Teamwork And Productivity Improvements In Mixed-Model Assembly Lines

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Abstract

Motivated by the practices of Japanese and European automotive manufacturers who use teams in car assembly processes, this paper develops two models of teamwork for assembly line workers. The implications of teamwork arrangements on productivity of the assembly line are studied. The findings support the conventional wisdom that teamwork improves productivity. However, there are situations when teamwork leads to a decline in productivity. The performance of the two team models were tested using the real assembly line data obtained from an automobile manufacturer. The approach developed in this paper provides computational means for evaluating the implications on productivity of different team structures, team sizes and position of teams in the line.

1. Introduction

This paper introduces and tests two models of teamwork in multi-product, labor intensive, repetitive assembly processes typical of modern automotive assembly lines. Both models are motivated by current practices of using teams in the automobile industry. The proposed models are analyzed using the mixed-model cyclic asynchronous assembly line framework. The findings are tested using real data from the assembly line of a major U.S. automobile manufacturer. The focus of this research is on evaluating the impact of teamwork and work sharing on productivity in mixed-model asynchronous assembly lines. While findings confirm the conventional wisdom that teamwork leads to improvement in productivity, they also show that this may not always be the case, as there are situations when teamwork arrangements nega-

tively affect productivity. This study is the first to bring analytical reasoning into the problems of team formation, team sizes, work sharing and reduction/expansion of labor force in flexible assembly lines.

One of the goals of this paper is to introduce quantitative machinery for evaluating some important issues of teamwork development in manufacturing. Although this study is based on two models of teamwork, some useful generalizations are made. The two models studied here are motivated by the existing practices of Japanese and Scandinavian auto manufacturers (discussed in Section 1.1 below). This study is a first step towards better understanding of teamwork and its implications on assembly processes. Quantitative analysis introduced in this paper does not address human related issues that are an integral part of any team based work system. However, the results of our analysis and the

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analytical approach proposed here provide a tool and a foundation for further complementary studies of team based production systems.

This paper is organized as follows. The remaining part of this section discusses two prevailing teamwork practices in the automobile industry. Section 2 describes the production environment and the modeling framework of mixed-model asynchronous cyclic assembly lines. In Section 3, two team models are introduced. Section 4 describes tests that were conducted using real data from an automobile assembly plant. The results show possibilities of substantially improving productivity if teams are employed. Section 5 discusses teamwork and workforce size changes. Finally, Section 6 concludes this paper with a brief discussion of non-quantitative aspects of teamwork implementation.

1.1 The Japanese and The Scandinavian Team Models.

Issues related to teamwork in manufacturing attract enormous interest from both practitioners and researchers. A large body of business press literature speculates the causes of successes and failures of team based manufacturing systems (see, e.g., *Business Week* 1987, Dataro 1988, Dupuy 1990, and *New York Times* 1991). Most of these case-studies are based upon experiences of automobile manufacturers, who have long being pioneers in implementing innovative methods of labor organization among assembly workers. The two different approaches to reorganizing assembly workforce into teams which have emerged during the last two decades are best known as the "Japanese Team Concept" and the "Scandinavian Team Concept" (see MacDuffie and Krafcik 1988). The former concept was developed by Toyota to complement the lean production process. The latter concept, also called "the group assembly", was modeled by Volvo after the craftsmanship era of automobile production, and was developed primarily as a result of socio-economic changes.

The differences between the two con-

cepts are reflected by the commitment of Japanese companies to moving assembly lines with well-defined and standardized production tasks, while Scandinavian companies tend to favor group assembly principles with autonomous production teams and no moving assembly line. The organizational structures of the two team models complement the philosophy of the corresponding production process. The Japanese team structure, with small teams (4-6 people at Toyota) performing standardized tasks, de-emphasizes the autonomy of a team but encourages technical problem solving by teams designed to improve the work methods. The Scandinavian team model is based on large (15-20 people at Volvo) autonomous work teams which have responsibilities encompassing not only all the production tasks, but some administrative responsibilities as well.

The two approaches to teamwork have been implemented for varying reasons in different parts of the world, and with varying levels of success and criticism (see Fuxman1998b for more details). The Japanese model has been criticized by Parker and Slaughter (1988) and Berggren (1992) for its inability to provide a democratic work organization and autonomous worker decision making, and for its "high degree of mental concentration on work that is still very standardized" (from Berggren 1992). Parker and Slaughter refer to the Japanese team as "Management by stress" model, questioning the use of the term "teamwork" to describe the system, and criticizing it for being progressively more "stressful" as the system becomes more efficient.

The Scandinavian model, with its neo-craftsmanship production principles, has been criticized for being inefficient and even wasteful (see Jones, Ross and Womack, 1990). Critics argue that long cycle times, departure from moving assembly lines, and large autonomous teams all lead to poor productivity. On the other hand, the improved morale and lack of stress are arguably the system's claims to fame. Even these claims, however, are being criticized. Under increasing competitive pressure the effectiveness of the

group assembly model is being questioned today even by the companies who are utilizing it (see *New York Times* 1991).

