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APPROXIMATION METHODS FOR DISCRETE LOT STREAMING IN FLOW SHOPS*

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Abstract

Lot streaming is the process of splitting a job or lot to allow overlapping between successive operations in a multistage production system. This use of transfer lots usually results in a shorter makespan for the corresponding schedule. In this paper, we present two quickly obtainable approximations of very good quality for the discrete lot streaming problem in flow shops.

1 Introduction

Lot streaming is the process of using transfer batches to move the processed portion of a production lot to downstream machines so that the makespan of the schedule can be shortened and the work-in-process inventory levels can be lowered. The term was introduced by Reiter[15], but the idea has been considered many times under different names. The increased interest in its applications over the last few years is probably due to the fact that it is consistent with the Just-In-Time (JIT) philosophy of making small sublots. It also agrees with the basic idea of the OPT scheduling package [7].

Szendrovits [16] analyzes the lot streaming problem in a flow shop for a single job with equal sublot sizes. Goyal [8] finds the optimal sublot sizes in Szendrovits' model. Moily [12], Jacobs and Bragg [10], Kulonda [11] and Graves and Kostreva [9] also demonstrate reductions in production time and cost by using transfer lots.

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Steiner and Truscott [17] find the optimal lot streaming schedules in an open shop with equal size transfer lots and no idling on the machines. Cetinkaya and Gupta [3] analyze the lot streaming problem for a single job in a flow shop with the total flow time criterion.

Most papers on lot streaming consider the objective of minimizing the makespan in an m-machine flow shop where each item is processed on the m machines in the order $1, \ldots, m$. Trietsch, in [18] and [19], and Baker [1] independently develop a conceptual framework for the problem. They present a classification scheme and review the most important results in [20]. Vickson [21] solves the lot streaming problem for multiple jobs in a two-machine flow shop with job setup times and sublot transfer times.

In this paper, we consider the problem of minimizing the makespan by splitting a single job of U items into s *discrete* (integer valued) sublots in an m-machine flow shop. More formally, we have m machines, denoted by $M_1, M_2, ..., M_m$, and each item of the job has positive processing times $p_1, p_2, ..., p_m$ on $M_1, M_2, ..., M_m$, respectively. If $x_{i,j}$ $(i = 1, \ldots, m,\ j = 1, \ldots, s)$ is the size of the jth sublot on M_i, then our objective is to find the integer $x_{i,j}$ values which minimize the makespan. If the integrality requirement for the $x_{i,j}$ is relaxed, we have the *continuous version* of the problem.

Under the assumption of *item availability* individual items become available for processing at the next machine as soon as they are finished on the current machine (unit size transfer lots). We use the assumption of *batch availability,* i.e., items become available for processing at the next machine after the current machine finished processing the last item in their sublot (batch). For $m = 2$ there is no difference between the two assumptions, and Vickson and Alfredsson [22] solve the continuous makespan minimization problem for this case. The same problem is solved with detached setups in [4] and with attached setups in [2]. Another, frequently used model further relaxes the batch availability assumption by considering only *consistent sublots*, i.e., $x_{i,j} = x_{i+1,j}$ for $i = 1, \ldots, m-1,\ j = 1, \ldots, s$. In this case, we can write x_j instead of $x_{i,j}$.

Most analytical results assume batch availability and apply to the continuous version of flow shop problems. Baker [1] shows that linear programming can be used to find the consistent sublot sizes which minimize the makespan. Potts and Baker [14] show that for a single job, it is sufficient to consider identical sublot sizes on the first two machines, and on the last two machines. The $m = 2$ case is solved in [14] and in [18]. Glass et. al. [6] develop the solution to minimize the makespan for a single job in a three stage production process. Their algorithms compute the minimum makespan in $O(log\ s)$ time for both the flow shop and job shop problem.

Although we need integer valued solutions for most practical applications, much less is known about the discrete version of these problems. Trietsch and Baker [20] give dynamic programming algorithms which solve the two- and three-machine problem in

$O(s^2U)$ time. Vickson [21] uses bisection search to find the optimal integer solution in $O(s \log U)$ time for $m = 2$. Chen and Steiner [5] give a strongly polynomial solution, requiring $O(s)$ time, for the same problem. As Baker [1] points out, the best consistent sublot solution for the discrete version of the m-machine flow shop problem can be found by integer linear programming, however, this is not a satisfactory solution method in general.

