INVESTIGATING THE INFLUENCES OF CROSS TRAINING CONFIGURATIONS IN ASSEMBLY LINES

TAI LEE ZHEN

UNIVERSITI SAINS MALAYSIA

2011

INVESTIGATING THE INFLUENCES OF CROSS TRAINING CONFIGURATIONS IN ASSEMBLY LINES

by

TAI LEE ZHEN

Thesis submitted in fulfillment of the requirements
for the degree of
Master of Science in Mechanical Engineering

May 2011

ACKNOWLEDGEMENTS

First of all, I would like to express my sincere gratitude to my supervisor Dr. Chin Jeng Feng. He has played an important role for improving my project, granted me an excellence of consultancy and has been guiding me very much for writing this thesis.

I also would like to thank to Pn. Zalila from School of Science Mathematics for her astute observation about this work, unconditional support and always setting the bar a little bit higher than I expected.

My utmost appreciations go to my parents, brother and sister for their love, continuous support and encouragement. Finally, I would like to express my appreciation to Universiti Sains Malaysia for funding me through USM Fellowship Scheme and all those who have helped me in this project.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

PR	pick and run
XP	expedite
WIP	Work-in-process
JCM	Job Characteristics Model
MPS	Motivating Potential Score
PDA	Personal Digital Assistant
IGP	Integer Goal Programming
DRC	Dual Resource Constrained
SR	Scheduled Rotation
FO	Floating Operators
ZW2	Zoned Worksharing – Two Skill Chaining
ZWH	Zoned Worksharing – Hierarchical
CR	Craft
L	Operator
W	Workstation
ASDWO	Average Skill Deviation Within Operator
ASDBO	Average Skill Deviation Between Operators
SPSS	Statistical Package for the Social Sciences
PC1	Product Changeover Once in Three Months
PC5	Product Changeover Five Times in Three Months
PC10	Product Changeover Ten Times in Three Months

LIST OF APPENDICES

KAJIAN TENTANG PENGARUH KONFIGURASI LATIHAN RENTAS DALAM GARISAN PEMASANGAN

ABSTRAK

Dengan membolehkan operator-operator kilang untuk melakukan tugas yang pelbagai dalam organisasi, suatu model latihan rentas telah dibangunkan. Tujuan utamanya ialah untuk menggalakkan kepelbagaian fungsi operator-operator tersebut dan seterusnya meningkatkan kefleksibelan tenaga kerja. Kajian ini bertujuan untuk mengkaji kesan-kesan pelbagai jenis konfigurasi latihan rentas, berfokuskan kepada garisan pemasangan di bawah pengaruh ketidakhadiran operator, pusing ganti operator, penukaran produk dan proses pembelajaran tugas oleh operator. Konfigurasi latihan rentas yang diujikaji adalah khususnya berkaitan dengan Giliran Berjadual, Operator Terapung, Perkongsian Kerja Berzon – Perantaian Dua Kemahiran, Perkongsian Kerja Berzon – Berhierarki dan Kraf. Manakala produktiviti, kemahiran purata operator, sisihan kemahiran purata dalam operator, sisihan kemahiran purata di antara operator dan kos bergerak tertanggung merupakan ukuran prestasi yang digunakan. Sebuah kilang pemasangan di Prai telah digunakan sebagai satu kajian kes di mana model simulasi pengeluaran yang stokastik telah dibina dengan menggunakan perisian simulasi WITNESS terintegrasi dengan Visual Basic dan pangkalan data Microsoft Access untuk pengumpulan data. Data asas yang diperolehi akan diperiksa terlebih dahulu secara statistik dengan ujian tak berparameter dan kemudian dibincangkan secara menyeluruh. Keputusan analisa menunjukkan perbezaan yang ketara dalam ukuran prestasi yang digunakan, oleh sebab itu klasifikasi yang sewajarnya telah dibina. Hasilnya adalah berpotensi untuk

memudahkan pemilihan konfigurasi latihan rentas yang dapat memenuhi prestasi tertentu yang diingini dalam aplikasi industri sebenar.

INVESTIGATING THE INFLUENCES OF CROSS TRAINING CONFIGURATIONS IN ASSEMBLY LINES

ABSTRACT

By permitting operators to perform a different part of the organization's work, a cross-training model is developed. Its chief purpose is to promote multi-functionality of operators thus improves workforce flexibility. This research intends to investigate the effect of cross-training configurations, focusing on assembly lines under the influences of operator absenteeism, operator turnover, product changeover and learning. The cross training configurations, specifically *Scheduled Rotation, Floating Operators, Zoned Worksharing – Two Skills Chaining, Zoned Worksharing – Hierarchical* and *Craft* were experimented. Productivity, average skill of operators, average skill deviation within operator, average skill deviation between operators and the travelling cost incurred were the performance measures employed. An assembly factory in Prai was used as the case study in which a stochastic production simulation model was built upon by using WITNESS simulation software integrated with Visual Basic and Microsoft Access database for data collection. The raw data obtained were first statistically examined with non-parametric test, and later thoroughly discussed. As results showed the significant discrepancies of a number of performance measures on cross training configurations employed, respective classifications were duly built. The result potentially facilitates the selection of cross training configurations to meet certain intended performance measures in real industry applications.

