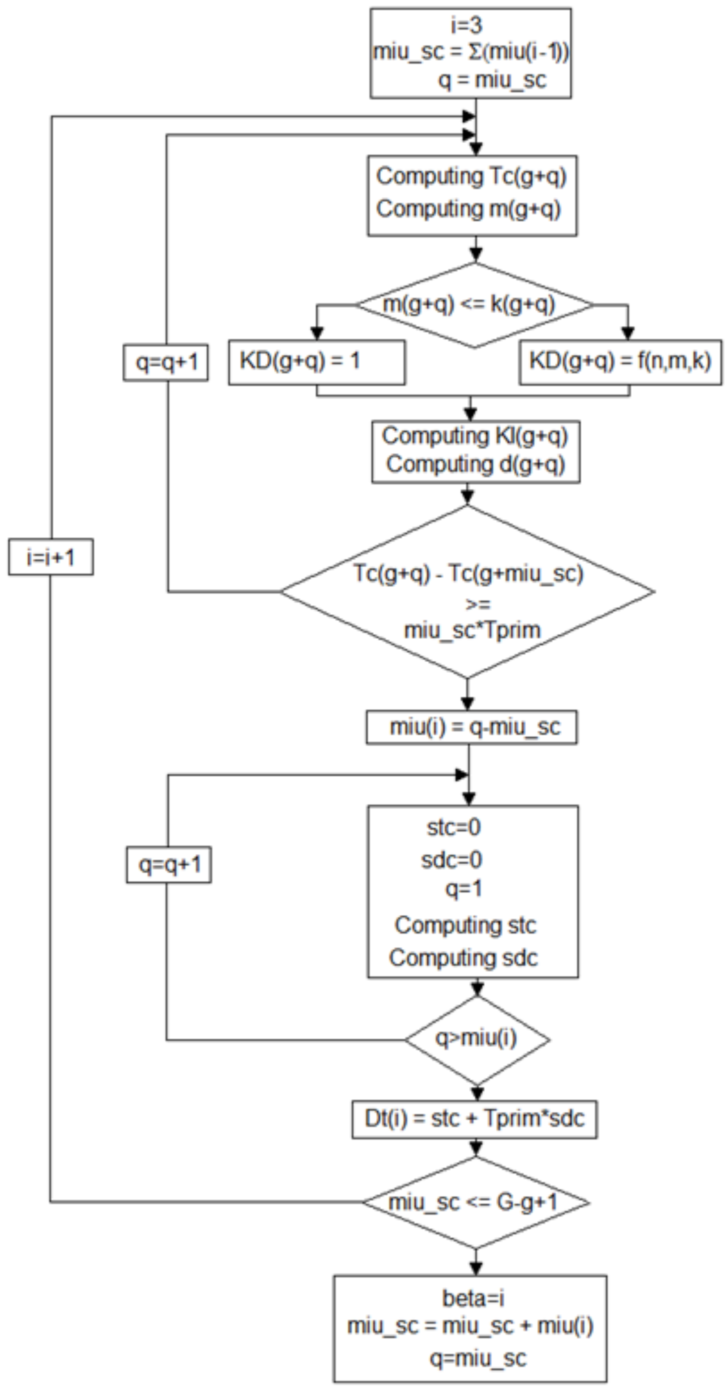

Fig. 7. Computation module flow diagram for case i>=3.

Simulation results are displayed as Dt(i) values for every TL section (i) and also the total damage following the perturbation occurrence is shown.
MSD characteristics diagrams resulted from simulation are presented in Figures 8, 9 and 10 for the following values of data:

T' = 4.8 minutes;

g = 2 - the disturbance occurs in group 2;

Tp(g) = 30 minutes;

n = [4 5 4 6 5 4 3 5 5 4 4 5 4 6 5 4 3 5 5 4] - number of WM;

k = [1 2 1 2 2 1 1 1 1 1 1 2 1 2 2 1 1 1 1 1] - number of backup WM;

V = [5 4 4 5 3 4 5 4 3 4 5 4 4 5 3 4 5 4 3 4] - number of processed products in a storage;

M = M(6,20) $\in$ [0,1.5] - productivities of WM.

