Team-oriented assembly system design: 
A new approach

Joseph Bukchin\textsuperscript{a,*}, Ezey Darel\textsuperscript{b}, Jacob Rubinovitz\textsuperscript{b}

\textsuperscript{a}Department of Industrial Engineering, Faculty of Engineering, Tel Aviv University, Tel Aviv 69978, Israel
\textsuperscript{b}Faculty of Industrial Engineering and Management, Technion I.I.T., Israel

Abstract

A new design methodology for team-based assembly systems is presented in this paper. Team-oriented assembly (TOA) systems support the objectives of modern assembly systems, while creating a more satisfactory working environment. Each team is defined as semi-autonomous with well-defined responsibilities. Design parameters are: number of teams, precedence relationship between them, team size, and work content of each team.

The problem-solving approach is product oriented and based on assigning Bill of Material (BOM) elements to teams. Performance measures are introduced, and a hierarchical design approach which consists of two stages is presented.

Keywords: Team-oriented assembly; New design method

1. Introduction

An assembly line is the most commonly used method in a mass production environment because it enables assembly of complex products by workers with limited training. The main objective of assembly system designers is to increase efficiency by maximizing the ratio between throughput and required costs.

In the last few decades there have been tremendous changes in market demands. The market has become more competitive with increasing consumer requirements for quality and specific demands from products. At the same time, socio-economic conditions have improved and workers have a greater interest in work satisfaction. These changes broaden assembly system objectives to include quality and flexibility, while satisfying humanitarian needs of the worker. These needs emphasize the disadvantages of current assembly design: low quality, poor working environment, high levels of work-in-process (WIP) and high costs of material handling (Burbidge, 1989; Gustavsson, 1984; Robinson et al., 1990).

A new type of assembly system is proposed, where workers are organized in teams, and each team is semi-autonomous with well-defined responsibilities. We propose the term “team-oriented assembly” (TOA). Despite the fact that TOA design has been applied in many places, no straightforward method for the design process exists in the literature. TOA systems support the new objectives of assembly systems while creating a more satisfactory working environment.

*Corresponding author. Tel.: 972 3 640 7941; fax: 972 3 640 7669; e-mail: bukchin@eng.tau.ac.il.
The rest of this paper is structured as follows: in Section 2, objectives of assembly systems are outlined. The macro stage design process is introduced in Section 3, while in Section 4, the micro stage methodology is discussed. The summary and conclusions are discussed in Section 5.

2. Objectives of an assembly system

2.1. Traditional assembly systems

Assembly systems can be classified according to several criteria. One is the manufacturing technology employed, namely, classifying according to the degree of automation: dedicated, flexible and manual work. Others include systems configuration: assembly lines (synchronous, asynchronous, with or without buffers, etc.), individual assembly and assembly teams.

Currently, the most common assembly system is the traditional assembly line. Related design problems and issues are characterized in the literature as the assembly line balancing problem, which usually refers to single product assembly lines. Most papers deal with a single objective: to maximize efficiency of the assembly line through minimization of idle time. Surveys on this subject are found in Baybars (1986), Gosh and Gagnon (1989) and Dar-El (1991). In these studies, the design objective is either:
(a) to minimize the number of stations subject to minimum production rate or,
(b) to maximize the production rate (minimize cycle time) for a given number of workers (stations).

Several papers deal with more complex systems such as mixed model assembly lines, which are used for assembling several models of the same product on the same line (Chakravarty and Shub, 1985; Fremery, 1991; Macaskill, 1972; Thomopoulos, 1970).

The drawbacks of traditional assembly lines designed by these methods are outlined below:
(1) Low flexibility: Assembly lines are characterized by low flexibility with respect to changes in demand. In addition, any change in product design, affects the entire system, and a line re-balance is necessary. Workers in traditional assembly line are generally narrowly trained, which creates difficulties in transferring them between stations. In fact, most changes accentuate the need for worker mobility.

(2) High balance loss: Balance loss results from imperfect balance of the line caused by stochastic task times or variations in model task times in a mixed model assembly environment. The symptoms of imperfect balance are blockage and starvation which impair performance.

(3) Poor quality: In traditional assembly lines there is no direct link between the worker and the final product. No direct feedback is given, and the worker cannot learn from his or her mistakes. It is not always possible to identify the worker who causes the defect, especially when others work on incomplete products (Robinson et al., 1990). All these issues lead to poor quality.

(4) Poor working environment: Workers in traditional assembly lines are treated like machines and are expected to improve throughput according to some learning curve. Workers perform repetitive tasks hundreds if not thousands of times each day, while the only objective is to do it faster each time. This policy depresses worker's motivation.

