A Simulation Study of Dynamic Job Shops with Sequence-Dependent Setup Times under a Periodic Release Policy

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Abstract

In this paper we examine an order review / release policy that attempts to save on set up times in make-to-order manufacturing by grouping parts into products with similar production requirements and then releasing orders for these groups on a periodic basis. The setup time requirements are then dependent on the sequence of production: similar parts require less setup than dissimilar parts. We report on a simulation experiment that compares this periodic release policy against the immediate release policy where jobs are released to the shop floor as soon as an order is received. We find that while time spent by resources on setups is definitely saved by periodic release, there is a penalty to pay in regard to on-time delivery. We also identify some future research avenues.

Keywords: Production scheduling, periodic release, order review and release, dispatching, group technology.

1. Introduction

Shop floor control (SFC) is concerned with the detailed execution of plans in the manufacturing planning and control (MPC) systems framework [11]. Order review / release (ORR) is a component of SFC that monitors the orders to the shop floor coming from the planning part of the MPC framework and releases these orders to the shop floor for execution. The parts needed for production are released together with the order release. The dispatching component of SFC consists of setting priority of the jobs when jobs compete for resources. The importance of both ORR and dispatching in MPC is well established in the published literature.

This paper is concerned with ORR and dispatching for a job shop whose production can be classified into groups so that products in a group have similar manufacturing requirements. This can occur, for example, in the implementation of group technology, which is a management concept that endeavours to take advantage of similarity of tasks. Similarity of manufactured parts may be exploited by creating manufacturing cells devoted to a subset of the parts that are similar in their manufacturing requirements. With or without the use of
manufacturing cells, manufactured parts may be grouped to facilitate scheduling. When similar parts are scheduled together, the time needed for setup of equipment for a change-over of production within the family of parts is smaller and this will save valuable production time.

Often the setup time required at the beginning of a job is included in the processing time, but the setup times for some jobs may be dependent on the previous job processed at a resource. In such situations the scheduler can exploit the dependence by sequencing the jobs so that the time spent in setups is reduced. Job shop scheduling with sequence-dependent setup times has been previously considered in the research literature. Dispatching rules, which prioritise jobs waiting for a resource, based on the similarity of the waiting jobs with the job that was processed on the resource earlier, have been proposed and tested [5, 10]. In this paper we test a new ORR policy that releases groups of similar parts on a periodic basis. This periodic release policy is tested in conjunction with existing dispatching rules.

Next section presents a brief literature review that sets the background of this research. The research question is proposed next. This is followed by a description of the simulation model and the experiments performed on the simulation model. The results of the experiments are presented next. Finally, some concluding remarks are made.

2. Literature Review

Among the various activities in SFC, the two activities of ORR and dispatching have received considerable attention from researchers. The orders may be released immediately under a so-called immediate release (IMR) policy, or held in a pre-release file and released at appropriate times depending on the conditions prevailing in the shop floor. Often this is done with a view to balance order release with the capacity of the shop floor and to avoid congestion and delays. When an order is released, the corresponding material, on which the work is performed, is released too. Once a job is released, its priority in machine queues is determined by the dispatching rule used. More than 100 such dispatching rules have been proposed [9].

Browne and Davies [3] created a simulation model of a machine tool manufacturing facility, and tested a job releasing strategy where the job release time was determined by deducting their flow time from their due date. They reported improvement in due date performance irrespective of the dispatching rule used.

Melnik and Ragatz [7] propose a framework for ORR, which consists of 1) the order release pool, 2) the shop floor, 3) the planning system, and 4) the information system. The order release pool, which holds all the jobs released by the planning system but not yet released to the shop floor, is the focus of ORR. They stress that the key to effective shop floor control is in controlling the release of orders.

Ahmed and Fisher [1] found that there was a three-way interaction between due-date assignment, order release, and dispatching rule on the total cost performance of job shops. This total cost consisted of penalty costs and holding costs on work-in-process and finished goods. Their results were based on the study of a simulated dynamic job shop where early shipments were prohibited.