CHAPTER 1

INTRODUCTION

1.0 Background

In a traditional production line, operators are permanently allocated to specific workstations in order to achieve task specialization. The ideas of Fordism are largely embraced, which are closely associated with any mass production system. According to the ideas, productivity can be improved by breaking down the total operations into simple tasks and performed by the operators with sufficient qualifications. Large number of operators, each performing the specialized tasks repetitively tends to reduce the cost and thereby enhance the competitive advantage.

In recent years, however, the need to thrive in an immensely volatile and competitive economy has compelled organisations to revise its operational flexibility. By definition, operational flexibility is the ability of an organisation to produce required variety and quantity of outputs in an efficient manner. The measuring of operational flexibility is manifold, largely related to the conversion of resources to end products. Operators are considered one of the resources. They are important because they are front-liners whom performances directly linked to the productivity and product quality. From the viewpoint of operator management, operational flexibility therefore has to reflect the property of changeover in work pattern to cope with varying environment, e.g. customer demand. However, the internal disruptions, e.g. absenteeism, turnover and morale issues can cause negative impact to the operational flexibility. In that context, revamping the operational flexibility includes introduction of new techniques such as cross-training. Cross-training is an instructional strategy in which each operator is trained in the duties of his or her colleagues (Volpe et al. 1996), resulting in acquisition of multiple skills in time and flexible assignment as the need arises (Hottenstein and Bowman 1998).

Nevertheless, research fostered on cross-training had indicated that practitioners are still attempting to comprehend the various effects inherent by the application on their shop floor operation. A perusal of the latest relevant literature has shown myriad varieties of cross-training which have been proposed, often in the disguise of different names, despite sharing certain traits of technical similarity. A lack of a universal framework of classification as well as a complete documentation of related performance measures complicate comparisons amongst the varieties. This leads to the belief that the research development in this area, separately embarked by groups of different disciplines, has yet to be consolidated into a unified whole.

The deftness in procuring an optimal balance of effects emanating from practicing cross-training will inevitably influence eventual production yielding in consequence to the pressures of a product-mix configuration, apart from having to assuage frequent set-up disruptions, distended time dispensed for conducting refresher training courses, the diverse learning rhythm or pace and the ultimate performance level achievable. Therefore, from the industry's perspective, the cross-training research is of paramount consequence. The results of the studies provide valuable insights to the performance prior to actual implementation. This leads to the confident deployment of cross-training to address issues affecting products' variation cycles, absenteeism and workers' rotational duties without undermining workers' morale and impairing output.

1.1 Research Problem

A perusal of a considerable number of literatures reveals that the studies of cross-training are largely unsaturated and often problem specific. The terminologies and classifications adopted are varied in literature. This entails difficulties in making valid comparison. In additions, as most studies are intended to gain theoretical insight, the corresponding simulations found seldom relate to real case study. The results obtained from the literature review can only provide limited guidance in view that every actual manufacturing shop floor is idiosyncratic in many aspects. Here, practitioners face such a situation where there is a dilemma in selecting a suitable cross-training configuration in a factory consists of multiple assembly lines. In this premise, there is a need to build a comparative study through the computer simulation reflecting a real case study, of the prevalent cross-training configurations.

1.2 Research Objectives

The purposes of this research are:

1. To establish the cross-training simulation models that representing the actual environment of manual assembly in the case study.
2. To investigate the effect of environmental factors including operator learning, absenteeism and turnover, also product changeover on the performance of the manual assembly environment.
3. To compare the effectiveness of different cross-training configurations including Schedule Rotation (SR), Floating Operator (FO), Zoned Worksharing (ZW) and Craft (CR) under the influence of the environmental factors.

4. To determine the best cross-training configuration by a set of performance measures such as productivity, average skill of the operators, average skill discrepancies within and between operator(s) and travelling distance incurred between workstations.

1.3 Thesis Outline

This thesis is organized as follows: the chapter 2 reviews on cross-training, classification of cross-training configurations, benefits and drawbacks of cross-training and performance measures that associated to cross-training. Besides, this chapter also describes the environmental factors that may affect the performances of the operators, computer simulation in cross-training. The chapter 3 discusses on the research methodology and the construction of the simulation study. Then, the chapter 4 presents the simulation results and the statistical analysis on the results. The chapter 5 gives the discussion on the results. Finally, the chapter 6 provides the conclusions of this study and the appertaining future works.