Despite the ongoing disagreements between researchers advocating either model, one of the more significant implications of the movement toward team building in manufacturing is the realization that as technological innovations occur, so must innovations in human resource organization. Discounting the role of the worker in the process can only lead to failure in the form of absenteeism, turnover, strikes, low productivity, and high defects. The Japanese model seeks to complement the lean production system with highly coordinated human effort. Evidence suggests that teamwork is used as means of achieving productivity advantages (see Schonberger 1982, Cusumano 1985). The Scandinavian model is also complementary to the use of advanced productivity techniques. It seeks to create a challenging and satisfying work environment while staying away from the standardization techniques of mass production.

Successful implementation of any team based manufacturing system must be supplemented by changes in production philosophy, intensive training programs, and enhanced labor management relations. These complementary systems require significant investment of capital and time, making team building a risky but potentially valuable venture. It is important, therefore, to know whether the introduction of teams guarantees adequate productivity gains to justify the investment.

American companies are learning from the experiences of Japanese and European rivals. The joint ventures of American and Japanese firms illustrate the development of new labor organization models and management practices in a domestic automotive industry (see Rehder 1988, Mankin and Reich 1986, Dutton 1991, and Holusha 1988). The success of transplants with all-American workforce shows potential for future development of team concepts in U.S. plants (see Adler 1991 and 1993).

2. Mixed-model asynchronous assembly line under cyclic production

In many industries including automotive, electronics, appliance and apparel, to name a few, the final product assembly process requires high degree of human labor. In such manufacturing environment the organization of assembly workers around their tasks is critical for the line performance. Mixed-model assembly lines have started to substitute the more traditional dedicated assembly lines as the need to bring more product variety to the customer has forced manufacturers to rethink traditional mass production methods. With this change, not only the production control strategies change, but worker's responsibilities and their organization around the assembly tasks change as well (see *Automotive News* 1992, Fisher, Jain and MacDuffie 1993, and Kochan and Lansbury 1997).

Instead of traditional constant paced lines, some modern plants implement unpaced assembly lines, where non-synchronized Automated Guided Vehicles (AGVs) carry the jobs between the work areas. The pace of the line is typically determined by workers who upon completion of a set of production tasks at workstation release the job via AGV to the next workstation. The newest state-of-the-art Nissan assembly plant in Kyushu, for instance, has adopted an asynchronous type of assembly line with AGV's throughout the final assembly process (see *Automotive News* 1992). Other plants have utilized the same concept. For example, the Volvo BV plant in Netherlands uses AGV's to move vehicles between stations: after completing about an hour of assembly tasks at workstation, a team of workers releases the AGV for the next set of tasks to be performed at the downstream station (see *Industry Week* 1992).

Mixed-model assembly lines require workers to be "flexible", where "flexibility" implies the worker's ability to perform various tasks on different models and/or products. Workers, thus, must be cross trained and multi skilled

(see Blackburn 1991 for importance of broadly trained workforce in JIT manufacturing).

The mixed-model assembly line considered in this paper is of unpaced asynchronous type, where multiple products (or different models of the same product) with deterministic processing requirements are manufactured at the same time. The concurrent production of a mix of products on the same line is attained through repetitive production of a small set of items, each set having the same proportion of items as the production requirement over the planning period. The modeling framework described below is based on models of asynchronous assembly lines studied by Levner (1969), McCormick et al. (1989a and 1989), Fuxman (1998a), and Karabati and Kouvelis (1996).

Under asynchronous job transfers on the assembly line, the movements of jobs at adjacent workstations are not coordinated. A job starts processing at a workstation as soon as the worker assigned to that workstation becomes available, and upon completion, the worker releases the job to the downstream workstation (or buffer) as long as there is space for it downstream. Under such job flow discipline, instances of blocking and starvation are possible. The worker is said to be blocked if upon job completion on the workstation, he/she cannot release the job to a downstream worker (or a buffer) because the downstream worker is occupied with a previous job (or a buffer is full). The worker is said to be starving if the completed job leaves the workstation, but the next job does not yet arrive from the upstream worker.

Typically the concurrent production of a mix of products on the mixed-model line is attained through repetitive production of a small set of items (called Minimal Product Set), each set having the same proportion of items as the production requirement over the planning period. Given that there are M different types of items to be assembled, if r_k denotes the number of units of type k in the production target for a given time period, then vector $r^* = (r_1/q, \dots, r_M/q)$, where q

is the greatest common divisor of integers $r_1, \dots, r_M$, is the smallest part set having the same proportion as the production target and is called the *Minimal Product Set* (MPS). Each product in MPS requires processing on all workstations on the line without deviations from the permutation job flow (i.e., by-passing of workstations by some jobs is not allowed).

Let the MPS contain n items ($n = \frac{1}{q} \sum_{k=1}^M r_k$) and

the line consist of m workstations. The processing time required by job j , ($j=1, \dots, n$) at workstation i , ($i=1, \dots, m$), is known and denoted by p_{ij} . The matrix of processing times for an MPS is denoted by: $P(m, n) = \{p_{ij}\}$, $i=1, \dots, m$; $j=1, \dots, n$

Under stockless production, only a limited number of buffers may be available between the workstations on the line. From the modeling prospective, each single unit capacity buffer can be treated as a workstation with all zero processing times. There is no need to assign workers to such a workstation. In automotive assembly line described in Section 4, buffers are used to de-couple the assembly line into sections. Each cluster of buffers between line sections is used by relief workers to either perform repairs or finish the tasks that were not completed during the fixed time-window of 64 seconds at upstream workstations. The line, however, is a constant paced line moving with a speed of 64 seconds per car. In this case, if a particular task cannot be completed within 64 seconds at a workstation, it will be left unfinished and thus requires additional work later. Under the asynchronous discipline, however, each job gets completed at a workstation. The pace of the asynchronous line is determined by workers who must finish the task before passing the job to the downstream worker. The role of buffers in such type of production environment becomes not that of de-coupling and providing space to finish some tasks, but rather to improve job flow through reduction of instances of blocking and starvation (see Fuxman 1998a for details).