(5) High work-in-process: Traditional assembly lines are characterized by long product flow times, which is an outcome of the sequential order of the assembly operations. According to Little formula (Little, 1961), high work-in-process is a consequence of long flow times. Additional safety stocks are required due to low flexibility with respect to demand fluctuations.

(6) High costs of material handling: Traditional assembly line consists of stationary workers with products passing between them. Such a configuration requires costly material handling systems, especially when a single synchronous system is used for assembling the entire product.

2.2. Team-oriented assembly (TOA) systems

2.2.1. Characteristics of TOA systems

The design of manufacturing cells is discussed by Black (1991), which mentions the possibility of making assembly operations within cells. The author assumes that a system, based on manufacturing and
assembly cells, is an alternative to a job-shop environment. Accordingly, the large and complex manufacturing system is replaced by a modular structured system based on linked cells. The approach of the proposed methodology is different from the above. Here we deal with a mass production environment, which is traditionally characterized by the assembly lines. In the proposed model, the TOA system becomes an alternative to the traditional assembly line, which minimizes the drawbacks of the traditional design process, as discussed in the previous section.

The subject of assembly teams is addressed by Burbidge (1989). Assembly systems are defined by Burbidge (1989) in two ways. The first definition is: “a small organizational unit which completes assemblies in a continuous flow and is provided with all the facilities it needs to do so”. The second is based on behavioral science methods and consists of a list of yes/no questions related to the state of a group of workers. The questions concern the products assembled by the team, team’s territory, team size, responsibilities of the team members, etc. Only if all answers are “yes”, then the group is defined as an assembly team.

We propose a new definition. A group of workers is defined as an “assembly team” under the following conditions:

1. The group completes assemblies in a continuous flow, namely, the transfer batch is equal to one item.
2. Group members are working at the same territory.
3. The group is small enough in order to enable the cohesiveness of the members.
4. Group members determine their own work orders.
5. Group members are responsible for the quality of products they assemble.

In Burbidge (1989), several types of assembly groups are discussed as illustrated in Fig. 1. These types range from simple mono and parallel groups, to a series of groups, which comprise a line of groups. Burbidge also discusses the work organizations within the group. However, he gives no clear explanation as to how to choose the correct form.

The design process in the proposed model is based on product structure, and the assembly system configuration is set according to product design. After defining the assembly team and describing optional configurations of a system based on teams, the characteristics of TOA systems can be summarized. The contribution of these characteristics to the objectives of assembly systems design will then be examined.

The characteristics of TOA systems are:

1. Semi-autonomous teams: One of the main characteristics of TOA teams is their semi-autonomous design. This is an outcome of the assembly team’s definition, work structure and quality assurance.
2. Orientation to the product structure: The TOA design process is based on the structure of the product which in turn, determines the assembly system configuration. The assembly system is then based on modular structure, while each team is responsible for the assembling of major one or more sub-assemblies.
3. Worker expertise: Unlike the traditional assembly line, we expect TOA workers to be highly trained, with each person capable of doing every task performed by the team.
4. Short flow times: TOA systems are characterized by short flow times. The reason for that is the fact that in TOA system tasks can be performed in parallel, while in traditional lines, tasks are performed in sequential order.
5. Continuous flow: The implication of “continuous flow” is that all elements in the system are synchronous, namely, teams have the same throughput and cycle time. As a result, effectively small lot sizes can be used.
6. High motivation: Two of the major advantages of using team configuration are the improvement of working environment and increase in worker involvement in the production process. These in turn, should increase motivation, which is the major requirement for a properly functioning production system.

2.2.2. Objectives of TOA systems

The main advantages of the TOA system are improving both flexibility of the assembly system and quality of the product, while maintaining the high efficiencies associated with traditional assembly lines.

A summary of relations between system characteristics and objectives is shown in Fig. 2. There the
positive effect of assembly teams characteristics on flexibility, quality and throughput are illustrated.

2.2.2.1. *Flexibility of the assembly system*. Flexibility is necessary because of market demand and tough competition which characterizes modern industry. Gustavsson (1984) divides flexibility into three types of changes:
(i) Changes in product design – new models, changes in design of an existing model.
(ii) Changes in assembly system design – new machines and assembly methods, technological improvements.
(iii) Changes in demand – fluctuations between models, during a period and between periods.