CHAPTER 2

LITERATURE REVIEW

2.0 Overview

This chapter presents a variety of cross-training configurations and its classifications, benefits and drawbacks of cross-training and performance measures that found in literature.

2.1 Cross-Training

Abrams and Berge (2010) defined cross-training as operators are trained to do more than one task within a company, while McDonald et al. (2009) described cross-training as operators are trained on the tasks, duties, and responsibilities of multiple tasks in a specific work cell or work area. To be consistent with the variety of cross-training configurations understudied in this research, a more descriptive definition is provided. Formerly, cross-training is work allocation method where an operator or a group of operators are intentionally repositioned to handle different type of tasks. The trigger for such repositioning can be at a predetermined interval or reactive, e.g. by event.

The preliminary stage in determining whether and how the cross-training should be applied in the organization depends on the organization's vision. In vision, an organization states their competitiveness in cost, delivery speed, product quality and variety by improving the capability of the production system. Therefore, it involves the implementation of cross-training in view of the associated advantages potentially in line with the attainment of abovementioned competitiveness. Once the organization decides to apply cross-training, the organization may have to consider issues related to the cross-training design. The first is the extensiveness of cross-training, secondly the cross-training configuration, and lastly operators assignment policy (Hopp et al., 2004).

i. Extensiveness of cross-training

Extensiveness of cross-training refers to the level of cross-training, which is a measure of the number of tasks each operator on the assembly line is trained to perform. One extreme of extensiveness of cross-training is to have total flexibility in which all operators for all workstations are to be cross-trained on all tasks. However the practicality and the cost issues are the major concerns (Slomp et al., 2005). Kher and Malhotra (1994) showed that a high level of operator flexibility leads to considerable losses in productivity, as time required to orientate new workstations, accessing information about the job to be performed at the new machine, and learning or relearning the setup procedures.

ii. Cross-training configurations

A cross-training configuration represents all trainings or qualifications of operators and indicates which operators are trained for which machines. It can be represented by an operator-machine matrix or by a bipartite graph with operators and machines as vertices and skills as edges. Several cross-training configurations found in literature are scheduled rotation, floating operators, zoned worksharing, craft, operator prioritized worksharing, and cherry picking.

- *Scheduled Rotation*

Scheduled rotation is the lateral transfer of operators among a number of different positions and tasks within jobs where each requires different skills and responsibilities. Operators learn several different skills and perform each task either for a specified time period or in a predetermined sequence. Rotating tasks facilitates operator to understand the different steps that go into creating a product, how their own effort affect the quality and efficiency of production, and how each member of the team contributes to the process. It is widely used in most production industry to balance lines, manage bottlenecks, and provide ergonomic relief as well as support skill development (Hopp and Van Oyen, 2004). *Scheduled rotation* also enables the training of operators to be backups for other operators so that managers have a more flexible work force and a ready supply of trained operators.

- *Floating Operators*

In a *floating operator* scenario, a group operators are permanently stationed at a particular workstation at the line, while floaters (can be fully cross-trained or partially cross-trained operators) in the line may roam freely to provide assistance where needed. They float to the most urgent task based on the congestion of the system. Two common uses of a *floating operator* are to replace an absent operator or a specialized operator taking a scheduled short break (i.e. an operator who is not cross-trained). They can be seen as an additional capacity to deal with imbalance during the production process. Managers or supervisors may use part of their working times to serve as a floater for the production operations which need their assistances. Hopp and Van Oyen (2004) mentioned that floating operators can be allocated to the production system to fill the operator gap if the staffing level varies from the planned absenteeism

- *Zoned Worksharing*

In *zoned worksharing*, teams of operators are cross-trained to work under a work zone. The operators are cross-trained with several neighbouring tasks at a zone and they obtain the skill successively in this case, so the elder operators possess the skills of the subordinate operators. There is overlapping and non-overlapping *zoned worksharing*. However, much more literatures have focused on overlapping *zoned worksharing*. One of the cases in overlapping z*oned worksharing* is the half-hull policy, where the workers choose jobs to try to keep inter-station buffers half full. Ostolaza et al. (1990) and McClain et al. (1992) further studied the half-full buffer policy in the *overlapping zoned worksharing* to identify the effects that occur in systems which rely on the worker flexibility. In the study of Gel et al. (2000), the authors studied two-stage production systems and establish a “fixed before shared” principle, which has the broadly skilled workers give strict priority to the task types for which only they are trained. In this way, the less-skilled workers are protected from starving for lack of tasks for which they are trained.

