Modelling Teams and Workgroups in Manufacturing

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Abstract

One of the major features of Japanese manufacturing techniques is the extensive use of teams, i.e., workers who as a group work together to produce sub-assemblies or finished products, or, alternatively, work together to accomplish a project. Many naive promoters of the team concept assume that the team members work together on the same tasks and activities and somehow accomplish them faster and better. However, observation of actual teams indicate that, unless a team member is new and quite inexperienced, teams split the required tasks or activities up so that each member has a unique task and most of the time members work independently. This paper develops models that try to describe the features of division of labour in teams and the way in which differences in capability between different team members impact performance. The models suggest that the advantage of teams probably lies primarily in the structure that enables faster/better workers to help out others.

Keywords: *Teams, projects, assembly lines, individual differences*

1 Introduction

There is extensive discussion in OM texts and popular OM literature about the advantages of using teams in manufacturing. Significant advantages have been claimed by firms that have switched to team manufacturing and, particularly in the apparel industry, there are a number of articles describing its advantages (Abend 1999, Fralix 1999). In general, writers have claimed superior quality, although the apparel industry experience is that there is no significant difference in quality; flexibility, i.e., the ability to make small lot sizes of diverse products economically and rapidly; and

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cost reduction, with much of the cost reduction coming from reduction in inventories of in-process and finished products combined with more rapid response to customer orders. (see Krajewski and Ritzman 1999: Chapter 5).

Nevertheless, the introduction of teams has led to union objections, perhaps stemming from the reduced clarity and hierarchy of job descriptions, and the perception that management introduce teams in order to produce more output with either fewer people or lower pay. Some workers do not like the reduction in individual autonomy, because individual incentive pay systems are replaced by an incentive system dependent on overall team performance. Such workers also do not like the change of authority from a single first line supervisor to the team. Almost all teams introduce some degree of team self management, at least for such decisions as who does what and dealing with minor quality or production problems, although never for the decision as to whether teams should or should not be used. A field study of worker attitudes to a change to team organization which provides valuable insights is Ezzamel and Willmott (1998).

There are various types of teams that can be found in manufacturing. One important distinction is between teams that are engaged in continuing manufacturing tasks, versus teams that have a single project to complete. In the case of project teams, often these consist of a group of people each with unique experience and competence so no team member can perform any of the functions of another team member. Yet this is by no means always the case for project teams, for example, our MBA students are expected to have competence in any area of business so any MBA student project can expect any team member to be able to perform any function.

In manufacturing, there is usually considerable commonality of capabilities among team members. Usually when teams are introduced, considerable effort is devoted to ensuring that team members learn a range of jobs so that jobs can be rotated among team members as the team decides. This means that better workers can help out others and so address problems more effectively.

The purpose of this paper is to develop models that provide insight into the strengths and weaknesses of teams. The emphasis is on the impact of the division of labour and its coordination on team performance. In particular I focus on the importance of "helping out" as the source of most of the advantages of teams when ability is unequally distributed among team members.

2 Towards a Model

In order to model teams two situations will be considered:

1. **Project Teams:** The goal is to complete a project in the least time using the team. It will be assumed that no resources external to the team are required so the team management issue is to divide up the various tasks that have to be done among the team members and complete the project as soon as possible.

2. **Production Teams:** Using the available capabilities within the team, maximize the production rate. Adequate external resources are available so they do not constrain any task, that is, the time for a worker to perform a task is determined only by the worker's capabilities.

