MŰEGYETEM 1782
BME-BUTE
Budapest University of Technology and Economics
Faculty of Mechanical Engineering
Department of Mechatronics, Optics and Mechanical Engineering Informatics

---

IMPROVING FMS SCHEDULING QUALITY BY LOT STREAMING

PhD —Thesis

By
Ezedeen Kodeekha

Supervisor:
Prof. Dr. Janos Somlo

Budapest
2009

1. Motivation and research field

Nowadays, the highest form of modern manufacturing technology is called Computer-Integrated Manufacturing (CIM) which is directing the technology of manufacturing towards Computer Integrated Factory (CIF). CIF is a fully automated factory (factory of the future). In order to develop CIF, we have to improve the performance of CIM which depends highly on the performance of Flexible Manufacturing Systems (FMS).

FMS meets two critical challenges: Highest Makespan Productivity (HMP) and Effective Delivery Reliability (EDR).These two objectives highly depend on the quality of scheduling. So, appropriate FMS scheduling is extremely, important.

Minimization of maximum production time of FMS scheduling close to the global minimum of production time may result HMP and EDR. But answering the question how close this goal can be approached is a very complicated problem. This research tries to answer this question.

Scheduling methods such as Scheduling Priority Rules (SPR) even with high quality computers are usually generating the batch schedule with low makespan productivity (utilization) and ineffective delivery reliability.

There are opinions in literature that lot streaming is much more effective improvement of the schedules qualities than the combinatorial approaches applied without lot streaming.

FMS scheduling problems, generally, are complicated NP hard combinatorial problems. Lot streaming makes the problems even much more complicated because of the formation of a large number of sub-batches.

1.1 State-of-the-art

The manufacturing scheduling is one of the topics most widely discussed in technical literature. Classical work of Conway R. E., et al. [1], French S. et al. [2], and many others give extensive coverage of the problems. From the newer literature one could use, for example: [3, 4, 5, 6].

Lot streaming is not as popular in literature as the general problem of scheduling with fixed batches. In this field, an attempt was made to formulate the problem from the point of view of inventory control by Szendrovits [7]. Dauzere-Peres and Lasserre [8, 9] proposed computation aspects for lot streaming in job-shop scheduling problems. Genetic algorithms (GA) for the above problem were proposed by F.T.S. Chan, Wong, and P.L.Y. Chan [10]. Many other works discuss the problem, too. The flow shop lot streaming are widely discussed in [11].

Hybrid Dynamical Approach (HDA) was proposed by Perkins and Kumar in 1989 [12]. HDA realizes lot streaming and overlapping production as it was shown by Somlo [13]. General theory was developed by Matveev, Savkin [14]. Pragmatic aspects of using HDA were published in [15 and 16].

In [17] the use of the, so-called, Brute Force Method (BFM) was proposed, which is based on the simple division of all of the part type series to the same number of sub-series. The goodness of the obtained results is estimated by simulation. General issues are formulated. Bottleneck scheduling idea is used to give theoretical background. In [18, 19, 20] for special cases ("joinable" schedules of job shop problems) optimal lot streaming policies were developed. In [21, 22, 23] the joinable schedules approach was extended for flow shop scheduling problems.

1.2 Problem definition

In lot streaming strategy, there are two processes to be performed; batch breaking and overlapping processing. In breaking process, new setup actions appear for the sub-batches; the number of sub-batches increases the number of setups (times) increase, consequently, the makespan increases. In contrast, by overlapping processing; the number of sub-batches increases the idle time decreases, consequently, the makespan decreases. Therefore, there is a trade-off optimization problem between the extra-time of additional setup times of sub-batches by batch breaking and the time saved by overlapping processing. The question to be answered is: what is the optimal number of sub-batches in order to attain the optimal objective and how to find it?

1.3 Content of the dissertation

The dissertation consists of eight chapters as follows:

In chapter 1, *Mathematical model of FMS scheduling problem* is defined.

In chapter 2*, Lot streaming technique* is given.

In chapter 3, *Global minimum of production time of job shop systems is analyzed.*
In chapter 4, *Joinable Schedule Approach (JSA)* is discussed.
In chapter 5, *Global minimum of production time of flow shop systems and the determination the effective delivery reliability* by *JSA are analyzed*
In chapter 6, *Break and Test Method (BTM) is discussed.*
In chapter 7, *Case studies of job shop and flow shop problems are given.*
In chapter 8, *Conclusions and recommendations* are discussed.

2. Scientific methods used and the research results

2.1 Global minimum of production time for job shop systems

We used in the dissertation a mathematical model of FMS scheduling which is described in [19 to 22]. This model consists of the following: jobs description, machine groups, processing time data, production time periods, production system types, setup times consideration, scheduling criterion, objectives to be achieved.

• *Jobs, machine groups*

The problem considered in this research is an FMS scheduling problem which can be formulated as a question: How to schedule FMS consisting of a set of **different** machine groups *M* (*1, 2…, m-1, m … M*) to process a set of **different** jobs (bathes) *J* (*1, 2… j-1, j …J*) of **different** volumes $n_1, n_{2\dots} n_j$ through a set of **different** operations (*1, 2…k…K*) by **different** processing time.

• *Processing time data*

The processing time of one part is determined as $\tau_{k,k',m}$ where *k* and k' express the given operation and the next operation to be processed on machine group *m*. The processing time can be also expressed as $\tau_{j,m,k}$ where *j* indicates the job index. The integer *k* expresses the order number of the given sequence. (That is, if the machine group consists of M_m number of machines, the time necessary for one machine is divided by M_m). The processing time values are determined by the process planning sub-system of CAPP, including manufacturing data determination (optimization). In this research, as in the most of the cases, only $\tau_{j,m}$ will be used (*k* – is omitted) because the order number of operations does not have any role.

This research deals with FMS scheduling problem for both types: Flow Shop System (FSS) and Job Shop System (JSS). These systems are based on the route (processing order) of the jobs to be processed. (Considering CIM systems it is supposed that the order of processing is determined by the manufacturing sequences planning sub-system of Computer Aided Process Planning (CAPP)). In FSS, all jobs visit the machine groups in the same route whereas in JSS, any route of the jobs among the machine groups is possible.

• *Setup times consideration*

When a machine group switches from processing one batch to another, setup time is necessary for preparing the new process. This is concerned with the necessary changes in machine conditions, tools, fixtures conditions; parts transport delays and so on. The setup time could be composed of different elements: changing time, handling time, break time, transport time, delay time and so on.

It is remarkable that the transport time and setup time are very different quantities. But, sometimes, these can be treated in the same manner.

In FMS, the setup times are usually much shorter than the process times; otherwise the systems could be hardly called flexible.

In the present research, setup times are considered. For simplicity, the setup time of any machine group *m* to process job *j* is indicated as $\delta_{j,m}$.