In this paper, we present two *very good quality* approximative solutions for the discrete lot streaming problem in flow shops. Both approximations are derived from the best continuous solution in $O(s)$ time, so they can be quickly obtained for practical applications. The paper is organized as follows. Section 2 introduces a network representation for the problem. Section 3 presents the approximations for the two- and three-machine problem. Section 4 contains the approximation results for the $m > 3$ case. Concluding remarks are presented in the last section.

2 Network representation

It is known [14] that there is always a consistent sublot optimal solution if $m = 2, 3$. If $m > 3$, then consistent sublots are not necessarily optimal, but these are the only solutions obtainable in reasonable time even for the continuous version of the problem. Nevertheless, these are very useful, as they are easy to implement in practice and lead to substantial reductions in the makespan.

Let $C_{i,j}$ denote the completion time of sublot j on machine i ($i = 1, 2, .., m,\ \ j = 1, 2, ..., s$). The following constraints must be satisfied by any feasible solution.

1) Machine capacity constraints :

$$C_{i,j} \geq C_{i,j-1} + p_i\, x_j \qquad (\ i = 1, 2, ..., m, \qquad j = 2, ...s\ );$$

2) Production constraints :

$$C_{i,j} \geq C_{i-1,j} + p_i\, x_j \qquad (\ i = 2, ..., m, \qquad j = 1, 2, ..., s\ \ );$$

3) Initialization constraint :

$$C_{i,1} \geq \sum_{j=1}^{i} p_j x_1 \qquad (\ i = 1, 2, ..., m\ ).$$

4) $x_j \geq 0$ is integer $\qquad (i = 1, ..., m,\ j = 1, 2, ..., s).$

Following the approach in [13], such a solution can be represented by a network $N(x)$ which contains a vertex for each sublot on every machine (see Fig. 1). In the network, x_i ($i = 1, 2, ..., s$) is the ith sublot size. The directed arc from vertex (i, j) to vertex $(i + 1, j)$ ($i < m$) represents the production constraint that sublot j can be processed on machine $(i + 1)$ only if it is completed on machine i. The directed arc from vertex (i,j) to vertex $(i,j+1)$ $(1 \leq j < s)$ represents the machine capacity constraint that sublot $(j+1)$ can start on M_i only when the jth sublot is completed on it. The vertex (i,j) has weight $p_i x_j, 1 \leq i \leq m, 1 \leq j \leq s$.

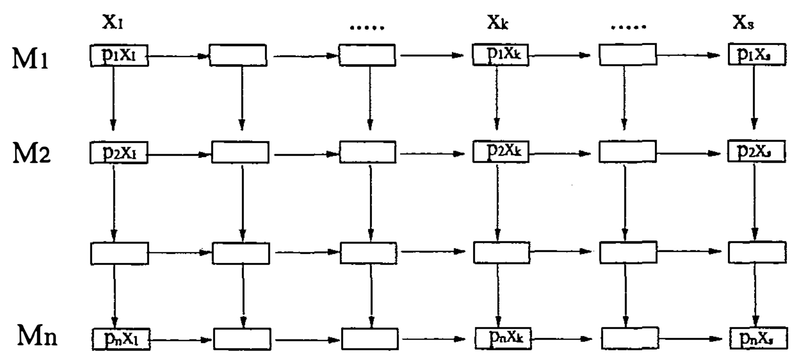

Figure 1: Network representation for a solution

Using the network representation, the objective becomes to determine the sublot sizes which minimize the length of the longest path in the network, where the length of any path is the sum of the weights of the vertices on it. Any longest path is referred to as a *critical path.* A subpath of a (critical) path is called a *(critical) segment.* Let $M(x)$ be the length of a critical path in $N(x)$.

Let $x^c = (x_1^c, ..., x_s^c)$ be the optimal solution (with consistent sublots) for the continuous version of the problem, with makespan M_c. Let $x^* = (x_1^*, ..., x_s^*)$ represent the optimal integer sublot sizes (with consistent sublots).