In order to achieve a high degree of flexibility, a change in a certain element in the system must have a relatively small effect on the rest of the system. Effects of changes must be kept as local as possible. Team configuration provides an adequate solution, because of the following reasons:
- Assembly teams are semi-autonomous and every technological change in the assembly system should only affect those teams that use the specific technology.
- System design is based on product structure, meaning that every team is responsible for a major sub-assembly of the product. In this way, the system reacts quickly to changes in product design. Such a change only affects the team responsible for the particular sub-assembly, unlike the traditional assembly line, which is totally affected by any change. An additional benefit is that there is a high potential for improvement of product design due to worker expertise.
Multifunctional workers are able to counteract disturbances to the assembly environment, such as: worker absence, worker turnover, changes in demand, and mobility of workers between bottlenecks.

2.2.2.2. Product quality. Creating a production environment that supports quality improvement, requires a commitment of the worker to error-free performance. In such an environment, workers rapidly learn from mistakes, and a high level of motivation is maintained. TOA configuration supports such an environment because of the following reasons:

- Allocation of work elements according to the product structure creates a stronger commitment of the worker to the quality of his work. Each team is responsible for production of one or more major sub-assemblies, and team workers are responsible for the quality of their products. In the traditional assembly line, a simple sub-assembly may be produced by many workers spread along the line with no particular person responsible for quality.

- Faster identification of defectives and problem by team members will result, along with rapid feedback to specific workers. Learning is more effective since the worker immediately performs a corrective action.

- High quality primarily depends on worker motivation. The proposed configuration creates a highly satisfying work environment, and as a result a high level of motivation.

2.2.2.3. Throughput. Throughput is actually related to system efficiency. An efficient system is characterized by high throughput generated with minimal use of resources. The traditional assembly line is highly efficient since its major objective is higher throughput.

The TOA system, as the traditional assembly line, is based on continuous flow. Relatively small production lots can be used which in turn reduces work-in-process. As with traditional assembly lines, the system needs to be balanced, but the difference between the two systems is the length of flow time.

Traditional assembly lines are characterized by long flow times, because of the sequential order of assembly tasks completion. Long flow time is
directly related to high work-in-process, resulting in high operating costs. Tasks in TOA configuration can be performed in parallel. Sequential production is kept at the minimum necessary due to technological precedence constraints. In traditional assembly lines all operations are performed in sequence due to the structure of the line (even those operations that could have been performed in parallel). Following this observation, flow times are expected to reduce dramatically.

3. The hierarchical assembly system design

3.1. Definitions and input parameters

The design process consists of macro and micro stages. Assembly system effectiveness is determined at the macro stage while assembly system efficiency is determined at the micro stage. The proposed process is hierarchical in that the results of the macro stage serve as an input to the micro stage.

The main parameters of the assembly system are determined at the macro stage, and include: the number of teams, precedence relationships between teams and tasks allocation. The micro stage, on the other hand, deals with decisions within each team, namely, assignment of work to each team member. This process is similar to mixed model assembly line balancing, while trying to make the team efficient as possible. This issue has been addressed many times: Chakravarty and Shub (1985), Fremery (1991), Macaskill (1972), Thomopoulos (1970) and others.

The macro stage is based on product structure, or, with several models, on the structure of the basic product mix. While the advantages of this concept were discussed earlier, this section focuses on practical aspects.

In most assembly line balancing research, the input to the process is the precedence diagram (Prenting and Battaglin, 1964). The main disadvantage of using the precedence diagram is that it ignores the product structure. In the proposed design methodology, the main input to the design process is a truncated bill of material (BOM) composed of sub-assembly elements. The lowest level of every BOM branch is a basic sub-assembly. Other elements of a regular BOM, representing raw material are ignored, since they are not required by the TOA design process. The truncated BOM is similar to the GOZINTO diagram presented in Chase and Aquilino (1985). A typical BOM, where the lowest level of each branch is the raw material required for the sub-assemblies is illustrated in Fig. 3. These elements are removed from the BOM diagram used in the design process.

The truncated BOM is actually an aggregation of all various models, and includes all sub-assemblies needed for each model. Since each item in the BOM represents a sub-assembly, it has its own processing time, calculated as the weighted average of the element time for all models. Let $f_1, f_2, \ldots, f_m$ be the expected demand for the $m$ models, then the duration of element $i$ is given by:

$$d_i = \frac{1}{\sum_{j=1}^{m} f_j} \sum_{j=1}^{m} f_j d_{ij}$$

The value of $d_{ij}$ is the assembly time of element $i$ in model $j$. $d_{ij}$ is obtained by summing assembly operations time needed to be performed in order to produce an element from its immediate descendants. The relation between the BOM illustrated in Fig. 3 and the precedence diagram derived from assembly operations is illustrated in Fig. 4. We observe that every sub-assembly or BOM element is actually a batch of operations, and the sum of the operation times yields the element time. The next step involves a calculation of the weighted average, as noted earlier.