For simplification of further exposition, it is assumed that there are no buffers on the asynchronous line (relaxing this assumption entitles to introducing dummy workstations with all zero processing times, while the rest of the model remains the same). The assembly line under consideration is not subjected to stoppages due to machine breakdowns. It is assumed that the first workstation never starves and the last workstation is never blocked. The sequence of jobs within the MPS is fixed. The transfer times between workstations are assumed to be zero. Without loss of generality, transfer times can be absorbed into processing times, unless they are sequence dependent. The setup times are assumed to be negligibly small and will be ignored.

With repetitive production of units of MPS, after an initial finite transient time, the asynchronous assembly line achieves a steady state (see McCormick et al. 1989, when the time it takes to process one set of MPS is constant, and is called the cycle time. The productivity of the assembly line will be measured as the number of MPSs processed per labor-hour in steady state:

$$Prod = \frac{1}{kL^{AS}}$$

where L^{AS} is the cycle time on the line and k is the number of workers on the line. The cycle time can easily be determined from the processing requirement matrix using a graphical representation of the asynchronous process. The largest n -node path on the matrix, or the critical path, determines the cycle time.

The benefits of cyclic production schedules in asynchronous assembly lines have been discussed in the literature. Low work-in-process inventories, leveled part consumption, more stable schedules, shortened flow time are among some of the well-known benefits. In addition, mixed-model assembly line, often referred to as flexible assembly line, has a benefit of reducing balance losses on the assembly line through ex-

ploiting job complementarities and careful mixing the jobs in the MPS. Consider the simplest example of a line with two workstations, A and B, and two jobs in MPS:

A	8	3
B	2	5

With traditional production techniques, the desired quantity of item 1 will be made, followed by the production of the desired quantity of item 2. The cycle time on such assembly line equals 13 min. per set of items 1 and 2 (item 1 will be ready every 8 minutes, while item 2 will be ready every 5 minutes). The balance losses of 6 min. per item 1 and 2 min. per item 2 are inevitable, since the production tasks are not divisible. However, if the two items are made in alternate sequence, the cycle time decreases to 11 min. per set with the total balance loss of 4 minutes for item 2 only. This is explained by the complementary nature of the processing times for the two items. Under the second scenario, item 2 is being processed on workstation 2 while item 1 is being processed on workstation 1. Thus, the two longer tasks for both products, as well as the two shorter tasks, are performed at the same time.

Throughput gains from job complementarities within MPS depend upon the job flow discipline on the line. Unpaced asynchronous line provides the greatest potential for productivity gains. With teamwork (which is formally described in the next Section) among assembly line workers, further productivity gains can be expected. In the above example, with Sequential Task Sharing team the cycle time decreases to 10 min per set and with Simultaneous Task Sharing Team the cycle time decreases to 9 min. per set.

3. Models of teamwork in asynchronous mixed-model assembly lines

In labor intensive asynchronous assembly lines each worker is usually assigned a specific production task or a collection of tasks. It is

assumed that the processing time of a task is independent of the individual worker assigned to perform that task. This study focuses on technical strategies for teamwork and the issues of learning, worker's experience and efficiency will be neglected. With one worker assigned to each workstation/production task, m workers will be needed on the assembly line with m workstations. Each worker performs one production task at a workstation on all jobs in MPS.

If more than one worker is assigned to a production task, the task will be completed faster. The matrix of processing requirements will reflect this change by changing the time it takes to finish the task on all the items in MPS. For the convenience of further exposition, it is assumed that processing time decreases proportionally to the number of workers assigned to the production task. Two practical and simple models of rearranging worker's responsibilities around the production tasks on asynchronous line are considered and tested. Both models are based on the ability of workers to share production tasks. Several assumptions are made in developing the models: Only workers organized into a team can share production tasks; Only workers assigned to adjacent workstations, or performing consecutive tasks can be organized into teams; Team's responsibility is a combined responsibility of all individual members of the team; Processing time of a direct production task is independent of the skills of the individual worker assigned to perform the task; Workers are cross-trained.

The following analysis of the performance of the two team models assumes a fixed job sequence in MPS. In practice, however, job sequencing aspects should not be ignored. In fact, evaluating the advantages of teams should be performed once the most efficient MPS schedules are in place (as it is in all the examples given below).

3.1 Sequential Task Sharing Team

Consider a task sharing strategy where

formation of a team (or production group) means combining individual responsibilities of each team member into a group's responsibility, and sharing those responsibilities in the uniform fashion by each member of the team.