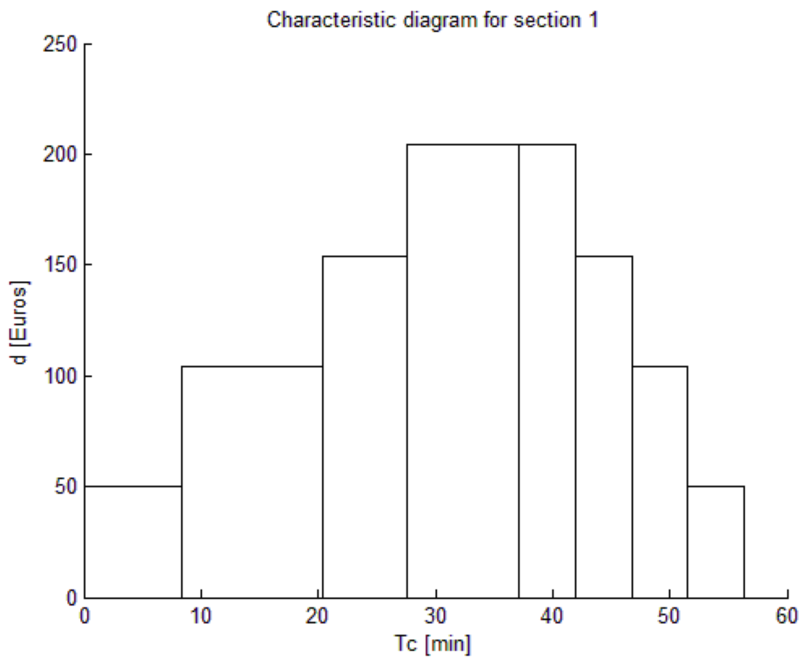

Fig. 8. MSD characteristics for section 1 of the FTL obtained after simulation.

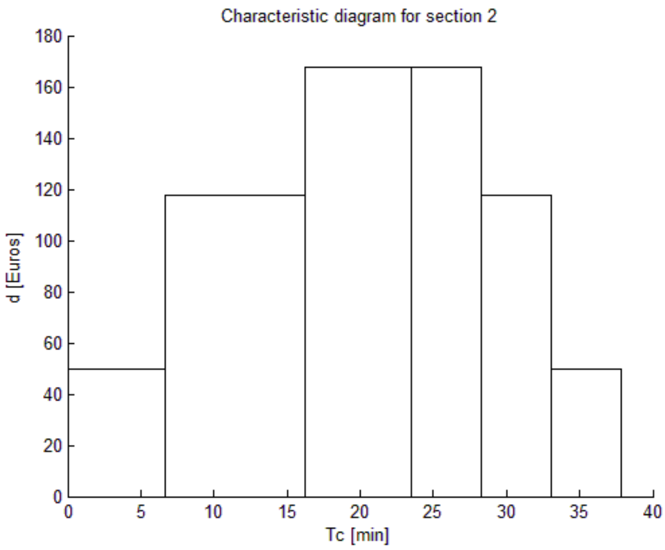

Fig. 9. MSD characteristics for section 2 of the FTL obtained after simulation.