Blue Collar	Crafts	Professional	Life Insurance Sales
0.20	0.32	0.50	1.2

Table 1: Standard deviation/mean of individual speed differences

Team size = 5

Blue collar	0.77	0.90	1	1.10	1.23
Crafts	0.63	0.84	1	1.18	1.37
Professional	0.43	0.75	1	1.25	1.57

Team size = 3

Blue collar	0.83	1	1.17
Crafts	0.72	1	1.28
Professional	0.59	1	1.41

Team size = 4

Blue collar	0.79	0.94	1.06	1.21
Crafts	0.67	0.90	1.10	1.33
Professional	0.50	0.85	1.15	1.50

Team size = 2

Blue collar	0.89	1.11
Crafts	0.82	1.18
Professional	0.72	1.28

Table 2: Expected relative speeds of workers in various sized teams

In both situations it is assumed that work can be broken down into tasks with one person doing one task. Different workers do different tasks. There are no synergies at the task level, that is, if more than one person works on the same task there is no reduction in the time required to perform the task. This means that the team advantage has to come from coordination and the ability for dynamic allocation of tasks to workers. Even if two people are working on the same job at the same time, it is usual for each to have specific tasks to do, although there may be frequent coordination, i.e., both have to finish subtasks before either can begin their next subtask.

Key to our model is the representation of the worker capability and performance. It is assumed that the work content of a task, task j, can be defined in terms of a standard time W_j which may be a random variable. If worker i is assigned to task j, then the time that worker i will take to perform the task is V_iW_j, where V_i is a random variable denoting the speed of the worker relative to the speed of the standard worker assumed in arriving at W_j. For most of the paper it is further assumed for a given worker $V_i = v_i$, a deterministic relative speed, but the deterministic relative speed of worker i is a number drawn from a Normal distribution with mean 1 and standard deviation σ.

There have been a number of studies of the differences between worker speeds in a variety of production contexts. Buzacott (2001) reports data from a variety of contexts that suggest that the typical standard deviation of differences in speed of different individuals is as shown in table 1 From this it is possible to determine the mean values of v for the members of teams of various sizes. Table 2 shows the values for teams of sizes 5, 4, 3 and 2.

2.1 Division of Labour and Coordination

The necessity for teams only arises when the work that has to be done to complete a project or job has to be divided up into tasks with different people responsible for different tasks. However, once work is divided up then it has to be coordinated as the job or project is not complete until all tasks are complete. So it is useful to develop some models that provide insight into the impact of this division of labour and coordination. In particular, as a base case it is useful to model the performance of systems where the task division is decided in advance of beginning the project or job. These models can be considered to indicate how a totally ineffective team would perform.

One of the key aspects of teams that is cited in much of the empirical literature is the way in which the perceived value of the team depends on the degree to which different activities have to be coordinated. For example, in manufacturing, if workers are engaged in machining operations on different jobs then coordination needs are slight and the implementation of teams is found not to bring much value. However, in assembly, where different workers need to coordinate their activities on the same job quite frequently then teams are perceived as having significant value. So I develop some models that try to capture how the degree of required coordination influences performance.

Consider first a manufacturing situation where a large number of identical jobs have to be produced. Suppose each job requires two tasks A and B and there are two workers 1 and 2. It will be assumed that the work content W of each task has identical distributions. Worker j, $j = 1, 2$, has speed v_{ij} when he performs task i, $i = A, B$. Then various ways of organizing manufacture can be considered, although some might not be technically feasible. The first is for the workers to work independently with each worker doing both tasks on a job, first task A and then task B. Thus the time required by worker 1 to complete a job is $(v_{A1} + v_{A1})W$ and the time required by worker 2 to complete a job is $(v_{A2} + v_{B2})W$. So, if there is a large number of jobs to be done, the throughput of the system, TH_I, will be given by

$$TH_I = \frac{1}{(v_{A1} + v_{B1})E[W]} + \frac{1}{(v_{A2} + v_{B2})E[W]}$$

Now suppose that it is decided that worker 1 will do task A and worker 2 will do task B but they will work independently so an inventory of incomplete jobs could accumulate between worker 1 and worker 2. Now the throughput of the system, TH_S, is given by

$$TH_S = \min\{\frac{1}{v_{A1}E[W]}, \frac{1}{v_{B2}E[W]}$$

Now suppose $v_{A1} = v_{B1} = v_1$ and $v_{A2} = v_{B2} = v_2$. Then it is clear that $TH_I > TH_S$ with the difference increasing with increasing difference between v_1 and v_2. In practice it would be assumed that the workers would become more productive if they focus on a limited set of tasks so the difference between TH_I and TH_S would diminish.