3 Two and three machines

We can obtain an integer solution $x' = (x_1', ..., x_s')$ from x^c as follows: Define $u = U - \sum_{i=1}^{s} \lfloor x_i^c \rfloor$. Let $x_i' = x_i^c$ if x_i^c is integer, and $x_i' = \lceil x_i^c \rceil$ for the first u sublots which are not integer in $N(x^c)$, and $x_i' = \lfloor x_i^c \rfloor$ for the rest of the sublots, where $\lceil x \rceil$ is the smallest integer greater than or equal to x and $\lfloor x \rfloor$ is the largest integer smaller than or equal to x.

3.1 Two-machine case

It can be easily seen that the optimal solution can be obtained in constant time for the case $p_1 = p_2$. Therefore, only the $p_1 \neq p_2$ case is of interest. The following result was proved in [5].

Theorem 1 $M(x^*) \leq M(x') < M_c + \min\{p_1, p_2\} \leq M(x^*) + \min\{p_1, p_2\}$.

3.2 Three-machine case

We must distinguish two cases, depending on whether $p_2^2 \leq p_1 p_3$ or $p_2^2 > p_1 p_3$.

Case 1 $p_2^2 \leq p_1 p_3$

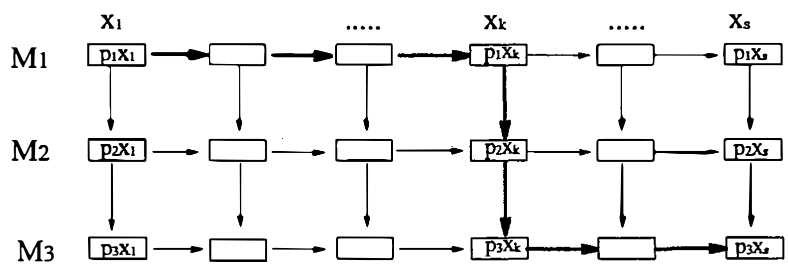

Figure 2: Network for the three-machine problem when $p_2^2 \leq p_1 p_3$.

For convenience, we assume that $p_1 \leq p_3$. We can similarly solve the reverse problem if $p_1 > p_3$, i.e., p_3,p_2,p_1 can be treated as the unit processing time on M_1, M_2, M_3, respectively.

Theorem 2 *If* $p_2^2 \leq p_1 p_3$, *then there exists a* k *such that segment* $(1,k)-(2,k)-(3,k)$ *is critical in* $N(x)$ *for* any *feasible solution* x.

Proof. Assume that no such sublot exists, then there must be i, j $(i < j)$ such that $(1,i) - (2,i) - ... - (2,j) - (3,j)$ is critical but $(2,i) - (3,i) - ... - (3,j)$ and $(1,i) - ... - (1,j) - (2,j)$ are not critical. Therefore, $(1,i) - (2,i) - ... - (2,j)$ should have a longer length than $(1,i) - ... - (1,j) - (2,j)$, i.e.,

$$p_1 \sum_{l=i+1}^{j} x_l < p_2 \sum_{l=i}^{j-1} x_l, \qquad (1)$$

and $(2,i)-...-(2,j)-(3,j)$ should have a longer length than $(2,i)-(3,i)-...-(3,j)$, i.e.,

$$p_2 \sum_{l=i+1}^{j} x_l > p_3 \sum_{l=i}^{j-1} x_l. \tag{2}$$

Multiplying (1) and (2) yields a contradiction with the assumption of $p_2^2 \leq p_1 p_3$.□

The critical path of Theorem 2 is shown with heavy lines in Figure 2.

Theorem 3 *If* $p_2^2 \leq p_1 p_3$, *then* $M(x^*) \leq M(x') < M_c + p_1 + p_2 \leq M(x^*) + p_1 + p_2$.

Proof. Let $\delta_i = x_i' - x_i^c$ for $i = 1, 2, ..., s$.