• Production time period

The production time period will be considered is the same for all of the jobs. The time period is indicated by "T_{sch}" which can be considered as the length of a shift, of a day, of the week, common delivery date or so on. In the present research, the time period is a common delivery date (*d*). $T_{sch} = d$. The other case when the jobs have individual delivery times is the topic of future research.

• ***Scheduling criterion***

In the present research, for estimation the goodness of schedules we will use the value of the maximum production (completion) time required to process all jobs. This dimension is called makespan. It is highly used in practice, simple and effective to apply. Makespan is usually indicated in the literature as C_{max} (see: [1, 2]). Here we use for that t_{pr}. Of course, $t_{pr} = C_{\max}$.

A very important quantity which is obtained from the mathematical model is the global minimum of production time. The global minimum is used as a reference value.

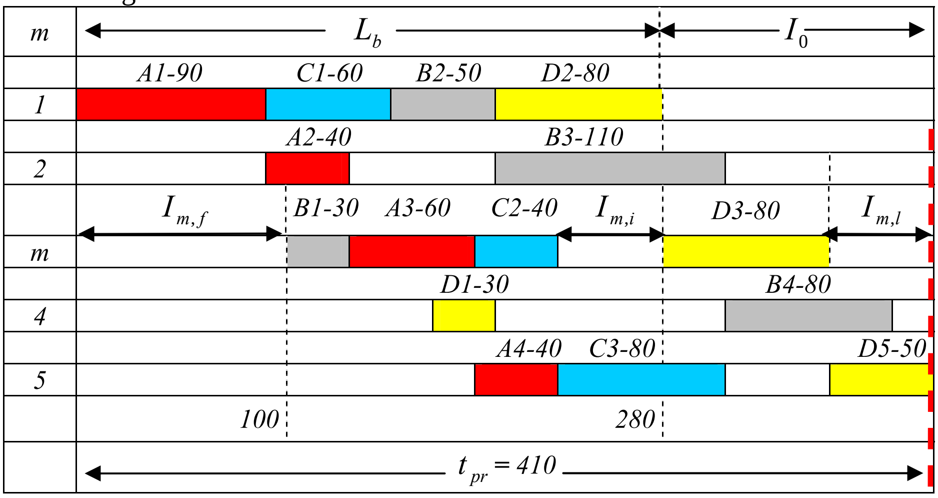

Figure 1: JSS Gantt chart of the initial schedule

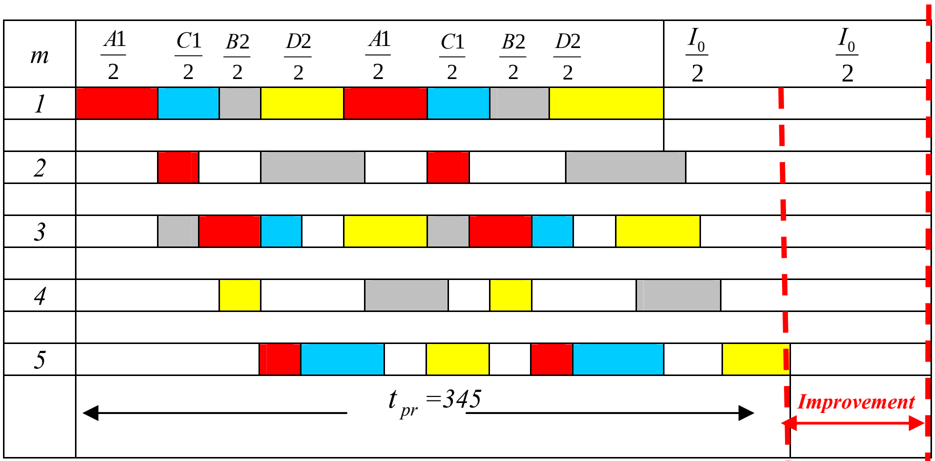

Figure 2: JSS Gantt chart of the lot streaming schedule

From the mathematical model we review here only the following:

The production time of a machine group with identification index *m*

$$t_m = L_m + S_m \qquad m=1, 2, 3...M \tag{1}$$

Where, L_m is the load time required time to process a number of jobs *J* on a machine group *m*. The load time of machine group *m* can be computed as follows:

$$L_m = \sum_{j=1}^{J} \tau_{j,m,k} n_j \qquad j=1, 2, 3 ...J \tag{2}$$

S_m is the sum of setup time of machine group *m* to process *J* jobs.

$$S_m = \sum_{j=1}^{J} \delta_{j,m} \tag{3}$$

The maximum load L_b values, generally, belongs to the bottleneck machine group.

$$L_b = Max \ L_m \quad (4)$$

We assume that the bottleneck machine group has the maximum sum of setup times among all the machine group of the system. So, it is always satisfied if

$$S_b = Max \ S_m \quad (5)$$

The minimum of the maximum production time which is the global minimum of production time can be computed by

$$t_g = Max \ t_m = Max \ (L_m + S_m) \quad (6)$$

Clearly, it is impossible to construct any order of processing which could result less than this global minimum. So, the global minimum of production time for job shop system is

$$t_g = L_b + S_b \quad (7)$$

The maximum production time of initial feasible schedule is determined by (see: Figure 1)

$$t_{pr} = t_g + I_b \quad (8)$$

Where, I_b is the last idle time of bottleneck machine group $I_b = S_{nb} + I_0$ (9)

S_{nb} is the non-bottleneck stream setup time.

I_0 is the last net idle time of bottleneck without setup times, $\delta=0$.

The maximum production time for non-zero setup time model is

$$t_{pr} = L_b + S_b + S_{nb} + I_0 \quad (10)$$

The planning goal is to minimize the maximum of production time of the system as close to the global minimum of production time as possible.
The global minimum of production time is discussed in the chapter 1 of the dissertation.

2.2 Excess time coefficient

A new quantity so-called *Excess time coefficient* C_r is proposed to measure the quality of FMS scheduling system.

$$C_r = \frac{t_{pr}}{t_g} \quad (11)$$

The goal is to construct a schedule which satisfies the following quality requirements condition:

$$1 \leq C_r \leq C_{\max} \leq \Omega \quad (12)$$

Where, $C_{\max}$ is the maximum excess time coefficient. Its value is chosen from the planning permission range Ω. According to the conditions (12) and based on practical experience, we propose to classify the real schedule ($C_r > 1$) into three types according to the goodness parameters of $C_{\max}$, for example: ($C_{\max} = 1.1, 1.15, 1.2$) as follow:

a. *High quality schedule,* if $C_r = 1.1$
b. *Medium quality schedule,* if $C_r = 1.15$
c. *Low quality schedule,* if $C_r = 1.2$

One can recognize that these values seem very much satisfy practical goals. If the condition (12) is satisfied the maximum production time is close to the global minimum and this can be a good criterion for the systems performance. For suitable planning, the conditions (12) should be checked. If it is not valid, the planning is not successful.

