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Implementation Problems of the Hybrid Dynamical Approach to FMS Scheduling

Ph.D. thesis book

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1. INTRODUCTION

The suitable solution of scheduling is one of the key problems in effective utilization of manufacturing systems. Scheduling is the art of utilising the available time and resources under given constraints. Scheduling in the manufacturing sector is performed as part of the production planning. Schedules are used as guides for establishing manufacturing resource requirements such as manpower, tooling, machine etc. The quality of schedules used at all levels of production has a major influence on the effectiveness of a manufacturing organisation.

Scheduling within a manufacturing organisation ranges from long-term projection to detailed task scheduling. The master schedule offers the overall plan for supplying material to execute production and sales over relatively longer period of time. A long-term scheduling is used to help planning for production and plant operations over a long period of time. The objective of this type of scheduling is to identify product batch sizes to reach a particular target, such as monthly forecast.

The short-term detailed schedule provides means of checking the progress towards achievement of production targets, which has been set in the master schedule. Targets include meeting the required delivery dates for completion of all work on the jobs; minimising in-process inventories; maximising machine and labour resource utilisation.

Job shop scheduling in FMS is a complicated task. There are different methods and approaches for solving scheduling problems (e.g. batch processing etc). But application any of them is state of the art.

A little bit more then ten years ago in a paper Perkins and Kumar [L2] a new direction, the use of Hybrid Dynamical Approach to the solution of manufacturing scheduling problems aroused. Somlo [L1] proposed a method for the determination of demand rates reflecting practical requirements, and also the so-called controlled buffer technique, which gives an opportunity to handle the multi-machine cases.

The mathematical model for the solution of FMS scheduling is well known. The mathematical model conceptions have originated from classical work of French [L5], and they are highly used nowadays in the solution of classical and modern batch processing problems. Extension of the model to the use of HDA may be found in [L2], see also (Matveev and Savkin [L4]; Somlo [L1]).

Let us shortly describe what are the hybrid dynamical systems and how one can apply the hybrid dynamical system approach for solving manufacturing scheduling problem. The hybrid dynamical systems are those that contain discrete and continuous dynamics. A typical hybrid system is a logical discrete-event decision-making controller interacting with a continuous-time process. This model can be used to accurately describe a wide range of real-time industrial processes and their associated supervisory control and monitoring systems. A simple example is a home climate-control system. Due to its on-off nature, the thermostat is modelled as discrete-event system, whereas the furnace and air conditioner are modelled as continuous-time systems. More examples of hybrid dynamical systems can be found in Matveev and Savkin [L4].

In our case we apply the above approach to discrete production process. Let us consider Figure 1. At the left side of the picture one can see a part of a real manufacturing process with one machine tool (server). Let us call this machine tool as Server *j*. The server processes three part types from the buffers at the input of the server. The server removes one part from the selected buffer and spends some time processing this part. This time is called as processing time and is denoted as τ_{ij} , where symbol *i* corresponds to part type and symbol *j* corresponds to server. The real manufacturing process is a discrete process. It means that the server in reality can remove from the buffer only one part and not one and a half for example. The left hand side of Figure 1 demonstrates the discrete nature of the processes.

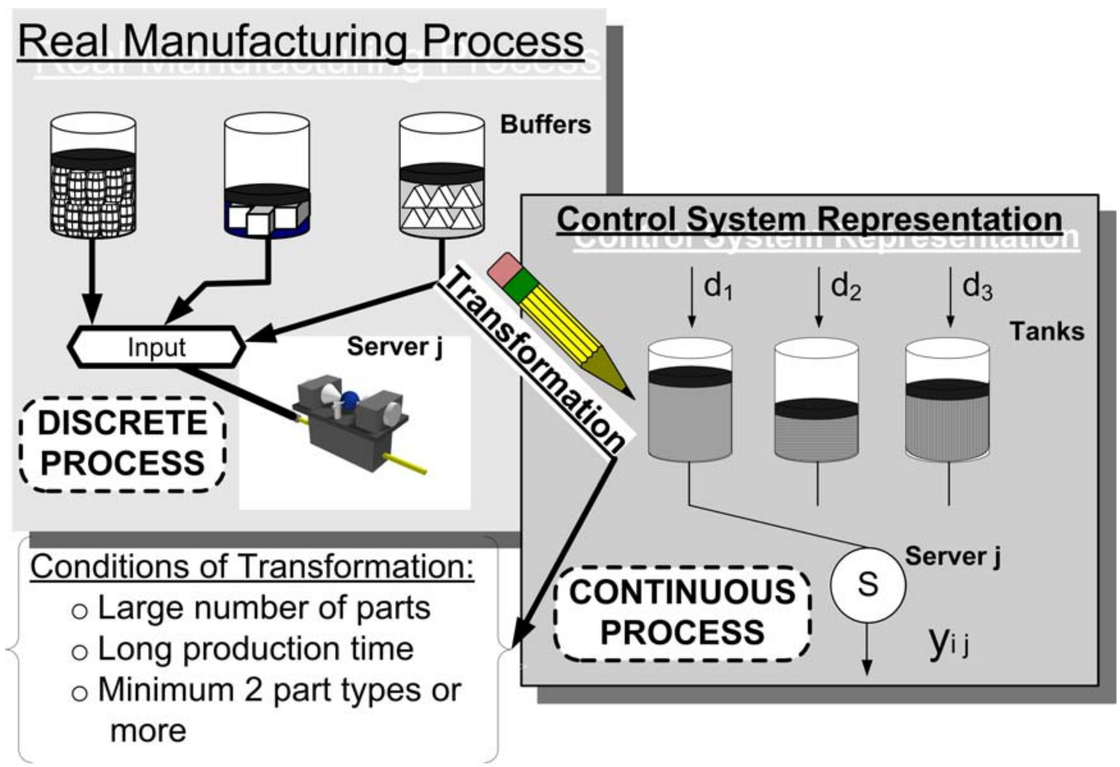


Figure 1. Continuous representation of manufacturing process

When one applies the HDA, the manufacturing control system represents the discrete manufacturing process as continuous. The control system representation is shown at the right side of Figure 1. The description of this part of the picture is given below.