The literature on ORR is mature enough that a few reviews have been published. Wisner [13] has reviewed the order-release literature published before 1995. His findings indicate that most of the literature consists of reports of simulation studies. Among these there is a
preponderance of studies comparing immediate release and another release method. He also noted that the literature is not conclusive on the usefulness of order release mechanisms vis-à-vis dispatching rules.

While there is plenty of reported research on shop floor control for a general job shop, manufacturing with sequence-dependent setups has not received as much attention. Kim and Bobrowski [5] examined the performance of dispatching rules that took account of sequence-dependent setup times in a simulated job shop. They compared these setup-based rules against rules that did not consider setup times. Their results showed that the setup-based rules performed better for shop utilisation and product flow time, but worse for job tardiness. In a similar vein Vinod and Sridharan [10] found that setup-based dispatch rules performed better than ordinary rules in a simulation of sequence-dependent job shop; this effect was more marked when the shop load increased or the ratio of setup time to process time increased.

Guide and Srivastava [4] examined the use of periodic order release where batches of orders are periodically released in a remanufacturing facility and found that this did not perform any better for due date adherence than a simple “level” order release strategy (this is a periodic order release strategy with batch size of one). However, the setups in their study were not sequence-dependent.

Ashby and Uzsoy [2] have presented order release heuristics for a make-to-order manufacturing environment with sequence-dependent setups and dynamic job arrivals. The order release policies primarily consider job due date and manufacturing lead time in the selection of orders to be released, but if there is additional capacity the pool of orders is expanded by selecting further orders that will reduce the setup requirements. They reported that the order release heuristics combined with dispatching rules had an impact on the due date performance, and simulation studies showed that their methodology was superior to existing practice. However they considered a single stage production scenario.

McGee and Pyke [6] report on a periodic production scheduling where part families were scheduled on a periodic basis. These part families consisted of parts that needed only minor setups to change production between the parts in a family. Major setups were required to change over from one part family to another family. The batch sizes for a family were determined by considering the demand, setup cost, and carrying costs and optimising the total cost. However this approach applies to a make-to-stock production on a single machine where the costs and the demand are known.

Missbauer [8] uses an approximate queuing model to show that, in a shop floor with sequence-dependent setups, when an order release policy sets its work-in-progress (WIP) target low, it may cause more setups than necessary because it limits the probability of selecting work from the WIP to reduce the setups. In this way the throughput of the shop floor will be reduced. This is an argument for an order release policy to have a higher WIP target than would be the case if the setups were not sequence-dependent.

Whybark [12] introduces a “periodic control system” (PCS) which schedules production taking advantage of similarity in production requirements of manufactured components. It can be regarded as an application of group technology to scheduling. Orders are released to the factory floor in batches of similar products. The scheduling of jobs within these batches takes into account the time taken for the production change-over, with a view to reduce the total time spent in the change-overs. Significant improvements were reported in inventory turns and on-time deliveries after the introduction of this system into a manufacturing facility in Finland. In the terminology of Melnyk and Ragatz [7] PCS follows a bucketed timing
convention because the orders can be released only at periodic intervals. This concept of periodic release of similar parts is an innovation in order review / release that has not been examined before. The research described in this paper aims to address this gap.

3. Research Question

Past research [5, 10] has shown that there are benefits to using dispatching rules that are based on sequence-dependence of setup requirements. The goal of our research is to see if periodic release is beneficial when used with or without these dispatching rules.

We test periodic release in a simulated job shop whose products can be grouped by the similarity in their production requirements. The setup time needed in the job shop is zero if the last setup was for a product in the same group, otherwise the setup time depends on the group to which the product belonged.

The performance measures used in this research are: 1) machine utilisation, 2) manufacturing lead time, 3) flow time, 4) due date tardiness, and 5) time spent in setups. A full factorial experiment is carried out on a simulation model to compare periodic release against immediate release. The null hypothesis is that performance of the periodic release policy is not different from that of immediate release. The alternative hypothesis is that periodic release policy performs differently from immediate release on at least one measure of performance.