- If $C_r = 1$ (13)

Then, the schedule is named by us ***ideal schedule***. The ideal schedule may generate when the maximum production time of the initial feasible schedule is equal to the global minimum of the production time ($t_{pr} = t_g$) and no idle time at the last of bottleneck machine group ($I_b = I_0 = S_{nb} = 0$).
For ideal schedule lot streaming is not necessary.
The excess time coefficient is discussed in section 3.4 of the dissertation.

2.3 Joinable Schedule Approach (JSA)

2.3.1 Joinable schedule approach for job shop systems

Joinable Schedule Approach (JSA) is a new analytical approach which can be used for specially formulated problems to find the optimal number of sub-batches. The basic idea of JSA is: “Feasible batch schedules are generated by a proper scheduling method. Then, joinability test is performed to check the possibility of joining the generated feasible schedule. If it is possible, the feasible schedule is a joinable schedule. Then, by lot streaming, the batches of the schedules are divided into integer number of sub-batches. The optimal number of sub-batches can be found using differentiation".

JSA procedures consist of 3-phases: *in building phase;* the initial feasible schedule is built using, for example, simulation methods. If the maximum production time of feasible schedules is very close to the global minimum of production time according to quality requirements condition the planning may be finished. If the production time does not satisfy the quality requirements, then, we will go to the next phase to find a suitable schedule the quality of which we intend to improve. *In testing phase,* joinability test is performed to find the joinable schedules in order to recognize whether the JSA method can be used or not. Particularly, a schedule is joinable if **a)** No idle times exist between the operations and in front of the bottleneck, $I_{bi} = I_{bf} = 0$. **b)** No overlapping occurs during joining for the active sections of the non-bottleneck machine-groups. JSA is given in chapter 4 of the dissertation.

If the initial feasible schedule is satisfying the following basic initial joinability condition, then, the schedule is joinable (see: Figure 1).

$$I_{mf} + I_{ml} \geq I_0 \qquad m = 1, 2, 3 \dots M \tag{14}$$

Where, I_{mf} , I_{ml} are the first (front) and the last idle times of machine group *m.*

In solving phase, let us assume that the initial schedule in Figure 1 is a joinable schedule. We can apply JSA by dividing the batches into equal number of sub-batches, for example, 2 sub-batches (Figure 2).

The lot streaming makespan for 2 sub-batches is $t_{pr}(2) = L_b + 2\,S_b + \frac{I_0}{2} + S_{nb}$ (15)

For *N* sub-batches, the makespan becomes $t_{pr}(N) = L_b + S_{nb} + N\,S_b + \frac{I_0}{N}$ (16)

The excess time coefficient is $C_r\,(N) = \beta_r + \varepsilon_r + N\,\theta_r + \frac{\phi_r}{N}$ (17)

Where, $\beta_r = \frac{L_b}{t_g}$, $\varepsilon_r = \frac{S_{nb}}{t_g}$, $\theta_r = \frac{S_b}{t_g}$, $\phi_r = \frac{I_0}{t_g}$ (18)

$\beta_r, \varepsilon_r, \theta_r, \phi_r$ are so-called bottleneck load coefficient, non-bottleneck stream setup time coefficient, setup relation coefficient, bottleneck idle time coefficient, respectively. The introduction of these coefficients is very much useful because they help to formulate results in dimensionless form.

To minimize C_r we differentiate $C_r\,(N)$ *w. r. t. N* of Equations (16) or (17) and equalizing to zero.

$$\frac{\partial t_{pr}}{\partial N} = \frac{\partial C_r}{\partial N} = 0$$

The optimal number of sub-batches can be determined by

$$N^* = \sqrt{\frac{I_0}{S_b}} = \sqrt{\frac{\phi_r}{\theta_r}} \tag{19}$$

It is easy to recognize that the optimal number of sub-batches can only be integer.

The integer values of real N^* *are:* $N_1^* = Int\left(N^*\right)$ *and*

$$N_2^* = Int\left(N^*\right) + 1 \tag{20}$$

The minimum makespan is

$$t_{pr}^* = L_b + S_{nb} + 2\sqrt{S_b I_0} \tag{21}$$

The optimum excess time coefficient is

$$C_r^* = \beta_r + \varepsilon_r + 2\sqrt{\theta_r \phi_r} \tag{22}$$

These equations give an opportunity to determine the maximum excess time coefficient decrease, the optimal values of setup time, sub-batch size, bottleneck utilization, the range of effective lot streaming, the lot streaming efficiency, and the optimal lot streaming time (*OLST*) diagram.

a) ***The maximum excess time coefficient decrease***, ΔC_r^*

$$\Delta C_r^* = (\sqrt{\phi_r} - \sqrt{\theta_r})^2 \quad (23)$$

Equation (23) estimates how the setup relation coefficient values affect the opportunity of improving the system performance. For bigger ϕ_r values significant improvement occurs. This improvement is restricted by the relation $\phi_r > \theta_r$. Lot streaming is always worth to apply if

$$\phi_r >> \theta_r \quad (24)$$

If the ϕ_r values for some feasible schedules are small the lot streaming is not needed to apply.

b) ***Estimation for optimal lot streaming time***

The lot streaming time is $T_{LS} = S_{b\,LS} + I_{b\,LS} = N\ S_b + \frac{I_0}{N}$ (25)

Where, $S_{b\,LS}$ is the lot streaming setup time, $I_{b\,LS}$ is the overlapping time.

The behavior of lot streaming time is shown in Optimal Lot Streaming Time *(*OLST) diagram in Figure 3. It is clear from Figure 3 that the T_{LS}^* occurs at the intersection where.

$$S_{b\,LS} = I_{b\,LS},\ N^* = \sqrt{\frac{I_b}{S_b}},\ S_{bLS}^* = I_{bLS}^* = \sqrt{I_b S_b} \quad (26)$$

The optimal lot streaming time is $T_{LS}^* = 2\sqrt{I_0 S_b}$ (27)

The lot streaming coefficient is $\zeta(N) = \frac{T_{LT}(N)}{t_g} = N\ \theta_r + \frac{\phi_r}{N}$ (28)

The optimal lot streaming coefficient is $\zeta^* = 2\sqrt{\theta_r \phi_r}$ (29)

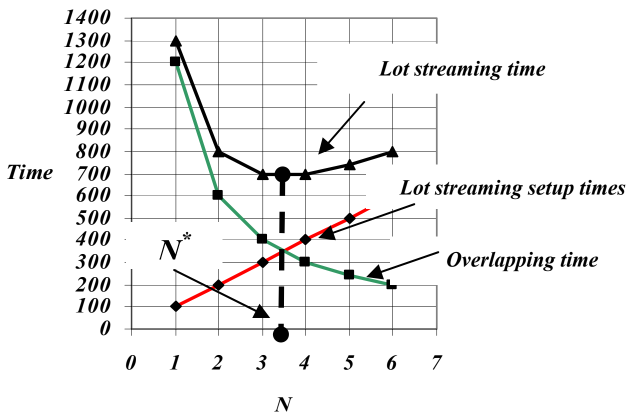

Figure 3: Optimal Lot Streaming Time (OLST) diagram

• ***Estimation for the optimal values of setup time***

It is extremely important to estimate how the setup time values affect the quality of scheduling.

