Worker flexibility in dual resource constrained (DRC) shops

Yue, Hong

APPENDIX

LITERATURE REVIEW ON LEARNING AND FORGETTING

In this appendix, we review previous literature on learning in Section 1 and forgetting in Section 2, and then compare a number of learning and forgetting models in Section 3. Finally, in Section 4 we present the learning and forgetting model used by this thesis, and specify the relevant parameters.

1 Learning

The learning curve phenomenon was first reported by Wright in literature (Wright 1936). It refers to the fact that as workers accumulate experience in production processes, their efficiencies improve. This phenomenon can approximated by a log-linear model (Crawford 1944), which assumes that as the number of units produced doubles, the required processing time per unit decreases at a uniform rate. There are situations in which the decrease of processing time will reach the bottom, in which a worker processes at a standard speed and no further improvement is possible. In such cases, a plateau log-linear learning model is considered to be more appropriate (Ballof 1966, Yelle 1979). For example, in a machine intensive environment, the final efficiency level will be determined by the machine speed. This model has been used in job shop environments (Malhotra et al. 1993, Kher et al. 1999, and Kher 2000), and in assembly lines as well (McCreery and Krajewski 1999, and Stratman et al. 2004).

To describe the learning curve in the plateau log-linear learning model of Ballof (1966), three parameters are needed, the learning rate, the initial processing time, and the final efficiency level. Parameter settings depend on many factors. These factors include the nature of the task being performed, e.g. machine or worker intensive (Hirsch 1956), pre-production planning, management of training programs, training facilities, monetary incentives provided to the learning workers, the effectiveness of instruction, and worker's learning capabilities, et cetera. As these factors are not constant across different industries, the learning rates, the initial processing time, and the final efficiency level can be expected to vary.

Learning rates have been studied extensively in the previous literature. Hirsch (1956) reported in an empirical study that the nature of operations affects learning rates. In particular, worker-paced operations are expected to have much steeper slopes in their learning curves than machine-paced operations. In other words, in a worker-intensive environment, workers are most likely to learn much faster than in a capital-intensive environment. In a machine-paced environment, the final speed of operation is to a certain extent determined by the output rate of a machine, whereas in a worker-paced environment, the final speed of operation is to a greater extent determined by the output rate of a worker. Our parallel shop is machine intensive, in which workers learn slowly, and their final speed is determined by machines.

Hirsch (1956) reported that the average learning rates in a highly machine-paced environment is around 85%, while in a worker-paced environment it is about 75%. These parameters have been used by later studies (Mahotra et al. 1993, Kher et al. 1999, Kher 2000, and Felan and Fry 2001, McCreery and Krajewski 1999, and Stratman et al. 2004).

2 Forgetting

In contrast to learning, forgetting received relatively less attention in the past. Only recently it has been addressed by a number of laboratory studies, as well as empirical studies. Mohamad et al. (2003) provided a summary of these studies and outlined the factors that are considered to influence worker's forgetting in industrial settings.

1. *The amount of experience gained prior to the interruption influences the level of forgetting*. This finding has been confirmed by Bailey (1989), Globerson (1989), and Shtub et al. (1993). They suggested that in general, less experienced workers are most likely to forget more, whereas workers with greater experience intend to forget less.

2. *The length of the interruption interval influences the level of forgetting*. It is supported by several studies (Bailey 1989, Globerson 1989, Shtub et al. 1993, Dar-El et al 1995a, and Dar-El et al 1995b) that for a given level of experience, a worker experiencing a longer break is most likely to forget more than one who experiences a short break.

3. *Relearning rate is the same as the original learning rate.* There are still some disagreements on this issue. Globerson et al. (1989), Sparks and Yearout (1990) and Shtub et al. (1993) are in agreement with this finding. Bailey and McIntyre (1997) partially support this result. However, Bailey (1989) and Hewitt et al. (1992) seem to suggest a lack of correlation between the original learning rate and the relearning rate.

4. *The power-based model is appropriate for capturing forgetting effects.* Globerson et al. (1989) and Shtub et al. (1993) support this finding.

5. *Learning and forgetting are mirror images of each other.* Globerson et al. (1989) report this behavior of forgetting in their study.

6. *The level of forgetting depends upon the rate at which a worker learns.* Recently, two studies (Nembhard 2000, Nembhard and Uzumen 2000) have been conducted in an industrial setting with several thousand episodes of learning and forgetting. They established that workers who learn faster also tend to forget fast, whereas workers who learn slowly are also inclined to forget slowly.