Let us represent the contents of the buffers as "work". It will be convenient to think of this work as a fluid, and of the buffers as tanks (see Figure 1 right hand side). In this case, the work can represent continuous approximation to the discrete flow of parts in a flexible manufacturing system.

Following the example in [L2] we assume that a rate of part flows through the system has a constant value for every part-type *i* and call it demand rate d_i. In other words, the work arrives to any buffer with index *i* at a constant rate $d_i>0$. The machine tool removes this work from selected buffers at some given rate y_{ij}. The value of this rate depends on which buffer is served with which server and can be expressed by the following equation: $y_{ij}=1/\tau_{ij}$. It is assumed that any server can only serve one buffer (or part-type) at a time.

As proposed in work [L1] by Somlo the buffers can be imagined as individuals for every parts type and every machine. But, in reality different part types (and even machines) can be served from the same “physical” buffer.

Let us define the conditions when Hybrid Dynamical Approach can be applied for manufacturing scheduling tasks. These conditions are shortly enumerated on Figure 1 . According to [L1] this method can be applied when manufacturing system produces high number of parts. Under high number we understand several hundreds, several thousand or more parts. Of course, the process of manufacturing depends not only on the number but also on the “size” of parts, as well (we use the word “size” here to describe process characteristics such as volume, complexity, etc.).

When using the Hybrid Dynamical Approach in manufacturing scheduling the following problem arouses. At the first server, the rough parts can be obtained from central buffer as a continuous flow. But at the consecutive machine groups the part flows have highly discontinuous behaviour due to the switching nature of the server actions. This makes impossible to use the results of the single machine processing in multi machine case. This difficulty can be eliminated by the use of the Control Buffer Technique (CBT) proposed by Somlo in [L1]. The CBT is based on the fact that it is possible to fill up some auxiliary buffers and use them to compensate the input flows.

It is proposed in the present Thesis to investigate the application of the Hybrid Dynamical Approach for manufacturing systems scheduling by discrete event simulation. The use of the simulation technique for the investigation of manufacturing systems is desirable in our case as it provides the opportunity to describe the performance of the real manufacturing systems and all processes inside it.

2. GOALS OF THE RESEARCH

Historically HDA was investigated from three points of view: processes inside a manufacturing system; applicability for multi machine case; parameters and a relational model (see **Figure 2**).

Processes investigation. Early works in this area (see [L2], [L3]) were concerned with dynamical behaviours of production process inside a manufacturing system controlled by HDA. The first research works introduce and determine such terms as: demand rates, stability idea and criteria of stability.

In the research that followed qualitative theory of hybrid dynamical systems was developed [L4] where stability questions have been thoroughly investigated and methods for determination of period of periodic regimes have been introduced. Qualitative theory provides useful tools for the analysis of manufacturing systems that can be modelled as hybrid dynamical systems.

Applicability. In the first publications on hybrid dynamical approach the realisation aspects of the method have not been taken into consideration. The authors of paper [L2] suggested the use of the demand rates as input qualities at the input of machine tools but defined no algorithm for demand rate determination. The applicability of this method for multi machine case was not considered.

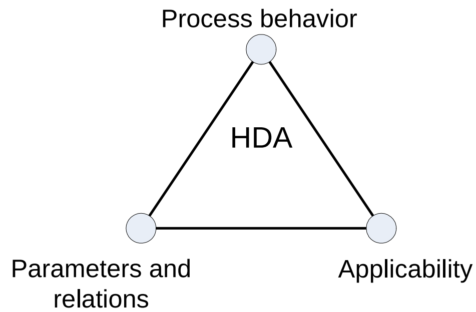


Figure 2. Views of HDA

The first open question was connected with determination of demand rates. Somlo in his work [L1] suggested a method for determination of demand rates. This method is based on scheduling time T_{sch}, minimal processing rate τ_{ij} and machine load vector. It is proposed [L2], [L1] to use the same demand rate for part type i at all of the servers:

$$d_{ij}=d_i \tag{1}$$

where $i=1,2,\ldots,I$; $j=1,2,\ldots,J$. Demand rates can be determined according to the relation.

$$\frac{n_i}{T_{sch}} \le d_i \le Min\left\{\frac{1}{\underset{j}{Max}(\tau_{ij})}, \frac{n_i}{\underset{j}{Max}(tl_j)}\right\}, \tag{2}$$

$$i = 1,2,\ldots,I.$$

Where n_i is number of parts and tl_j:

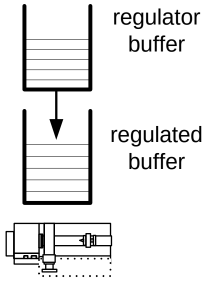
$$tl_j = \sum_{k=1}^{1} n_k \tau_{kj}, \quad j = 1,2,\ldots,M \tag{3}$$

The quantity tl_j – is a component of the so-called machine group load vector. (If a part type is not machined on some server: $\tau_{ij}=0$.)