The practical experience shows that most frequently the following relation is valid $I_0 \leq 0.5\, t_g$ **.** Then the following value $\phi_r = 0.5$ can be used for estimations.

From Equation (29), we get $\theta_r = \frac{1}{2}\zeta^{*2}$ (30)

Let us investigate the effect of lot streaming coefficient on the θ_r, for example,

$\theta_r(\zeta = 0.15) = 0.01125$, $\theta_r(\zeta = 0.1) = 0.005$, $\theta_r(\zeta = 0.2) = 0.02$

So, if the sum of setup times to the global minimum of production time is less than one hundreds, the processes obtained by using the JSA seem favorable. By relaxing the conditions the requirements for the quickness of setups are significantly decreasing. The opposite can be recognized at the increase of quality requirements. Therefore, the optimal values of θ_r^* is determined by

$$\theta_r^* \le \frac{1}{4}\frac{\zeta^{*2}}{\phi_r} \tag{31}$$

For suitable production planning and production system design (FMS design), the condition (31) should be provided. In practical cases the fulfillment of this condition should be checked. If it is not valid, the planning is not successful.

- ***The range of effective lot streaming*** is specified by :

$$1 < N < N^{*2} \tag{32}$$

- ***The optimal sub-batch size*** of job *j* is determined by:

$$Z_j^* = n_j \sqrt{\frac{S_b}{I_0}} \tag{33}$$

- ***Estimation for optimal delivery sub-batch number***

At the effective delivery reliability, the optimal delivery sub-batch number is determined by

$$N_{d1,2}^* = \frac{(d - L_b - S_{nb}) \pm \sqrt{D_b}}{2S_b} \tag{34}$$

Where, d is the common delivery date,

D_b is so-called *bottleneck discriminant*, where, $D_b = (L_b + S_{nb} - d)^2 - 4S_b I_0$ (35)

There are three values of bottleneck discriminant as follows:

a) *Positive bottleneck discriminant*: *If* $D_b > 0 \rightarrow d > t_{pr}^*$, there are two optimal (N_{d1}^*, N_{d2}^*) (Figure 4)

b) *Zero bottleneck discriminant:* *If* $D_b = 0 \rightarrow d = t_{pr}^*$, there is one optimal N_d^*.

c) *Negative bottleneck discriminant: If* $D_b < 0 \rightarrow d < t_{pr}^*$, there is no optimal.

The effective delivery reliability is formulated and analyzed in sections: *1.3.4, 5.5* of the dissertation.

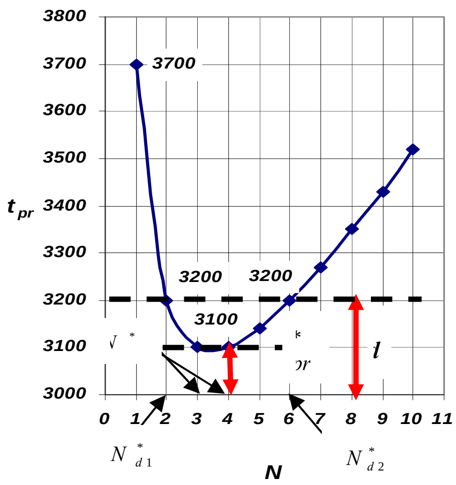

Figure 4: makespan curve and the delivery date.

The basis idea of JSA and its procedure are discussed in chapter 4 of the dissertation.

2.4 Global minimum of production time for flow shop systems

There is a difference between the global minimum of job shop systems and that of flow shop systems. In flow shop systems, the estimation of global minimum of production time the upstream and downstream processes of the bottleneck machine group should be taken into consideration (Figure 5). To determine the global minimum of the production time for the system, not only the production time of the bottleneck machine group should be considered but also the minimum of production time of the upstream and downstream processes of the bottleneck should be included.

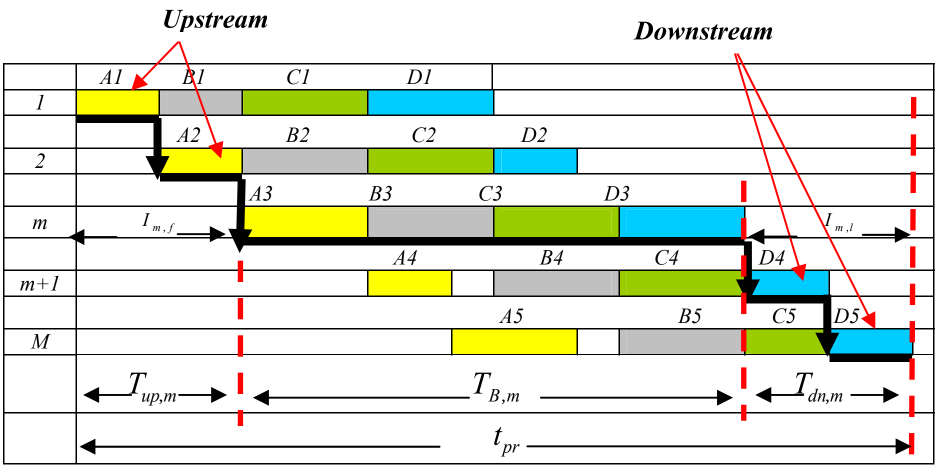

Figure 5: FSS Gantt chart with upstream, body and downstream production times

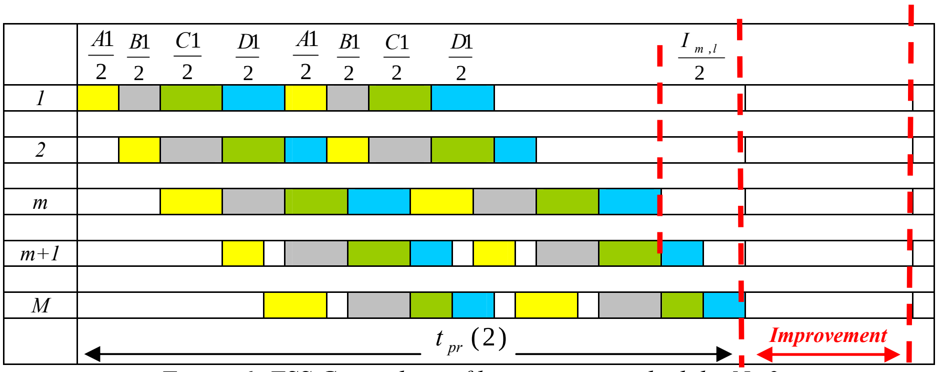

Figure 6: FSS Gantt chart of lot streaming schedule, N=2

The path production time of machine group *m* (see: Figure 5) is computed by.

$$t_{m,F} = T_{up,m} + T_{B,m} + T_{dn,m} \tag{36}$$

Where, $T_{up,m}$, $T_{B,m}$, $T_{dn,m}$ are the upstream , body and downstream production times.

