Agile Workforce Evaluation:
A Framework for Cross-training and Coordination[*]

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Abstract

This paper outlines approaches for assessing and classifying manufacturing and service operations in terms of their suitability for use of cross-trained (flexible) workers. We refer to our overall framework as Agile Workforce Evaluation (AWE). The primary contributions of this paper are: (1) a strategic assessment framework that structures the key mechanisms by which cross-training can support organizational strategy, (2) a tactical framework that identifies key factors to guide the selection of an architecture and worker coordination policy for implementing workforce agility, (3) a classification of workforce agility architectures, (4) a survey of a broad range of archetypical classes of worker coordination policies, (5) a survey of the literature with an operational perspective on workforce agility, and (6) identification of opportunities for research and development of architectures for specific production environments.

Keywords: cross-training, worksharing, teams, division of labor, work design.

1. Introduction

Global competition has elevated the role of operating practices in manufacturing and service business strategies. Competing on multiple dimensions of cost, quality, delivery time, and product variety requires efficient operations that are tailored to the specific needs of a firm's customers. We refer to the ability to achieve this heightened level of efficiency and flexibility while meeting objectives for quality and customer service as *production agility*.

Production agility can be viewed as having three distinct facets (see Malecki 1996). The first facet is inter-firm relations, which include for example, supply chain management, purchasing contracts, and strategic partnerships. The second facet of agility is the firm's resources and infrastructure. Examples of these include information technology (IT), flexible manufacturing systems (FMS), improved processes, desirable locations, and effective layouts. The third facet, upon which this paper focuses, is the workforce itself. Aspects of workforce agility include the use of contingent and temporary workers (see Milner and Pinker 2001 and Pinker and Larson 2003), flexible working hours (including banked and annualized working hours or dynamically requested time-off in exchange for voluntary overtime as in Yang et al. 2002), worker training, skill breadth and depth, knowledge, and the use of cross-trained workers with effective coordination mechanisms among other things (see Sumukadas and Sawhney 2002). It is this latter mechanism which we feel is broadly applicable, powerful, and also highly complex. Upton (1995) closely examined the fine paper manufacturing industry in North America and concluded that rather than technological sophistication being the key driver, "Operational flexibility is determined primarily by a plant's operators and the extent to which managers cultivate, measure, and communicate with them." Although these are important attributes in any work system, they are particularly important in those with cross-training.

Part of the motivation for workforce agility via cross-training is that cross-trained workers represent *flexible capacity*. That is, workers can be shifted dynamically to where they are needed when they are needed. Hence, cross-trained workers should be able to achieve higher performance (or the same performance with a smaller workforce) than specialized workers. But workforce agility architectures and policies can also provide a host of benefits beyond near-term efficiency improvements, such as quality improvement, learning curve acceleration, better customer service, improved organizational culture, economy of scope, and economy of depth (Herzenberg et al. 1998). For industries such as the call center industry, cross-training is a critical decision for both service quality and profit (Stuller 1999). Identifying which issues are central in a given system and what policy should be followed to address them depends on the environment. However, while there has been significant recent research into various control/management architectures and policies for making use of cross-trained workers (see e.g., Bartholdi et al. 1999a, 2001, Bartholdi and Eisenstein 1996, Hopp and Spearman 2000, McClain et al. 2000, McClain et al. 1992, Ostolaza et al 1990, Schultz et al. 1998, and Treleven 1989), there is as yet no broad conceptual framework for the evaluation of systems in terms of whether and how they can take advantage of workforce agility. In this paper, we suggest a structure for such an evaluation, which we term *Agile Workforce Evaluation (AWE)*.

To develop a practical framework for AWE, we first introduce terms and concepts for understanding the role of cross-training. Second, we present a conceptual framework for the strategic assessment of the role of cross-training in an organization. Third, we propose a model to understand the basic components of workforce agility architectures. Fourth, as an aid for system design, we develop a tactical level framework to identify and describe the key system factors that influence how cross-training may suit a specific environment. Fifth, we classify design and control policies into broad categories and examine much of the literature through this lens.

In our view, a framework should accomplish several things if it is to be successful. First, it should break new ground in carefully defining the terms, concepts and structures that are sufficient to analyze a broad range of systems with regard to their potential for agility. Second, it should be simple and tractable enough for practitioners to apply to real systems. Third, the framework should be an asset in categorizing the extant research literature and in identifying new research opportunities.

Our evaluation framework is based on the perspective that all work done in any production or service environment can be broken down into *tasks*. To define a task, we first identify its constituent *elements*, which are:

1. *Labor*
2. *Entities*
3. *Resources.*

Labor refers to workers of any sort who accomplish the tasks (e.g., operators, supervisors, and support staff). An *entity* refers to the output that the system "produces" as appropriate to the context. In manufacturing, we often refer to an entity as a job, while in a call/service center an entity often refers to a customer, and medical care usually refers to one as a patient. Tasks are performed on entities to transform them through various phases from raw to finished. Entities can include a physical component (e.g., part) and/or a logical component (e.g., work order or resource repair job). *Resources* refer to machines, processes, technology, and any other associated equipment required to perform work in the system.

We can now define a task as an activity that applies labor and/or resources to an entity over time. Tasks are broadly construed to represent any of the activities that are required to accomplish production and service. Thus, activities such as machine maintenance and repair or quality control, which are key areas of cross-training advocated under the Just-In-Time (JIT) philosophy, are included as tasks. The entity associated with a repair task is a purely logical one (e.g., a repair order), since it is not associated with any particular production output. A *task-type* is defined as a category of related tasks (e.g., welding) and therefore is not associated exclusively with any particular entity. In general, enabling workers to perform multiple task types (e.g., welding and final assembly) or the same task type on two or more entities (e.g., performing a welding task on two physically distinct production lines) is considered *cross-training* for our purposes.

These elements are brought together in a particular system by what we call the *system architecture*, which captures the logical, integrative relationships among labor, entities, and resources over time.

Our AWE framework consists of strategic and tactical level assessment structures that examine the key system factors that influence the relative effectiveness of using cross-trained workers as opposed to specialized workers and the types of workforce organizations that are best suited to a given environment. The process consists of two levels:

1. *Strategic Assessment*: We define a *strategy matrix* that identifies mechanisms by which cross-training can support the strategic priorities for the organization.
2. *Tactical Assessment*: We describe a tactical framework that evaluates key structures and constraints found in the system environment and uses these factors to guide the selection of a workforce agility policy.

To our knowledge, our AWE framework is distinct from other approaches for classifying production systems – both in terms of scope and comprehensiveness (see for example Iyer and Askin 1998, Crandall and Wallace 1998, Hayes and Wheelright 1988, Hopp and Spearman 2000, Sethi and Sethi 1990, and Van Oyen and Veatch 2002). AWE is a conceptual and theoretically-based construct, but it has been put into practice. Hundreds of business undergraduates and MBA's have used this assessment framework at the authors' institutions for real-world case studies. They have reported that it has provided a structured procedure that greatly enhances their ability to analyze a system thoroughly and helps suggest design solutions.

The remainder of this paper is organized as follows. In Section 2, we outline our strategic assessment framework for evaluating whether workforce agility should be applied in an organization. In Section 3 we offer a conceptual model of the elements of a workforce agility architecture. Section 4 develops a tactical framework for

environmental assessment that supports the determination of how cross-training can be applied in the context of a given environment. Section 5 uses the definitions and perspectives of this paper to identify a suite of canonical policy classes; moreover, we review the literature and gain insights into research opportunities. Section 6 uses industrial case studies to illustrate the tactical framework. Section 7 provides a map to link the tactical framework factors to our suite of canonical policies. We conclude in Section 8.

2. Strategic Assessment Framework

The strategic mission of the organization should be the starting point for determining whether and how workforce agility should be used. A good basis for business strategy is to offer customers a value proposition that consists of some mix of the following dimensions: price (which hinges on cost), time (delivery speed and reliability), quality (with regard to product quality and customer service) and variety (customization). The operations of the system must provide the necessary capabilities to achieve the desired performance along these dimensions.

Cross-training workers and allocating them to tasks in dynamic ways can play an important role in supporting an organization's strategy. As an example introducing our perspective, we outline a case which the first author worked on:

> **IBM** produced unpopulated printed circuit boards (PCB's) in the early 1990's using a tandem flow line. The primary strategic concern of this plant was cost, because other units in IBM could obtain PCB's from outside suppliers if the internal plant was not cost competitive. Therefore, it was critical for tactical policies, including those related to workforce issues, to support the cost reduction objective. At the outset, each process in the line was staffed by a set of operators assigned specifically to that process. One operation, which applied a plastic coating to the PCB's, was experiencing severe capacity problems and forcing the plant to outsource part of the coating volume to an (expensive) outside vendor. So, management decided to cross-train workers from a non-bottleneck process to increase output of the entire line and thereby save on vendoring cost. In addition to using cross-training for direct capacity benefit, management chose to rotate workers between task types in order to reduce their fatigue and make them more productive, and hence more cost effective. This case illustrates: (1) whether and how to use workforce flexibility techniques depends on the capabilities the firm is trying to create to support its business strategy, and (2) the potential effectiveness of a workforce agility policy depends on tactical details of its implementation in the particular environment under consideration.

Our intention is to create a framework to guide the assessment of whether and where workforce agility fits into the strategic objectives of the firm. To provide a visual illustration of the connection, we make use of a device we call the *strategy matrix*, which is illustrated in Figure 1. Thinking through the strategy matrix in conceptual terms enables the decision maker to systematically identify the direct and indirect links between worker cross-training and strategic objectives. The output is a structured list of ways in which cross-training can support the strategic objectives of the particular system under consideration.