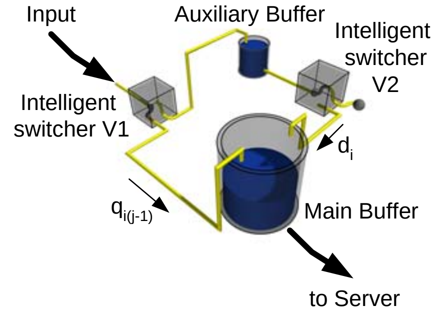
The above described method gives possibility to determine demand rate range and for every value from this range the manufacturing process will be stable.

Another realisation problem was connected with the following. At the first server the rough parts can be obtained from the central buffer as a continuous flow. But at the consecutive machine groups the parts flows have highly discontinuous behaviour due to the switching nature of the servers' actions. This makes it impossible to use the results of the single machine processing to multi machine case.

The first idea to solve this problem was suggested by Perkins, Humes, Kumar [L3]. They proposed to use the so-called regulated buffer stabilizing techniques to reach stable performance for FMS scheduling problems. The essence of this technique is that the real buffer can be split into two virtual components, a regulator buffer and a regulated buffer (see Figure 3a). Only parts in the regulated buffer are available for processing by the machine. Unfortunately this proposal was not developed fully and no algorithm for application this idea in industry was suggested.



a)



b)

Figure 3. Regulated buffer stabilizing technique (a) and controlled buffer technique (b).

Later in Somlo [L1] the use of the Controlled Buffer Technique (CBT) was proposed. The CBT is based on the fact that it is possible to fill up some auxiliary buffers and use them to compensate the input flows. This technique is demonstrated in Figure 3b. If there is no part flow at the ”Input” the control system keeps a demand rate from the “Auxiliary buffer”. The switcher *V2* is switched on and the parts flow from the “Auxiliary buffer” into the “Main buffer”. When a part flow at the “Input” exists the parts are directly delivered into “Main buffer” through switcher *V1*, and the “Auxiliary buffer” is fed back because $q_{i(j-1)}>d_i$. Where $q_{i(j-1)}$ is processing rate of previous server. This is how the “Controlled Buffer Technique” works.

All previous results have been achieved for continuous systems. There is no guaranty that those are valid in discrete cases and processes. The goal of the present work was *to develop methods and devices for application of HDA in discrete case*.

3. METHODOLOGY OF THE RESEARCH

The methods of the research used in this Thesis were computer simulation and case studies. Taylor ED (Enterprise Dynamics) simulation software was taken for model building.

Taylor Enterprise Dynamics (Taylor ED) is an object-oriented software system used to model, simulate, visualize and monitor dynamic-flow process activities and systems. By "dynamic-flow" (see [L6]) we mean the discrete flow of products, people, data, paper, or information through a system. Taylor ED is widely used for modelling manufacturing, warehousing, and material handling processes and modelling, simulating, visualizing, and monitoring process flow activities. Under process flow activities we understand processes like, electronic data flowing through an information network, or the flow of people through an amusement park ride.

The Taylor ED software system is based on the "Atom Concept". An atom is an object with four dimensions (x, y, z, and time). Each atom can have a location, speed, and rotation (in x, y, and z) and dynamic behaviour over time. Atoms can inherit their behaviour from other atoms, atoms can contain other atoms, atoms can be created, atoms can be destroyed, and atoms can be moved into one another. Atoms can be viewed dynamically and simultaneously in 2D and 3D animation.

A number of case studies were made based on simulation models. The most important features of the models are:

- Due to the discrete simulation nature of Taylor ED the real discrete part production process is modelled.
- The system provides wide scope of demonstration opportunities. In this line 2D and 3D animation, different graphical and numerical result presentation, etc., are available.
- It is convenient and easy to change the system parameters and follow the effects of these changes.
- Any time-slice of the work of the simulated manufacturing process is stored in excel based database and can be viewed and analyzed.

For the investigation of the features of the processes controlled by HDA a number of different case studies have been done. More than 20 cases were studied where the system parameters were changed widely. The processing times have been changed randomly in 9 cases. The set-up time value was changed in 4 cases and in the other cases the manufacturing sequences, number of part-types (parts as well) and machines was changed too (5 cases). In 3 cases the scheduling period was increased 3 times. This was made in order to have an opportunity to investigate the processes in a longer run. In all cases it was possible to find parameters with which the HDA could be applied.

The main aim of case studies was to investigate the following questions:

- What is the effect of the demand rate choices?
- How does the set-up times affect the processes?
- What is the effect of initial conditions?
- What is the effect of the choice of the switching policies?
- How are the results related to the results of the classical scheduling methods?
- etc.

4. THE NEW SCIENTIFIC RESULTS OF THE WORK

Thesis 1

> *I developed a model of FMS controlled by the Hybrid Dynamical Approach. I called this model as a Generalized Model of the Hybrid Dynamical Approach application. The developed model is suitable for continuous and discrete cases. This model contains all parameters of the manufacturing process scheduled by HDA and describes relationships among parameters. The algorithm of the application of this model is developed as well.*

I performed a high number of simulation experiments. More then 20 case studies on different manufacturing examples were investigated. On the base of these investigations the behaviour of production processes scheduled by Hybrid Dynamical Approach have been clarified and parameters of processes have been discovered and formulated

This model leads to better understanding of HDA for manufacturing scheduling method.