The global minimum of production time is determined by the summation of the maximum body production time and the minimum values of the sum of upstream and downstream production times. The last term may be computed considering all the permutations of the jobs on the bottleneck group. The global minimum of production time is (see Figure 5)

$$t_{g,F} = T_{up,g} + T_{B,g} + T_{dn,g} \tag{37}$$

Where, $T_{up,g} = Min\, T_{up,m}$ is so-called bottleneck upstream production time

$T_{B,g} = Max\ T_{B,m}$ is the bottleneck production time.

$T_{dn,g} = Min\, T_{dn,m}$ is so-called the bottleneck downstream production time

The maximum production time of non-zero setup time model for FSS is

$$t_{pr} = t_{g,F} + I_{g,F} \tag{38}$$

Where, $I_{g,F}$ is the production idle time. It is the non-productive time of the overall production time.

The makespan is

$$t_{pr} = L_b + L_{up,g} + L_{dn,g} + S_b + S_{nb} + I_{g,F} \tag{39}$$

The global minimum of production time of job shop systems is discussed in chapter 5.

2.5 Excess time coefficient for flow shop systems

The excess time coefficient for flow shop systems is determined by

$$C_{r,F} = \frac{t_{pr}}{t_{g,F}} \tag{40}$$

The value of $C_{r,F}$ may be less than one, in contradiction with job shop case

According to the values of $C_{r,F}$ we can classify the real schedule into 4-types:

a. Feasible schedule if $t_{pr} \rangle t_{g,F} \rightarrow C_{r,F} \rangle 1$

b. Low quality schedule if $t_{pr} = t_{g,F} \rightarrow C_{r,F} = 1$

c. Medium quality schedule if $t_{pr} \langle t_{g.F} \rightarrow C_{r,F} \langle 1$

d. High quality schedule if $t_{pr} \langle\langle t_{g.F} \rightarrow C_{r,F} \approx 0$

2.6 Joinable Schedules Approach for flow shop systems

We suppose that the FSS initial feasible schedule in Figure 5 is joinable schedule.

From Figure 5, we get $L_{up,g} = I_{g,f}$, $L_{dn,g} = I_{g,l}$ (41)

We assume that the net idle time for flow shop system, $I_0 = I_{g,f} + I_{g,l} + I_{g,F}$ (42)

The makespan of flow shop system is

$$t_{pr} = L_b + S_b + S_{nb} + I_0 \quad (43)$$

In Figure 6, the batches are divided into 2 equal sub-batches.
The lot streaming makespan for 2 sub-batches is

$$t_{pr}(2) = L_b + 2\,S_b + \frac{I_0}{2} + S_{nb} \quad (44)$$

So, the lot streaming makespan is

$$t_{pr}(N) = L_b + S_{nb} + N\ S_b + \frac{I_0}{N} \quad (45)$$

Equations (43, 44, 45) are similar to the Equations (10, 15, 16) of job shop system.
So, the lot streaming flow shop problems can be treated similarly as the job shop problems; the equations for determining the optimal number of sublots stay the same; the estimation process of the effects of setup times is the same, too.
Generally, the equations of JSA using to solve JSS lot streaming problems can be used to solve FSS problems. The difference is the determination procedure to find the values of net idle time (I_0) and the non-bottleneck stream setup time (S_{nb}). This is because the operation characteristics of upstream and downstream production times of the bottleneck machine group have important role.

2.7 Conclusions of JSA applications for FMS lot streaming problems

When looking for the solution of scheduling problems for an FMS problem we can use a number of different approaches. In some of the cases (depending on the database of the problem) we can find some (at least one) feasible schedules which give very close to the global minimum completion time. If the schedule is suitable from other point of views, too, the planning may be finished. If the production time do not satisfy the quality requirements, and one can find joinable schedules, the outlined above can be used to find suitable schedules. The success of the above methodology depends on the values of the setup times. Of course, when the setup time values are big the given approach may not be used. What is big and what is small is always an open question. We have the conjuncture that when the setup times sum on the bottleneck machine-group is less then a hundreds of the production time of this machine-group the given approach gives good results. The reasoning which is given above highly supports this conjuncture.
The use of the “Joinable Schedules Approach” may lead to significant improvement of the quality of FMS schedules. The investigation of the problems and the realization of the results are extremely simple. The results outlined in the previous sections throughout the determination of the optimal number of sub-batches, give an opportunity to analyze the effect of the parameters of feasible schedules, setup times values, the effect of lot streaming, etc. In general, by applying JSA we can achieve the optimal number of sub-batches, minimum makespan, minimum excess time coefficient, maximum makespan utilization, maximum workflow acceleration, minimum idle time, optimal sub-batch size, maximum lot streaming efficiency, optimal lot streaming time, and optimal delivery sub-batches number. Finally, but not the last, by JSA method, the objective to be achieved are achieved, namely, highest makespan productivity, and effective delivery reliability.

2.8 Break and Test Method (BTM)

The basic difficulty in practical use of JSA is that it is not easy task to find the initial joinable schedule. To eliminate this difficulty, we propose a new method called *Break and Test Method (*BTM*)*. The essence of BTM is an enumeration search optimization method to find the suitable solution of lot streaming problems in order to achieve HMP and/or EDR. BTM is a sort of brute force approach. In BTM, the batches of proper feasible schedule are broken into a number of sub-batches using computer program as described in [17] and comparison test is made at each break until finding the proper number of sub-batches according to the specified objective. By BTM, we can solve the problem by a large number of solutions and compare them until a suitable solution is found; try many times until getting the best. BTM can be used for multi-machine group to process multi-job problems of both basic manufacturing systems: flow shop and job shop systems. BTM is given in chapter 6 of the dissertation.

2.8.1 BTM for job shop systems

By apply BTM phases; and using computer program [17] we can improve the productivity of job shop systems as shown in figures (7, 8). Figure 7 is the Gantt chart of the initial batch schedule for job shop system using FIFO rule. Figure 8 is the Gantt chart of lot streaming schedule using FIFO rule with *N =8*. It is clear that the makespan is decreased; consequently, the productivity (utilization) is improved. The excess time coefficient curves for FIFO and MS rules using BTM are illustrated in Figure 9.
The application of BTM for JSS problems are given in 6.3 of the dissertation.