We outline some of the direct mechanisms through which cross-training can positively impact each of the strategic goals as follows:

1. **Cost:** Cross-training can support lower labor costs by increasing labor productivity. Three ways this can happen are: (a) cross-trained workers are able to perform more work during the scheduled work hours (i.e., labor or resource utilization is increased because of greater flexibility), (b) the increased flexibility permits the system to reduce the investment in inventory, or (c) cross-trained workers are able to work faster (e.g., by developing a cross-trained team that exploits synergies, tasks are accomplished more quickly). In order to realize a cost savings from these improvements the system must either reduce labor costs (headcount), increase production volume, or reduce the cost of production (e.g. WIP reduction). The above discussion highlights some of the intrinsic complexity of the strategy matrix. The items listed in Figure 1 are not guaranteed to create the desired effects, but instead represent possible mechanisms by which cross-training, if properly implemented, could support business objectives. Another likely point of confusion is that a mechanism–increased task speed for example–may have multiple benefits. For instance, if cross-training can facilitate increased task speed, then it may very well reduce labor costs *and* improve responsiveness by reducing process time. For clarity, we have listed the mechanisms in their most obvious matrix location while avoiding repetition, which in this case is the Time dimension.

2. **Time:** Cross-training can enable shorter lead time quotes and more reliable delivery by reducing the mean and variance of the cycle time (and hence lead time) to produce a product or service. Increasing worker flexibility, improving task speed, reducing the effective setup and handoff times, or minimizing task time variation can reduce congestion to facilitate shorter average cycle times and hence support this goal. Because congestion is frequently significant and generates waiting times that may constitute a dominant fraction of total lead time, we emphasize the impact that labor flexibility has on reducing congestion and hence lead time. (Note that if the organization's strategy is weighted more heavily toward responsiveness than price, then it may make sense to maintain, or even increase, labor costs.) Finally, since mean lead time and customer service are both influenced by cycle time variance, cross-training can also address the time criterion by making cycle times more regular (e.g., by shifting capacity to short-term bottlenecks in order to smooth flow).

3. **Quality:** Cross-training can support better internal quality (e.g., lower yield loss or rework), better external (customer-perceived) quality (e.g., compliance with customer-oriented product specifications), and reduction of the frequency of entity handoffs by enabling the system to develop broad capabilities that provide better ways of meeting customer needs. We should note, however, that if workers are matched to tasks according to other criteria (e.g., speed or regularity), then it is possible that cross-training could lead to a degradation in quality. So, in addition to identifying paths by which cross-training can improve performance, the Strategy Matrix should also be used to note possible mechanisms by which performance could be hurt.

4. **Variety:** Cross-training can increase the production flexibility of an organization, thereby helping it effectively deliver a broader range of products and/or services to customers by: (a) equipping the workforce with a larger set of skills, so that they can to do more things efficiently, and (b) providing redundancy of tasks so that the system can provide variety more reliably (e.g., when one worker is absent or on break, another can perform his/her task to produce the desired product or service for a customer).

The above mechanisms can impact the four strategic goals directly, but there are important indirect means that could affect any of the above strategic dimensions. (Figure 1 illustrates this by showing the indirect issues applying to all four strategic dimensions.)   Cross-training may facilitate *learning*, which enables workers to become faster, more regular, or more reliable over the long term. Blake et al. (1964) outlined how team learning links individual learning to organizational development. Other relevant literature on learning and forgetting includes Argote and Epple (1990), Bordoloi and Matsuo (2001), Goldstein (2002), Nembhard (2000), Nembhard (2001), Nembhard and Osothsilp (2001), Noe (2002), Shafer et al. (2001), Smunt (1987), Nembhard and Norman (2004), and Misra et al. (2004). Cross-training may enable *communication*, which helps workers better coordinate their tasks (e.g., cross-training an upstream worker to do a downstream task may make him/her more capable of communicating information to a downstream worker that will facilitate that worker's task). Buzacott (2004) used quantitative modeling to yield insight into the cultural dynamics of faster workers helping out slower ones. By making more people responsible for each task type, cross-training may facilitate *problem solving* (e.g., finding better work methods, diagnosing causes of quality problems, improving team-based kaizen initiatives, etc.). By giving workers more of a global perspective on the enterprise, cross-training may provide *motivation* to increase effort levels and cooperation (see Hackman et al. 1978, Ichniowski and Shaw 1999, Paul et al. 1969). Schultz et al. (1998) studied the motivational effects of visible feedback such as work-in-process (WIP) and concluded that it can increase work pace, and that reducing ambiguity of feedback enhances this effect (see Powell and Schultz 1998 for other operational implications). In addition to short-term motivation, there is the longer term issue of employee *retention* through job satisfaction, compensation, and/or career path development (see Ichniowski and Shaw 1999 for a comparison of Japanese and U.S. approaches). Foegen (1993) mentions psychological factors and compensation issues related to retention. Crandall et al. (1997), Holmstrom and Milgrom (1994), Rao (1990), and Lal and Srinivasan (1993) also investigate compensation issues, among other things. See Gans and Zhou (2000) for analysis of retention issues. Cross-training may also facilitate improved performance due to *ergonomic* effects (e.g., less fatigue, boredom, or repetitive stress) of greater task variety. In some instances, the cultural or organizational impacts of cross-training, represented by these indirect mechanisms, may be the most important motivation for pursuing a workforce agility strategy. Hence, in filling out a Strategy Matrix for a given system it is essential to think carefully about potential indirect benefits of cross-training.

The operations literature has addressed many aspects of how workforce agility supports strategic objectives. Nembhard et al. (2002) and Van Mieghem (1998) examined how to weigh the costs of cross-training and/or flexibility against the resulting system performance benefits and/or profits. Sethi and Sethi (1990) provided an extensive categorization of various forms of manufacturing flexibility with implications for cross-training (see also Choi and Kim 1998 and Stecke 1985). A related literature studies cross-training and labor issues under the term "dual resource constrained" (for example, see Kher 2000). Croci et al. (2000) considered the complexity of cross-training when task-times are machine-dominated. We cite additional operational literature later in our discussion of categories of cross-training policies.

Regarding the goal of quality, Womack et al. (1990) discussed the broad area of lean production, noting cross-training as an important element that impacts not only cultural and operational efficiency, but quality as well. In addition to productivity, the work of Pinker and Shumsky (2000) emphasized the dimension of learning based on experience and its impact on a quality-based performance measure.

The goal of variety is closely related to production flexibility. Bessant and Haywood (1988) discussed flexibility, noting that it is much more an organizational property than a technical one. Spear and Bowen (1999) pointed out that cross-training that includes teaching workers problem solving skills using the scientific method has been an important element of the Toyota Production System, which creates an innovative, performance-driven work culture that cannot be attained simply by the addition of technology or technical manufacturing and control approaches. Upton (1994, 1995) described the dynamics that create flexibility, stressing the key role of workforce agility as opposed to flexible infrastructure. Knudsen and Boggs (1996) characterized the transition from Fordist production to flexible production, which they argue was initiated by the global recession in the early 1980's. Malecki (1996) framed workforce agility as one component of a firm's overall agility. Benjaafar and Gupta (1998) explored high-level flexibility issues. Iravani et al. (2002) quantified structural flexibility via an index which is shown to relate closely to the performance of queueing network models and provides evidence that chain structures maximize flexibility. Similarly, Aksin and Karaesmen (2002) proved certain dominance principles with respect to the flexibility inherent in a particular skill pattern selection. While not couched in the context of cross-training per se, Jordan and Graves (1995) and Graves and Tomlin (2003) offered relevant and insightful model-based treatments of the operational benefits of flexibility under chained flexibility strategies.

Strategic Objective	Direct Mechanisms	Indirect Mechanisms
Cost	Higher Labor Productivity: • improved labor utilization • improved resource utilization • decreased WIP and inventory	⇑
Time	Increased Responsiveness: • reduced congestion via flexibility • increased task speed • reduced task time variation • reduced setup and handoff times	Learning Communication Problem Solving Motivation
Quality	Improved Internal/External Quality • improved labor/task matching • improved customer service • fewer entity handoffs	Retention Ergonomics
Variety	Broadened Offerings of Products/Services • expanded task range • increased production flexibility	⇓

Figure 1: Strategy Matrix Template to Help Identify Direct and Indirect Mechanisms by which Cross-training can Support Workforce Agility

To illustrate the use of the Strategy Matrix, we now consider some industrial cases with widely differing motives where workforce agility architectures were used effectively. Later we will return to these examples and discuss how these strategic differences, combined with environmental differences, led to very different architectures. The first case, IBM, has already been given, so we begin by suggesting Figure 2 as a rough summary of the Strategy Matrix for IBM.

John Deere makes a wide mix of planters in its Seeding Division. Originally, the planters were built in bays and some unusual models were outsourced. Furthermore, many planters were kitted in the plant for final assembly

at the dealer, which supported a high level of variety, but also caused quality problems. Because quality and customization were key sales drivers, management sought a major overhaul to support these at efficient cost levels. They did this by first identifying six modules that made up all planters. They then reconfigured the plant as a moving assembly line fed by six cells responsible for fabricating, subassembling and assembling each module. Cells were staffed by cross-trained workers to handle the workload variability and to help bring outsourced products back into the plant. Furthermore, because the cell teams were responsible for all functions associated with a module, these teams were clearly accountable for the quality, especially internal, of their portion of the final products. At the same time, the tasks requiring the most skill (i.e., welding tasks) were usually covered by the most experienced workers because the incentive system gave them priority for them. The result was an effective matching of worker skill to tasks, which also enhanced quality. Thus, the Strategy Matrix for Deere would have looked something like Figure 3.