The extended model can be formulated in the following way:

- Let us represent a manufacturing production process as "black box" which can be measured, estimated, controlled and characterized by different parameters. Because of the complexity of the production process the hybrid dynamical approach to manufacturing scheduling can be characterized not only by one value for each parameter but by some set of parameters (values) of the same type.

This statement needs some comments. For example, the value for demand rate parameter of the i^{th} part type can be chosen from the range $\{d_i^{min};d_i^{max}\}$, where d_i^{min} and d_i^{max} are determined by equation (2). The all-possible values of d_i can be considered as a set. It is subset of "Set of demand rates" which is a parameter of the generalized model. The whole parameter is built from subsets for each part type.

Most of the parameters of the generalized model are sets.

- Let us classify the different sets of parameters into three groups. The first group is the group of input parameters, which are determined by the technological constraints. Let us call this group as "hardly determined input parameters". These parameters can not be changed for improving the behaviours of the production processes. There are two sets of these parameters: the "Set of processing times" and the "Set of set-up times". In the next group are the sets of parameters which can be changed in some range for the improvement of the characteristics of the manufacturing processes. The "Set of input strategies", "Set of demand rates" and "Set of initial conditions" belong to this group. The last group consists of "Set of buffer content", "Set of auxiliary buffer content" and "Type of process". They are output parameters of the manufacturing process.

During the present investigations some of the relations among the parameters of the manufacturing process have been discovered. Some of these relations have been found theoretically and some of them have been found using simulation investigations. This fact gives us the possibility to extend the above-described model by the following statement:

- It is possible that the changes in the set of some input parameters can influence not only the manufacturing production process (characterized by output parameters) but also other sets of input parameters.

The graphical interpretation of this model is shown on **Figure 4**. The model is represented as circle-spoke diagram. The central circle represents the manufacturing production process which is scheduled by the hybrid dynamical approach. The circles around represent different sets of parameters and characteristics of production process. These relations are shown as arrow-headed lines on **Figure 4**. These lines show that the changes in one set can cause the changes in other sets. For example, the changes in the set of processing times can cause changes in the set of demand rate values.

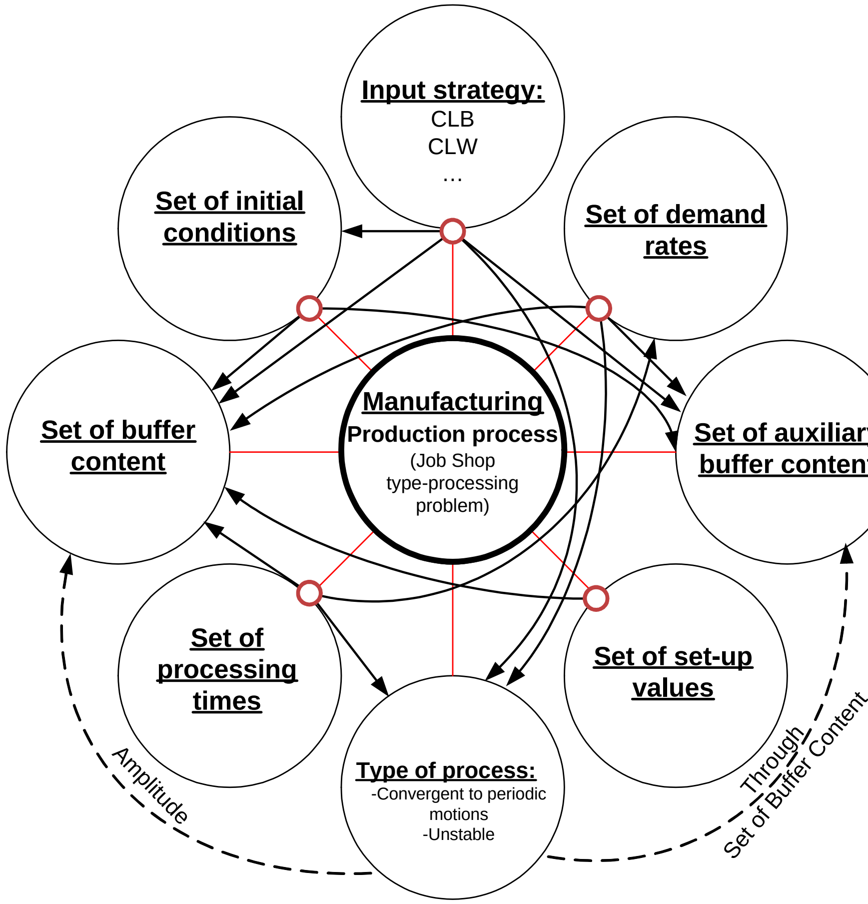


Figure 4. Generalized Model for HDA

The following algorithm for the practical application of HDA can be suggested on the base of the Generalised Model.

Step 1. At this step manufacturing production task is analysed using the mathematical model. At this step the real manufacturing task is compared with mathematical abstraction. If the real system satisfies the model then step 2 is involved. If it does not, the HDA is not applicable for the investigated task. The following parameters of the generalized model are determined (loaded from CAPP) at this step: “Set of processing times” and “Set of set-up values”.