Most of the empirical studies mentioned above were conducted in controlled laboratory settings, except for the studies by Nembhard (2000) and Nembhard and Uzumen (2000). Therefore, the direct application of the results from laboratory studies in manufacturing settings may not be appropriate for two reasons (Globerson et al. 1989). Firstly, the tasks used in these studies (memorizing lists of words or syllables) are not representative of the tasks in manufacturing settings (operating machines). Secondly, the interruption intervals considered in some of these studies are not necessary representative of those occurring in actual manufacturing setting. Despite this limitation, these laboratory studies do offer insights into the relationship between learning, forgetting, prior experience, and the length of the interruption interval in the learning process in manufacturing settings.

3 Comparison of models

Many theoretical models concerning learning and forgetting effects are available in literature. Here we discuss four different models, which might be used in our study. These models include the power-based, four parameter learning and forgetting model by Nembhard (2000), the variable regression invariable forgetting (VRIF) model by Elmaghraby (1990), the learning forgetting curve model (LFCM) by Jaber and Bonny (1996), and the learn-forget-learn (LFL) model by Carlson and Rowe (1976). The forgetting phenomenon is associated with many factors as noted above (see, Section 2.). It could be argued that a successful model should incorporate most of these characteristics of forgetting. Nembhard (2000)'s model considers interruption duration and the recency of experience in calculating forgetting. However, this model ignores the amount of experience prior to the interruption (see, Section 2, factor 1), does not model the learning and forgetting as mirror images (see, Section 2, factor 5), and does not correlate the worker's forgetting rate with their learning rate (see, Section 2, factor 6).

The LFL, the VRIF, and the LFCM models all satisfy factors 1 to 4 in Section 2. These models account for the amount of prior learning experience and the interruption duration. They use a relearning rate equal to the original learning rate, and power-based equations. However, they differ in calculating the extent of forgetting, which mainly concerns factor 5 in Section 2, learning and forgetting are mirror images of each other. It has been argued by Mohamad et al. (2003) that, with respect to factor 5 in Section 2, LFCM allows to the most approximation, whereas LFL provides a reasonable fit, and VRIF has some mathematical limitations. Furthermore, they suggested that LFCM has some advantages in capturing factor 6 in Section 2, which implies that the level of forgetting depends on the rate at which a worker learns. In addition, they compared the LFCM and the LFL models in their studies. Though these two models differ slightly in results, they all provide a reasonable fit with respect to forgetting effects.

The focus of our study is not on the development of a mathematical model to approximate the learning and forgetting process. We only look for a model that provides a reasonable fit to the learning and forgetting effects. The LFL model has been used in studies concerning lot sizing (e.g. Adler and Nanda 1974a and b, and Sule 1978), and in studies of worker flexibility (e.g. Kher et al. 1999 and Kher 2000). In accordance with previous research, we choose the LFL model of Carlson and Rowe (1976). This model can also incorporate factor 6 in Section 2 (i.e. the level of forgetting depends upon the rate, at which a worker learns) by using the same rates for learning and forgetting.

4 LFL model of Carlson and Rowe (1976)

In this section, we explain the learn-forget-learn (LFL) model (Carslon and Rowe 1976) further in detail and specify the relevant parameters.

This model assumes that when an interruption occurs during a learning process, the worker will move back on the learning curve. The extent to which experience deteriorates depends on the amount of experience gained prior to the interruption, the forgetting rate, and the length of the interruption interval.
The LFL model determines the processing time for the (n+1)th job in accordance with equation (1). The resumption point after every interruption is calculated by the means of equation (2). The notations in equations (1) and (2) are explained in Table A.1.

$$Y_{n+1} = \text{Max}[(U_1(X_{n+1}^{-L}), a] \qquad (1)$$

$$X_{n+1} = [X_n^{(1+F/L)}(X_n + \varepsilon)^{-F/L}] + 1 \qquad (2)$$

Table A.1 Notations

Y_{n+1}	= the time required to process the (n+1)th job;
U_1	= the time required to process the 1st job;
X_{n+1}	= the first job to be processed after the interruption interval;
L	= a constant determined by $\log_{10}$ (learning rate)/$\log_{10}$(0.5);
X_n	= the virtual number of jobs that has been processed at the moment that the processing of job n starts;
F	= a constant determined by $\log_{10}$ (forgetting rate)/$\log_{10}$(0.5);
ε	= the number of jobs that could have been processed during the interruption interval.
a	= the final efficiency level

The parameters in this model include the learning rate, the forgetting rate, the initial processing time, and the final efficiency level.