Let us denote the length of the path containing segment $(1,i)-(2,i)-(3,i)$ in $N(x')$ by $M_i(x')$. Then

$$\begin{aligned} M_i(x') &= p_1 \sum_{l=1}^{i} x_l' + p_2 x_i' + p_3 \sum_{l=i}^{s} x_l' \\ &= M_i(x^c) + p_1 \sum_{l=1}^{i-1} \delta_l + (p_1+p_2)\delta_i + p_3 \sum_{l=i}^{s} \delta_l \\ &= M_i(x^c) + p_1 \sum_{l=1}^{i-1} \delta_l + (p_1+p_2)\delta_i - p_3 \sum_{l=1}^{i-1} \delta_l \\ &< M_c + p_1 + p_2, \end{aligned} \tag{3}$$

where the third equality holds because $\sum_{l=1}^{s} \delta_i = 0$, and the inequality is true since $|\delta_i| < 1$ and $p_1 \leq p_3$.

Based on Theorem 2, $M(x') = \max_i M_i(x')$, so from (3) we obtain that $M(x^*) \leq M(x') < M_c + p_1 + p_2$. □

Case 2 $p_2^2 > p_1 p_3$

Theorem 2 is not necessarily true in this case. Let $g \leq h$ be such that the path $(1,1)-...-(1,g)-(2,g)-...-(2,h)-(3,h)-...-(3,s)$ is critical. The network structure is shown in Figure 3.

The first approximation x' reassigns all the fractional parts in the s sublots of the continuous solution to the *first* u noninteger sublots. In the following, we define a second integer approximation, denoted by $x'' = (x_1'', ..., x_s'')$, which redistributes the fractional parts in a more balanced fashion over the entire range of the sublots:

1. Define $\Delta_i = x_i^c - \lfloor x_i^c \rfloor$ for $i = 1, ..., s$. Let $x_i'' = x_i^c$ if x_i^c is integer for $1 \leq i \leq s$.

2. If x_j^c is the first noninteger sublot and $k \geq j$ is the first index such that $\sum_{l=j}^{k} \Delta_l \leq 1 < \sum_{l=j}^{k+1} \Delta_l$, then let $x_j'' = \lceil x_j^c \rceil = x_j^c + (1-\Delta_j)$, $x_l'' = \lfloor x_l^c \rfloor$ for $l = j+1, ..., k$.

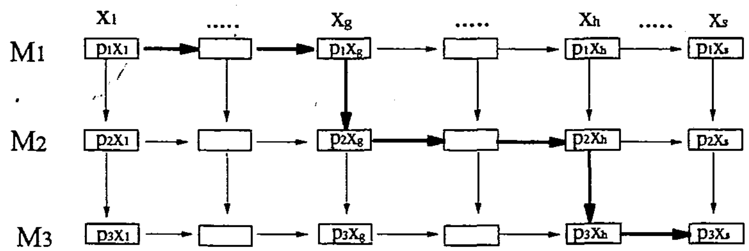

Figure 3: The network structure when $p_2^2 > p_1 p_3$.

Reduce x_{k+1}^c by the fractional amount $(1-\Delta_j) - \sum_{l=j+1}^{k} \Delta_l$ (what we have reassigned from it to $x_j^{"}$), and repeat the process from 2. for the next fractional j ($j \geq k+1$) in x^c.

For example, if we had $x^c = (12.3, 15.4, 18.7, 27.8, 36.3, 49.5)$, then $j = 1$, $1-\Delta_j = 0.7$ and $k = 2$ in the first iteration. We obtain $x_1^{"} = 13, x_2^{"} = 15$ and reduce x_3^c to 18.4, since 0.3 unit were moved from it to $x_1^{"}$. The next j is 3, $1-\Delta_j = 0.6$ and $k = 3$. We get $x_3^{'} = 19$ and reduce x_4^c to 27.2. Finally, the next j is $4, 1-\Delta_j = 0.8$ and $k = 6$, resulting in $x^{"} = (13, 15, 19, 28, 36, 49)$.

The following lemma states more precisely the balanced nature of the integer feasible solution $x^{"}$.

Lemma 4 *If $\delta_i^{"} = x_i^{"} - x_i^c$ for $i = 1, ..., s$, then*

i) $\left|\delta_i^{"}\right| < 1$ *for* $i = 1, ..., s$;

ii) $0 \leq \sum_{l=1}^{i} \delta_l^{"} < 1$ *for* $i = 1, ..., s$.

Proof. Both properties follow immediately from the definition of $x^{"}$.□

Theorem 5 $M(x^*) \leq M(x^{"}) < M_c + p_1 + p_2 \leq M(x^*) + p_1 + p_2$.