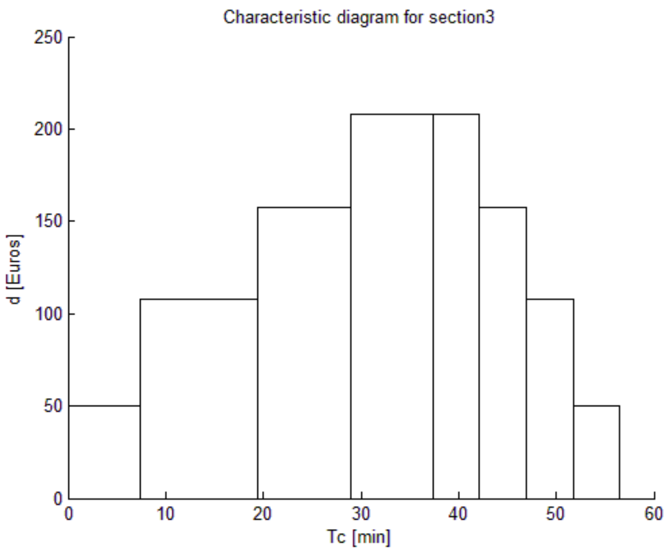

Fig. 10. MSD characteristics for section 3 of the FTL obtained after simulation.

4. Algorithm Testing Results

In order to test the described algorithm, the program has been run for different situations and a series of comparative diagrams had been plotted. The aim of these simulations is to show that the calculations in the algorithm are well done and the algorithm was implemented correctly in the simulation program. In order to test the algorithm and the implementation we had to use TL structures and values of parameters (g, T, Tp(g) and V(j)) which allows us to check the results against some results known from practice and from what we obtain as a result of logical reasoning about the TLs behavior for the given parameters. Systematic examination of the system response under combinations of control parameters (g, T', Tp(g), V(j)) at different sets of values can also be done but it would be very hard to assess the correctness of the results using logical reasoning. This type of examination would have meaning only if we could compare the results with thorough statistical data which at the moment we do not have. This kind of testing of the system should require a large number of experiments conducted on a real system, which the authors aim to realize in the near future, if support from the industry will be provided. Also the authors could not find other researches in the field which would present results suitable for comparison. The TL structure we choose to test is as follows:

n(j) $\in$ [3,4,5,6], j = 1...40 - total number of WM;

k(j) $\in$ [1,2], j = 1...40 - number of backup WM;

M(h,j) $\in$ [0.75..1.5], h = 1...6, j = 1...40 - WM productivities;

d_M = 120 - cost of disturbance per minute (in Euro).

a. Parameter T'

Evolution of Dt (disturbance costs) were studied as a function of recovery time for a MG mode in minutes (Figure 11). The diagram of total disturbance costs as function of T' is shown in figure 12. The total disturbance had been computed by summing the disturbance costs for all sections in the TL. The parameter T' was set to the following values: 3, 3.5, 4, 4.5, 5, 5.5, 6, 6.5, 7 (in minutes).

The other parameters were set as follows:

g = 2 - number of MG where the disturbance appear;

Tp(g) = 30 - disturbance duration (in minutes);

V(j) $\in$ [3,4,5] - number of products in deposits and j = 1...40.

b. Parameter Tp(g)

The Dt values diagram as a function of duration of disturbance Tp(g) is shown in Figure 13. The diagram of total disturbance costs as function of Tp(g) is shown if Figure 14. The parameter Tp(g) was set to the following values: 20, 25, 30, 35, 40, 45, 50, 55, 60 (in minutes).

Other parameters were set as follows:

g = 2 - number of MG where the disturbance appear;

T' = 4.5 - disturbance duration (in minutes);

V(j) $\in$ [3,4,5], j = 1...40 - number of products in deposits.