Consider, for instance, a case of a two-worker team. If the two workers were originally assigned tasks i and $i+1$ respectively, then the integrated task for the team requires a total of $(p_{ij} + p_{i+1,j})$ time units of processing for job j in MPS. Under the *Sequential Task Sharing* arrangement (or QTS team), each of the two workers performs $(p_{ij} + p_{i+1,j})/2$ time units of work. If $p_{ij} \leq p_{i+1,j}$, the first team member will complete the i -th task on job j and start working on the $(i+1)$ -st task. The unfinished $(i+1)$ -st task is then passed on to a teammate who will complete that task while the first teammate starts working on the next job in MPS.

With QTS teams, the job flow discipline on the assembly line is of an asynchronous type with blocking and starvation possible within the boundaries of the team as well as outside. Team members do not work simultaneously on the new combined production task, but rather perform the necessary work sequentially. Even though team members uniformly share the responsibilities, each worker still works independently. Each team member still has a well-defined task to perform, which however, may differ from the original one. Work sharing in a team, in this case, provides opportunity to rebalance production tasks.

The assumption of equal distribution of processing times within the team may not be justified in situations when some team members are more experienced than others, thus able to perform the same task faster. Forming teams of workers with similar experiences helps to avoid situations of unequal division of labor. In practice, frequent rotation of workers within the team brings their skills and efficiency to a similar level.

The numerical example below illustrates

the concept of QTS teamwork.

Example 1: The QTS Team

Consider an asynchronous production line where three items are repetitively produced, each requiring processing at three workstations. Let workers assigned to these three stations be labeled A, B, and C respectively. Matrix $P(3,3)$ below gives the processing times for the three items (in minutes):

$$P(3, 3) = \begin{matrix} A \\ B \\ C \end{matrix} \begin{vmatrix} 1 & 2 & 3 \\ 3 & 4 & 2 \\ 4 & 3 & 1 \end{vmatrix}$$

$$Prod(P(3,3)) = \frac{1}{3L^{AS}} = \frac{1}{3 * 10 \text{ min}} =$$

2 (MPS/labor-hour)

The cycle time on this line is 10 minutes per MPS (since the largest 3-node path consists of nodes p_{21} , p_{31} , and p_{32} with the total weight of 10, or alternatively, nodes p_{21} , p_{22} , and p_{32}). The productivity with the three workers equals 2 MPS/per labor-hour. By forming a QTS team of workers A and B, the processing requirement matrix, $P(QTS)$, changes as follows:

$$P(QTS) = \begin{matrix} A \\ B \\ C \end{matrix} \begin{vmatrix} 2 & 3 & 2.5 \\ 2 & 3 & 2.5 \\ 2 & 3 & 1 \end{vmatrix}$$

$$Prod(P(QTS)) =$$

$$\frac{1}{3L^{AS}(P(QTS))} = \frac{1}{3 * 9 \text{ min}} =$$

$$= 2.22(\text{MPS/labor-hour})$$

Productivity improves to 2.22 MPSs per labor-hour, since the cycle time decreases from 10 min. to 9 min. per MPS. It should be ob-

served that if workers B and C were organized into a QTS team, the productivity would not have improved, while with all three workers in one QTS team the productivity improves to 2.22 MPSs per labor-hour. The critical path on the processing requirement matrix determines the change in productivity once the QTS teams are formed. Since the number of workers on the line remains the same, the change in productivity is triggered by changes in the cycle time. To improve the cycle time, one has to look at only those tasks that are spanned by the critical path. These production tasks constitute moving bottleneck of the cycle. Forming teams of those workers who are assigned to such production tasks may lead to cycle time improvement, although it is not guaranteed. The number of candidates for task integration and team formation is greatly reduced: those production tasks that are not on the critical path can not trigger the decrease in the value of the current critical path and thus can be eliminated from the consideration for a team formation. In addition, those production tasks that are not on the critical path, but adjacent to either the first or to the last production task spanned by the critical path (as it is the case in the above example), are also candidates for integration into a team.

3.2 Simultaneous Task Sharing Team

Under the Simultaneous Task Sharing arrangement (or MTS team) the workload is still uniformly divided between the team members, however, members of MTS team perform the assigned work simultaneously rather than sequentially. For a two-person team described earlier, under the simultaneous work sharing rule both workers work together on the integrated task finishing it in $(p_{ij} + p_{i+1,j})/2$ time units. Once completed, the item is released for a downstream set of tasks in accordance with the asynchronous job flow rule.

The MTS task sharing arrangement implicitly assumes that members of the team are able to work on their tasks simultaneously. This could be a restrictive assumption, especially for

large teams, however, careful design of the teams and individual tasks (such as, e.g. having tasks performed on the opposite sides of a vehicle) will help to avoid this potential problem. Example 2 illustrates the changes on the asynchronous assembly line occurring when MTS teams are formed.

Example 2: The MTS team.

For the same assembly line as in Example 1, when workers A and B form an MTS task sharing arrangement, the matrix, $P(MTS)$, changes as follows:

$$P(MTS) = \begin{array}{c|cc} A \& B & 2 & 3 & 2.5 \\ \hline C & 4 & 3 & 1 \end{array}$$

$$Prod(P(MTS)) = \frac{1}{3L^{AS}} = \frac{1}{3 * 9 \text{ min}} =$$

2.22 (MPS/labor-hour)

As it was the case with the QTS team of A and B, the productivity with an MTS team of A and B improves to 2.22 MPSs per labor-hour. With workers B and C forming an MTS team, the productivity further improves to 2.35 MPSs per labor-hour. And finally, with a single MTS team of A, B, and C, the productivity improves to 2.61 MPSs per labor-hour (in this case the idle time on the line is completely eliminated, thus leading to the highest attainable productivity). Example 3 illustrates the situation in which neither type of a team structure yields any improvement in productivity.