4. Simulation Model

A computer simulation model was constructed to test the performance of the periodic release policy. This model was a discrete-event model programmed in Visual Basic®. The model duplicates the model presented by Kim and Bobrowski [5] to a large extent. Jobs arrive at the job shop dynamically, following an exponential distribution of time between arrivals. The time between arrivals was set at 104 minutes, which was selected to cause an approximate machine utilisation of 90%. Arriving jobs are assigned randomly to one of six job types. There are 15 single-machine work centres in the job shop. The number of machines visited by a job is randomly picked from a uniform distribution of (1, 15). The particular machines visited are picked randomly from the 15 work centres, except that a job leaving a work centre may not visit the same work centre immediately afterwards. The processing time is assigned from an exponential distribution with a mean of 150 minutes. There is a setup time required at each work centre for each product type; the time for this depends on the previous product type processed at the work centre. The setup time matrix is given in Table 1. This setup time provides a mean set up time that is approximately 20% of the mean processing time.
Table 1

Setup Time Matrix (Minutes)

<table>
<thead>
<tr>
<th>Preceding product type</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>36.6</td>
<td>26.4</td>
<td>35.4</td>
<td>31.8</td>
<td>18</td>
</tr>
<tr>
<td>2</td>
<td>47.4</td>
<td>0</td>
<td>58.2</td>
<td>46.8</td>
<td>28.8</td>
<td>27.6</td>
</tr>
<tr>
<td>3</td>
<td>15.6</td>
<td>36.6</td>
<td>0</td>
<td>31.2</td>
<td>34.2</td>
<td>15.6</td>
</tr>
<tr>
<td>4</td>
<td>24.6</td>
<td>25.2</td>
<td>31.2</td>
<td>0</td>
<td>37.2</td>
<td>9</td>
</tr>
<tr>
<td>5</td>
<td>31.8</td>
<td>18</td>
<td>45</td>
<td>54</td>
<td>0</td>
<td>36.6</td>
</tr>
<tr>
<td>6</td>
<td>28.8</td>
<td>27.6</td>
<td>37.2</td>
<td>30.6</td>
<td>47.4</td>
<td>0</td>
</tr>
</tbody>
</table>

Some of the assumptions in the simulated job shop are:

- A job started on a machine could not be interrupted until it was finished.
- Each work centre could process only one job at a time.
- The work centres suffered no breakdowns.
- The processing requirements for the jobs are known upon arrival of the job.

5. Experimental Factors

A complete factorial experiment was carried on the simulation model, with three factors: 1) order release rule, 2) dispatching rule, and 3) due date tightness. These factors are described next.

5.1 Order Release Rule

The order release rule could be either immediate release (IMR) or periodic release. With immediate release rule, jobs are released to the shop for processing as soon as they arrive. The material for the job is released and is placed in the queue of the first work centre on its routing.

With the periodic release rule, when a job arrives at the job shop, it is placed in a pre-release file. Periodically, jobs of the same type are released to the shop floor along with the components needed to process them. Figure 1 shows an example with a periodic release with a period of 100 minutes. At time 100, all products of type 1 in the pre-release file are released followed by product type 2 at time 200, etc. The cycle is complete at time 700 and repeats itself. The sequence of the product types is pre-determined by minimising the time needed to go through a cycle of setups i.e. through the solution of the corresponding travelling salesman problem.

![Figure 1. An example of periodic release sequence](image_url)
There is no clear theoretical basis for deciding on the period of the periodic release. If the period is small, it will not have much effect on the performance measures. On the other hand, if the period is large, there will be excessive tardiness in delivery. We implemented three levels of periodic release: with periods of 200, 500, and 1000 minutes. These are denoted by P200, P500, and P1000 respectively. Thus the levels of order release rule in the simulation experiments are: IMR, P200, P500, and P1000.

5.2 Dispatching Rule
Four dispatching rules were implemented in the simulation model: 1) critical ratio (CR), 2) similar setup (SIMSET), 3) job of smallest critical ratio (JCR), and 4) similar setup with critical ratio (SIMCR). These rules are described next.

Critical ratio (CR). This is a due-date based rule that picks a job from a work centre queue for processing based on the formula:

\[
CR = \frac{(Due \ date - time \ now)}{(total \ remaining \ process \ times)}
\]

The job with the least value of CR is picked first for processing. Any tie is broken by using the first-come-first-served rule.