D-skill chaining, which proposed by Jordan and Graves (1995) is another case in overlapping *zoned worksharing*. It is easier to illustrate this by setting the D equal to 2 (D represents the number of skills each operator possess), operators in 2-skill chaining are trained for a base and a second task type. The assignment of task types to operators is overlapped to form a chain. The chain is complete if every work zone has a backup operator from another work zone, operator from each work zone is cross-trained on a task in another work zone and all work zones are interconnected (Jordan et al., 2004).

- *Craft*

Craft is a practise where completely cross-trained operators carry an entity from start to finish and perform the required tasks on it without others' help. The basic case in *craft* is pick and run (PR), where the operators perform all the tasks required to complete the current unit solely before processing the next unit. Toyota gear manufacturing process is a successful example of effective application of the PR form of c*raft* production (Monden, 1983). Van Oyen et al. (2001) showed that PR is generally very effective and possesses a near-optimal policy in a demand constrained (make-to-order) setting. It can be shown to be optimal in capacity-constrained systems with a constant WIP level as well. Instead of performing all the required tasks individually, c*raft* can also be implemented in teams, and this is termed as expedite (XP). Operators work on an entity from the beginning to the end as a team.

- *Operator Prioritized Worksharing*

In o*perator prioritized worksharing*, the tasks are assigned to the operators based on the prioritization of operators. Gel et al. (2000) modeled an example of this approach based on two operators and two task production system. The priority rule is established for a project leader who is broadly skilled to assist in one task and for the task types that he/she is trained in.

- *Cherry picking*

Cherry picking assigns the operator with surplus capacity to the workstations that need help (Hopp et al., 2004). This configuration is especially applicable to the production line, where the average work content of the operators is unbalanced. Production lines that are unbalanced with respect to average work content will cause some operators to idle periodically. *Cherry picking* allows such an operator to split his/her effort over time to improve operator utilization and throughput of the line.

iii. Operators assignment policy

A number of operators assignment policies will be discussed here which includes *First-Come First-Served*, *Fixed-Before-Shared Policy*, *Maximum Queue Policy*, *Maximum load Policy* and *Buffer Policy*.

- *First-Come First-Served Policy*

Common in production, in *First-Come First-Served Policy*, operators process the tasks in the order of the task type arrival. For example, an operator who has qualified for Task A and Task B in workstation 1 will perform the task he/she first receives.

- *Fixed-Before-Shared Policy*

This policy is applicable under situations when there is a mix of cross-trained operators and static operators (specialists) in the production line. Each operator performs a base (fixed) task and another cross-trained task. The cross-trained operators are given priority to the task type that he/she is uniquely qualified before helping out other operators. In other word, cross-trained operators always process a base task whenever they are available at a decision epoch. Gel et al. (2007) showed that it is optimal for the cross-trained operator to always process the tasks that only he/she can do before helping out the static operator (specialist). This policy also found to be effective for systems with hierarchical cross-training (Gel et al. 2000).

- *Maximum Queue Policy*

This policy allows the operators to work on the workstation which has the maximum task queue length regardless of the work content. For instance, supposed if an operator must choose between two workstations: one with three tasks in the queue and an expected total processing time of twenty minutes and the other with eight tasks in the queue and an expected total processing time of one minute, operators choose the workstation with the longest queue length under this policy. Askin and Iyer (1993) implemented this policy to reduce throughput times in cellular manufacturing systems.

- *Maximum Load Policy*

This policy assigns the operator to the workstation with the largest workload. For the example above as in maximum queue policy, one with three tasks in the queue and an expected total processing time of twenty minutes and the other with eight tasks in the queue and an expected total processing time of one minute, operators will choose to perform at workstation with three tasks in the queue and total processing time of twenty minutes for each task.

- *Buffer Policy*

The idea in this policy is that buffer between the workstations is assigned with a certain threshold value. A threshold is introduced in the buffer as an indicator for the operators to process the task on next workstation if the buffer of that workstation exceeds a preset threshold values after he/she completes the task in the current workstation. This policy is specifically applicable to 2-skill chaining where has been discussed above, in part (ii) cross-training configuration (Hopp et al., 2004). Hopp et al. (2004) considered two different buffer threshold values in their study which are uniform buffers and the time buffers.

2.2 Classification of Cross-Training Configurations

Cross-training configurations can be further categorized into degree of overlapping and exchange interval as shown in Figure 2.1. Degree of overlapping indicates the extensiveness of the operators been cross-trained and the amount of the overlapping skills that own by the operators which can be further divided into partial cross-training, full cross-training and heuristic-base. While exchange interval shows timing of the operators to move to other workstation to further perform the assembly tasks in the line after completing the task in the current workstation and this can be further divided into time based trigger, dynamic event trigger and remain. Table 2.1 summarizes the criteria that must be fulfilled by a cross-training configuration. For example, if a cross-training configuration that fulfill the requirements such as varying degree for the degree of overlapping and vacancy for the exchange interval then it is *zoned worksharing – hierarchical*.