	Direct	Indirect
Cost	Labor Utilization, Resource Utilization	Productivity from reduced fatigue
Time		
Quality		
Variety		

	Direct	Indirect
Cost		
Time		
Quality	Improved labor/task matching	Accountability for module quality
Variety	Flexible cell staffing	

Figure 2: IBM Strategy Matrix   **Figure 3: John Deere Strategy Matrix**

Elgin Digital Color Graphics (EDCG) is a pre-media print operation of R.R. Donnelley & Sons, whose primary function is to receive photographs/images and text material, combine these elements with proper color and layout into a publication such as a mail order catalog, and then generate the computer files for the printing presses. Some of the task-types include scanning, proofing, color console editing, page-building, output formatting, and sheet proofing. As is traditional in this industry, specialized workers were assigned to tasks, making the system operate like a conventional flow line based on functional silos. But, because quick response times and customer service were paramount, management cross-trained the workers to improve responsiveness by reducing queueing within the line. It also improved service quality by (a) reducing handoffs of jobs within the line, which could lead to a loss of information, and (b) giving customers a single contact person (the team leader) throughout the production process. Hence, the Strategy Matrix for EDCG would have looked something like Figure 4.

Continental Plastic Containers (CPC) makes plastic bottles using an extrusion blow molding process. Each line consists of several automated stations (molding wheel, labeling, inspection, packaging) connected by automated material handling equipment. Operators are responsible for setup, monitoring, troubleshooting, and some manual operations at packaging. Since these products are commodities, cost is critical. Quality problems (yield loss) were one major source of cost. To improve yield, CPC cross-trained some operators to float between stations and troubleshoot problems. This had the added benefit of providing a career path for operators, which could help reduce the high level of turnover and therefore provide more experienced workers to troubleshoot problems beyond those causing the quality concerns. Hence, the Strategy Matrix for CPC would have looked something like Figure 5.

	Direct	Indirect
Cost		
Time	Labor utilization	
Quality		Internal/external communication
Variety		

Figure 4: EDCG Strategy Matrix

	Direct	Indirect
Cost		Motivation, retention via career opportunities
Time		
Quality		Improved problem solving
Variety		

Figure 5: CPC Strategy Matrix

GE Financial Assurance (GEFA) operated a call center in the late 1990's, which supported about 8 major product offerings. In addition to fundamental skills for customer service, call handling, and using computer-telephony integration equipment, each product (task-type) required unique skills from the customer service representatives (CSR's). Significant levels of employee turnover and high variability in demand levels made good labor utilization and quick customer response times difficult to achieve. Automated skills-based call routing and workstation information technology nearly eliminated the delays in switching from one task-type to another. Thus, they could easily allocate labor capacity to meet changing demand patterns in real time. Most CSR's responded favorably to the cross-training and increased pay, which helped reduce turnover. Thus, the Strategy Matrix for GEFA would have looked something like Figure 6.

	Direct	Indirect
Cost	Labor utilization	Employee retention via job satisfaction
Time	Skills-based routing	
Quality		
Variety		Organizational skill development

Figure 6: GEFA Strategy Matrix

3. Classification of Workforce Agility Architectures

Strategic justification of cross-training can be presented in general terms; however, to reach the level of tactics, it is helpful to develop a more detailed vocabulary and perspective on cross-training implementation. To begin with, we note that a workforce agility architecture consists of three basic parts:

1. *Cross-training skill pattern*, which defines which task-types each worker is qualified/authorized to perform.

2. *Worker coordination policy, which* allocates workers to tasks (or tasks to workers) over time.

3. *Team structure*, which determines the manner in which workers collaborate, communicate, and otherwise relate to one another in the workplace.

To help visualize these components, we define a thought experiment in which the basic outcome of a workforce agility architecture is displayed in a hypothetical table that we call the *worker/task matrix*. This matrix would have a row for each worker in the system and a column for each task to be performed over some time

horizon. Highlighted cells (e.g., colored green) represent tasks for which a worker is qualified/authorized. Super-highlighted cells (e.g., colored red) could contain a task number to denote the task or tasks being performed by workers at the present time. By watching this worker/task matrix evolve over time, one could see the cross-training and assignment aspects of an agile workforce architecture. Some aspects of team structure (e.g., whether or not two workers are collaborating on the same task simultaneously) would also be apparent from the matrix. However, some subtler elements of team structure (e.g., who had authority to make task assignments and what type of incentives were in place) would not be evident from the worker/task matrix alone.

Since we are interested in the inputs to a workforce agility architecture more than the outputs, we want to describe the range of possible policies that could be used to control the worker/task matrix. Although it is impossible to comprehensively list all possible policies, we can offer a high level structure.

3.1 Cross-Training Skill Pattern

We can think of an architecture for cross-training as specifying answers to the following three inter-related questions (among others) related to the skill pattern: Who? (i.e. the workers to be cross-trained); Where? (i.e., the task-types to be included); and How much? (i.e., the extent of each worker's cross-training). To consider the question of where to do cross-training, we first observe that the assignment of task-types to particular workers (the columns of our worker/task matrix) can be classified by the following three dimensions:

1. *Skill type:* It is common for different tasks to involve similar skills. For instance, a manufacturing system may involve several types of welding tasks, all of which can be done by welders. Traditional process layouts organize manufacturing operations largely on the basis of function. In modern cellular layouts, functional skills are distributed throughout the plant, which is one reason cross-trained workers are typically used to staff manufacturing cells. Hopp et al. (2004) used operational perspectives to gain managerial insights into how to strategically select an effective set of skills for each worker. They showed that commonly held approaches based on capacity bottlenecks can be inferior to chaining approaches. A call center that services a variety of inbound calls distinguished primarily by product type also fits this category. Automated skills-based call routing technology makes it easy to route any inbound call to any available agent with the appropriate skill set.

2. *Entity:* Sometimes, the tasks associated with a given job, customer, or other entity type, are strongly related. In such cases, the identity of the entity becomes the dominant basis for selecting the tasks that a worker will be given. For instance, a number of tasks must be completed to process an application for a consumer loan at a bank. If all (or at least many) of these are done by the same person, then the customer has a clear contact for information, progress reports, quality control, etc. Consistent with such reasoning and the customized nature of the service, realtors are trained and organized using this concept. A classic, but ultimately unsuccessful, case of cross-training workers with respect to entities was the Volvo team-build approach to auto assembly, in which a team of workers was assigned to do all or most assembly tasks on a particular vehicle. It is important to note that our perspective on cross-training includes cases in which workers are utilized to perform the same task-type on two or more types of entities. For example, cross-training is sometimes done to facilitate a change from a functional layout to a cellular layout, which may not require workers to learn new skills.

3. *Resource:* Task-types are often linked to the resources used to accomplish them. For example, a machinist may be able to perform any operation associated with a particular milling machine. However, since the milling

machine is also required to perform maintenance/repair tasks, which may require a different worker, it is not necessarily the case that workers are qualified for all tasks on a resource. On the other hand, a common practice in JIT systems is to cross-train machine operators to do much of their own maintenance and quality control, thereby achieving closer to full cross-training on each resource.

These three dimensions suggest options for cross-training. For instance, we can think of training workers by skill type (e.g., training welders to perform assembly tasks) so that they can cover tasks associated with different groups of skills. Or we can think of training workers in terms of managing entities (e.g., customer service representatives are sometimes trained for a particular group of clients with all the necessary skills to follow an inquiry through the process end-to-end). Or we can think of certifying workers to operate various resources in the system (e.g., training pilots to fly particular types of aircraft).

Various combinations of these dimensions are possible. For example, an operator might be cross-trained to operate a subset of the resources required to service a given entity. A specific example of this occurred at EDCG, where cross-trained graphic arts technicians executed pre-print production tasks throughout the entire process with the exception of a few specialized tasks, such as color registration/editing and final output formatting. The cross-training was largely organized around entities, but was restricted by resources requiring specialization.

3.2 Worker Coordination Policy

To provide a framework for classifying assignment/coordination policies we note that workers can be assigned to tasks on the basis of the following information structures:

1. *Clock time*: Workers can be rotated to specific task types, resources, or entities according to a schedule. For instance, a worker might spell (i.e., take over) an operation during a break or lunch.

2. *Labor*: Instead of thinking in terms of assigning workers to tasks, we can think of assigning tasks to workers. This allows us to give workers priorities, based on speed, skill, relationship to customer, etc. An example of a labor priority policy is the bucket brigade policy, which gives priority to the downstream worker to preempt a task from an upstream worker (Bartholdi and Eisenstein 1996). For another example, it is currently U.S. law that a commercial pilot over the age of 60 may not perform the landing task. In foreign airlines flying from countries without this rule, captains over 60 hand over control to let a co-pilot under 60 to land the craft on U.S. soil.

3. *Entity*: Workers may be assigned to tasks based on specific characteristics of the tasks. For example, information about an entity (e.g., its task-type and/or the customer demanding it) can be used to prioritize which worker will be assigned to it. For example, a customer that makes a follow-up troubleshooting call to a technical support call center may benefit from service by the same technician as in the past to increase efficiency and customer service.

4. *System status*: The worker/task assignments can be decided dynamically on the basis of the best available system information at that time. For example, a policy that allocates a floating worker to the process with the largest work backlog is a system status policy. Likewise, using arrival and departure times of delivery trucks to determine the tasks assigned to a worker at a United Parcel Service shipping dock is a system status policy. Because there is an unlimited number of parameters and structures that could be invoked for dynamically allocating workers to tasks, it is impossible to specify all possibilities. We see significant opportunity for creativity in formulating effective approaches to workforce agility.

In practice, combinations of these information types can be used to make task assignments. For example, a worker might be assigned to cover a particular operation during a lunch break if the work backlog is above a specified level (i.e., using a combination of clock time and system status).