Similar setup (SIMSET). This is a rule that exploits the similarity of setup. It picks a job from a work centre queue that will require the least setup time. Any tie is broken by using the first-come-first-served rule.

Job of smallest critical ratio (JCR): This rule is a compromise between the above two rules. It examines the work centre queue for any job of the same product type for which the work centre is currently set up. If a job is found that job is processed next, but if no such job is found the critical ratio is used to pick a job for processing next. Any tie is broken by using the first-come-first-served rule.

Similar setup with critical ratio (SIMCR): This is another compromise between SIMSET and CR, where jobs are prioritised based on the SIMSET rule, above, but any tie is broken by the CR rule.

5.3 Due Date Tightness
Due dates are assigned to incoming jobs at two levels: 1) loose and 2) tight. The due dates are determined by the formula:

\[
Due \ date = tightness \ factor \times (sum \ of \ processing \ times \ for \ the \ job + number \ of \ machines \ in \ the \ routing \times average \ setup \ time)
\]

This tightness factor was determined before the simulation experiments by running the model with immediate release and dispatching on a first-come-first-served basis. The loose due dates were set to render 20% of the jobs late, and the tight due dates were set to make 50% of the jobs late.
6. Response Variables

Five performance measures were monitored in the experiments: 1) tardiness, 2) manufacturing lead time, 3) flow time, 4) time spent in setups, and 5) machine utilisation. These measures are described below.

**Machine utilisation.** Machine utilisation is the ratio of the actual time spent by a work centre in processing and setup operations to the time the work centre is available.

**Manufacturing lead time.** This is the time from the arrival of a job at the job shop until its processes are completed. This includes the time spent in the pre-release files if a job is not released immediately on arrival.

**Flow time.** This is the time spent by a job after its release on the shop floor until all its processes are completed. It may be noted that manufacturing lead time and flow time are the same for the IMR order release policy.

**Tardiness.** When a job is finished, its tardiness is measured against the due date assigned on arrival. If the job is not late, the tardiness is zero; otherwise tardiness is the difference between the due date and the finish date.

**Time spent in setups.** This is the time spent by work centres on setups for a job.

7. Simulation Experiments

The simulation model described above was run for each level of each factor, in a factorial design, for a simulated time period of 12000 hours. To avoid the effect of starting up on an idle and empty state, the data collected in the initial 8000 hours were discarded. Each cell was replicated 15 times. To reduce variance, common random number streams were used for generating the jobs across the different factorial cells in the experiments.

7.1 Simulation Results

The results of analysis of variance (ANOVA) for the main effects are shown in Table 2. Order release rules are found to be significant for manufacturing lead time, flow time, tardiness, and time spent in setups. Dispatching rules are found significant for all the performance measures included in this analysis. Due date tightness was significant for all the measures except machine utilisation.
Table 2  
Results of ANOVA for the Main Effects – F and (p) Values

<table>
<thead>
<tr>
<th>Response Variable</th>
<th>Order Release</th>
<th>Dispatching Rule</th>
<th>Due Date Tightness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Machine utilisation</td>
<td>1.454 (0.226)</td>
<td><strong>253.75 (0.000)</strong></td>
<td>0.006 (0.941)</td>
</tr>
<tr>
<td>Manufacturing lead time</td>
<td><strong>104.56 (0.000)</strong></td>
<td>950.25 (0.000)</td>
<td>9.597 (0.002)</td>
</tr>
<tr>
<td>Flow time</td>
<td>3.429 (0.017)</td>
<td>951.25 (0.000)</td>
<td>9.774 (0.002)</td>
</tr>
<tr>
<td>Tardiness</td>
<td>435.85 (0.000)</td>
<td>293.20 (0.000)</td>
<td>352.84 (0.000)</td>
</tr>
<tr>
<td>Time spent in setups</td>
<td><strong>124.93 (0.000)</strong></td>
<td>8044.6 (0.000)</td>
<td>7.309 (0.007)</td>
</tr>
</tbody>
</table>

Values in bold are statistically significant at $p = 0.050$ level

To see which order release rules resulted in better performance, a Tukey pairwise comparison of means was carried out. The ranking of the order release rules and their mean performance measures is given in Table 3. The periodic release rules had a better mean utilisation than the immediate release rule, but the differences were not statistically significant. Immediate release produced significantly smaller manufacturing lead time than periodic release. Periodic release rules were better for flow time, but not significantly (the difference between P1000 and IMR was significant, but IMR was bracketed with P200 and P500; and P1000 was bracketed with P500 and P200). Immediate release performed better for the tardiness measure, compared to all levels of periodic release. In regard to time spent in setups, the P1000 was found significantly better than P500, which was again significantly better than P200 and IMR, which were bracketed together.