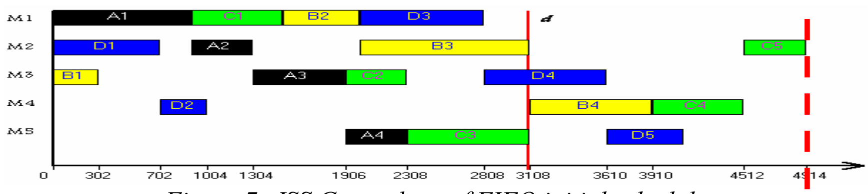

Figure 7: JSS Gantt chart of FIFO initial schedule

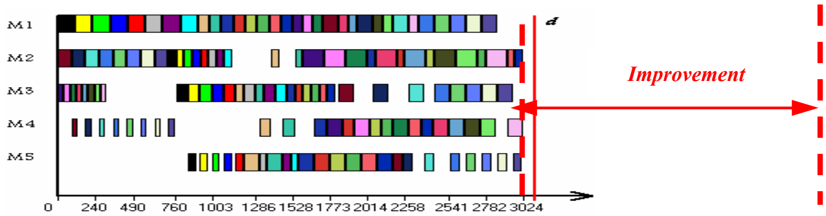

Figure 8: JSS Gantt chart of FIFO Lot streaming schedule, N = 8,

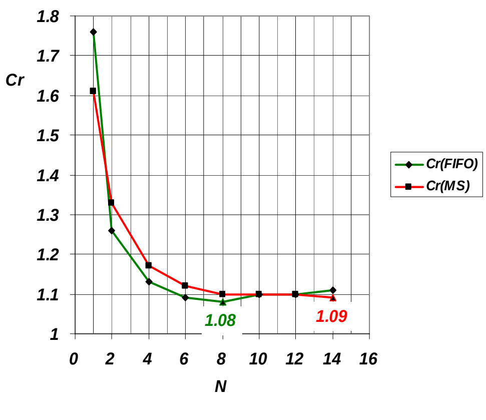

Figure 9: JSS Excess time coefficient curves of FIFO and MS

2.8.2 BTM for flow shop systems

Using BTM procedure, (similar to that of job shop systems) we can improve the productivity of flow shop systems. The Gantt chart of the initial schedule of certain flow shop system using FIFO rule is shown in Figure 10. Figure 11 illustrates FIFO Gantt chart of lot streaming schedule with *N =4*.

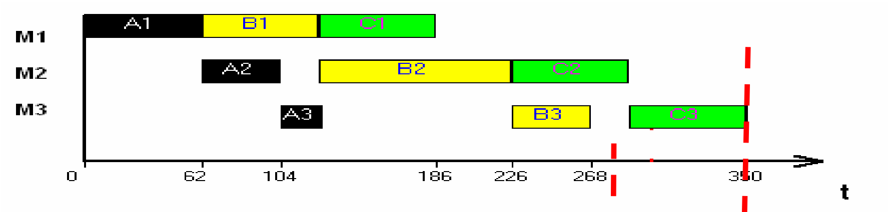

Figure 10: FSS Gantt chart of FIFO initial schedule

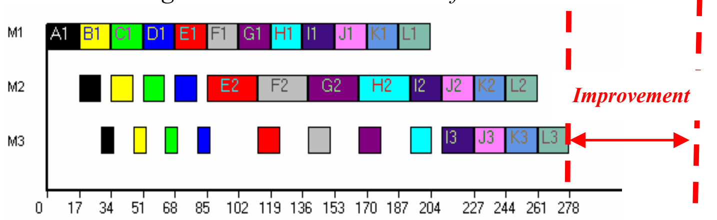

Figure 11: FSS Gantt chart of FIFO lot streaming schedule, N=4

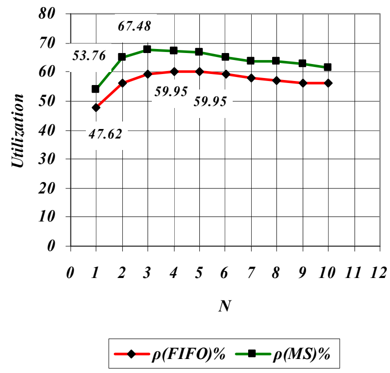

Figure 12: System utilization curves by BTM of FIFO and MS rules

As it is observed that the makespan is decreased, consequently, the productivity (utilization) is increased. The utilization curves for FIFO and MS rules using BTM for flow shop systems are illustrated in Figure 12.

The application of BTM for FSS problems are given in 6.5 of the dissertation.

2.9 Case studies

2.9.1 JSS case studies

The BTM is applied for the case studies of job shop systems. The productivity is improved by different rates (Figure 13) except one case where the global minimum is equal to the makespan, and $C_r = 1$ (Figure 14). In this case, lot streaming is not effective; JSA and BTM are not needed to apply.