3.3 Team Structure

Beyond the approaches for cross-training and assigning workers to tasks, a workforce agility architecture is shaped by decisions that affect whether and how workers interact in teams (see Thompson 1999 for an overview of issues involved in designing and managing teams). Although it is possible to have a team without the use of cross-training (i.e., specialists organized with a sense of teamwork), the concept of teamwork is especially relevant to issues related to cross-training, including:

1. *Collaboration:* Whether and how to form collaborative teams to perform some of the tasks is an important workforce agility. Workers can collaborate on the same task (e.g., the Volvo team build method) or work separately on tasks (e.g., the common practice of auto assembly lines with single workers at stations).

2. *Authority:* The concept of the worker/task matrix as a summary of who is qualified for and assigned to each task raises the question of how to make the decisions leading to this matrix. In practice, the rules governing these decisions may be complex and change in response to events. Hence, the question of who has authority to make decisions governing team behavior is a central one. Indeed, the whole notion of empowerment is premised on the idea that shifting authority to worker teams can promote more nimble and accurate decision-making. The range of possibilities is large. A team may be governed by an outside authority (e.g., an exogenous schedule, possibly generated by optimization software), an internal authority (e.g., a lead technician or foreman), or communally (e.g., by group consensus).

3. *Communication:* Closely related to authority is communication, which also includes organizational learning. Communication describes how workers share information pertinent to system operation. The use of devices like post-shift meetings, suggestion boxes, quality circles, etc., can have a major influence on the extent to which teams function effectively.

4. *Incentives:* Although it is beyond the scope of this operations-oriented paper, a critical issue in many agile work systems is the incentive scheme. Organizations of teams that share work among individuals should consider incentive systems that reward people at least in part based on team performance in addition to individual performance (see Sumukadas and Sawhney 2002 and Wageman and Baker 1997). The manner and extent of collective compensation can have a large impact on worker satisfaction and productivity. For example, the authors are aware of a firm that implemented an aggressive form of team compensation that led to emotional and physical conflict between workers who felt that some members were not pulling their weight. The size of the teams can also be a determinant of how the incentive system will work (e.g., the authors encountered a company in which small teams of 15 people regularly achieved their production goals but large teams of 100 people did not, presumably because "free ridership" issues were more severe in large teams).

Collectively, the team structure component addresses ways in which organizational culture affects decisions about workforce agility. These can be subtle (e.g., a firm with a history of using collaborative teams may attract employees with a propensity for teamwork, while a firm just introducing teams might have difficulty recruiting the

right kind of people to work in them). Also, because there are so many facets to organizational issues, the range of possible environments is very wide. Discussing them in any depth is beyond our scope. For issues affecting team structure and performance see Cannon-Bowers and Salas (2000), Coovert et al. (1995), Gladstein (1984), McGrath (1984), and Powell (2000).

4. A Tactical Framework for Environmental Assessment

The above elements of a cross-training architecture can be implemented in many different ways. The design of an effective architecture depends on both the strategic objectives of cross-training (as identified in the Strategy Matrix) and on the production environment (which we characterize using tactical level factors). In this section, we present a tactical-level framework for assessing environments with respect to the factors most relevant to the choice of how best to implement workforce agility. We implicitly assume that the overarching tactical objective seeks to achieve an operational regime that emphasizes work-in-process (WIP) reduction, high target throughput (TH), and minimal cycle time (CT), subject to quality (both engineered and customer-perceived quality) and employee satisfaction targets.

Although we have presented the strategic decision process and analysis of architectures first, in practice these decisions are iterative and linked. For instance, once a decision maker has stated the strategic objectives, he/she may have to consider the policies suited to his/her environment in order to make a case that cross-training can support these objectives. So, the decision maker should start with a preliminary strategy matrix, like those in the examples of Section 2, and then update these as more detailed consideration is given to specific policies.

The factors that influence architecture design most strongly are those features of the production environment that influence the alternatives for cross-training skill pattern, worker coordination and team structure. Factors that drive the selection of a cross-training skill pattern are those that affect which tasks each worker is capable of doing. This aggregate effect, which we term *training efficiency*, gauges how effectively workers can be trained for these new skills. Factors that affect worker coordination are those that influence how workers can be assigned to tasks and task-types over time. We divide these into two categories: *switching efficiency*, which measures how efficiently workers can shift between task types, entities and/or resources, and *multi-tasking efficiency*, which measures the extent to which workers can perform tasks in parallel. Finally, factors that affect team structure are those that arise from worker competency synergies or an economy of scale gained through the size of a team. We aggregate these under the heading of *collaborative efficiency*, which measures whether and how grouping workers on tasks improves productivity.

These factor categories are very general, and may serve in some cases only as guideposts in the design process. It is impossible to list every environmental detail that might influence the design; however, we can organize the dominant categories of factors with respect to the three basic parts of a workforce agility architecture, as shown in Figure 7. For instance, the team structure dimensions of authority, communication, and incentives are considered indirectly via their effects on these efficiencies. Below we describe each category in more detail and give common examples of factors in each category.
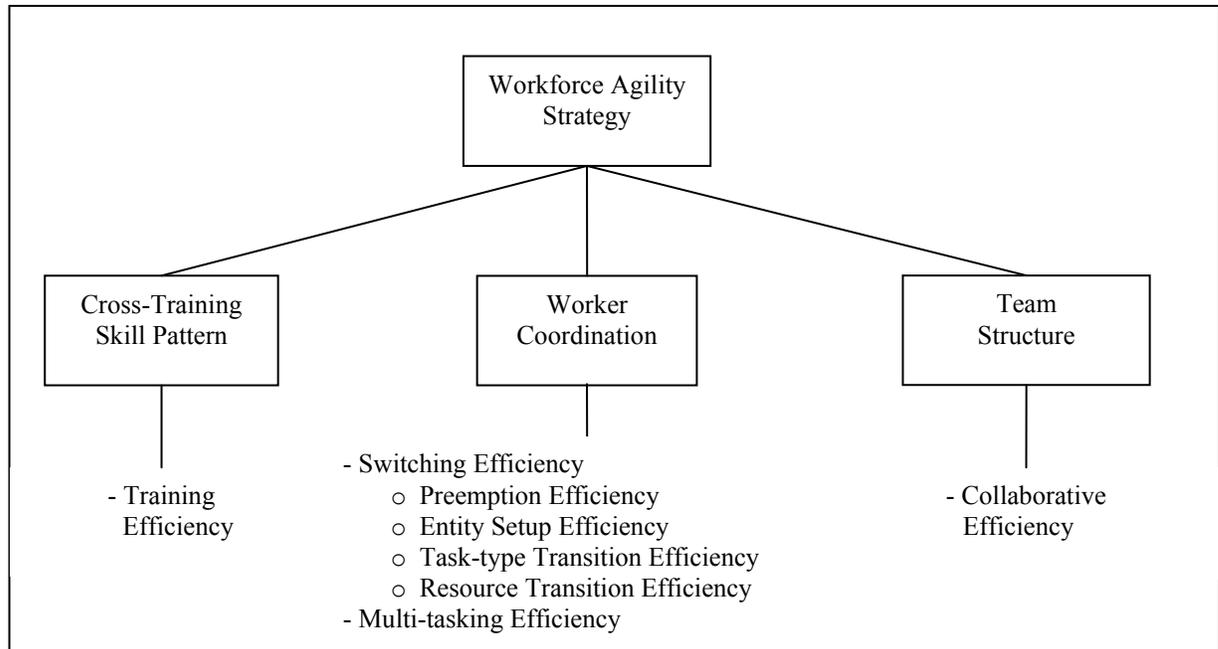
Figure 7: Environmental Factor Categories

Training Efficiency: If any worker could be trained to do any task, then any skill-pattern could be used. However, since tasks require skills, there are often costs and limitations on the types of tasks a given worker can do (see Gill 1997). Some tasks may be highly specialized, meaning that only a small number of workers can do them. Training other workers to be able to cover these tasks (or hiring more highly trained workers who can learn to do them) may be prohibitively expensive. Of course, individual-dependent learning curves and forgetting of skills, in addition to equipment, layout, ergonomics, career path and other issues, can have a strong influence on how difficult it is for workers to acquire and retain new skills. So the training efficiency factor can be intentionally improved to some extent by management.

At any point in time, this factor can be characterized by two key measures: First, *cost of skill acquisition* captures the average expense of training workers to cover and to retain new task types. If this is very high across all skills, then opportunities for cross-training may be limited. For instance, in a steel casting finishing operation, the various tasks (i.e., finishing different portions of the casting) might be similar, which would make it possible for workers to easily learn new tasks (which would also be called skills for the discussion at hand). But, if different tasks require different equipment (e.g., sets of gauges), then cross-training workers would necessitate buying them additional equipment, which would increase the true cost of skill acquisition. Similarly, for medical imaging technicians to perform procedures, they need to be certified, which represents a tangible cost in addition to any wage increase that may be appropriate. Second, *skill level variation* considers the range of difficulty of acquiring different types of skills. Speed variation can be an issue. For example, Buzacott (2002) concluded that an optimal coordination policy is very sensitive to worker speeds, but that good policies exist which are insensitive to worker speed (see also Hopp et al. 2004). If some skills are highly specialized, while others are quite general, then it may be possible to train highly skilled workers to cover lower level tasks, but the reverse may not be possible. For example, in the EDCG pre-media print operation, color registration was a highly specialized operation requiring an

experienced worker to achieve a high level of quality. So, while workers could be (and were) cross-trained to do almost all of the other task types in the system, color registration was left to a specialist. The reason was that the skill level variation was simply too high to allow full cross-training across the entire system.

   Switching Efficiency: An important reason organizations use cross-training is to be able to rotate workers over time to the tasks where they are most needed. But, if the benefit of changing tasks is offset by inefficiencies (e.g., the worker must waste time walking to a different department), then certain types of worker coordination may be impractical. There are several distinct factors under the umbrella of *switching efficiency.* It is important to separate these factors, because specific design efforts are needed to modify these factors; moreover, they affect the architecture in unique ways.