Step 2. The switching policy (or “Input strategy” parameter of generalised model) is chosen at this step. Here, any of the two following policies CLB and CLW can be applied. Other rules can be considered in the future but these investigations are outside of this dissertation. When switching policy for servers is chosen the next step is involved.

Step 3. At this step the demand rate range for each part type is determined and explicit demand rate value for every part type is chosen. If for some part type the demand rate range does not exist then HDA is not applicable. The set of all chosen demand rate values is the parameter of the generalised model – “Set of demand rates”. When this parameter is determined the next step follows.

Step 4. At this step the initial content for every buffer is chosen. As it is discussed above the production process controlled by HDA consists of two modes. There are transient and periodic modes. Both of them can be chosen for production. If one wants to use periodic mode then initial conditions should be taken close to process determined value. If initial conditions are taken very far from the process determined value then the transient mode is longer. The choice of the initial conditions gives us the possibility to use the transient mode of the production process (see paragraph above).

The process determined value can be found by running a simulation or a computation models of the manufacturing system.

This thesis is discussed in Chapter 5 of the dissertation. The related author publications are [A5], [A6], [A8], [A10], [A11].

Thesis 2

I developed a mathematical model for the application of the hybrid dynamical approach for discrete manufacturing process. This model is applicable for solving a general job-shop class of scheduling problems in FMS.

I have shown that for the general job-shop class of problems there exist sets of initial conditions for buffer contents and sets of auxiliary buffer contents, which at the given method of determination of demand rates, provide successful application of Hybrid Dynamical Approach to FMS scheduling. For that I used discrete event simulation techniques and developed the suitable simulation system.

Hybrid Dynamical Approach is one of the most promising one's for the solution of FMS Scheduling problems. New proposals were obtained for the determination of one of the basic parameters - the demand rate (Somlo [L1]), also a new proposal the control Buffer Technique was proposed for effective use of the method. But it was not clear whether the above proposals could really be applied for the solution of practical tasks. I used the methods of computer simulation and case studies.

For successful application of these methods the continuous mathematical model of HDA scheduling have been modified into the following form:

- The task is to produce I different part types $(J_1,J_2,J_3,\ldots,J_I\ ;\ J_1,J_2\ \ldots$. are the names of the part types) in given $n_1,n_2,\ldots n_I$ number of pieces, during the given time period, on the given production system. A part type will be identified with index $i\ (\ i=1,2,\ldots I\ )$. The production system consists of a given number of machine groups. These are denoted by $M_1,M_2,\ldots,M_M$; where M – is the number of machine groups. In the following $j=1,2,3,\ldots,M;$ will be used to indicate $M_1,M_2,\ldots,M_M$ machine groups. It means that a general job shop type-processing problem is considered, like in French [L5].
- The capacity of the machine tool is limited to one part. Due to the discrete nature of production the machine tool cannot start production of a new part before finishing processing with the previous one. The processing time of the machine tool is determined

as τ_{ij} where *i*, indicates what part type on which machine *(j)* has the given manufacturing time.

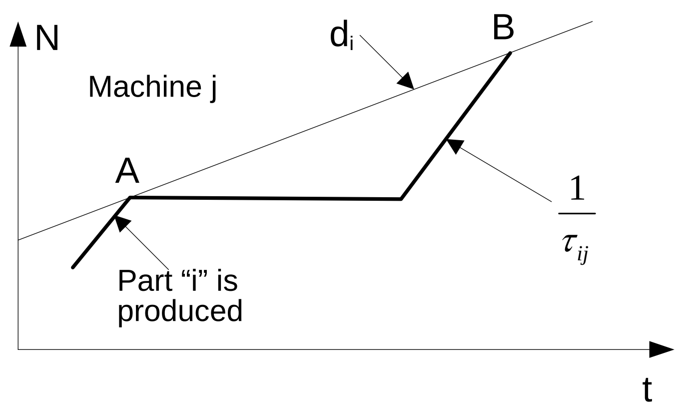
- The server switches production to another part type when the buffer content is zero. Every time when the server changes production from one part type to another some set-up time is involved. The choice of the buffer is determined by the switching law.

In continuous case the server can switch production from one type to another even if the buffer content is smaller then one part.

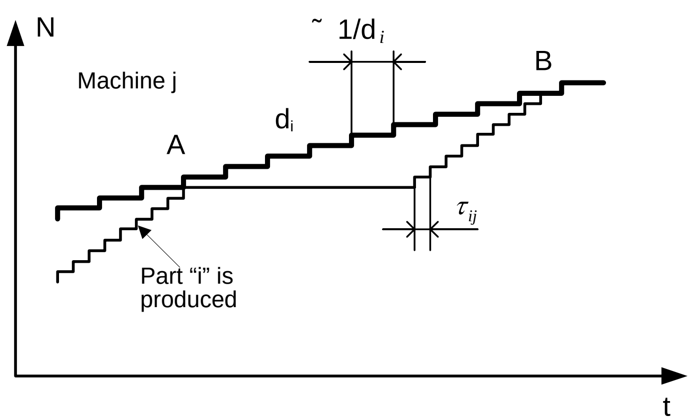
- At hybrid dynamical approach the items (the individual parts) are introduced to the input buffer as continuous flows with given demand rates d_i. Where *i* corresponds with part type. Due to the discrete nature of the process the demand rate is substituted by regular appearance of the parts with time interval 1/ d_i (see Figure 5b).