An even further degree of required coordination would be to require both workers to complete their task on a job before they can start the next job. The throughput, TH_C now becomes

$$TH_C = \frac{1}{E[\max\{v_1 W_A, v_2 W_B\}]}$$

If W_A and W_B have identical exponential distributions with parameter λ then the distribution of the time required by worker 1 to complete task A will be given by

$$F_A(t) = 1 - e^{-\lambda t/v_1}$$

and hence

$$E[\max\{v_1 W_A, v_2 W_B\}] = \frac{v_1}{\lambda} + \frac{v_2}{\lambda} - \frac{1/(1/v_1 + 1/v_2)}{\lambda}$$

It is generally true that $TH_C \leq TH_S$. The impact of individual differences can be seen by writing $v_1 = 1 + y$ and $v_2 = 1 - y$. It follows that

$$E[\max\{v_1 W_A, v_2 W_B\}] = \frac{1}{\lambda}\left(2 - \frac{1 - y^2}{2}\right) = \frac{1}{\lambda}(3/2 + y^2/2)$$

and as the difference y increases TH_C will decrease. However, the difference between TH_C and $TH_S = \lambda/(1 + y)$ diminishes as y increases.

This succession of simple examples indicates that, as the dependence or inter-relationship between workers increases, overall performance worsens. The remedy to this is advocated to be the use of teams, where the key feature of teams is the ability to dynamically allocate tasks between team members.

3 Project Teams

A simple model of a project team will be assumed. The team has m members and there are m tasks to be done. Any team member can do any task but the speed of team member j will be v_j. That is, I consider teams where there is no unique functional specialization or expertize for specific team members. The project is very simple in structure: all m tasks must be completed in order for the project to be complete.

No Dynamic Task Allocation Suppose initially one task is allocated in advance to each team member. Then the time to complete the project will be $\max_j v_j W$. If the task contents are identically and independently distributed with mean $1/\lambda$ then the expected completion time of the project is

$$\begin{aligned} E[T] &= \frac{1}{\lambda}\left(v_1 + v_2 + v_3 - \frac{1}{1/v_1 + 1/v_2} - \frac{1}{1/v_2 + 1/v_3} - \frac{1}{1/v_3 + 1/v_1}\right. \\ &\qquad \left. + \frac{1}{1/v_1 + 1/v_2 + 1/v_3}\right) \end{aligned}$$

Dynamic Task Allocation Because task times are exponentially distributed the expected remaining completion time of a task has a distribution which is independent of the amount of time already spent on the task. This means that when a fast worker completes their initial task, then if that worker takes over the task of a slower worker then the expected time to complete the task will be less than if the slower worker continued with the task. So if $v_1, v_2 < v_3$, if worker 1 finishes their initial task first, then worker 1 should take over from worker 3's task. This means once one task is complete only workers 1 and 2 would continue working, while once two tasks are complete only worker 1 would continue because if worker 1 finishes first he would take over worker 2's task. This means that with dynamic task allocation the overall

Type	Fixed allocation	Dynamic allocation
Equal speed (=1)	2.28	2.28
Blue collar	2.32	1.90
Crafts	2.37	1.66
Professional	2.48	1.27

Table 3: Impact of task allocation on a 5 worker project

completion time of the project will be given by

$$E[T] = \frac{1}{\lambda}\left(\frac{1}{1/v_1 + 1/v_2 + 1/v_3} + \frac{1}{1/v_1 + 1/v_2} + v_1\right)$$

In a group of five workers, and assuming that the worker speeds are given by table 2, table 3 compares the project completion time between a fixed task allocation and dynamic task allocation. The times are expressed as a multiple of the mean time to compete a task. Note that as the differences between individuals becomes larger the advantages of dynamic task allocation increase. There are a number of conclusions that can be drawn from these results