- *Preemption Efficiency:* This factor assesses the efficiency level attained given the additional time required to complete a task if the original worker is preempted during the task by a second worker. Inefficiency can occur because the preemption breaks the rhythm of the task (see Schultz et al. 1998), because there is a physical transition required (e.g., the second worker must perform a set up for this task such as putting on a face shield), or because an information exchange is required (e.g., the first worker must explain to the second worker precisely which steps remain unfinished). Regardless of the cause, significant preemption delays can preclude policies that call for tasks to be frequently handed off between workers. We note that cost may be used in place of delay as a more appropriate basis for assessment in some systems.

- *Entity Setup Efficiency:* Although we are conditioned to think of assembly lines, which usually require this factor to be high, the setup delay (or setup cost) associated with a worker taking over an entity for the first time can be significant. For instance, if a lawyer takes over a case, he/she must read all of the legal briefs associated with it. As long as the original lawyer follows the case through its various tasks, he/she does not need to re-read these initial documents, so the delay is tied to the entity, not the particular task-type. But if another lawyer joins the team during some phase of work, he/she will need to read the briefs in order to get started. Some difficult systems with low entity setup efficiency can be handled by policies that have workers follow entities through the system. To enable cross-training to effectively execute setups and changeovers, an investment in infrastructure may be required. Thus, cost can be incurred to avoid time delay, thus leading to a cost efficiency measure. For example, call centers typically invest in databases, scripting, and skills-based routing technologies to enable quick setups and changeovers such as this sub-factor as well as those captured in the next two sub-factors.

- *Task-Type Transition Efficiency:* Some time is usually lost when a worker switches between task types (as distinct from entities) due to a loss of work rhythm (Schultz et al. 1998) and/or physical switching time. For instance, a customer service representative at a call center who shifts from handling sales calls to handling service calls may need to close one database on his/her computer and open another. He/she might also have to take time to move to a different station (say to handle fax communications), which would hurt resource transition efficiency, as described below.

- *Resource Transition Efficiency:* It frequently takes time for a worker to switch between resources. For example, a worker who switches from running one machine tool to running another may have to shut down the first machine, walk between the two stations and start up the second machine. The sum of these times would represent resource transition delay, and thus be used to determine resource transition efficiency. Reducing the delay to zero is an important objective, but not the only one. As an example, if rotating a

worker between two physical activities that use different muscle groups reduces fatigue and thereby reduces delays due to resting or quality problems, then ergonomic effects can make switching between resources a benefit to productivity even with setups.

Collaborative Efficiency: Many modern work environments, with and without cross-training, make use of teams to accomplish some tasks. Therefore, to accurately assess the potential for cross-training, we need a factor that identifies specific task-types that can benefit from teamwork. While the reasons for using teams are many (e.g., motivation, ergonomics, learning, career advancement, employee retention, quality, etc.), frequently, the fundamental justification is that teamwork will ultimately improve productivity. There are many mechanisms by which teams can accomplish more work than sets of workers working individually. People might have complementary skills, which make the whole of the team greater than the sum of its parts. For instance, paint crews and construction crews often work in groups of two or more because this facilitates some tasks, such as setting up ladders and scaffolding. In other cases such as the Deere example, teaming might improve quality, thereby reducing productivity loss due to rework and/or yield loss. For Deere, having teams associated with specific product modules made them clearly accountable and therefore more concerned with quality. Other means by which teams can increase productivity are by improving motivation, reducing fatigue, or otherwise providing incentive for workers to work harder over the long term.

The basic measure of collaborative efficiency is the relative percentage increase in average task speed (or labor productivity) that results from assigning multiple workers to the same task. That is, if two workers can finish a task exactly twice as fast as one worker, then collaborative efficiency is zero (Medium). If two can work more (less) than twice as fast as one, then collaborative efficiency is positive (negative). Papers that explore the use of collaborating workers include Andradottir et al. (2001), which treated blocking in limited buffer models, while Mandelbaum and Reiman (1998) and Van Oyen et al. (2001) treated team craft approaches.

Multi-Tasking Efficiency: In much of the above discussion, we implicitly assume that workers are assigned to at most one task at a time. But in most manufacturing environments, and many service environments, some tasks are automated or partially automated. In such environments it is possible for a worker to perform multiple tasks simultaneously (e.g., he/she loads up two automated machines and then monitors both, or she/he uses a voice/audio warehouse order picking system that enables the picker to hear picking instructions and to confirm picks while driving a forklift). Clearly, cross-training a worker to be able to set up and monitor multiple automated tasks can have a significant effect on his/her productivity. The potential for multi-tasking efficiency must be considered when selecting a workforce agility architecture. As with collaborative efficiency, a score of zero (Medium) is appropriate when multi-tasking results in neither loss nor benefit.

5. Worker Coordination Policies: Examples, Literature Classification, and Open Problems

Although our factor analysis and review of implementation options suggest that a very wide range of approaches to workforce agility is possible, the technical literature has focused on a relatively small set of environments and policies. It is useful to review the main groupings, which we refer to as canonical classes of policies, to organize what is known and to highlight potential opportunities for further research. These classes of policies also include some other aspects of an architecture, notably the skill pattern. Because most of the research

literature is aimed at particular policies, we organize it according to the cross-training policy used and note the environment to which it applies. Subsection 5.6 then discusses open areas for further research.

5.1 Scheduled Rotation:

A very broad class of workforce agility policies includes those that schedule cross-trained workers to resources or tasks on the basis of clock time or a predetermined sequence of tasks. The matrix defining worker skill sets need not take on any particular structure. In some cases, there is an established pattern of rotation, while in other cases, the labor movements occur due to managerial intervention on an as-needed basis. It is common to use scheduled rotation to balance lines and to manage bottlenecks. When staffing level variability (e.g., from planned absenteeism), is a significant concern, pools of floating labor can be assigned on a daily basis to fill in the labor gaps (we treat dynamic floating in the next section). The transition efficiency factor set must support the frequency of rotation prescribed. When task-type set-up efficiency and/or station transfer efficiency are very low, one strong point of scheduled rotation is the fact that daily assignments of workers can be used to minimize the use of long set-ups and changeovers. A more common motive driving the decision to adopt scheduled rotation is ergonomics and/or organizational learning. When tasks are ergonomically stressful, some companies have opted for regular, periodic rotations that provide ergonomic relief, and also support skill development.

In general, selecting a scheduled rotation policy presents a constrained optimization problem, in which workers, like equipment, are resources to be scheduled according to an objective function. While it is difficult to say much about the completely general case, research has been done into specific instances of this problem where the cross-training follows a particular pattern. Much of this research relies on mathematical programming approaches. For example, a significant literature exists for crew scheduling in airlines, railways, and buses (a representative, but far from complete, sample of this research includes Beasley and Cao 1998, Chu et al. 1997, Chu and Chan 1998, Ferland and Taillefer 1992, Fischetti et al., 1997, Graves et al., 1993, Hoffman and Padberg 1993, Smith and Wren 1988). Research into worker scheduling in other applications, such as health care workers and call center operators has also been done (see Bard 2004, Berman et al.1997, Billionnet 1999, Campbell 1999, Eaves and Rothblum 1988, Evenson et al. 1998, Henderson 1976, Kenny et al.1995, Siferd and Benton 1992, and Trivedi and Warner 1976). Literature from a scheduling or sequencing-based perspective, often using mathematical programming, is relatively large (see as examples Bard 2004, Daniels et al. 1996, Daniels and Mazzola 1994, Daniels et al. 2002a, 2002b, Emmons and Burns 1991, Narasimhan 2000, Lee and Vairaktarakis 1997, Treleven 1989, Vairaktarakis and Winch 1999).

5.2 Floating Workers

Systems with a floater type of structure employ specialists augmented by a smaller number of generalists who float to the operation at which they are needed. This category restricts attention to systems in which cross-trained workers float dynamically to the most urgent task-type based on the congestion of the system. If the cross-trained workers are assigned solely on the basis of clock time, then we categorize it as a scheduled rotation policy. In some cases, a manager may serve as a floater, spending part of his or her day working in the operation on an as-needed basis. In such a case, it may be helpful for the floater to be providing on-the-job training of the specialists as he/she works at one or more stations. The potential performance benefits achievable with a floater in serial production

systems were analyzed in Farrar (1993) and Sennott and Van Oyen (2001) using Markov decision process models of lines with two and three stations. For floaters with two skills in a parallel environment, see Hopp et al. (2002b).

5.3 Zoned Worksharing

A significant amount of research has focused on zoned cross-training coupled with system status assignment rules. The defining characteristic of a zoned worksharing approach is the use of worker skill sets that represent a physical or logical set of successive tasks that are a strict subset of the full task set. These policies are applicable to systems in which processing time variability is a key problem. Furthermore, the models treated in the literature primarily assume only a single worker is allowed at each station (low collaborative efficiency), this worker is dedicated to the task during execution (low multi-tasking efficiency), and that job handoffs from one worker to another are common (high entity setup efficiency).

A simple form of zoned worksharing is the case of *nonoverlapping zones*, in which teams of workers are assigned to cover distinct groups of resources or task types. This policy is practiced in industry (e.g., in some call centers). One advantage of no-overlapping zones is in the cost of training, because there will tend to be fewer skills and distinct skill patterns than in the case of overlapping zones, treated next. In addition, it is efficient to put all of the members of a zone through the same, standardized training course (e.g., as is the case with aircraft pilots).