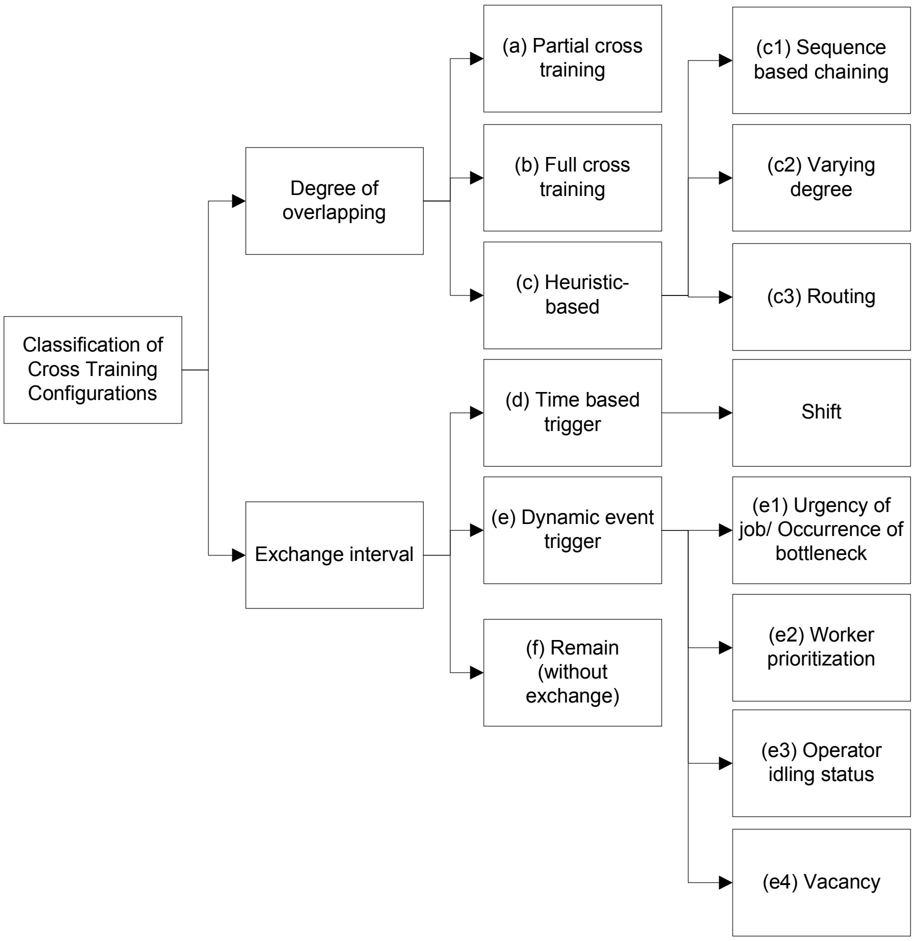

Figure 2.1: Classification of Cross-training Configurations

Table 2.1: Summarized table of the classification of cross-training configurations

Cross-training configurations	**Degree of overlapping**					**Exchange interval**					
	(a)	*(b)*	*(c1)*	*(c2)*	*(c3)*	*(d)*	*(e1)*	*(e2)*	*(e3)*	*(e4)*	*(f)*
Scheduled rotation					●	●					
Floating operator	●	●					●				
Zoned worksharing – hierarchical				●						●	
Zoned worksharing – D-skill chaining			●							●	
Craft	●	●									●
Operator prioritized worksharing	●	●						●			
Cherry picking	●	●								●	

2.3 Benefits and Drawbacks of Cross-Training

Cross-training, on an immediate term, if according to Hopp et al. (2004), offers benefits of “capacity balancing” and “variability buffering”. The former is achieved by allowing operators to split their efforts over time in a production line with respect to average work content. In spite of the fact that operators are deliberately idled periodically, overall operator utilization and line throughput will be improved. The latter is achieved by allowing the operator of an assigned workstation to switch to other workstations if starving is encountered in his or her workstation. This practice is particularly common in production lines with workstations having varying processing time. Variability buffering is achieved without significant additional investment of equipment or operator (Hopp et al. 2004). The studies of Monden (1983) and Inman et al. (2004) have showed that a group of cross-trained operators will be more productive than a group with the same number of specialized operators, because there is more opportunity to balance workloads among operators.