Example 3: The QTS and MTS teams.

Consider an asynchronous assembly line with seven production tasks each assigned to a single worker:

$$P = \begin{array}{|c|c|c|} \hline 1 & 0 & 7 \\ \hline 0 & 4 & 1 \\ \hline 4 & 1 & 0 \\ \hline 1 & 0 & 7 \\ \hline 0 & 2 & 1 \\ \hline 1 & 1 & 0 \\ \hline 1 & 2 & 5 \\ \hline \end{array}$$

$$Prod(P) = \frac{1}{7L^{AS}(P)} = \frac{1}{7 * 8 \text{ min}} =$$

1.07 (MPS/labor-hour)

Any combination of QTS teams, including a single team of all seven workers, cannot improve productivity on this line. With an exception of a single MTS team of all workers (which always improves productivity) and two MTS teams one consisting of workers A, B, and C, and second one consisting of the remaining four workers, no combination of MTS teams can improve productivity.

The principles of work sharing embedded into the QTS and MTS models are drawn from the principles of Japanese and Scandinavian team models respectively. The increase in the number of tasks performed by each team member, typical for both the Japanese and the Scandinavian models, is reflected in the QTS and MTS teamwork arrangements. Members of either team arrangement are no longer attached to a specific production task, while the definition of each direct production task remains the same. Under the QTS work sharing scenario, team members perform their tasks independently, never working together on the same task. Under the MTS scenario, team members work on the integrated set of production tasks together as a group. Not only they share direct production tasks, but also work methods.

Of the two team structures, intuitively, MTS team should lead to a higher productivity

compared to QTS team since simultaneous job processing reduces the flow time. On the downside, idleness in an MTS team (i.e. blocking or starvation) forces *all* team members to be idle at the same time. With large teams, this may cause a substantial reduction in productivity. However, a *single* MTS team of all workers always leads to the highest productivity attainable on the line since it completely eliminates the idle time.

From the implementation point of interest, major limitation of the MTS work sharing rule is the physical constraint imposed by the need to simultaneously work on each job in MPS. For large MTS teams, redesigning a large number of individual production tasks for a group assembly is not always feasible. Assembly line changes, such as parallel workstations for workers in a team, as well as subassemblies for parallel teams may be required. At Volvo, for instance, traditional moving assembly is replaced by sophisticated material handling systems (such as AGV) that carry vehicles from work area to work area. In each work area a group of workers, working as a team, performs a number of tasks. These workers work together on the set of tasks their team is responsible. When the team is finished, the vehicle is transferred to the downstream work area where a next group starts working on their tasks. In some cases, the team may be responsible for assembly of the entire car. This is equivalent to having one MTS team of all workers. Volvo's Uddevalla facility had a

structure where in each of its six assembly plants, four teams (7-10 people) assembled the entire car (4 cars per shift). This is equivalent to having four parallel MTS teams.

QTS teams do not require major changes to either production tasks or assembly line layout, they can be readily used on the existing asynchronous assembly lines. The two types of work sharing arrangements can be implemented on the assembly line at the same time.

4. Can teamwork work? --- Results of testing teamwork models.

The QTS and MTS teamwork models were tested using the assembly line data from a large U.S. automobile manufacturer. (It should be noted that although the company was interested in the results of this study, the two models were not implemented due to unrelated reasons.) The assembly line under consideration, or rather a self contained segment of the assembly line called Trim area, consisted of 180 workstations (refer to Table 1). The trim area is the first stage of the final assembly and includes wiring, carpeting, body moldings and outside trim. The variety of products assembled there is represented by eight car models with up to twenty three options. A total of over 1600 production tasks are being performed. The current assembly line is a constant paced line with a cycle time of 64 seconds: a finished vehicle leaves the assembly line

Table 1
Characteristics of the Assembly line.

	<i>Trim Area</i>	<i>Total number of workstations</i>	<i>Number of non-value adding workstations</i>	<i>Number of production workers</i>	<i>Number of relief workers</i>
1	Wiring section	31	7	32	14
2	Headliners	22	7	31	13
3	Side Glass	20	5	33	10
4	Urethane	26	3	31	9
5	Carpets	27	4	33	9
6	Body Side Moldings	13	3	12	4
7	Door Trim Panels	15	4	20	6
8	Final	26	13	15	16
	Total	180	46	207	81

every 64 seconds. The assignment of production tasks to workstations, as well as the assignment of workers to workstations on the line is determined with the help of assembly line balancing techniques. Those jobs that exceed the cycle time of 64 seconds (over cycled jobs) and cannot be finished during its time window are finished at the end of the line by relief workers who also perform repair if needed. Management attempts to minimize such instances through careful job sequencing, e.g., longer jobs will be followed by shorter ones to provide worker the opportunity to finish long job using the leftover time from the short job. The initial job sequence, however, frequently gets altered after the paint shop, from where the vehicle arrives to the Trim area portion of the assembly line.