Figure 5 introduces the parts flow process in the case of continuous (a) and discrete (b) processes.

The completed case studies show that HDA can be applied for scheduling of discrete manufacturing processes.



a)



b)

Figure 5. The HDA for continuous (a) and discrete (b) cases

This thesis is outlined in Chapter 5 of the dissertation. The related author publications are [A3], [A7], [A9], [A11].

Thesis 3

I investigated and formulated processes in manufacturing systems controlled by HDA in case of discrete production process.

I modified the Control Buffer Technique (CBT) to make it applicable for discrete case. I interpreted the work of CBT as work of double buffer structure. This structure is a discrete representation of the CBT.

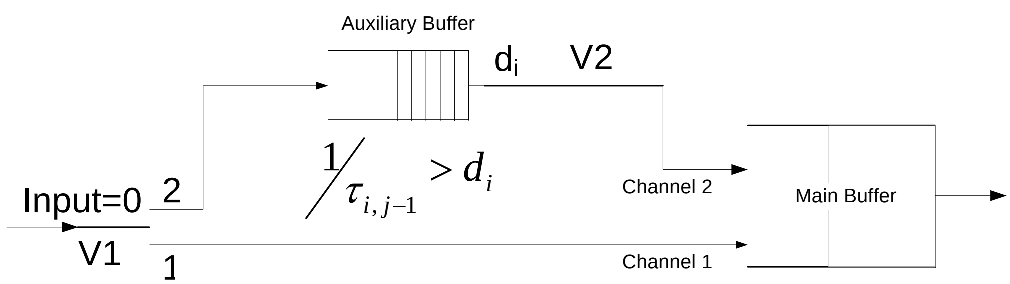
I developed new algorithms, which give possibility to build discrete event simulation models. These models have been realized in Taylor Enterprise Dynamics simulation software and were used as base for simulation investigation.

Although previous proposers have suggested some ideas about the realization of the Hybrid Dynamical Approach for manufacturing scheduling the task was not clearly formulated. My formulation gives clear understanding of the processes inside manufacturing system and was used for development of algorithms.

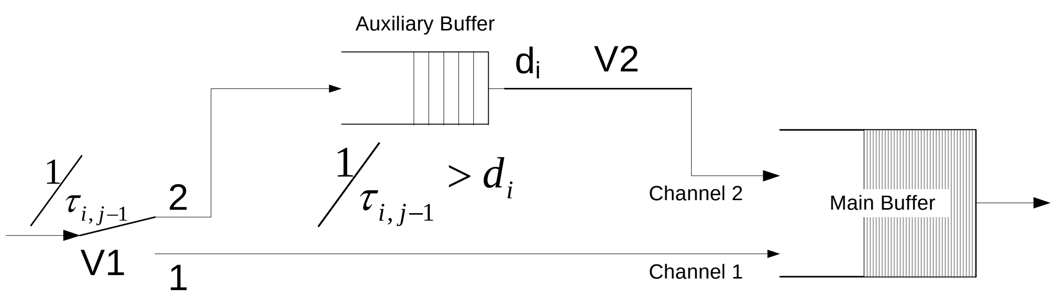
The discrete event simulation was chosen as the main instrument for investigation of the Hybrid Dynamical Approach as this method can clarify the discrete nature of the real manufacturing process.

Although the CBT is very easily applicable in the case of the continuous processes in the case of the discrete production the application of this technique was not clear enough.

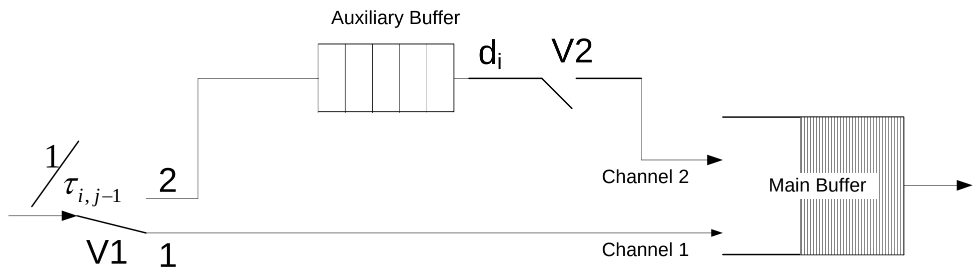
Let us formulate the work of Double Buffer Structure. The double buffer structure is discrete realisation of CBT. Like in case of CBT the double buffer structure consists of the “Main Buffer”, the “Auxiliary Buffer” and two switchers V1 and V2 (see Figure. 6). When Auxiliary Buffer is activated it delivers the parts to the input of Main Buffer with constant rate d_i.



a) Active state



b) Compensation state



c) Inactive state

Figure 6. Double Buffer structure and its work

Let us consider the double buffer structure of part type *i* at the input of the machine (*j*). If there is no signal from machine (*j-1*) at the input of Double Buffer then switcher *V2* is switched on and Auxiliary Buffer goes to active state. This condition of double buffer structure we called as **<u>“active state”</u>** (see Figure 6a). This situation appears in case of machine (*j-1*) processing with parts of some part type k. When machine (*j-1*) starts to produce part type *i* these parts appear at the input of switcher *V1*. *V1* switches to channel 2 as Auxiliary Buffer is not full. At the same time the switcher *V2* is switched on and Auxiliary Buffer goes on to send out parts. The processing rate of machine (*j-1*) $\tau_{i,(j-1)}$ is more then demand rate d_i .

$$\frac{1}{\tau_{i,j-1}} > d_i$$

It means that the content of Auxiliary Buffer is growing and machine (*j-1*) compensates the spent parts in Auxiliary Buffer. This state is called **<u>“compensation state”</u>** (see Figure 6b). When content of Auxiliary Buffer has reached the maximum capacity value the switcher *V1* switches to channel 1 and *V2* is switched off. The Auxiliary Buffer is deactivated. All parts from the output of previous machine go to the Main Buffer directly. This state of double buffer structure is called **<u>“inactive state”</u>** (see Figure 6c). During all production cycle the double buffer structure changes its states cyclically. This is the work of the double buffer structure.