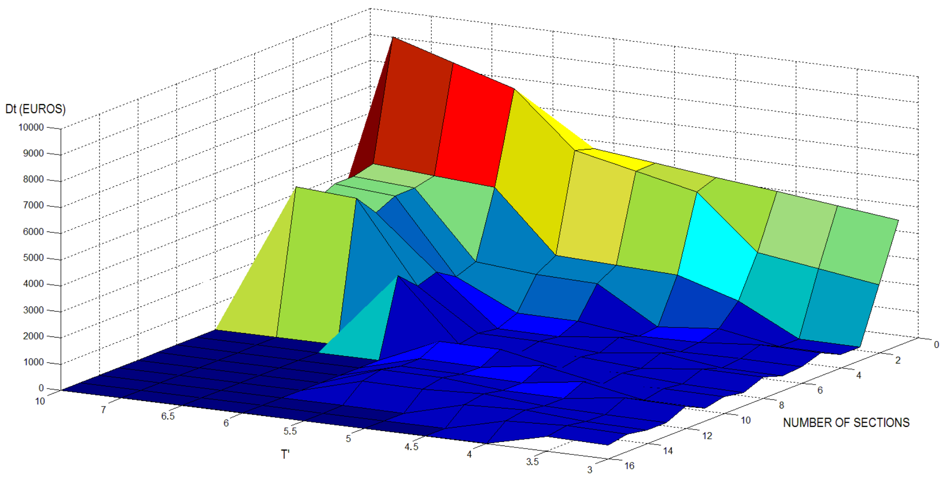

Fig. 11. Diagrams of Dt for different values of T'.

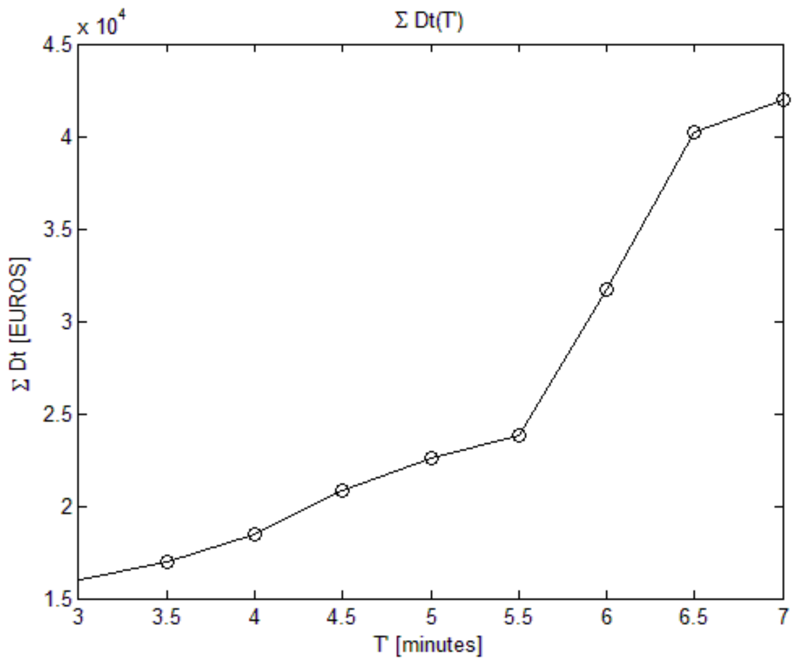

Fig. 12. Diagram of total disturbance cost for different values of T'.

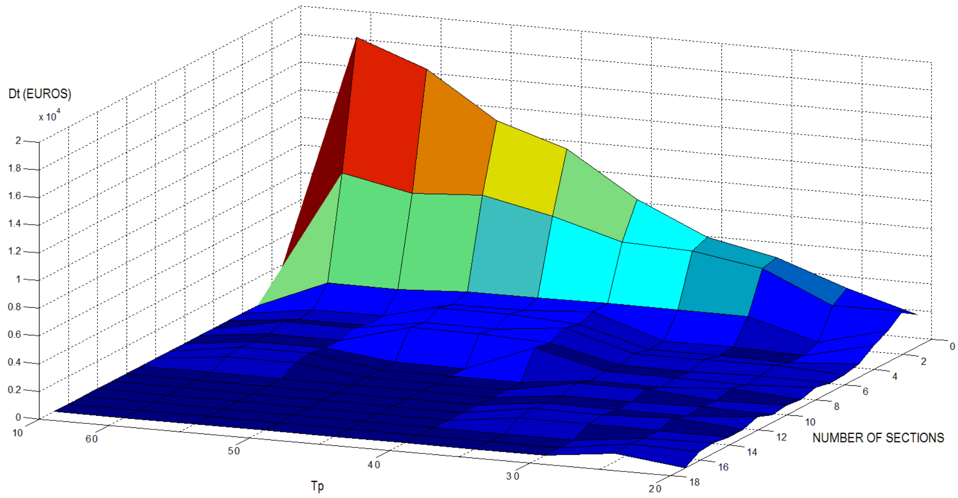

Fig. 13. Diagrams of Dt for different values of Tp(g).