It is obvious from Table 3 that releasing similar jobs together helps periodic release significantly in reducing setups. Even though statistical significance was not attained, the results are better for periodic release policies in terms of machine utilisation and flow time as well. However, holding jobs in a pre-release file is detrimental to periodic release for its performance in manufacturing lead time and tardiness.
Table 3
Tukey Comparison of Means for Order Release

<table>
<thead>
<tr>
<th>Response Variable</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Machine utilisation</td>
<td>P1000 (0.86469)</td>
<td>P500 (0.86551)</td>
<td>P200 (0.86724)</td>
<td>IMR (0.86867)</td>
</tr>
<tr>
<td>Manufacturing lead time</td>
<td>IMR (150.86)</td>
<td>P200 (157.32)</td>
<td>P500 (170.15)</td>
<td>P1000 (192.92)</td>
</tr>
<tr>
<td>(hours)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flow time (hours)</td>
<td>P1000 (142.98)</td>
<td>P500 (145.18)</td>
<td>P200 (147.32)</td>
<td>IMR (150.86)</td>
</tr>
<tr>
<td>Tardiness (hours)</td>
<td>IMR (45.286)</td>
<td>P200 (62.560)</td>
<td>P500 (111.63)</td>
<td>P1000 (260.63)</td>
</tr>
<tr>
<td>Time spent in setups</td>
<td>P1000 (2.4125)</td>
<td>P500 (2.5388)</td>
<td>P200 (2.5755)</td>
<td>IMR (2.5865)</td>
</tr>
<tr>
<td>(hours/job)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figures in parenthesis are mean values. Rankings sharing the same underline are not statistically different at $p = 0.050$ level.

The results of Tukey pair-wise comparison of means for the dispatching rules are shown in Table 4. Dispatching rules taking cognizance of similarity of setups (SIMSET, SIMCR, and JCR) were found to be better than CR for the utilisation measure. These differences were all statistically significant. Same results followed for the measures of manufacturing lead time and flow time. CR and JCR were bracketed together and ranked better than SIMCR and SIMSET for the tardiness measure. SIMCR and SIMSET were bracketed together, and were better than JCR, which in turn was better than CR for the time spent in setups. It is noteworthy that SIMSET and SIMCR were bracketed together for all these measures; breaking ties in SIMSET rules with CR did not make a significant difference.

SIMSET and SIMCR are setup-oriented dispatching rules. They actively try to reduce time spent in setups by looking for similar jobs in the queues of resources. This is borne out by the results. Improvement in this area has the effect of reducing machine utilisation, manufacturing lead time, and flow time as well. CR is a tardiness-oriented dispatching rule and it does achieve its purpose by expediting jobs that are closer to being tardy. By single-mindedly pursuing tardiness, it lags behind in terms of the other measures.
Table 4

Tukey Comparison of Means for Dispatching Rule

<table>
<thead>
<tr>
<th>Response variable</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Machine utilisation</td>
<td>SIMSET (0.85206)</td>
<td>SIMCR (0.85479)</td>
<td>JCR (0.85761)</td>
<td>CR (0.90166)</td>
</tr>
<tr>
<td>Manufacturing lead time (hours)</td>
<td>SIMSET (137.19)</td>
<td>SIMCR (140.75)</td>
<td>JCR (141.63)</td>
<td>CR (251.69)</td>
</tr>
<tr>
<td>Flow time (hours)</td>
<td>SIMSET (115.98)</td>
<td>SIMCR (119.49)</td>
<td>JCR (120.41)</td>
<td>CR (230.46)</td>
</tr>
<tr>
<td>Tardiness (hours)</td>
<td>CR (45.79)</td>
<td>JCR (55.71)</td>
<td>SIMCR (183.01)</td>
<td>SIMSET (195.59)</td>
</tr>
<tr>
<td>Time spent in setups</td>
<td>SIMCR (2.1700)</td>
<td>SIMSET (2.1889)</td>
<td>JCR (2.2664)</td>
<td>CR (3.4880)</td>
</tr>
</tbody>
</table>

Figures in parenthesis are mean values. Rankings sharing the same underline are not statistically different at \( p = 0.050 \) level.