Much more literature (although perhaps not much more practice) has focused on *overlapping zones*. We refer the reader to Juran et al. (1996), McClain et al. (1992), McClain et al. (2000), Ostolaza et al. (1990), Schultz et al. (1998), and Zavadlav et al. (1996) for central works in this area. In these papers, the environment is characterized by systems with more stations than workers, non-collaborative workers that are cross-trained across a number of adjacent tasks (a zone), and at least one station in the line at which zones overlap. An example of this is the *Toyota Sewn Products Management System (TSS)*, in which each worker is restricted to a zone of machines (Bartholdi and Eisenstein 1996). The basic allocation rule is that workers dynamically use information on the number of jobs waiting at the overlapping stations to determine which worker is "ahead" of schedule, so that the "ahead" worker will perform the overlapping task in an effort to help out the worker who is "behind" schedule This concept was studied further in Gel et al. (2002), McClain et al. (1992), McClain et al. (2000), Ostolaza et al. (1990), in which workers choose jobs to try to keep inter-station buffers half full. Gel et al. (2002) formulated a model and an MDP to explore the optimal control of systems with two workers and evaluates the surprising effectiveness of half-full buffer type policies. Askin and Chen (2002) further built upon the above model under non-preemptive and granular shared task assumptions to define the tradeoff between the cost of work-in-process inventory (investment on WIP) and the cost of cross-training (investment on worker). The half-full buffer policy is also used in an empirical study described in (Schultz et al. 2003) which identifies several "negative side effects" that occur in systems that rely on worker flexibility. Ahn and Righter (2003) partially characterize optimal coordination policies for a broad class of zoned worksharing.

A special case of the overlapping zoned cross-training policy is the *hierarchical zoned policy*, in which the skills of some workers are subsets of the skills of other workers. This policy applies to the same basic environment as that of general zoned policies, but is practical where workers do or can acquire skills sequentially, which means that senior workers will possess all the skills of junior workers. The literature on this policy area is sparse, but we point the reader to Gel et al. (2000), and Narasimhan (2000). In 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. Bard (2004), Emmons and Burns (1991) and Narasimhan (2000) addressed the optimal deterministic scheduling of workforces with hierarchical skill sets to achieve seven-day-a-week operation. Studies such as these address the increased complexity of labor scheduling (and hence the increased value of labor flexibility) faced by organizations that never close (partly in response to e-commerce and customer response initiatives).

Another special case of overlapping zoned worksharing uses *D-skill chaining*, which is derived from the capacity chaining idea proposed by Jordan and Graves (1995) and applied to cross-training in Brusco and Johns (1998). A simple, idealistic model of this policy organizes workers into N groups, where N is the number of task-types and work-zones are staggered in a symmetrical way so that each worker has D skills and the skill sets overlap to form a chain. This is easy to illustrate in the case of D equal to 2 skills per worker. Suppose there are task types denoted as A, B, C, and E. There are exactly D = 2 skills per worker, so it is natural in a serial line to use the four work-zones: (A,B), (B,C), (C,E), and (E,A). In contrast, a nonoverlapping approach might use (A,B) and (C,E) as the two work-zones. Hopp et al. (2004) showed that simple worker assignments policies such as "serve the longest queue" are robustly effective in chained systems. Moreover, they showed that returns to cross-training may not be diminishing. The greatest marginal performance improvement from adding a skill often comes when the "last" skill is added to complete a 2-skill chain. Sheikhzadeh et al. (1998) also investigated chaining flexibility under many conditions, including setup times, while Gurumurthi and Benjaafar (2001) focused on routing flexibility. Jordan et al. (2004) explored the robustness of chaining in the maintenance and repair of automotive production lines.

5.4 Worker-prioritized Worksharing

Some approaches to team-based production allocate workers to tasks in real-time based on a prioritization of workers. For example, a project leader in a two-person team may make the decisions on what tasks to do herself and what to hand off to the other worker (taking the role of an assistant in this case). This type of two-worker scenario was modeled in Gel et al. (2000), in which the authors studied two-task production systems and established a priority rule for the project leader under the assumption that the assistant can only perform one of the two tasks. The leader, who is broadly skilled, gives strict priority to taking on the task-types for which only he or she is trained. A more complex scenario is addressed in the literature on bucket brigades and related approaches. The *bucket brigade (BB)* policy represents an approach to cross-training and coordination that has found use in a number of systems including warehouse picking (see Bartholdi and Eisenstein 1996). The BB policy is similar to the Toyota Sewn Products Management System (TSS), but differs in that there are no a priori worker zones to limit the movement of workers. Under the BB policy, each worker picks up a job and processes it at each station in order until he/she is either blocked from working by a downstream worker, or gets bumped (that is, the job is taken from him/her) by a downstream worker. The bumping mechanism captures the essence of the worker priority structure as the mechanism for allocating tasks to workers. One drawback of the BB approach as modeled in the literature is the fact that all workers must be trained in principle for all tasks, and it remains to be seen how far an effective system can deviate from this assumption. BB's are most successful in applications where the skills required to perform the operations on the line are all very similar, such as warehouse picking, fast food preparation, and textile sewing operations. The worker/task assignment rule can be classified as labor oriented, with a fixed priority order that places downstream workers in the position of dictating who will work on a given task at any time.

The BB policy is a good design candidate when a number of factors are properly aligned. First, the nearly full cross-training requires high skill acquisition efficiency, so that workers can economically acquire the necessary tasks. The assumption of allowing at most one worker at a station at any given time tends to cause blocking, so these systems typically have multiple machines or workstations per worker (or at least more machines than workers). In the standard model, only a single worker is allowed at each station (consistent with low collaborative efficiency), the worker is dedicated to the task during execution (low multi-tasking efficiency), and the ordering of workers on the line is preserved. A key feature of the BB policy is mid-task handoffs, otherwise known as job preemption. Thus, the standard BB policy requires high task preemption efficiency, as well as a fairly low job handoff cost. Because the workers must function together effectively as a team, further work is needed to identify how to fairly compensate employees while encouraging high productivity levels.

Bartholdi and Eisenstein (1996) analyzed systems using the bucket brigade policy under the assumption of deterministic processing times and non-identical workers, each with a processing rate that depends on the particular task performed. They show that although movement of the workers can be chaotic under some circumstances, sequencing workers from slowest to fastest causes a stable partition of work to eventually emerge, which is independent of the stations at which workers begin. In this respect, the system is self-balancing and will re-establish its rhythm or balance after a breakdown, worker replacement, or other system disturbance. Related analyses of BB's were given in Bartholdi et al. (1999a, 2001). Bischak (1996) used simulation to analyze TSS lines and underscored the ability of moving workers to provide flexibility as an alternative to WIP. Downey and Leonard (1992) also simulated systems with more stations than workers. For bucket brigade policies, Doerr et al. (2000) examined the effects of worker variability.

5.5 Craft (XP, PR)

The craft approach refers to the time-honored practice of having fully cross-trained workers individually handle the tasks associated with an entity from start to finish. In the most basic case, which we call *pick and run (PR)*, each worker is a generalist who serves jobs without the assistance of others by using the task sequence information of the current entity to complete the current entity before taking up the next. Although FCFS is typical, system status information can be used to decide on the entity sequence to be executed. High transition efficiency is assumed (in terms of station transfers and task set-ups; job and task handoffs are irrelevant since workers stay with jobs), so workers are free to roam from station to station without interfering with each other. Askin and Iyer (1993) and Van Oyen et al. (2001) investigated the PR policy, a natural one for this environment. The simulations of Downey and Leonard (1992) exhibited this craft behavior as an output. Although Van Oyen et al. (2001) showed that PR is not necessarily a truly optimal policy in a demand-constrained (make-to-order) setting, the evidence suggests that it is generally very effective and near optimal. Moreover, it can be shown to be optimal in capacity-constrained systems with a constant WIP level set to ensure that there is at least one job per worker at any given time. The approach used at EDCG is very nearly a craft policy (i.e., workers follow jobs through the entire system with the exception of a few specialized stations). Monden (1983) described a Toyota gear manufacturing process which used the PR form of craft production effectively. He writes, "… the Toyota set-up involves 16 machines which perform different types of operations … The laborer as a multi-function worker first picks up one unit of a gear brought from the preceding process and sets it on the first machine. At the same time, he detaches another gear already processed by this machine and puts it on a chute to roll in front of the next machine… and so on, until he

has worked on all 16 machines and finally returns to his initial process. This is done in exactly the cycle time necessary, perhaps five minutes, so one unit of a finished gear will be completed in five minutes. With this method, only one item of stock is involved in the work in process in each machine, and the goal of single-unit production and conveyance is realized between different types of machines." In another example, the authors have observed Subway® sandwich shop franchises using a PR policy during slow periods and then switching to a BB policy (with more workers on the line) during rush periods.

The craft policy can also be implemented in teams, when the collaborative efficiency factor favors it. Under the assumption that the processing rate for a job is proportional to the number of servers allocated, an optimal policy for worker coordination is the *expedite (XP)* policy (see Van Oyen et al. 2001). The XP policy assigns a team of workers to the next job (according to FCFS or a sequence based upon system status information) and they proceed to work on each task as a team to bring jobs through the system one at a time from start to finish. Since it requires full cross-training, XP is only applicable to environments in which the resource transition efficiency and training efficiency factors do not rule out this degree of cross-training. However, it is well suited to environments where having teams follow entities promotes customer service. The Volvo Uddevalla plant's use of a team craft approach was based on the idea that the gains provided by a quality orientation rooted in pride of workmanship and team performance would be superior.   By focusing too much on indirect mechanisms, their strategy lost sight of the operational tradeoffs and direct mechanisms. As a result, poor operational performance ultimately caused the plant to close (Sandberg 1993 and Womack et al. 1990).