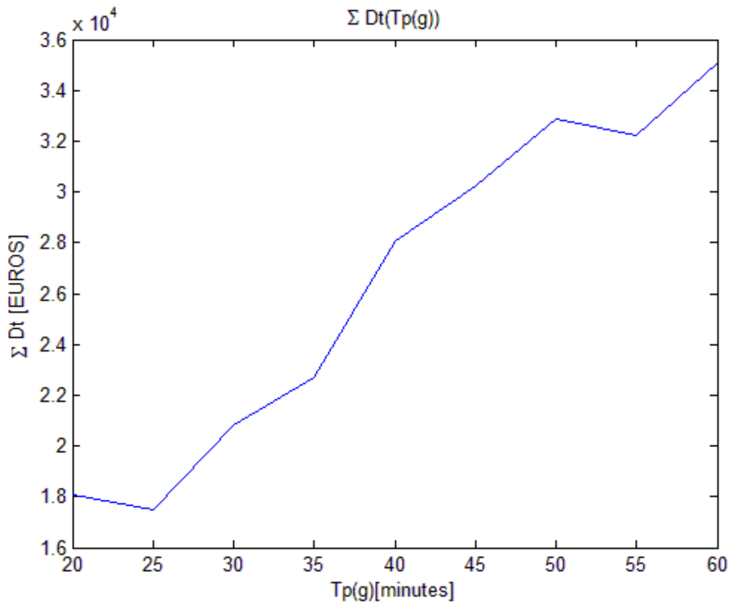

Fig. 14. Diagram of total disturbance cost for different values of Tp(g).

c. Parameter 'g'

Parameter g represents the MG where the disturbance occurs. Figures 15 and 16 show the diagrams of Dt and total disturbance costs ($\sum$Dt) on the whole TL if the disturbance occurs in MG: 1,2,3,4,5,6,7,8,9 or 10.

Other parameters were set as follows:

T' = 4.5 - disturbance duration (in minutes);

Tp(g) = 30 - disturbance duration (in minutes);

V(j) ∈ [3,4,5], j = 1...40 - number of products in deposits.

d. Parameter V

In order to study the effect of the quantity of product units (V(j)) in the deposits on the disturbance costs, to the initial number of products, quantities of 1 up to 9 product units had been added for each diagram shown in Figure 17 and 18.

Other parameters were set as follows:

T' = 4.5 - disturbance duration (in minutes);

Tp(g) = 30 - disturbance duration (in minutes);

g = 2;

n(j) ∈ [3,4,5,6], j = 1...40 - total number of WM;

k(j) ∈ [1,2], j = 1...40 - number of backup WM;

M(h,j) ∈ [0.75..1.5], h = 16, j = 1...40 - WM productivities;

d_M = 120 - cost of disturbance per minute (in Euro).

Based on obtained results, the company that owns the system can have the necessary data to proceed in applying adequate methods for planning, control, re-configuring or restructuring the analyzed system.