Proof. Let path $(1,1) - ... - (1,g) - (2,g) - ... - (2,h) - (3,h) - ... - (3,s)$ be a critical path in $N(x^{"})$ with makespan

$$M(x^{"}) = p_1 \sum_{l=1}^{g} x_l^{"} + p_2 \sum_{l=g}^{h} x_l^{"} + p_3 \sum_{l=h}^{s} x_l^{"}$$

$$\begin{aligned}
&= M_c + p_1 \sum_{l=1}^{g} \delta_l^{"} + p_2 \sum_{l=g}^{h} \delta_l^{"} + p_3 \sum_{l=h}^{s} \delta_l^{"} \\
&\leq M_c + p_1 \sum_{l=1}^{g} \delta_l^{"} - p_2 (\sum_{l=1}^{g-1} \delta_l^{"} + \sum_{l=h+1}^{s} \delta_l^{"}) + p_3 \sum_{l=h}^{s} \delta_l^{"} \\
&\leq M_c + p_1 \sum_{l=1}^{g} \delta_l^{"} + p_2 \sum_{l=1}^{h} \delta_l^{"} - p_3 \sum_{l=1}^{h-1} \delta_l^{"} \\
&\leq M_c + p_1 \sum_{l=1}^{g} \delta_l^{"} + p_2 \sum_{l=1}^{h} \delta_l^{"} \\
&< M_c + p_1 + p_2. \qquad (4)
\end{aligned}$$

In the inequalities, we have used the fact that $\sum_{l=1}^{s} \delta_l^{"} = 0$ and Lemma 4. □

4 The m-machine case

We study the two integer approximations individually. Let $\delta_i^{'} = x_i^{'} - x_i^c$ for $i = 1, ..., s$, and let $n(u)$ be the last index for which we rounded up, i.e. for which $x_i^{'} = \lceil x_i^{'} \rceil > x_i^c$.

Lemma 6 *At least one of following two properties should hold for the feasible solution $x^{'}$ in the $m-$machine case:*

1) $n(u) \leq s/2$ *or*

2) $\sum_{l=1}^{n(u)} \delta_l^{'} \leq s/2$.

Proof. Assume neither of the two holds, then $n(u) > s/2$ and $\sum_{l=1}^{n(u)} \delta_l^{'} > s/2$. Since $\sum_{l=1}^{s} \delta_l^{'} = 0$, we have

$$\begin{aligned}
\sum_{l=1}^{n(u)} \delta_l^{'} &= - \sum_{l=n(u)+1}^{s} \delta_l^{'} \\
&= \sum_{l=n(u)+1}^{s} \left| \delta_l^{'} \right| \\
&< s/2,
\end{aligned}$$

where the second equality follows from the definition of $n(u)$, and the inequality holds by the assumption $n(u) > s/2$ and the fact that $|\delta_l| < 1$. This yields a contradiction with the original assumption. □

Theorem 7 *For $m > 3$, the makespan of the approximation $x^{'}$ is within $\sum_{l=2}^{m} p_l + p_{\max} s/2$ of the optimal makespan, where $p_{\max} = \max\{p_1, ..., p_m\}$. More precisely,*

$$M(x^*) \leq M(x^{'}) < M_c + \sum_{l=2}^{m} p_l + p_{\max} s/2 \leq M(x^*) + \sum_{l=2}^{m} p_l + p_{\max} s/2.$$

Proof. Let $1 \le k_1 < k_2 < ... < k_f \le s$ denote the sublot on which a critical path "turns" in $N(x^{'})$, i.e., the path $(1,1) - ... - (1,k_1) - ... - (m_1,k_1) - ... - (m_1,k_2) - ... - (m,k_f) - ... - (m,s)$ is critical in $N(x^{'})$. Then