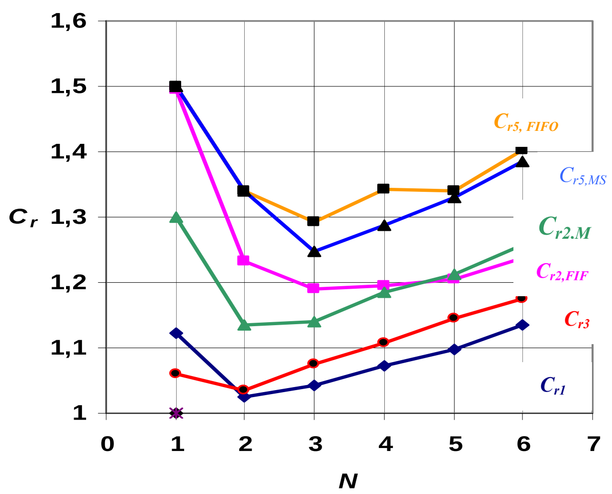

Figure 13: Excess time coefficient curves of 5-JSS case studies using BTM

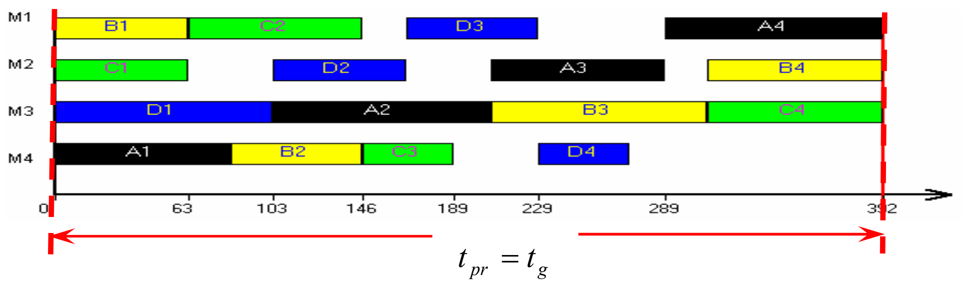

Figure 14: FIFO, MS Gantt chart of JSS initial schedule of case No 4

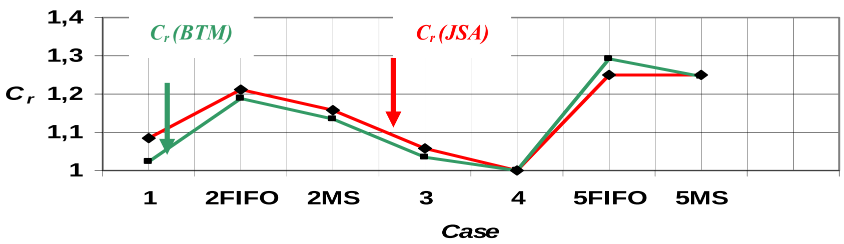

Figure15: Optimum excess time coefficient curves of JSS cases using BTM and JSA

The comparison analysis between the results of BTM and JSA is performed. The values of applications of both methods BTM and JSA for the given cases are almost the same. The curves of BTM and JSA are illustrated in Figure 15.

Generally, the results are favorable. As a result, it can be concluded that JSA and BTM are effective approaches to solve lot streaming problems for multi-machine /multi-job of FMS scheduling for both: job shop systems and Flow shop systems.

The engineering database of case studies and comparison results are given in 7.2 of the dissertation.

2.9.2 The effect of setup times

The improvement of the productivity by lot streaming approach highly depends on the setup time values. As the setup times increase, the improvement decreases until certain point at which no improvement can be achieved (See: Figure 16).

The effect of setup time is discussed in the sections 7.4 of the dissertation.

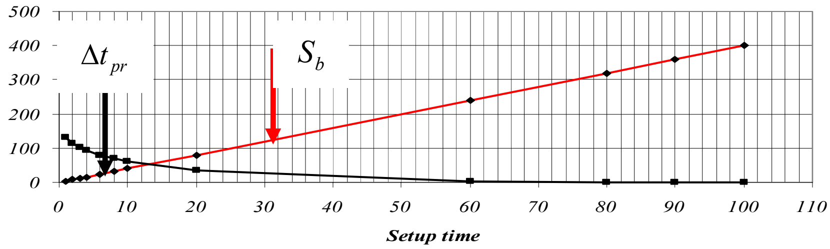

Figure 16: Effect of setup time on the makespan

2.9.3 FSS case studies

The BTM is applied for a number of case studies of flow shop systems. The productivity is improved by different rates (Figure 17). The comparison analysis between the results of BTM and JSA is performed. The values of applications of BTM and JSA for the given cases of FSS lot streaming problems are the same results. The curves of BTM and JSA are totally conformance (Figure 18)

The engineering database of case studies and comparison results are given in 7.5 of the dissertation.

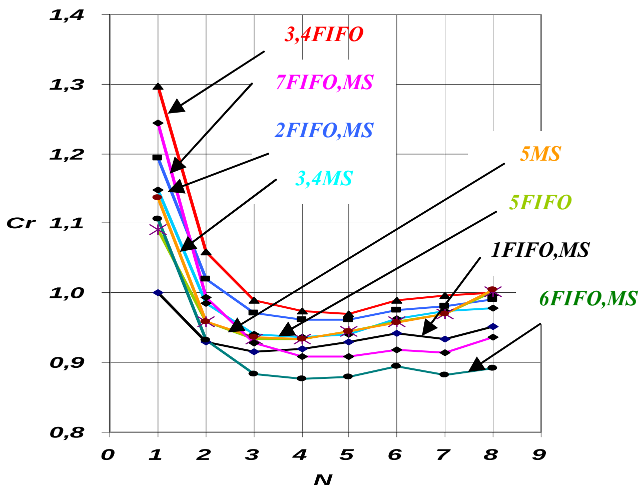

Figure 17: Excess time coefficient curves of 7- FSS case studies using BTM

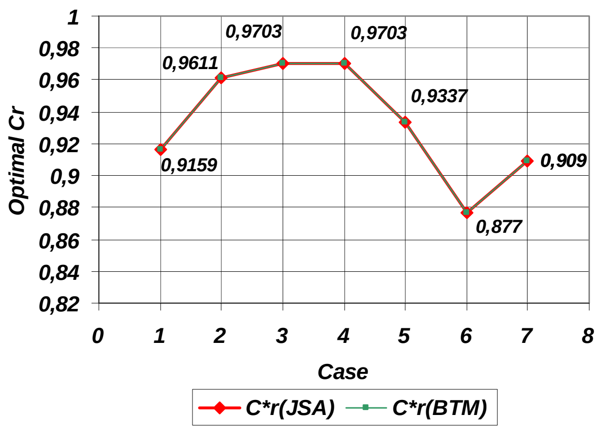

Figure 18: FSS Optimal excess time coefficient curves BTM and JSA

3. New Results (Thesis points)

The new contributions of PhD work are the following thesis points:

Thesis 1

A new lot streaming strategy was proposed for solving FMS scheduling problems of job shop systems, using so-called *Global minimum of production time* as *reference value* and based on the bottleneck scheduling approach. The global minimum of production time is determined by the production time of bottleneck machine group which has the maximum summation of the load time and the sum of the setup time (if it is taken into consideration). The goal is to determine the effective lot streaming strategies by going as close to the global minimum of production time as possible. When at least one feasible schedule is found which realize the global minimum (or a value slightly over this) lot streaming should not be applied. In other case, lot streaming, due to batch breaking and overlapping production, may result very favorable, effective and efficient schedules.

This thesis was published in (19)

Thesis 2

I proposed a new criterion to measure the goodness (quality) of the schedule for job shop systems based on the global minimum of production time so-called *Excess time coefficient*.

Excess time coefficient is defined as the mathematical ratio of the maximum production time (Makespan) to the global minimum of production time of the manufacturing system.

If the excess time coefficient of the feasible schedule is equal to one, the schedule is so-called *ideal schedule*. In this case, lot streaming is not necessary.