Two type of constraints are defined as an additional input to the design process:

(a) Attached elements – Elements that must be assembled by the same team. This requirement can arise for example, from the use of expensive assembly equipment.

(b) Separate elements – Elements that must be assembled by separate teams. For example, different environmental requirements for dependent tasks (hot versus cold, clean versus dirty, etc.).

Additional information related to the assembly system is the required production rate, which determines the minimal production cycle time.
Fig. 3. Bill of material.

Fig. 4. Precedence diagram partition according the BOM structure.
This parameter affects the amount of work allocated to each team as well as the number of teams. Team size is also subject to constraints. There are some variations in the literature regarding the ideal size of a team. Johnson and Johnson (1991), suggest a range of two and six members, while focusing on face to face interaction. They claim that the smaller the team, the clearer it becomes to individual team members that their contributions and efforts are needed. There are obvious disadvantages, however, when the team becomes too small. It can limit the range of ideas and the variety of skills. Peterson (1991) raises this point, and suggests a size of six to twelve members. Peters and Waterman (1982) claim that team size should be between five and ten, with the ideal number around seven. In the proposed methodology, minimal and maximal values of the team size are set as an external constraints. These values have to be determined in order to achieve high cohesiveness of each team, and still support other qualitative performance measures discussed in detail in the next section.

3.2. Performance measures of the macro stage

Performance measures are essential for the proposed methodology. The following measures are required for selecting between alternatives and in evaluating solutions. Valid performance measures are highly correlated with the objectives of modern assembly systems.

Six performance measures are proposed:

1. CSA (Complete Sub-Assembly) – The total number of sub-assemblies produced by a single team. A sub-assembly is considered “complete” if the sub-assembly element in the BOM and all its descendants are assembled by the same team.

2. ISA (Immediate Sub-Assembly) – The number of BOM elements that are assembled with their immediate descendants by the same team summed over all teams.

3. NT (Number of Teams) – The number of teams determined by the design process.

4. FT (Flow Time) – The time difference between start of work on the first sub-assembly and product departure from the system as a finished item.

5. NL (Number of Links) – The number of “links” among teams. A link is defined by some flow of material between two teams. This is also a measure of the assembly system complexity.

6. NW (Number of Workers) – The total number of workers included in all the teams.

The first two measures are autonomy measures. High values for these measures indicate that work allocation is product oriented. Advantages of product orientation were noted earlier. The second measure complements the first, by dealing with “partial completeness” of elements, particularly in the upper levels of the BOM.

The total number of teams relates to two objectives. The first is system complexity, and it is obvious that a small number of teams improves this factor. The second objective is to minimize the balance loss. An assembly system is based on continuous flow, and requires to be well balanced in order to perform well. Johnson (1991) deals with assembly groups, and claims that a large number of teams impairs system balance. The best scenario for balance is having one team only. In the proposed methodology the number of teams is affected by team size constraints, and system cycle time.

Flow time is a common performance measure for production systems. This measure is highly correlated to the WIP level (Little, 1961), and inventory costs are directly proportional to WIP levels. High WIP levels tend to increase variance in the system, making it difficult to predict performances, and therefore increases operational costs.

Total number of links is a measure of system complexity. A large number of links indicates that there are many sub-assemblies handled by more than one team which impairs team autonomy. It might indicate the need for a complex material handling system.

Efficiency of the assembly system is related to the total number of workers. A design objective is to improve this factor by reducing the number of workers subject to an external constraint of production cycle time.

A typical feasible solution at the macro stage is illustrated in Fig. 5. Input for this example was: team size between six and twelve workers, and
a cycle time of three time units. Hence, team capacity was determined to be between 18 to 36 time units (the product of the minimal and maximal number of workers times the cycle time). The solution includes BOM elements divided into six teams, while the duration of each element is given in parentheses. The value of CSA is five, as seen in the figure (elements: 4, 10, 19, 20, 21); ISA equals eight, since it includes the CSA elements plus three other elements (2, 3, 5). There are six links between teams (1–5, 2–5, 2–6, 3–6, 4–6, 5–6), and the FT is equal to 100 time units. The flow time is equal to the length of the critical path which is the amount of work allocated to teams 2, 5 and 6. In comparison, the flow time of a traditional assembly line, with the same input is 192 time units, nearly double compared to the TOA value.