5.6 Research Gaps and Open Problems

Although workforce agility has been addressed from a number of perspectives in the research literature, much remains to be done. A fundamental shortcoming of the industrial engineering/operations management models that have been used to gain insights on where and how to use cross-trained labor is that they greatly simplify human behavior. For example, they often overlook fundamental issues such as learning, motivation and communication, which, as we saw in our discussion of strategic implications, can be key reasons for adopting a cross-training policy. At the same time, the literature that deals with human behavior in the workplace often does so in a context independent way (e.g., it treats motivation as a generic condition rather than something related to the specific way a worker interacts with a system). Boudreau et al. (2003) discussed various specific types of research that could be used to better integrate the perspectives of the operations management and human resources fields. Research of this nature will be critical to extending the concepts of workforce agility to white collar environments, because in such environments the benefits of cross-training are largely the indirect ones (learning, motivation, etc.).

More directly related to the AWE framework of this paper is the literature that deals with operational level models trying to capture some aspect of flexibility. While many of these fall into the categories we defined above, and hence were cited earlier, some are more difficult to classify. For example, the research of Askin and Iyer (1993) studied manufacturing cells with batch production and both fully and partially cross-trained workers. They showed that system performance deteriorates with less cross-training, fewer workers, greater processing time variability and greater machine utilization. Other examples include: stochastic control oriented work on flexibility (see Ahn, et al. 1999, Farrar 1993, Harrison and Lopez 1999), work on flexible manufacturing (Benjaafar 1996, Benjaafar and Gupta 1998, Stecke 1985) and fundamental work in scheduling and queueing (see Aksin and Harker 2001, Govil and Fu 1999, Pinedo and Schrage 1982, Smith and Whitt 1981, Weiss 1982).

Comparing the range of environments described by the AWE framework with those addressed by the literature suggests that the following production environments present opportunities for further research:

- Systems with low resource transition efficiency and/or low task-type transition efficiency. These conditions require implementations that limit the number of switchovers that occur during the course of a shift. Scheduled rotation approaches are an obvious solution, and they have been studied for specific environments. In many environments, however, there may be ways to make use of more dynamic policies, which are more effective at buffering variability. Optimal policies that balance the switching time/cost with efficiency improvements are likely to be complex, so research is needed to find effective heuristics. The existing literature focuses primarily on systems with a single flexible server. Iravani et al. (1997a, 1997b) developed structural results and a near-optimal heuristic for arbitrary-length lines with a single fully cross-trained server and without job arrivals. Sennott and Van Oyen (2000) numerically analyzed MDP models to examine lines with specialized workers in addition to a fully cross-trained floating worker in the context of job arrivals and set-up times and costs. Kula et al. (2004) model a production system with multiple machines that require setups, which are performed by a limited number of setup crews who are cross-trained to perform all setup operations. Models with a single flexible worker are already difficult, and applications call for more work on multi-server models with setups.

- Systems with medium training efficiency. These have issues similar to those of the previous case, but are even more complex and hard to quantify. Policies will have to limit the number of skills per worker as dictated by the learning curves for individuals and/or the organization. Thus, the design must judiciously apply the cross-training over time, since neither specialization nor full cross-training will be practical.

- Systems with high multi-tasking efficiency. Virtually all of the research in the literature deals with one-person-one-machine systems, as opposed to systems in which workers tend to multiple automated machines (but see Kher 2000, Croci et al. 2000, and Hopp et al. 2002a for starting points and see Iravani and Krishnamurthy 2002 for similar issues arising in maintenance). Since such systems are common in practice, this is an important research need.

- Systems with a large number of specialized workers and a limited number of cross-trained individuals make for an interesting and complex environment that is common in industry because of the use of floaters or "utility workers". This can result from individual preferences for cross-training, turnover that keeps the labor force inexperienced, or low switching efficiency for many workers and task-types. Research is needed to determine conditions when it is best to cross-train only a limited number of workers and how they should then interact with the specialists (see Pinker and Shumsky 2000 for an example).

6. Industrial Examples of the Tactical Framework

System design using appropriate cross-training can be assisted by both the strategic framework and the tactical framework. The latter summarizes some key factors that must be considered when choosing a workforce agility strategy for a given environment. To illustrate how this might work, we revisit the industrial examples we introduced in Section 2.

IBM had a line with a problematic bottleneck, as described in Section 2. Continuing with that example, the line had similar, modest skill level requirements at both the bottleneck task and another task with excess capacity, so training efficiency was medium to high. However, switching efficiency was quite low due to low task-type

transition efficiency (the bottleneck task was inside a clean room and hence required a time-consuming setup step for a worker to start or stop a task-type) and due to low resource transition efficiency because of the distance between the two corresponding activity centers. Because of these considerations, management opted for a rotational schedule using staggered "lunch" breaks during each of three shifts. Workers from an underutilized resource (team A) would take over the bottleneck resource from the shift's start until the late lunch break, at which time the original bottleneck operators (team B) would switch from team A's former task to take over work at the bottleneck for the remainder of the shift. They gained 90 minutes of working time each day at the bottleneck.

John Deere had high training efficiency for some workers (e.g., it was generally easy to train a welder to do fabrication or final assembly) and lower for some other workers (e.g., a machine tool operator might not easily learn to weld). Also, by organizing equipment into a compact cellular layout, management increased switching efficiency within each cell to a high level. By paying workers according to the highest grade of task they did during a shift (i.e., workers were paid as welders if they did any welding during a shift), they were able to gain union support for their cross-training plan. (Indeed, union workers were part of the committee that designed the plan.) In recognition of these factors, Deere made use of high levels of cross-training (many, but not all, workers could staff all of the task types of fabrication, welding and final assembly if necessary). To facilitate the flexibility needed to support the broad range of products (and bursty workloads), they implemented self-directed teams within the cells, so that the workers themselves decided when to switch between task types to keep up with the workload.

Elgin Digital Color Graphics (EDCG) had fairly high training efficiency, except for the color registration operation. Also, because most operations were performed on networked computer workstations (so the tasks came to the workers, rather than workers going to the tasks), task-type transition efficiency and resource transition efficiency were both high. However, entity setup efficiency was low, because customized work required significant information about the requirements and quality demands of a particular job/customer. Because of this, EDCG made use of a very high level of cross-training, which enabled almost full cross-training. Then they had workers follow jobs through the system (except for specialists at color registration) in a craft policy similar to pick-and-run. This dramatically improved operator utilization (because a worker following a job through the system will not be starved as much as a specialist staffing a single station) and greatly reduced WIP and response times. The creation of teams with team leaders improved customer service quality by giving customers a single contact person at all times.

Continental Plastic Containers (CPC) had high training efficiency for tasks associated with operating the machinery (e.g., loading labels, changing molds and packing bottles in boxes). It was lower, however, for tasks involving troubleshooting problems. To turn a machine operator into a troubleshooter required significant training. So, if one viewed the system in steady state terms, it made sense to hire one kind of worker as an operator and another as a troubleshooter. The problem, however, was that the system was not in steady state. Due to a lack of upward mobility, excellent machine operators often left the firm once they had mastered their tasks. So, management made a conscious effort to articulate a career path, in which an operator would be cross-trained for different kinds of machines (following a scheduled rotation policy) and gradually gain experience in troubleshooting them. With more responsibility and higher pay ahead of them, the best operators were more likely to stay with the company, eventually becoming troubleshooters able to dynamically respond to problems in the manner of a craft policy. This had an indirect benefit of providing better resolution of quality problems and thus improved efficiency by reducing yield loss.

GE Financial Assurance (GEFA) had moderate training efficiency, but the success of cross-training depended quite strongly on the individual. Those workers with greater experience, motivation, and proficiency were more likely to be cross-trained. For customer service reasons, preemption delays hurt quality and were therefore avoided. Database and information technology kept the other switching efficiency factors at very acceptable levels, which gave great freedom for dynamic worker allocation. Multi-tasking efficiency was low in this case (although other call centers effectively multi-task with on-line chat sessions for technical support or use off-line work as fill work). The result was that GEFA was able to use an overlapping zone type architecture with dynamic worker/call assignment (queue length and customer time on hold were used) supported by skills-based routing technology. With labor cost representing a majority of the cost of operation in many call centers, cross-training is of strategic importance in this industry.

7. Sketching a Map from Factors to Workforce Agility Policies

Our survey of the literature emphasized, but was not restricted to, quantitative modeling of cross-training. Not surprisingly, this literature tends to perform detailed analyses of models that are appropriate only under particular assumptions. For this reason, it is useful to summarize at a high level the environments to which specific policies are suited. We can do this by identifying the environmental factors that are most attractive for a given cross training approach. In addition to clarifying the applicability of research into specific policies, it is our hope that this map, even though it is only a modest sketch, will serve as a starting point for practitioners as they design systems. While the environmental summary given by the factor analysis does not rigidly determine the best workforce agility architecture, it does show us what to look for. Hence, it can be used to pare down the options and suggest which type of architecture might be effective.

To illustrate very roughly some characteristics of architectures and policies, we offer Figure 8, which summarizes the factor levels that are typically well-suited to a particular policy class. While we cannot offer a comprehensive map based on all the policy types described in Section 5, we can identify a spectrum of approaches from the literature that are appropriate for manufacturing and services. The broad class of zoned worksharing is represented by two canonical classes: (1) Zone: non-overlapping zones with two or more workstations covered by the typical worker, and (2) 2SC: D-skill chaining with D=2 skills per worker. Factor scoring indications are as follows: high (H), medium (M), and low (L). For example, training efficiency should be H for the XP or PR policies to be suitable, because XP and PR both require full cross-training. This is a rough map, so many of our elements in the matrix allow for multiple scores. For example, 2SC requires two skills per worker and therefore must avoid a score of L on training efficiency, which is indicated by the designation "M L." The "H M" designation is analogous. The designation of "Any" is used when an implementation scheme can be effective regardless of the factor's score. In the case of the specialist policy (Spec), the avoidance of cross-training makes this approach insensitive to training efficiency, so we indicate "Any" with a black box.