Some of the two-factor interactions between the three factors of the experiment were also found statistically significant at the \( p = 0.050 \) level. There were no significant interactions for the utilisation measure. For the manufacturing lead time measure, the significant interactions were between due date tightness and the dispatch rules, and between dispatch rules and order release rules. Interaction plots showed that combining CR with loose due dates markedly increased the lead times. This effect was seen for the flow time measure as well. On the other hand, using IMR with setup-oriented dispatching rules reduced lead times markedly. The effect of IMR in increasing the flow time was enhanced when CR was used as a dispatching rule. All the three 2-factor interactions were significant for the tardiness measure. Interaction plots showed that 1) combinations of SIMSET or SIMCR with tight due dates produced especially high tardiness. 2) P1000 was sensitive to due date tightness in increasing the tidiness; and 3) periodic release performed much worse with the SIMSET and SIMCR rules in regard to tardiness. As for the time spent in setups, there was significant interaction only between dispatch rules and order release rules: combining CR with immediate release resulted in especially high setup times.

8. Discussion

Any improvement in the performance of a job shop by a periodic release policy is brought about by the reduction in the time spent in setups. This is borne out by our experiments. The time spent in setups was significantly reduced by using periodic release policies. Higher periods between order-releases resulted in better performance. This was particularly accentuated under the SIMSET and SIMCR rules, which, by themselves, endeavour to reduce the setup times.
As a result, periodic release policy performed better than immediate release in regard to utilisation; however the differences were not significant statistically. The only significant arbiter of this performance measure was the dispatching rule used: SIMSET and SIMCR performed better than JCR, which was better than CR.

For the manufacturing lead time measure, immediate release was preferable to periodic release, similarity-seeking dispatching rules (SIMSET, SIMCR, and JCR) were better than CR.

For the flow time measure, SIMSET, SIMCR, and JCR performed about the same, but CR showed inferior performance. The performance of the similarity-oriented dispatching rules was obviously better because they exploited the sequence-dependence of the setups. This is in keeping with the findings of Kim and Bobrowski [5]. Comparing the order release rules, flow time was reduced by the periodic release policy, particularly with the higher periods between order releases. Flow time was significantly reduced by P1000 in comparison to IMR. The best performing dispatch rule (SIMSET) performed significantly better in conjunction with the best performing order release rule (P1000).

Periodic release paid a tardiness penalty by holding jobs in a pre-release file until the release period. This penalty increased with the length of the release period. CR, which is a due-date oriented measure, performed best for tardiness. JCR, which minimises setups while trying to use due-dates as a secondary objective, is bracketed with CR. SIMSET, solely focusing on setups, performs the worst. Combinations of SIMSET, periodic release with higher periods, and due date tightness accentuated their individual effect on tardiness.

9. Conclusion
The contribution of this research is the investigation of periodic release as an ORR policy, which has not been done earlier. The results show that periodic release does perform better compared to immediate release on measures of performance related to resource use: flow time, setup time, and utilisation. However the effect on manufacturing lead time and tardiness were worse, and was expected. The effect of periodic release is highlighted when used in conjunction with setup-saving dispatching rules such as SIMSET.

In regard to the continuing controversy about dispatching rules and ORR [13], our experiments came out in support of both the ORR and the dispatching rules. In our experiments they worked together, ORR enhancing the effect of dispatching rules.

Further research in this area may be carried out: 1) by extending this research to products with multi-level product structures, 2) by investigating periodic release for flow shops with sequence-dependent setup times, 3) by investigating the effect of shop load in addition to the factors examined in this research, and 4) by extending this research to include more dispatching rules.

10. References