The assembly line is divided into eight functional sections that are separated by buffers. Buffers are non-value adding workstations, where each vehicle gets its "time-window" of 64 seconds, but no production tasks are performed. These areas are usually used to complete over cycled jobs. In all the tests that were conducted, the eight assembly line sections were treated separately.

The processing time requirements for eight basic car models differ due to difference in labor content. The option content of each car model (e.g., automatic transmission, sunroof, etc) adds additional processing time to the basic required processing time. The processing requirements matrix for each of the eight line sections was constructed based on the given processing times and the option content of each model. The actual job sequence during 11 days of two-shift production was used as the MPS job sequence.

In analyzing the effectiveness of the two team models on the existing assembly line, two directions were

pursued: (1) Evaluating how the change from the existing paced assembly line to the asynchronous unpaced line affects productivity; and (2) Evaluating how work sharing through teamwork can be used to further enhance productivity once the assembly line is of an asynchronous type.

The change from a constant paced line to an asynchronous production discipline has a number of advantages. Asynchronous job discipline reduces balance losses and increases capacity utilization in multi-product environments when job complementarity is exploited (see Fisher, Jain and MacDuffie 1993, and Fuxman and Jain 1997). Also, asynchronous lines do not require relief workers since every task gets completed at a workstation before moving to the downstream work areas. In the assembly line described, the advantages of tailoring the product mix to find complementary jobs could not be realized, since the jobs were well balanced (the company uses fairly standard assembly line balancing techniques). However, as Table 2 shows, substantial productivity benefits could be realized when changing to an asynchronous flow because of elimination of the need for relief workers. Although with the change to the asynchronous production discipline, the cycle time in five out of eight sections slightly increased over the current 1.067 min/job (in sections 1, 4, 5, 6, and 7), productivity improved dramatically because fewer workers were needed. In the last section on the assembly line, where the gap in productivity is the greatest, half of the workstations

Table 2
Productivity Comparison: Constant-Paced Line vs. Asynchronous Line

<i>Section</i>	<i>Current productivity (jobs/labor-hour)</i>	<i>AS Cycle time (min/job)</i>	<i>Productivity on AS line (jobs/labor-hour)</i>
1	1.2	1.17	1.6
2	1.3	1.05	1.8
3	1.3	1.07	1.7
4	1.4	1.25	1.5
5	1.3	1.26	1.4
6	3.5	1.15	4.3
7	2.2	1.29	2.3
8	2.0	1.03	3.9

were non-value adding ones, where inspection and repair work is performed. Since productivity of the AS line is computed based on the number of workers involved in the direct production only, the difference in productivity here is almost twofold.

When team formation and its effect on productivity were investigated, it was found that in each line section there were only a handful of workstations being picked up by the critical path. This suggested that several workstations in each line section require consistently long processing times, making them bottleneck operations. These observations helped to substantially reduce the number of candidates for team formation. Sections two, three, and eight were further eliminated from consideration for team formation. These three sections, as Table 2 indicates, already have asynchronous cycle times lower than 64 seconds.

The impact of teams on productivity was evaluated in each of the remaining sections. First, the workstations on the critical path were identified as candidates for being integrated into a team. Then various assignments between the workers assigned to these workstations and various team structures were considered. The re-

sulting improvements ranged from just about 3% to almost 30% compared to the productivity when no teamwork was employed. Table 3 summarizes the obtained results. In choosing the team structures for each line section, the goal was to reduce the cycle time on the AS line to 64 seconds. No attempt was made to further reduce the cycle time, although such a reduction is possible in some line sections (except section one). If the company does not desire to increase the production volume, there is no need to further reduce the cycle time. The priority of the company was to find the most efficient way to attain the desired level of output.

In finding the appropriate team types for the line, a preference was given to the QTS work team arrangement over the MTS team arrangement. This was motivated by the lack of information on the feasibility of having workers perform direct production tasks simultaneously. To avoid practical complications, we only considered the MTS work teams of no more than two or three workers.

The biggest challenge in reducing the cycle time while using teams was presented by the very first line section. Here, the critical path picked up only the last five workstations, thus

Table 3
Team structures and line performance when the size of the workforce remains unchanged.

Section	Number of teams	Type of team	Number of workers in each team	Cycle time (min/job)	Productivity (jobs/ labor-hour)
1	3	QTS	2,2,4	1.14	1.6
1	2	QTS	2,5	1.14	1.6
1	2	QTS	4,4	1.14	1.6
4	2	QTS	3,4	1.04	1.9
4	1	MTS	3	1.04	1.9
4	2	MTS, QTS	2,4	1.04	1.9
5	2	QTS	3,5	1.04	1.7
5	2	QTS	3,6	1.04	1.7
5	3	QTS	3,2,6	1.07	1.7
6	3	QTS	3,2,3	1.07	4.7
6	3	QTS	3,3,2	1.07	4.7
6	4	QTS	3,3,2,2	1.07	4.7
7	5	QTS,QTS,QTS,QTS,MTS	2,8,4,4,2	1.24	2.4
7	5	QTS,QTS,QTS,QTS,MTS	2,8,4,3,3	0.92	3.3
7	5	QTS	2,8,4,3,3	1.05	2.9

considerably reducing the number of choices for team formation. The resulting improvement in cycle time is not as significant as in other sections of the line (the number of workers on the line was kept constant in all of these experiments). The largest productivity improvement was found in section seven. This is explained by the fact that the critical path on the processing requirement matrix for section seven picked up nodes on all workstations, providing the largest number of candidates for forming a team.