$$\begin{aligned}
M(x^{'}) &= p_1 \sum_{l=1}^{k_1} x_l^{'} + x_{k_1}^{'} \sum_{l=2}^{m_1} p_l + p_{m_1} \sum_{l=k_1+1}^{k_2} x_l^{'} + ... + p_m \sum_{l=k_f+1}^{s} x_l^{'} \\
&\le M_c + p_1 \sum_{l=1}^{k_1} \delta_l^{'} + \delta_{k_1}^{'} \sum_{l=2}^{m_1} p_l + p_{m_1} \sum_{l=k_1+1}^{k_2} \delta_l^{'} + ... + p_l \sum_{l=k_i+1}^{n(u)} \delta_l^{'} \\
&< M_c + \sum_{l=2}^{m} p_l + p_{\max}(\sum_{l=1}^{k_1} \delta_l^{'} + \sum_{l=k_1+1}^{k_2} \delta_l^{'} + ... + \sum_{l=k_i+1}^{n(u)} \delta_l^{'}) \\
&\le M_c + \sum_{l=2}^{m} p_l + p_{\max} s/2,
\end{aligned}$$

where the first inequality is true, as we omitted only nonpositive terms, and the last inequality holds by Lemma 6. □

Theorem 8 *The makespan of the approximation $x^{"}$ is within $\sum_{l=1}^{m-1} p_l$ of the optimal makespan. More precisely,*

$$M(x^*) \le M(x^{"}) < M_c + \sum_{l=1}^{m-1} p_l \le M(x^*) + \sum_{l=1}^{m-1} p_l.$$

Proof. Suppose the path $(1,1) - ... - (1,j_1) - (2,j_1) - ... - (2,j_2) - ... - (m,j_{m-1}) - ... - (m,s)$ is critical in $N(x^{"})$ for some $1 \le j_1 \le j_2 \le ... \le j_{m-1} \le s$. We have

$$\begin{aligned}
M(x^{"}) &= p_1 \sum_{l=1}^{j_1} x_l^{"} + p_2 \sum_{l=j_1}^{j_2} x_l^{"} + ... + p_m \sum_{l=j_{m-1}}^{s} x_l^{"} \\
&= M_c + p_1 \sum_{l=1}^{j_1} \delta_l^{"} + p_2 \sum_{l=j_1}^{j_2} \delta_l^{"} + ... + p_m \sum_{l=j_{m-1}}^{s} \delta_l^{"} \\
&= M_c + p_1 \sum_{l=1}^{j_1} \delta_l^{"} - p_2(\sum_{l=1}^{j_1-1} \delta_l^{"} + \sum_{l=j_2+1}^{s} \delta_l^{"}) - ... \\
&\quad - p_{m-1}(\sum_{l=1}^{j_{m-2}-1} \delta_l^{"} + \sum_{l=j_{m-1}+1}^{s} \delta_l^{"}) - p_m \sum_{l=1}^{j_{m-1}-1} \delta_l^{"} \\
&\le M_c + p_1 \sum_{l=1}^{j_1} \delta_l^{"} - p_2 \sum_{l=1}^{j_1-1} \delta_l^{"} + p_2 \sum_{l=1}^{j_2} \delta_l^{"} - ... - p_{m-1} \sum_{l=1}^{j_{m-2}-1} \delta_l^{"} \\
&\quad + p_{m-1} \sum_{l=1}^{j_{m-1}} \delta_l^{"} - p_m \sum_{l=1}^{j_{m-1}-1} \delta_l^{"} \\
&< M_c + p_1 + p_2 \sum_{l=1}^{j_2} \delta_l^{"} + ... + p_{m-1} \sum_{l=1}^{j_{m-1}} \delta_l^{"} \\
&< M_c + p_1 + ... + p_{m-1},
\end{aligned}$$

where we have repeatedly used $\sum_{l=1}^{s} \delta_l^{"} = 0$ and Lemma 4. □

It is clear that the approximations $x^{'}$ and $x^{"}$ can be obtained in $O(s)$ time from x^c.

5 Concluding remarks

We have presented two quickly obtainable solutions for the discrete lot streaming problem in an m-machine flow shop. Both represent very good quality approximations of the optimal solution with consistent sublots. For $m = 2$ or 3, the best continuous solutions are known to be balanced in the sense that the processing time of sublot j on M_i is as close to the processing time of sublot $j-1$ on M_{i+1} ($j = 2, ..., s$) as possible [14] and [6]. Since our approximations change the size of any sublot in the best continuous solution by less than 1, the resulting integer solutions are also close to being balanced. This is a very desirable property in practice, as it implies very low idle times in the corresponding schedule.

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