Figure 8 highlights some of the key distinctions between our canonical classes of policies. To begin with, we observe that the Spec and the rotational (Rota) policies can work well in similar environments. This fits with the observation that many companies have selected rotational approaches is their transition from specialists. Rotational approaches can approximate specialists better than others, because they can keep the frequency of rotation small enough to operate very much like a system using only specialists.

We turn now to a row-by-row discussion of Figure 8, we begin with training efficiency. The one environmental requirement for a rotational or other cross-training policy to be a good option is that training efficiency must be somewhat higher for it than for Spec. The craft based approaches (XP, PR) are the most dependent on high training efficiency, while Zone and Rota are broad policies that can be more easily tailored to avoid cross-training of task-types that are slow or costly to learn. It is tempting to indicate that a training efficiency of L is best suited to the Spec approach, but that would presume that it is undesirable to use Spec when other skills can be learned efficiently. Rather, we designate it by "Any", since Spec avoids cross-training and can therefore tolerate any level. Similar logic applies in the following factor, preemption efficiency.

Preemption efficiency is vital to the standard bucket brigade (BB) policy of Bartholdi and Eisenstein (1996), which must by its very nature require frequent task preemption. The preemption efficiency row of Figure 8 does not distinguish the other policy classes, because they are sufficiently general to avoid the occurrence of preemption and thus any score is suitable. This row reflects the highly aggregated level of the map which serves only as a starting point. In contrast, the tactical framework is more detailed and serves to guide a designer toward an effective solution.

When the entity setup efficiency factor is relatively low, we interpret this to mean that it is important to limit job handoffs. Because they do not pass entities between workers, XP and PR can support any level of entity setup efficiency. In contrast, Zone, 2SC, Rota and Spec require high levels due to the relatively large number of workers involved in completing an entity. It is worth noting that assembly lines are so prevalent in practice that it is easy to forget that they presuppose that standardization of parts, processes, and labor facilitate high efficiency and high quality despite having many workers contribute to each entity.

The third switching efficiency factor, task-type transition efficiency, should typically be high to support XP and PR, because each worker has an extreme level of switching between task types. On the other hand, Rota can be implemented to minimize setups so it is insensitive to this factor. 2SC may or may not effectively limit the task-type changeover frequency (this depends on the WIP level), while the Zone and BB will tend to require significant task-type efficiency. For this rough map, these are all are given a HM score range.

Resource transition efficiency must be treated separately from task-type transition efficiency in many applications. However, in systems where each workstation is associated with a task-type, task-type transition efficiency and resource transition efficiency go together and so these two rows will be the same. For simplicity, we have made this assumption in Figure 8.

Collaborative efficiency should identify particular task-types that benefit from collaboration and teamwork, therefore the generic nature of the map makes it hard to distinguish the policies, with one notable exception. This factor should be generally be either zero (a score of M for this factor) or higher to be well suited to XP, an intrinsically collaborative policy. Zone, scored "Any", can be adapted to avoid collaboration altogether, or may define the zones to facilitate collaborative teamwork across the appropriate task-types. The remaining policies are scored ML. PR and BB are policies that are carefully specified in ways that preclude collaborative teamwork, while the other policies do little to facilitate teamwork (except for the case of collaboration on a single task-type, which even Spec supports).

The ability of workers to multi-task (i.e., use cross-trained skills simultaneously) is another important environmental consideration, and high scores will benefit policies with more task-types per worker. The restrictions of the BB, 2SC, Rota and Spec policies preclude or limit multi-tasking, making them well-suited to environments

that do not benefit from multi-tasking (i.e, ML). A positive benefit from multi-tasking can be effectively exploited by XP, PR and Zone, but they can also be adapted to any level of multi-tasking.

Finally, looking vertically down the columns, we can draw a variety of other contrasts from Figure 8. Specifically, it supports our intuitive judgment that Zone, Rota, and Spec type policies will be applicable in a very broad range of systems. This is because most systems are designed to keep entity setup efficiency high and because these are defined as fairly general classes of policies. Figure 8 is congruent with the fact that XP, PR, and BB are quite narrowly defined policies, since they are restrictive on a few key factors. It is worth noting that the 2SC approach must allow for a complete "chain" of cross-training to live up to their full potential (see Hopp et al. 2002b, Iravani et al. 2002, Jordan and Graves 1995, and Jordan et al. 2004). Still, Hopp et al. (2002) showed that even partial chains can be highly effective. The Zone policies are easily adapted to many situations by using small zones, large zones, or mixed-size zones.

The policy map of Figure 8 is by no means comprehensive. Given the complexity and diversity of production environments and workforce agility policies, perhaps a rough map is the best we can hope for. Still, as the above discussions indicate, it helps us gain broad insights into the kinds of policies that fit specific environments. More fundamentally, it graphically illustrates the important point that no single policy is appropriate for all environments. Seemingly small differences from one environment to another can greatly change the type of policy that is suitable. Hence, this policy map may be an important conceptual and educational tool for training managers to manage the multi-dimensional complexity of designing an effective workforce agility system.
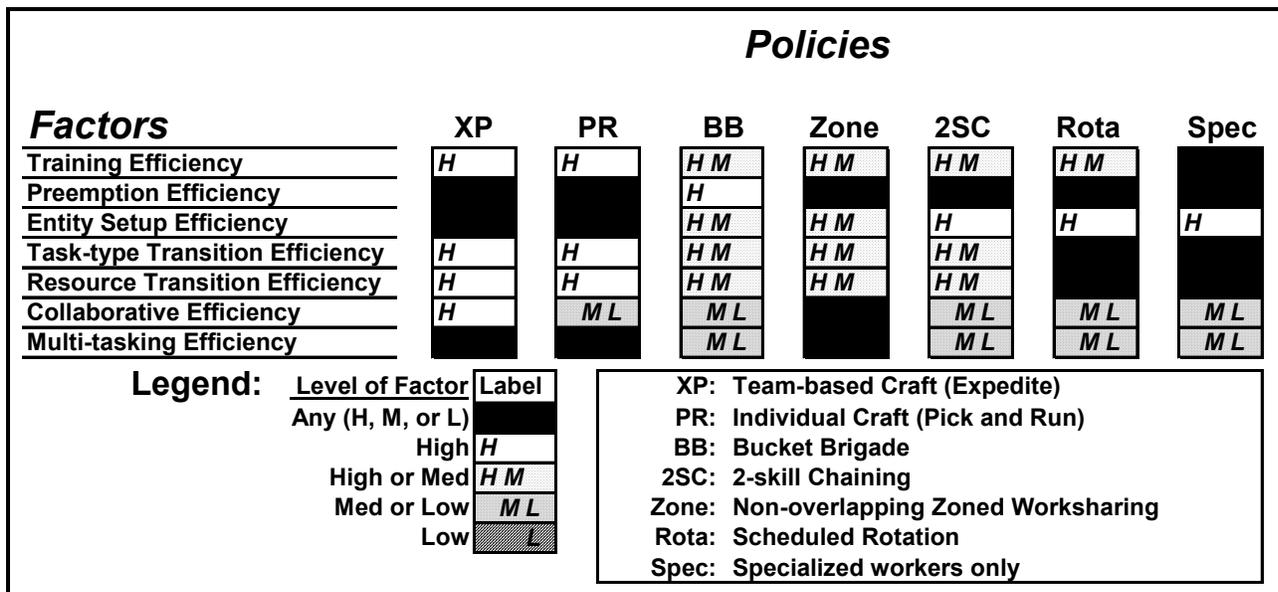
Policies

Factors	XP	PR	BB	Zone	2SC	Rota	Spec
Training Efficiency	H	H	H M	H M	H M	H M	Any
Preemption Efficiency	Any	Any	H	Any	Any	Any	Any
Entity Setup Efficiency	Any	Any	H M	H M	H	H	H
Task-type Transition Efficiency	H	H	H M	H M	H M	Any	Any
Resource Transition Efficiency	H	H	H M	H M	H M	Any	Any
Collaborative Efficiency	H	M L	M L	Any	M L	M L	M L
Multi-tasking Efficiency	Any	Any	M L	Any	M L	M L	M L

Legend:

Level of Factor	Label
Any (H, M, or L)	(black)
High	H
High or Med	H M
Med or Low	M L
Low	L

XP: Team-based Craft (Expedite)
PR: Individual Craft (Pick and Run)
BB: Bucket Brigade
2SC: 2-skill Chaining
Zone: Non-overlapping Zoned Worksharing
Rota: Scheduled Rotation
Spec: Specialized workers only

Figure 8: Typical Environmental Factors Levels Appropriate for a Policy

8 Conclusions

In this paper, we have (1) developed a *strategy matrix* to clarify the fundamental motives for making use of agile workforces, (2) characterized through a *tactical framework* the essential factors that determine how

workforce agility should be matched to a given work environment, (3) laid out a conceptual model of the basic components of workforce agility architectures, (4) described a broad range of canonical worker coordination policies, (5) used our frameworks to organize a wide literature on operational issues related to on cross-training, and (6) described areas needing further research attention. We have illustrated the use of our frameworks on several real-world examples, indicating how the structure we propose can provide insight into industrial cases. While our overall AWE framework does not reduce the problem of identifying an effective workforce policy for a given environment to a simple checklist, it does assist the practitioner in systematically analyzing the key issues involved. Given the magnitude and complexity of the task of developing a framework for workforce agility, we are aware that this work represents only a first step. One direction for future work is to create a micro-economic framework that provides a mechanism for incorporating costs in order to supplement our framework for addressing strategy and tactics. We eagerly await this and further efforts that deepen our understanding of workforce agility

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