1. With fixed allocation worker differences increase the completion time but the impact is not large.
2. With dynamic allocation worker differences reduce the completion time and the reduction is large.
3. With dynamic allocation the slowest worker has very little value, for example if the slowest professional worker does nothing, i.e., one of the other workers does his task, then the completion time only increases by 0.019, (1.5%) and the slowest worker is only used about 15% of the time.
4. With dynamic allocation the fastest workers are much more heavily used than with fixed allocation, for example, the fastest worker is busy 100% of the time with dynamic allocation while he is only busy 20% of the time in fixed allocation.
5. Equal allocation of any team bonus for task completion will, with dynamic task allocation, almost inevitably lead to perceptions of unfairness by the fastest workers. (It is not surprising that the biggest complaints about team activities in course projects tend to come from the best students.)

4 Manufacturing Teams

In manufacturing there is usually a stream of jobs that have to be done, so more than one job is being worked on at the same time by the team. If the team all work on the same job then the team performance can be analyzed in the same way as a project team. However, much more typical of manufacturing is where each worker works on a different job.

Clearly maximum production is achieved by each worker doing all tasks on a job as this ensures that each worker is fully occupied all the time. However, this also requires that each worker have a full set of equipment to perform all tasks so it is not necessarily the overall most cost effective approach. So it is of interest to consider manufacturing situations where with m workers there are m tasks to be done on each job. Assume that these tasks must be performed in a unique sequence $1 \to 2 \to 3 \to \cdots \to m-1 \to m$. This means that the following approaches can be considered for organizing manufacture

1. Assign each task to one specific worker. Permit in-process inventory between each task/worker.
2. Assign each task to one specific worker. No in-process inventory permitted between each task/worker.
3. Use dynamic task allocation. No in-process inventory permitted between each task.

Each of these alternatives can be analyzed in order to determine whether they are consistent with a team approach and what the resulting system performance will be. It is assumed that each task has the same work content W and that if worker i is assigned to task j his task time is given by $v_i W$, that is, a given worker can do any task equally well (or equally badly).

4.1 Infinite Buffer Fixed Task Allocation

Suppose that with a given task allocation the time to perform task j is T_j. Then it is well known that the throughput of the system is given by

$$TH = \min \frac{1}{E[T_j]} = \min \frac{1}{v_j} \frac{1}{E[W]}$$

It also follows that the mean time between successive jobs leaving the system, $E[D]$, will be given by $E[D] = \max v_j E[W]$.

Note that the system performance does not depend on which worker is assigned to which task so it can be concluded that if the workers were identified as a team, the team has no decision making responsibility that makes any difference to system performance.

4.2 Zero Buffer Fixed Task Allocation

Assuming that task times have exponential distributions then there are formulae giving the throughput of systems consisting of 2 and 3 workers (see Buzacott and Shanthikumar 1993) and it is relatively straightforward to develop results for larger teams. Performance now depends on task allocation but it is symmetric in task allocation, i.e., if a given task allocation *abcd* is used, then the reversed task allocation *dcba* has the same performance.

If workers are ranked in accordance with v_j, i.e., workers are labeled 1,2,3,4 with $v_1 < v_2 < v_3 < v_4$, then the maximum throughput with $m = 3$ is obtained by the allocations 213 or 312, while with $m = 4$ it is obtained with the allocation 3214 or 4123. The worst allocation with $m = 4$ is 1342 or 2431. with professional workers the mean time between job completions is 1.9842 in the best allocation and 2.1675 in the worst allocation, that is a difference of about 10%. With blue collar workers the difference is about 5%.

This means that if the workers form a team then the choice they have is how to allocate workers to tasks but once the team has determined the ranking of the workers then there is no further opportunity for them to influence the system performance.