We set the learning rate and forgetting rate at the same level to approximate the empirical findings (Nembhard 2000, Nembhard and Uzumen 2000) that fast learners learn fast but tend to forget fast, and slow learners learn slowly but are inclined to forget slowly. Therefore, we assume that fast learners have learning and forgetting rates 80% and 80%, and slow learners have learning and forgetting rates 85% and 85%. Kher et al. (1999) and Kher (2000) used the forgetting rates 85% and 95%.

As for the initial processing time, very limited guidelines are available in the literature. Fauber (1989) provided an empirical example, in which the initial processing time is 200% of the standard processing time. Malhotra et al. (1993) used this setting to present a relative short learning period. In addition, they used a 400% of the standard processing time to depict a relative lengthy learning period. These settings have been used by later studies (Kher et al. 1999, Kher 2000, Felan and Fry 2001).

As for the final efficiency level, Nembhard and Uzumeri (2000) reported that fast learners are associated with a lower final efficiency level, whereas slow learners are related to a higher final efficiency level.

The differences in the initial processing time between fast and slow learners are still unknown (Nembhard 2000, Nembhard and Uzumen 2000). Further research is warranted. For simplification, we set the initial processing efficiency at the same level for both fast learners and slow learners. Furthermore, we set the final efficiency level for a fast learner at 37.5% of the initial processing time, and 25% for a slow learner. Similar settings have been used by some previous studies (Mahotra et al. 1993, Kher et al. 1999, Kher 2000).

The assumptions regarding the parameters of the LFL model are summarized as follows:

1. Both fast learners and slow learners have the same initial processing time.
2. Fast learners have the learning and forgetting rate 80% and 80%, and slow learners 85% and 85%.
3. The LFL model is a plateau curve. For fast learners, the bottom is 37.5% of the initial processing time, and 25% for slow learners. If the product life cycle is long enough, slow learners finally reach an efficiency level 50% higher than fast learners.

To show the range of these parameters, we draw the learning and forgetting curves for fast and slow learners in Figure A.1. These two curves are depicted under the condition that no interruption occurs in the learning processes. Basically, these are two learning curves. When an interruption occurs, workers forget and move back along the learning curves. Furthermore, the number of jobs being produced on X axis follows a log scale.

Figure A.1 shows the learning and forgetting processes for fast and slow learners. In the early stage of the learning process, i.e. the number of jobs being produced from 1 to 64, fast learners have a steeper slope than slow learners. It captures the fact that fast learners learn fast, while slow learners learn slowly. In the later stage of the learning process, i.e. from the number of jobs being produced 64 up, slow learners have a higher efficiency level, while fast learners have a lower efficiency level.

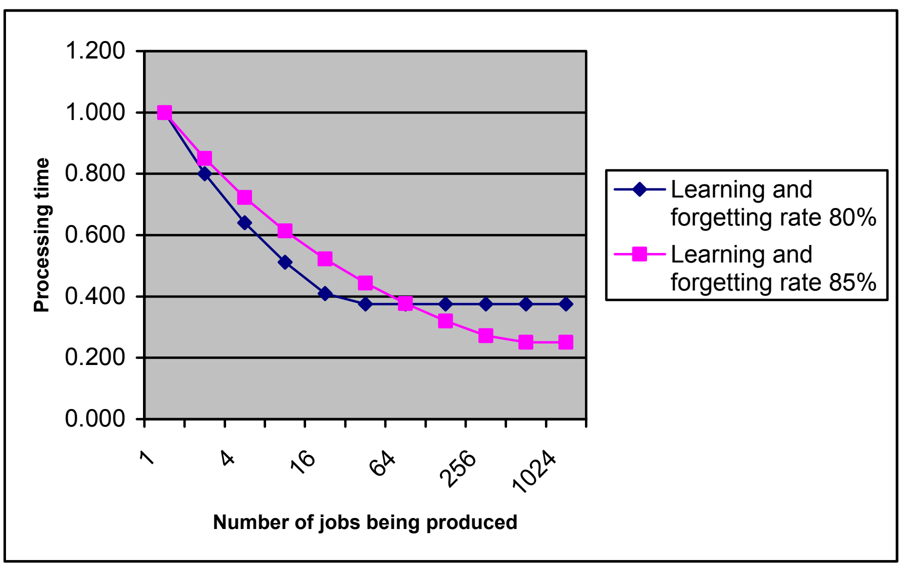

Figure A.1 Learning and forgetting curves for fast and slow learners

Summary

This appendix reviewed the literature concerning learning and forgetting effects, and compared the pros and cons of a number of mathematical models that are created to approximate these effects. The LFL model by Carlson and Rowe (1976) was chosen, and the relevant parameters in this model have been selected.