It should be emphasized that finding the teamwork arrangement that optimizes productivity benefits was not the goal of these experiments. Rather, finding the most efficient organization of existing workers on the AS line to achieve the cycle time of the existing constant paced line was the goal. The results provide very promising avenues for improving the assembly line performance through careful design of work teams. Perhaps even more important is that the modeling framework of asynchronous mixed-model assembly lines provides the means of effectively computing and evaluating such work team models.

5. Expansion and reduction in workforce

It has been assumed thus far that there are enough workers on the assembly line to assign each to a single production task. For reasons such as absenteeism, there may be fewer workers available to perform the same set of production tasks. Some workers will have to be assigned more than one task, or if there is a pool of relief workers, the unattended task will be assigned to a relief worker. In the former case, the task can be split between workers who perform immediately adjacent production tasks, or the whole task can be picked up by an adjacent co-worker. In a latter case, if the pool of relief workers gets depleted, production tasks can once again be split between all involved workers. Most of these changes trigger a loss in productivity.

When some workers end up working on more than one production task, one expects the cycle time to increase: as there are fewer workers to do the same number of tasks, it takes them longer to produce one set of MPS. Changes in productivity, however, depend on the margin of the increase in the cycle time. The following example illustrates the case when, in the absence of a worker, no matter how the task is reassigned, the productivity decreases:

$$\begin{array}{c|cccc} A & 5 & 6 & 1 & 3 \\ B & 4 & 2 & 5 & 4 \\ C & 3 & 4 & 6 & 4 \end{array} \quad \text{Prod} = \frac{1}{3L^{AS}} = \frac{1}{3 * 19 \text{ min}} = 1.05 \text{ (MPS/labor-hour)}$$

With three workers, labeled A, B, and C, productivity is 1.05 (MPS/labor-hour). In the absence of worker B, for instance, the second production task could be absorbed by the remaining workers A and C (assuming there is no relief pool). However, having either one of them perform an additional task decreases productivity. In case a) below, the second task is performed by worker A, while in case b), the same task is performed by worker C.

$$\text{a) } \begin{array}{c|cccc} A & 9 & 8 & 6 & 7 \\ C & 3 & 4 & 6 & 4 \end{array} \quad \text{Prod} = \frac{1}{2L^{AS}} = \frac{1}{2 * 30 \text{ min}} = 1 \text{ (MPS/labor-hour)}$$

$$\text{b) } \begin{array}{c|cccc} A & 5 & 6 & 1 & 3 \\ C & 7 & 8 & 11 & 8 \end{array} \quad \text{Prod} = \frac{1}{2L^{AS}} = \frac{1}{2 * 34 \text{ min}} = 0.88 \text{ (MPS/labor-hour)}$$

In both a) and b), the cycle time increases enough to offset the savings from having two workers instead of three, thus leading to a decrease in productivity. It can be easily verified that when a second task is split equally between workers A and C, productivity also decreases. Thus, with no relief workers, in the absence of worker B productivity is expected to fall. Task sharing helps reducing such productivity loss associated with absenteeism. Consider having all three workers organized in to a single QTS team:

$$P(QTS) = \begin{array}{c|cccc} A & 4 & 4 & 4 & 3\frac{2}{3} \\ B & 4 & 4 & 4 & 3\frac{2}{3} \\ C & 4 & 4 & 4 & 3\frac{2}{3} \end{array} \quad \text{Prod}(P(QTS)) = \frac{1}{3L^{AS}(QTS)} = \frac{1}{3 * 16 \text{ min}} = 1.25 \text{ (MPS/labor-hours)}$$

If a team member is absent, the team is still responsible for completing all three production tasks. When worker B is absent, the two team members can split the second task. The new processing requirement matrix becomes:

$$P(QTS) = \begin{array}{c|cccc} A & 6 & 6 & 6 & 5.5 \\ C & 6 & 6 & 6 & 5.5 \end{array} \quad \text{Prod}(P(QTS)) = \frac{1}{2L^{AS}(QTS)} = \frac{1}{2 * 24 \text{ min}} = 1.25 \text{ (MPS/labor-hour)}.$$

If workers A and C decide to work simultaneously on each job, their MTS team will further improve productivity. Although the cycle time increases in the absence of worker B, there is no loss in productivity. There will be, however, a loss in throughput due to increase in cycle time, which has to be compensated to meet the target production quantity over the planning horizon. This can be done through overtime.

Similar arguments can be used to show that expansion of workforce does not always lead to improvement in productivity. With more workers on the line, even though the cycle time should decrease, productivity may decline. In such situations, it may be advantageous to have teams on the line.