Cross-training has even greater impact on throughput time and delivery performance of jobs, on condition that there are appropriate operating rules (Treleven 1989). Cross-training can be seen as one of the ways to cushion against the impact of uncertainties and variation in workforce supply such as absenteeism. Inman et al. (2004) introduced the concept of chaining to staffing assembly lines by cross-training each section’s utility operator on one task in the downstream section and it is shown that chaining is a practical and effective strategy for prioritizing cross-training to compensate for absenteeism on assembly lines. Nembhard et al. (2005) established a real option framework for a simple sequential production system to evaluate the effectiveness of cross-training policies on product dynamics, labour dynamics, task heterogeneity and workforce heterogeneity. Results suggest that cross-training can effectively enhance the capability of production systems to respond to changes in demand and the competitive environment. In the study of Molleman and Slomp (1999), the adverse effect of absenteeism is lessened by simply having each task to be mastered by two operators as a general training policy.

Another benefit subtlety manifested at a longer term is the elicitation of task content sharing when exposing the roles and responsibility of one operator to others (Marks et al. 2002), which is crucial for a comprehensive understanding on how everyone contributes to the collective success of a production. Consequently, operators are able to compensate their colleagues' limitations, such as to anticipate their needs and assist them when required. More profoundly, by enabling mutual sharing of workloads, feelings of interpersonal justice and equity (Austin, 1977) can be enhanced, and also lead to an increased job satisfaction, operator motivation, and reduced ergonomic stress (Hopp et al. 2004).

Cross-training should be used judiciously (Inman et al. 2004) as it can be very costly and time-consuming. According to Nembhard et al. (2005), there are direct training cost involved and also hidden cost inherent from potential efficiency loss and system transition to be considered in the implementation of cross-training. Under cross-training, operators now have to accommodate a much slower learning curve to be proficient on wider task variety (Marentette et al. 2009). In additions, it is likely for one operator to have uneven exposure to different skills. The operators can get confused while handling the complicated tasks due to increasing task complexity and product variety (Nembhard, 2001). In addition, forgetting and relearning of skills due to the elapsed time of interruption will degrade their performance.

Behavioural changes may complicate the implementation of cross-training (Schultz et al. 2003). As task boundaries diminish due to cross-training, so is the feeling of one specialized operator of being unique, indispensable and having easily recognizable individual contribution to group performance (Clark 1993). This may entail motivational deficits (Fazakerley 1976). Cross-trained operator may perceive lowering of status differentials within teams, particularly among the higher-status operators who resist learning and performing the lower-status jobs (Cordery et al. 1993; Hut and Molleman 1998). Finally, high levels of operator flexibility may cause social loafing for tasks less appealing for some reasons (Wilke and Meertens 1994).

2.4 Performance Measures Associated to Cross-Training

To evaluate the effectiveness of cross-training, a number of performance measures can be employed. A standard set of notations is first illustrated to facilitate the comprehension of the mathematic formulation of performance measures. The relationship of the performance measure with the benefits claimed is shown in Figure 2.2.