4.3 Zero Buffer Dynamic Task Allocation

With dynamic task allocation, every time a worker finishes a task, a decision is made as to which task he should do next. Given the assumption of exponential task durations, performance can be improved by allowing a worker to take over an incomplete task from another worker. If jobs are blocked, for example, a job has completed task 2 but there is a job still in process at task 3, then less than m workers will be busy. It is clear that if only $k < m$ tasks can be performed because jobs are blocked, then it is optimal to have the best k workers busy and leave the worst $m - k$ idle. However, it is not obvious how to allocate the k workers to tasks. So it is necessary to develop a Dynamic Programming model to find the optimal dynamic allocation policy of workers to tasks in each system state. System state when an allocation is made is characterized by at least one job having completed a task, and other jobs either having a task in process, or a task completed. It is also possible that there are fewer than m jobs in process so a task may have no job, however, it would never be optimal to have the first task idle or stop a job from moving on to the next task when it is not blocked.

Characteristics of the optimal policy: The optimal policy appears to be characterized by the following properties:

1. If there is a station with no job then the fastest worker should be assigned to the first upstream station with a job.

2. In a four station line the assignment 1-2- is preferable to 2-1-, where '-' denotes that the station has no job.

3. If all stations have jobs then it is preferable to put the fastest workers at the end of the system.

4.4 Comparison

Table 4 shows the mean time between successive jobs leaving the system for the different systems considered for $m = 3$ and $m = 4$. Note that with zero buffer fixed allocation the blue collar system performs slightly better than the equal worker system. This is a well known result in production line analysis. Systems with the inner stations somewhat faster than the outer stations perform better than a system with equal stations.

Number of tasks		Infinite buffer fixed allocation	Zero buffer fixed allocation	Zero buffer dynamic allocation
3	Equal workers	1.000	1.773	1.773
	Blue collar	1.169	1.768	1.549
	Craft	1.271	1.779	1.406
	Professional	1.411	1.810	1.197
4	Equal workers	1.000	1.943	1.943
	Blue collar	1.206	1.929	1.636
	Craft	1.329	1.942	1.443
	Professional	1.498	1.984	1.164

Table 4: Mean time between job completions. of serial systems

The conclusions that can be drawn from these results are very similar to the project team

1. With infinite buffer fixed allocations worker differences increase the mean time between job completions and because of the slowest worker being the bottleneck the increase is significant
2. With zero buffer fixed allocation slight worker differences reduce the mean time between job completions but as they increase the mean time increases but the impact is not large.
3. With dynamic allocation worker differences reduce the mean time between job completions and the reduction is large.
4. With dynamic allocation the slowest worker has very little value. For example if, once it has been observed which is the slowest professional worker when $m = 4$, that worker does nothing, then the mean time between completions only increases by 0.013, (1.1%).
5. With dynamic allocation suppose it is decided from the beginning to only use 3 workers for four professional tasks then the mean time between completions increases from 1.164 to 1.386, a 19% increase. It is clear that it is better to hire four workers and then remove the worst worker rather than hiring just three from the beginning.
6. With dynamic allocation the fastest workers are much more heavily used than with fixed allocation, for example, the fastest worker is busy 100% of the time with dynamic allocation while he is only busy 25% of the time in fixed allocation. By contrast the slowest worker is used only 18% of the time with dynamic allocation but is used 75% of the time with dynamic allocation.
7. Equal allocation of any team bonus for task completion will, with dynamic task allocation, almost inevitably lead to perceptions of unfairness by the fastest workers.

5 Conclusions

It is clear that the advantages of teams arise primarily from their ability to exploit individual differences in worker capabilities. However, the team has to be given the ability to make dynamic task allocation to workers to obtain the maximum benefit. If it does not have this capability then the team has little value. Teams gain their effectiveness by ensuring that the best workers are kept fully utilized while the worst workers are only used when a job would otherwise be idle. While a team incentive means that each worker is better off than with a fixed allocation when worker differences are large, equal sharing of the team rewards can eventually be perceived as inequitable as the best workers are much more heavily utilized than the worst worker. Once a team has discovered the capabilities of its members, the best workers would be better off to reduce the team size and share a slightly diminished reward among fewer people. It is likely that, when team size is imposed from outside as in most manufacturing environments, there will be eventually considerable dissatisfaction experienced by the best workers.

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