Consider the same example. In an attempt to boost productivity, let an extra worker be added. The new worker, labeled R, can be assigned to help either one of the three workers. In each case productivity declines, although the cycle time improves:

$$\text{a) } \begin{array}{c|cccc} A, R & 2.5 & 3 & .5 & 1.5 \\ B & 4 & 2 & 5 & 4 \\ C & 3 & 4 & 6 & 4 \end{array} \quad \text{Prod} = \frac{1}{4L^{AS}} = \frac{1}{4 * 18 \text{ min}} = 0.83 \text{ (MPS/labor-hour)}$$

$$\text{b) } \begin{array}{c|cccc} A & 5 & 6 & 1 & 3 \\ B, R & 2 & 1 & 2.5 & 2 \\ C & 3 & 4 & 6 & 4 \end{array} \quad \text{Prod} = \frac{1}{4L^{AS}} = \frac{1}{4 * 17 \text{ min}} = 0.88 \text{ (MPS/labor-hour)}$$

c)	A	5	6	1	3
	B	4	2	5	4
	C,R	1.5	2	3	2

$$Prod = \frac{1}{4L^{AS}} = \frac{1}{4 * 18 \text{ min}} = 0.83 \text{ (MPS/labor-hour)}$$

If all three workers A, B, and C are organized into a single QTS team, and the team is assigned an extra worker R, the cycle time substantially decreases while productivity remains unchanged:

A	3	3	3	2.75
B	3	3	3	2.75
C	3	3	3	2.75
R	3	3	3	2.75

$$Prod(P(QTS)) = \frac{1}{4L^{AS}(QTS)} = \frac{1}{4 * 12 \text{ min}} = 1.25 \text{ (MPS/labor-hour)}$$

These examples illustrate that teamwork helps alleviating negative impact of contingencies such as absenteeism and thus provides management with a powerful tool to deal with these unpredictable events. To take full advantage of teamwork, management can transfer workers between the teams, to have fewer workers on one segment of the assembly line while adding more workers to another segment. The disadvantage, however, is that once workers are used to working with their team, they would not feel comfortable being transferred to another team, where they would have to learn again the dynamics of the new team. Such strategy may be reserved for crisis situations to provide management an additional flexibility to adjust to contingencies as they occur.

6. Concluding remarks

Two models of teamwork for assembly line workers, both based on work sharing, have been proposed and analyzed. Japanese manufacturers use teams on the assembly line to improve productivity. However, no quantitative evidence exists in a research literature to support it. Simple yet practical models of teamwork proposed in this study represent a very first step towards better understanding the implications of teamwork on productivity. The Sequential Task Sharing team model was motivated by manufacturing practices in Japanese auto plants where teams play an integral role in the overall manufacturing strategy by providing the necessary human support for implementing JIT production. The Simultaneous Task Sharing model was designed to reflect principles of the Scandinavian team based production system, which has socio-technical roots resulting in group assembly manufacturing strategies.

Both types of teams may lead to positive or negative effects on productivity in an asynchronous assembly line. The modeling framework of cyclic mixed-model assembly lines offers computational means of finding the type of team arrangement, the size of the team, and the position of the team on the assembly line to improve productivity. Implications of changes in the workforce size on productivity and the role of teamwork when such changes are made can also be analyzed within the scope of the model.

The results obtained using the data from an automobile manufacturer show that both QTS and MTS models can improve productivity on the existing assembly line. Changes in the assembly line discipline must be made in order to benefit the most from work sharing through teamwork. Once an asynchronous job flow discipline is implemented, there is no need to balance the jobs in a traditional assembly balancing fashion. Rather, work sharing through teamwork should be used to further improve productivity.

The QTS and the MTS team models rest on a number of assumptions. Some of the assumptions, such as the equal division of workload between the team members and the independence of production task times from the individual performing the task, are made to make the models tractable. Mixed-model assembly line framework allows relaxing these assumptions by appropriately modifying the processing requirement matrix. The workload distribution among the team members can be tied to worker's efficiency. Although this will necessitate measuring efficiency of each team member, which in turn may damage the morale of the team and discourage the less efficient workers from learning fast, the compensation system with incentives toward fast learning would help to alleviate the differences in efficiency.

6.1. Implications for Future Research

Teamwork, as a mechanism for task sharing, will have an effect on the work methods within the team, ultimately affecting the efficiency and the work standards for workers involved. Management literature suggests that there is a tradeoff between the scope of work and the efficiency of an individual (see e.g., Kochan, Cutcher-Gershenfeld, and MacDuffie 1992, MacDuffie and Kochan 1995, MacDuffie 1995, and Nowlin 1990). The extent to which this tradeoff is applicable to the two work team models (QTS and MTS types) is a question for further research. Once teamwork is implemented, rotation within the team contributes to a significant enhancement of the job scope: work becomes less repetitive, more interesting, and thus more satisfying. These factors lead to increased motivation for working in groups and learning new skills. Knowledge of a variety of production tasks by team workers facilitates motivation for improving work methods, which in turn affects the workload and labor division among team members leading to *kaizen* improvements.

On the other hand, increase in the scope of work may negatively affect worker's efficiency at least in a short run, while workers be-

come accustomed to the new production tasks and work sharing arrangements of their team. In the long run, however, as workers get used to new skills acquired through teamwork, to the idea of sharing work with their co-workers, as they begin finding ways to make working together more efficient by modifying work methods and by better balancing their production tasks, the efficiency should improve without sacrificing the scope of the work. In order to incorporate workers efficiency into the modeling framework, there is a need to understand this tradeoff from a quantitative perspective. Although the focus of this study was on developing technical strategies for teamwork, we emphasize the importance of understanding a multitude of human related issues which are an integral part of any team based assembly production process.

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