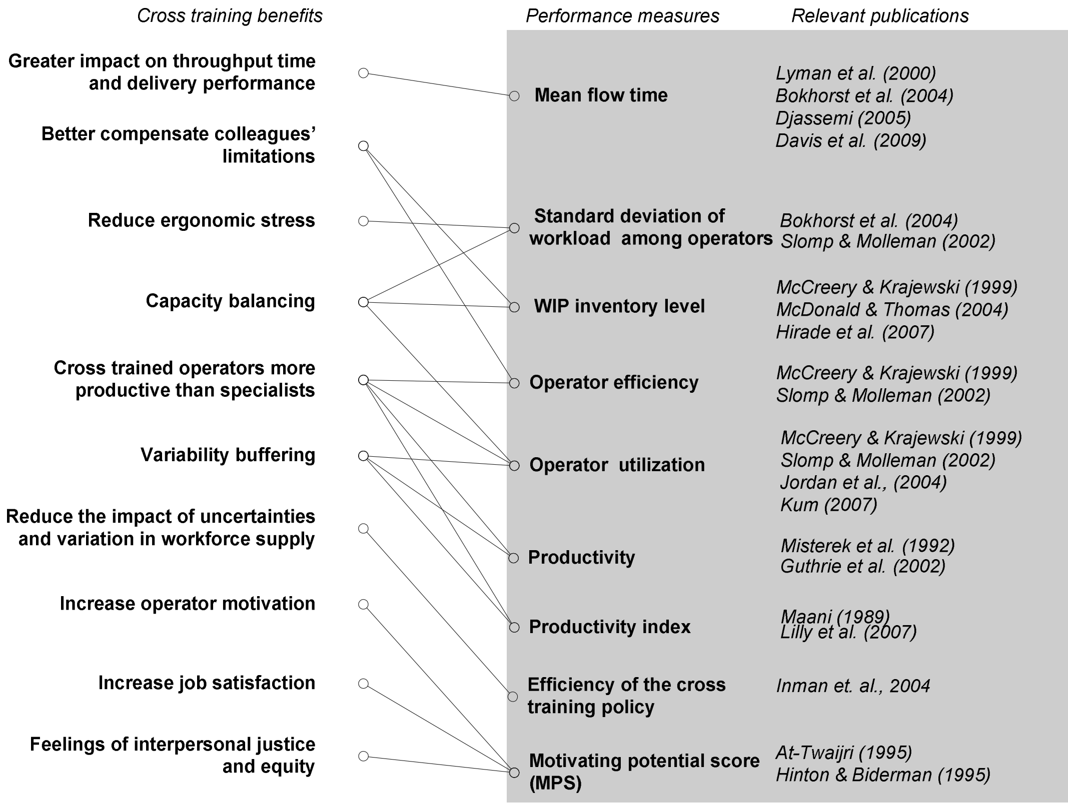

Figure 2.2: Relationships between benefits of cross-training, performance measures, and the studies which applied the performance measures

Notation:

N_c = number of cross-trained operators

N_l = number of operators

N_m= number of machines in the system

$\overline{N_T}$ = average number of task in the system

Q= quantity of units to be produced during the period

$\bar{F}$ = mean flow time

P_{cr} = productivity from cross-trained operators

P_{sp}= productivity from specialists

MPS = motivating potential score

SV = skill variety

TI = task identity

TS = task significance

AU = autonomy

FB = feedback

$\sum T_a$ = total available time of the operator

T_c = cycle time required per unit

T_{LT} = lead time

T_p = productive time of the operator

T_{sh} = actual hours worked during the shift or other period (typically 8 hours)

T_{std} = standard time of tasks accomplished during shift or other period

E_l = operator efficiency

E_p = efficiency of the cross-training policy

UTIL = operator utilization

$\overline{U}$ = average utilization of the machines/workstations

λ = mean arrival rate of the task

PR = production rate

P = productivity

PI = productivity index

O= output

L= operator cost

M= material

E= energy

C= capital

$\bar{p}$ = average work content of the task in the system

WIP = work-in-process inventory level

σ= standard deviation of the workload among operators

WL_i = workload of the i^{th} operator

$\overline{WL}$ = average workload of the operators

WL = workload scheduled for a given period

ΔR = increase in workforce reliability of a cross-training policy over the no cross-training policy *i. Mean flow time*

Mean flow time can be related to the speed and delivery performance of manufacturing teams. There are several ways to get the mean flow time. Many studies such as Lyman et al. (2000), Bokhorst et al. (2004a), Djassemi (2005) and Davis et al. (2009) obtained the mean flow time through simulation. Mean flow time is equal to the mean time between arrivals multiplied by the mean number of tasks in the system. Its theoretical formula for a steady state process (the number of jobs in the system is finite) is equal to (Conway et al., 1967),

$$\bar{F} = \frac{\overline{N_T}}{\lambda}$$

Conway et al. (1967) also proved that this relationship can be expressed in terms of average utilization and average amount of work per task, which is

$$\bar{F} = \frac{\overline{N_T} \times \bar{p}}{N_m \times \overline{\overline{U}}}$$

With cross-training, the mean flow time of the product can be reduced due to sharing of tasks/bottleneck tasks between the operators.

ii. Work-in-process (WIP) inventory level

Work in process (WIP) are components or raw materials that have undergone some changes but are not completed. WIP exists because the processing time for a unit to be in each workstation varies. Studies such as McCreery and Krajewski (1999) and Hirade et al. (2007) had used the WIP inventory level as one of the performance measures in their study. Little's Law, an equation for relating Lead Time (LT), Work-in-Process (WIP) and Production Rate (PR) for any process states that:

$$WIP\ (units) = T_{LT} \times PR$$

High level of work-in-process inventory may cause the capital of an organization to be tied up, changes in design are made difficult and throughput rates are difficult to adjust to match the sudden changes in demand.

iii. Productivity

Productivity is the ratio of outputs divided by the inputs. Examples of input are operator, capital, material and miscellaneous and output refers to the product produced. The use of one resource input to measure productivity is known as single factor productivity (Heizer and Render, 2007).

$$P = \frac{O}{T_p}$$

The above equation can be regarded as *operator productivity*, to determine the time required to produce one unit of output (Groover, 2007). A broader view of productivity is multifactor productivity which includes all inputs such as capital, operator, material and energy. Multifactor productivity is also known as total factor productivity and is calculated as follows (Heizer and Render, 2007):

$$P = \frac{O}{L + M + E + C}$$

Productivity is one of the major concerns for managers to compute the profitability of an organization. Among the studies that apply this as one of the performance measures are Misterek et al. (1992) and Guthrie et al. (2002).