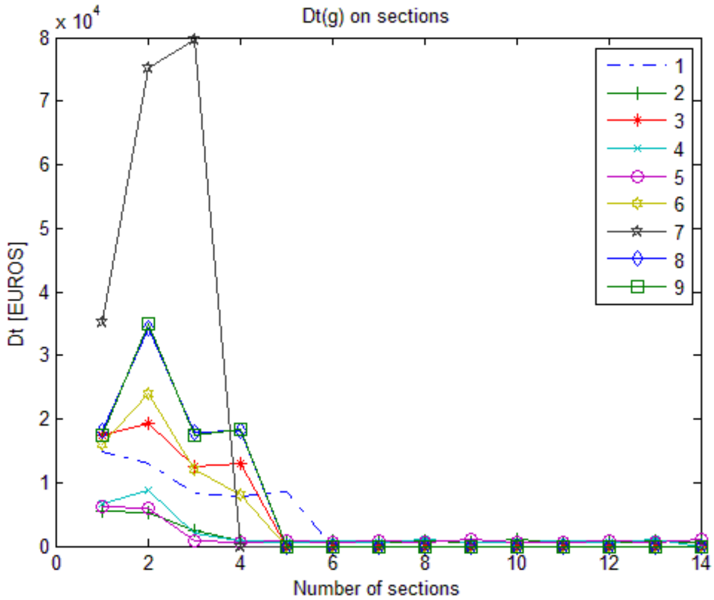

Fig. 15. Diagrams of Dt for different values of 'g'.

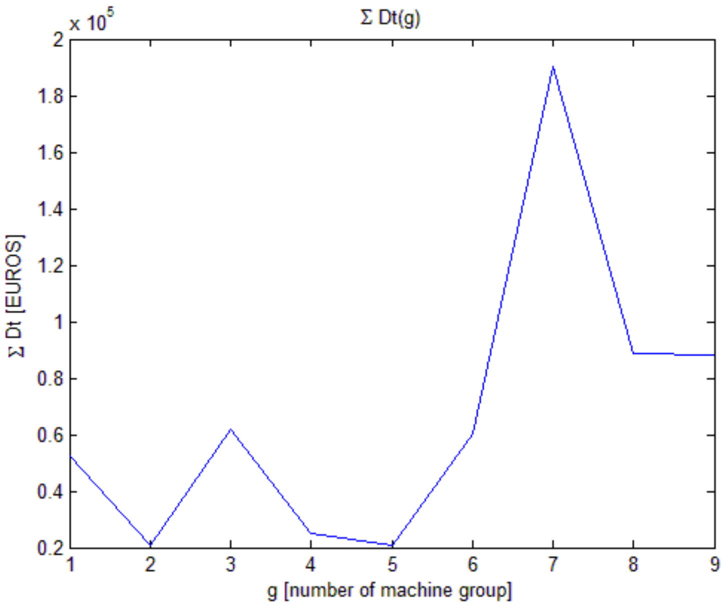

Fig. 16. Diagram of total disturbance cost for different values of 'g'.

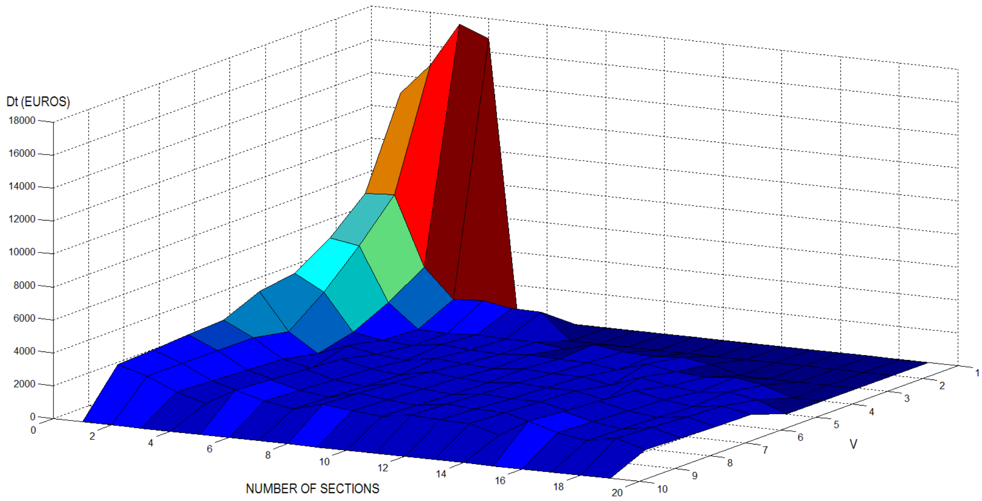

Fig. 17. Diagrams of Dt for different values of number of products stored in the deposits.