The CBT and demand rate determination method gives possibility to apply HDA for manufacturing scheduling.

Let us formulate the work of manufacturing system scheduled by HDA. The formulation of the HDA has been published in the paper Anufriev [A7].

Logically the work of manufacturing system can be split into three main states. The first connected with the fact that all auxiliary buffers should be pre-filled with some content due to the nature of CBT. In this case the first state the system fills out the Auxiliary Buffers and Auxiliary Buffers do not keep demand rates. Let us call this state as **<u>PreRun</u>** state. When Auxiliary Buffers are filled up and capacities of the Main Buffers reach their initial conditions (if it is demandable) the system goes to **<u>Run</u>** state. When the last entity entered to the production system from the central warehouse (external buffer) and demand rates are not kept at the input buffers of production system the system goes to **<u>PostRun</u>** state. At this state the system cleares up all contents of auxiliary and main buffers.

Let us analyze these states. It is clear that the HDA cannot be implemented for every state. In the PreRun state the auxiliary buffers are empty and they could not keep demand rate. In this case the production task can be formulated by the following way: *Fill up all auxiliary buffers and main buffers with initial conditions for the shortest time*.

Similarly, the production task can be formulated for the PostRun state: *Clearing up all auxiliary buffers content and the rest of the parts in the main buffers for the shortest time*. The HDA is not the optimal solution for this task due to the following reason. Let us consider the part of production system in PostRun state which consists of one machine and *J* double buffers at the input of the machine. Let us suppose that all main buffers are empty and some amount of parts is remained just in one auxiliary buffer. Due to the demand rate determination method demand rate *d* should be smaller then the processing speed of server *y*. If one solves this task by batch processing method the production time T_{batch} is determined by the processing rate of the server $T_{batch}=n_{\mathrm{remain}}*y$. In case of applying HDA the production time is $T_{HDA}=n_{\mathrm{remain}}*d$. It is clear that $T_{batch}<T_{HDA}$.

Simulation investigations (see Anufriev [A5], [A7], Somlo, Anufriev, Lipovszki [A6]) shows that batch processing is an effective solution for PreRun and PostRun states.

This thesis is discussed in Chapter 4 of the dissertation. The related author publications are [A1], [A2], [A4], [A6], [A7], [A11].

Thesis 4

In the frame of the simulation investigations I found a special method for the determination of maximum auxiliary buffer capacity. I called this method as Method of Independent Source.

I developed and implemented an algorithm that gives possibility to effectively use the Method of Independent Source for investigation of Manufacturing Scheduling by Hybrid Dynamical Approach.

Although previous proposers suggested to use Auxiliary Buffers for the realization of Hybrid Dynamical Approach they had no idea about what maximum capacity Auxiliary Buffer should use. My method was realized and a simulation model, which used this method, was created.

The realization of this method decrease the number of simulation cycles and the time of each cycle during the simulation sufficiently. This is the simulation-based method and the essence of the method is the following.

This is possible to substitute the auxiliary buffer by a Source object. In discrete event simulation the source creates parts for the system. The source like auxiliary buffer should keep demand rate d_i. It means that the source sends out one part in a time interval δt . Where δt is

$$\delta t = \frac{1}{d_i}$$

Let us describe the work of the independent source. When Double Buffer has a signal at the input the switcher V2 is disconnected.

Under "have input signal" I understand the condition when a new part arrives to the input of DoubleBuffer in a time interval $\Delta t \leq \delta t$. The DoubleBuffer have not got input signal when $\Delta t \geq \delta t$.

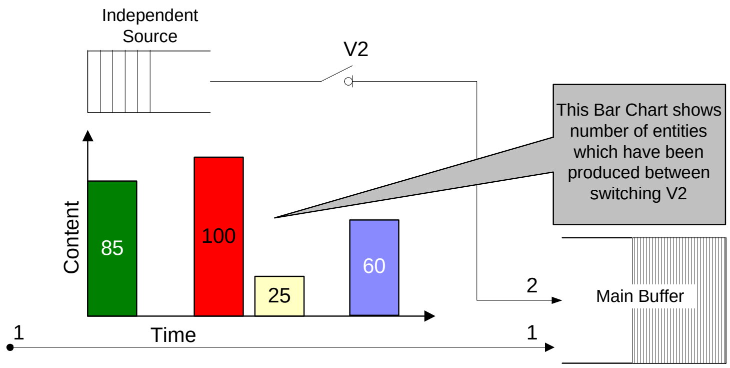


Figure 7. Method of Independent Source.