Another performance measure that relates to this is the *productivity index* (PI) which has been measured in Maani (1989) and Lilly et al. (2007). Assuming that specialists are in the production line before implementing cross-training, the productivity obtained using cross-training as opposed to specialists may be measured by the index (Iravani et al., 2005):

$$PI = \frac{P_{cr}}{P_{sp}}$$

High value of PI indicates that the benefits gained from the production line that implements cross-training is substantial compared to the one that does not implement cross-training.

iv. Operator utilization

It indicates how busy operators are involved with production activities on the shop floor. Applied in McCreery and Krajewski (1999), and Slomp and Molleman (2002), *operator utilization* is computed as the total time that an operator is busy divided by the operator's available time per day.

$$UTIL = \frac{T_p}{\sum T_a}$$

Jordan et al. (2004) and Kum (2007) demonstrated that operator utilization can also be found using simulation techniques. High operator utilization induces less operators' idling time, hence greater productivity.

v. Operator efficiency

Operator efficiency is defined in (Groover, 2007) as the ratio of the number of standard hours to accomplish the tasks to the actual hours worked during a shift. Another word, it is the actual work rate of the operator relative to work rate under standard or normal performance. This measure is used in the studies of McCreery and Krajewski (1999), and Slomp and Molleman (2002). E_l is calculated as a decimal fraction but usually expressed as a percentage, with formula as:

$$E_l = \frac{T_{std}}{T_{sh}}$$

vi. Standard deviation of the workload among operators

The measure of standard deviation of the workload distribution among the operators relates to the social dimension of a manufacturing team. This measure is employed in Bokhorst et al. (2004a), and Slomp and Molleman (2002). Workload is defined as the total amount of work, and is figured as the quantity of units to be produced during the period of interest. The standard deviation of workload among operators is:

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{l}(WL_i - \overline{WL})^2}$$

A high value of the standard deviation indicates that the workload variations among the operators are high. This variation, which is due to the pressure towards equity, should be reduced to balance the workload among operators.

vii. Motivating potential score

Hackman and Lawler (1971) proposed that a substantial portion of the variation in operator outcomes could be explained by the characteristics or specific attributes constituting the job and how operators perceive these attributes. Hackman and Oldham (1975, 1976 and 1980) developed this theory into the Job Characteristics Model (JCM), in which the objective changes to a given job are expected to change how the operator perceives the job along five core job dimensions: skill variety, task identity, task significance, autonomy, and feedback. These five core job dimensions integral to the JCM theory is a summary index that serves as an estimate of the (internal) motivating potential of a given job. The Motivating Potential Score (MPS) is calculated as follows:

$$MPS = \frac{(SV + TI + TS)}{3} \times AU \times FB$$

Skill variety refers to the degree to which the job requires a variety of different activities, so that the operator can use a number of different skills and talent. For task identity, it is the degree to which the job requires completion of a whole and identifiable piece of work. Task significance measures the degree to which the job has a substantial impact on the lives or work of other people. Another job dimension is autonomy which evaluates the degree to which the job provides substantial freedom, independence, and discretion to the individual in scheduling the work and in determining the procedures to be used in carrying it out. Lastly, feedback is the degree to which carrying out the work activities required by the job results in the individual obtaining direct and clear information about the effectiveness of his/her performance. At-Twaijri (1995) and Hinton and Biderman (1995) had measured these parameters in their studies.

viii. Efficiency of the cross-training policy

An organization may wish to measure a cross-training policy's efficiency, which is a measure of the enhancement from the cross-training policy over no cross-training policy. The measure is calculated by the augment of workforce reliability over no cross-training policy and divided by the number of cross-trained operators needed (Inman et al., 2004).

$$E_p = \frac{\Delta R}{N_c}$$

High value of E_p indicates that the improvement on the production line with cross-training policy over no cross-training policy is huge. However, the cost involved in applying cross-training should also be taken into consideration.

2.5 Environmental Factors Considered

There are few environmental factors that usually affected the performance of manual assembly lines which can be represented by (i) operator absenteeism, (ii) operator turnover, (iii) product changeover and (iv) learning. The environmental factors are described below.

i. Operator absenteeism

Absenteeism is one of the significant factors that affect the functioning of the manual assembly line (Marteo, 2006). Mayne and Clanton (2004) reported that the absenteeism rates at some large automotive assembly plants are as high as 20% which includes vacations, paid personal days off, medical leave and some operators skipping work. When an operator is absent unexpectedly, an immediate replacement of the operator from the pool of substitute operators is needed. The substitute operator may not be sufficiently trained to perform the absentee's tasks, therefore likely to give rise to slower pace and higher chance of mistakes. This threatens the