4. Micro stage balancing problem

In this section the mixed model assembly line balancing problem is briefly discussed. Inter-team configuration is similar but not identical to the traditional mixed model assembly line balancing problem. Due to this difference a new approach is proposed.

Sub-assemblies are assigned to teams at the macro stage. In the micro stage, work elements are assigned to manned workstations within each team. Production is kept synchronized due to a pre-determined cycle time of the assembly system.

System effectiveness is achieved in the macro stage through restructuring the assembly system in a way that modern assembly systems objectives are met. The micro stage problem increases system efficiency by creating a balanced flow of work
within each team. Idle time caused by starvation and blockage should be minimized. This problem is described in the literature as the “mixed model assembly line balancing” (Chakravarty and Shtub, 1985; Fremery, 1991; Macaskill, 1972; Thomopoulos, 1970 and others).

An underlying assumption used in traditional mixed model assembly line balancing models is that a task common to several models, is performed at the same station for all models. The reasons for this constraint are:

1. Specialization: One of the main principles of the traditional assembly line is the division of work among many workers, while each worker performs a small number of assembly tasks. Complex products can be assembled by workers with limited skills. The implication of the above constraint is that the work content of each workstation is kept constant.

2. Learning: An additional implication of the above constraint is that the number of assembly tasks for each worker is kept to a minimum. This way workers can achieve better performance in a relatively short time since the learning process is shorter and more efficient.

3. Equipment cost: Assignment of common assembly tasks to several stations requires duplication of the assembly equipment at an additional cost. Assignment of common assembly tasks to the same stations creates a strong interdependency between models. Therefore solution procedures use a combined precedence diagram which is a single representation of precedence constraints of all various models. A preliminary requirement for such a representation is that various models need to be “similar” (without contradicting constraints). By using the combined precedence diagram all models are balanced at once. The result is assignment of combined diagram elements to stations.

In fact, the above constraint may actually generate low quality solutions, characterized by significant blockage and starvation effects. For example, consider the following two precedence diagrams illustrated in Fig. 6. The numbers within circles are task identifiers. The common assembly tasks are: 2, 3, 5, 6, 7, 9. If common tasks are to be assigned to the same workstation, assignment of task 5 poses the problem: the work content preceding task 5 is larger in the second model, while work content of succeeding tasks is larger in the first model. Assuming that task 5 is assigned to the same station for both models, the balanced solution would be characterized by high idle time. In the first model, idle time is introduced in stations preceding the station to which task 5 is allocated, and in the second model in stations succeeding this station. However, if the two models were balanced separately, task 5 would probably be allocated to a station closer to the start of the line in the first model, and to a later station in the second model.

The TOA environment differs from the traditional assembly line in many respects. The above constraint which impairs the quality of solutions may be relaxed. Since the teams are relatively small and team members are highly skilled, the assignment of common tasks to the same stations is not always necessary. The assignment of common assembly tasks to different stations requires different workers to perform the same tasks, and as a consequence, each worker will have a wider range of tasks to perform. TOA workers, as opposed to traditional assembly line workers, are highly skilled and capable of performing a wider range of assembly tasks. Learning characteristics of TOA workers and traditional assembly line workers are different. In the traditional assembly line learning is mostly motoric while in the TOA environment,
learning is likely to be more cognitive and based on understanding of the assembly process by each team member. The above constraint holds in situations where expensive tools are required for assembly. Therefore, duplication of tools can not always be justified.

The proposed methodology is based on the classification of tasks into two groups. For tasks of the first group the above constraint can be relaxed. For tasks of the second group the assignment constraint cannot be ignored, because of tooling cost considerations. Elements of the first group are balanced for each model separately, therefore the design process becomes more flexible and yields better solutions.

5. Summary and conclusions

A new design approach for team oriented assembly (TOA) is presented in this paper. This is the first time a well structured design approach for hierarchical design of TOA is introduced. TOA system supports the objectives of a modern assembly system such as: system flexibility, product quality and throughput.

The design methodology consists of two stages, macro and micro. In the first stage, system parameters are identified: number of teams, team size, precedence relationship among teams, and work allocation. The proposed methodology is product oriented rather than process oriented. A truncated BOM is used for structuring the assembly system instead of the regular precedence diagram. Performance measures are developed and illustrated.

The micro stage problem is essentially a mixed model assembly line balancing problem with an important constraint relaxed. The difference between the traditional problem and the proposed methodology are discussed, and general recommendations for solving the TOA line balancing are given.

References