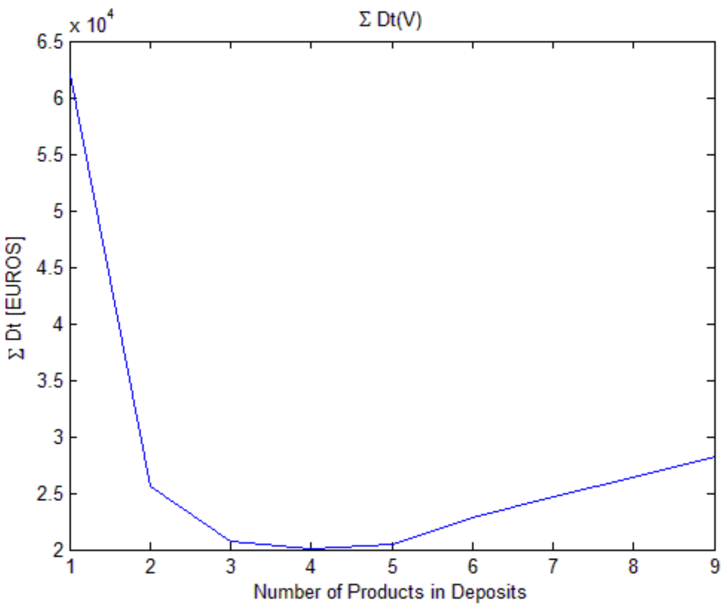

Fig. 18. Diagram of total disturbance cost for different values of number of products stored in the deposits.

5. Conclusions

Disturbances in MS are undesirable, which enabled intense preoccupation for the control, self-diagnosis and reconfiguration of MS subjected to disturbances, and for the assessment of their effects. The paper aims at modeling and simulating the effects of disturbances that cause partial or total unavailability of working machines in technological lines, due to internal or external causes such as power supply interruptions, and catastrophic or parametric failure of working machines. Whatever the topology of the analyzed system, in terms of reliability, it is reduced to one represented by an equivalent serial diagram, which allows the development of mathematical model adopted in the case of the three TL types that covers most manufacturing processes: RTL, FTL and CTL. The paper shows how propagation of the disturbance occurs and presents a model of evaluation of some indicators which describe the disturbance consequences for the more general case of FTL. The model permits tracking the disturbance propagation process, depending on its depth, the mode of self-division of the TL in sections, and the evaluation of indicators: critical times, unavailability factors, the number of influenced MGs (on each section and the production line total), the technological disturbance and recovery time, specific and total damage for each group of machines, for each section and for the TL total. The mathematical model had been generalized and implemented in a program, allowing real-time performance analysis of TL and manufacturing processes, in order to optimize their operating regimes. The developed software is a very useful tool to study the disturbance propagation phenomena in FTLs.

Following the simulation tests we can observe that the model behaves well for predictable (by logical reasoning) or known (obtained from previous experiments) cases. From the presented diagrams we can observe that increasing the time needed to the production units to recover (T'), (figures 11 and 12) or the disturbance duration (Tp(g)), (figures 13 and 14) will increase the disturbance costs. Increasing the number of products in the deposits (V) (figures 17 and 18) will decrease the disturbance costs. In future works we will test the algorithm for real case data. Collection of real case data need a long period of time and has to be supported by a research project funding. Increasing the number of products in the deposits (V) will decrease the disturbance costs. Changing the place of the disturbance in the first section of the TL (g) has no major effect on the disturbance costs which depends more on the other parameters of the TL (machine productivities, number of backup machines and so on). Numerical values used in our tests are compatible with those for a machine building factory. The proposed algorithm can be easily applied for real TLs and MSs, input variable values of the mathematical model being suitable to express conditions of real systems. In a future work the authors are planning to rigorously test the algorithm in machine tool, automobile and electronic device manufacturing companies.

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