This thesis was published in (23)

Thesis 3

I proposed a new method to improve the quality of FMS scheduling for job shop systems called *Joinable Schedule Approach (JSA).* The objective is to find the optimal number of sub-batches for multi-machine group/multi-job problems. The sub-batches are considered by breaking the original number of products in the jobs by same number. I stated the basic idea of JSA and its procedures. JSA may be used to improve the quality of schedules when the feasible schedule is joinable. This means a) The schedule provides operations for the bottleneck machine group without idle times and b) Moving the schedules together (join) the operations do not overlap. The joined schedules provide a model for the determination of the production times taking into account setup times, too. Then, through an optimization procedure the optimal number of sub-batches may be determined. Using the relations the effect of setup times can be estimated. Joinability can be checked by the proposed *joinability test.* The new relations developed during the research work are:

The optimal number of sub-batches is $N^* = \sqrt{\frac{I_0}{S_b}} = \sqrt{\frac{\phi_r}{\theta_r}}$ (1)

The integers of real N^* *are:* $N_1^* = Int(N^*)$ *and* $N_2^* = Int(N^*) + 1$ (2)

The minimum makespan is $t_{pr}^* = L_b + S_{nb} + 2\sqrt{S_b I_0}$ (3)

The optimum excess time coefficient is $C_r^* = \beta_r + \varepsilon_r + 2\sqrt{\theta_r \phi_r}$ (4)

These relations give an opportunity to determine the optimal values of very important quantities such as setup time, sub-batch size, bottleneck utilization, the range of effective lot streaming, the lot streaming efficiency, and the optimal lot streaming time diagram. It makes possible to analyze the effect of setup times.

This thesis was published in (20)

Thesis 4

A new lot streaming strategy was proposed for flow shop scheduling problems. The lot streaming flow shop scheduling problems can be treated similarly as the job shop problems. The great difference with job shop problems is that of the determination of *global minimum of production time*. In flow shop systems, the upstream and downstream operations of the bottleneck machine group should be also taken into account.

A similar idea of *excess time coefficient* can be used for flow shop systems. But the essence and the parameters significantly differ for job shop systems and flow shop systems. In flow shop systems, by lot streaming the value of excess time coefficient becomes lower than one.

The *joinable schedule approach (JSA)* is equally applicable for flow shop problems when the feasible schedules are joinable.

This thesis was published in (21, 22)

Thesis 5

I proposed in this research a new other method to solve lot streaming problems for both systems: flow shop system and job shop system in order to achieve highest makespan productivity and effective delivery reliability. This method is so-called *Break and Test Method (BTM).*

I stated the basic idea of BTM and its procedure. It is based on the scheduling objective and the initial condition of the problem. The jobs are also divided into equal number of sub-batches and the processes are determined by simulation.

In comparing BTM with JSA, BTM has a different basic idea, different procedure and different test.

This thesis was published in (17)

Publication

1. Conway R.W., W.L. Maxwell, L.W. Miller, 1967. "Theory of Scheduling" Dover Publications, Inc. New York.

2. French S., B.A., M.A., D.Phil., 1982.”Sequencing and Scheduling: An Introduction to the Mathematics of the Job-shop” ELLIS HORWOOD Ltd. England.
3. Pinedo M., 2001. “Scheduling Theory, Algorithms, and Systems”, 2nd Edition, Prentice Hall, New Jersey.
4. T’kindt V., J. Billaut, 2002. “Multicriteria Scheduling, Theory, Models and Algorithms”, Springer, New York.
5. Brucker P., 2004. “Scheduling Algorithms” 4th Edition, Springer-Verlag, Berlin, Heidelberg, New York.
6. Pinedo M., 2005. “Planning and Scheduling in Manufacturing and Services” Springer series in Operations Research.
7. Szendrovits A.Z., 1975, "Manufacturing cycle time determination for multi-stage economic production quantity model" Management Science, 22, 3, 298-308.
8. Dauzere-Peres S., J. Bernard Lasserre, 1993 “An Iterative Procedure for Lot Streaming in Job-shop Scheduling” Computer and Industrial Engineering, V. 25, Nos 1-4, pp. 231-234.
9. Dauzere-Peres S., J.-Bernard Lasserre 1997 ”Lot Streaming in Job-Shop Scheduling” Operations Research, 4, V. 45, pp. 584-595.
10. Chan F.T.S., T. C. Wong and P.L. Chan, (2004). “Equal Size Lot Streaming to Job shop Scheduling Problem using Genetic Algorithms”, proceedings of the IEEE International Symposium on Intelligent Control, Taiwan.
11. Sarin S. C., P. Jaiprakash, 2007, "Flow Shop Lot Streaming" Springer, Science Business Media, LLC, Virginia, USA.
12. J. R. Perkins and P. R. Kumar, 1989. “Stable, Distributed, Real Time Scheduling of Flexible Manufacturing/ Assembly/ Disassembly Systems” IEEE transaction automatic control, V. 2.
13. J. Somlo, 2001. “Hybrid Dynamical Approach Makes FMS Scheduling More Effective” Periodica Polytechnica Series Mechanical Engineering. V.45, No. 2, pp. 175-200
14. Matveev, A. S., Savkin, A. V., 2000. “Qualitative Theory of Hybrid Dynamical Systems” Birkhauser, pp. 348.
15. J. Somlo, A. V. Savkin, 2006. “Periodic and Transient Switched Server Schedules for FMS” Robotics and Computer-Integrated-Manufacturing, 22, 93-112.
16. J. Somlo, A.V. Savkin, A. Anufriev, T. Koncz, 2004. “Pragmatic Aspects of the Solution of FMS Scheduling Problems Using Hybrid Dynamical Approach” Robotics and Computer-Integrated-Manufacturing 20, 35- 47.

Related publications of the author

17. Kodeekha Ezedeen, 2007 “Brute Force Method for Lot Streaming in FMS Scheduling Problems” Proceedings of 11th International Conference INES2007 at June 29 -July 1, pp.:179 – 184 on Intelligent Engineering Systems, , Budapest Hungary.
18. Kodeekha Ezedeen, 2004 "A new method of FMS scheduling using optimization and simulation" Proceedings 16th European Simulation Symposium, SCS Press.
19. Janos Somlo and Kodeekha Ezedeen, 2007 “Improving FMS Scheduling by Lot Streaming” Journal of Periodica Polytechnica Series (BUTE), Mechanical Engineering, 51/1, 3-14 Budapest -Hungary.
20. Janos Somlo and Kodeekha Ezedeen, 2007, “Optimal Lot Streaming for a Class of FMS Scheduling Problems-Joinable Schedule Approach-” Proceedings of IFAC International Federation of Automatic Control Symposium CEFIS’07 on October 9-11.Istanbul- Turkey.
21. Janos Somlo and Kodeekha Ezedeen, 2008 “Improvement of FMS Scheduling Efficiency by Optimal Lot Streaming for Flow Shop Problems”, Proceedings of 6th National Conference ME2008, Faculty of Mechanical Engineering, BME, 29-30 May. Budapest-Hungary.
22. Kodeekha Ezedeen, 2008, "Case Studies for Improving FMS Scheduling by Lot Streaming in Flow-Shop Systems" International Journal of Applied Sciences, Vol. 5, No. 4, pp. 125-143.
23. Janos Somlo and Kodeekha Ezedeen, 2008 “Optimal Lot Streaming for FMS Scheduling of Flow Shop Systems” proceedings of 12th International Conference INES2008 Intelligent Engineering Systems, on February 25-29 2008. Miami, USA.