When the input signal has disappeared the switcher V2 is connected and the source is activated. At the same time the simulation program calculates the number of produced parts (see Bar Chart on **Figure 7**). When machine *(j-1)* starts to produce the part type *i* and these parts appear at the input of DoubleBuffer the switcher V2 is disconnected. The counter of produced part is getting to equal zero. This process repeats every time when an input signal disappears from input of DoubleBuffer. The maximum number of produced parts by the source between two switching of V2 is the minimal Auxiliary Buffer capacity.

This solution can be used for the determination of minimal auxiliary buffer capacity.

This thesis is discussed in Chapter 4 of the dissertation. The related author publication is [A4].

Thesis 5

In the frame of working idea for the determination of the demand rate range I developed and realized an algorithm for finding the upper demand rate value which satisfies the condition of stability of scheduling policy.

The method for determination of a demand rate range was suggested previously (see Somlo [L1]). This method was widely used during the case studies. The case studies have shown that when the demand rate value is taken from the middle area of the demand rate range the HDA is applicable.

The HDA is applicable to minimize a makespan time of the scheduling (see [L1, L2, L3, L4]). It is clear that HDA will give the maximum efficiency when a demand rate value is close to the upper border of the demand rate range. This is true because the higher the speed of parts flow the earlier the production process will be finished. The simulation experiments have shown that if the demand rate value is taken very close (or equal) to the upper border of the demand rate range the manufacturing process becomes unstable. This is due to the fact that equation (2) does not take into consideration the set-up times.

When the demand rate range is determined an explicit demand rate value can be taken according to equation (3), where *k* is coefficient which is $0 \le k < 1$.

$$d_i = d_i^{min} + k(d_i^{max} - d_i^{min}) \quad (3)$$

The case when the demand rate value is near to the lower border *k=0* (see **Figure 8**). This is not desirable due to the efficiency of the production process. If *k =1* then d_i belongs to the upper border of the range but production process is unstable. The maximum value of the demand rate for which production process will be stable lays inside of demand rate range. Let us call the value of *k* , which corresponds to maximum value of demand rate as k_{kr} and call this demand rate as “practical upper border”. There was not any algorithm for the determination of a practical upper border.

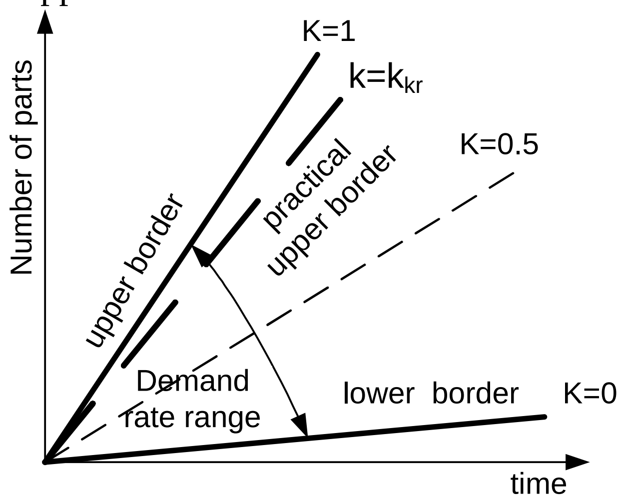


Figure. 8 The demand rate range

I developed and implemented an algorithm for finding practical upper border value for demand rate.

This algorithm is the following. At the first step one should enter technological constraints like processing times of the servers, technological routes of part types through manufacturing system and time of scheduling. At the second step d_i^{max} and d_i^{min} are calculated with equation (2). The third step is the calculation of d_i for $k=0.5$ with equation (3). Let us call this demand rate value as $d_i^{current}$. Then a simulation run is fulfilled.

If simulation shows that the process is stable and the output parameters of the process are acceptable then let $d_i^{min} = d_i^{current}$ and go to the third step. These calculations are going on until the simulation will show that the process is unstable.

If the process is unstable then $d_i^{max} = d_i^{current}$ and new $d_i^{current}$ is calculated with equation (3).

Let us introduce the sensitivity parameter $\mu > 0$. This parameter should be given at the first step of algorithm.

The end condition of calculation is when sensitivity parameter μ is smaller or equal value $\frac{1}{d_i^{\max}} - \frac{1}{d_i^{\min}}$.

This thesis is discussed in Chapter 5 of the dissertation. The related author publication is [A10].

5. UTILISATION OF THE RESULTS

The achieved results and simulation devices developed during this research work can be used for solving job shop scheduling problem of manufacturing systems.

The following possible applications, based on behaviour of HDA, investigated in the frame of current research work, have been discovered. Let us represent a situation when there are two parallel production lines. Both lines (Line 1 and Line 2) are identical and produce similar products. These lines are scheduled by HDA. During production one of the servers at Line 2 has been broken and raw parts from this line have been given as production assignment for the Line 1. How partly processed parts, stored in the auxiliary and main buffers of the broken server, can be produced? Due to the behaviour of the method these parts can be put into the main buffer of an identical machine in Line 1. These parts will be considered as perturbation influence on the production process and will lead to transient mode. When this transient mode will be finished all process characteristics will be as before it.

The overall research work is not over and presented results are used in further research. The new direction of HDA scheduling has been discovered during this work. This direction is under investigation now and it is called as “Periodic and Transient Schedule”.

The results of this work have been presented on international conferences and in an international IFAC journal “Robotics and Computer-Integrated Manufacturing”. The results have been presented in Brussels by Hungarian Ministry of Education.

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