CHAPTER 9

EVOLVING TO INTEGRATE LOGICAL AND PHYSICAL LAYOUT OF ASSEMBLY LINE

Small is beautiful.

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Keywords: assembly line design, equal piles, logical layout, physical layout, workcenters.

1. Introduction

Assembly line design (ALD) is well known as the elaboration of the logical layout (LL) and the physical layout (PL) of the line. The LL consists in the distribution of tasks among stations along the line. The PL decides about the disposition of the stations, conveyor(s), etc. on the shop floor. Little work has been done on modelling the full range of practical considerations of ALD. The goal of most approaches consists in the equalisation of the workload of stations to the cycle time or the minimisation of the number of stations, whereas other factors may also heavily affect the system. Some of these, such as traffic problems, station congestion and transportation network are often considered to be marginal in the design stage of the assembly line.

The concept of concurrent engineering (CE) allows the interaction among the different levels of the design of flexible manufacturing systems. We propose a new method yielding a logical layout taking the topology of the line (facility) into account. This architecture represents a rough idea of the physical layout of the future line. We are not concerned with fine tuning such as the specific position and angular orientation of worker's bench or location of the power outlets. The accent is more put on the balancing of the stations.

A method is introduced to solve the interrelated problems. We present a new algorithm to treat the ALD problem (balance and architecture). The main task of the ALD *integrated method* is to cluster the tasks in two different ways. First, tasks are assigned to workcenters (a set of linked stations): tasks performing alike activities are grouped together, this lead to a number of workcenters (workcenter clustering). Then, for each workcenter tasks are assigned to stations, this leads to a number of stations (station clustering). The main concern of the method is the quality of the resulting line in terms of balancing and its suitability to the material flow requirements of the production system.

Background and motivation of the presented approach is briefly described in section 2. In section 3, the assembly line layout problem is presented. We put the accent on the utility of the 'workcenters *clustering*' phase and we explain the benefits of the proposed architecture. The integrated approach is presented in section 4 where the interactive as well as the optimisation phases are detailed. Before drawing conclusions and guidelines for further works, results of the approach on an industrial case study are presented and discussed.

2. State of the art

Several very complete works were published about facilities planning (Askin, 1993) (Francis, 1996) (Sule, 1994) (Tompkins, 1996), but none seems to bridge the gap between the logical layout and physical line layout. Most of the time flows are analysed, but the planning is done at the department or the factory level, not at line level. Authors also tackled the cell formation problem in various ways (De Lit, 2000) (Kusiak, 1988) (Miltenburg, 1991) but these approaches are more focused on cellular manufacturing (CM) and group technology (GT) and material flows, and are unable to deal with the logical layout.

A global approach was a result of the SCOPES project (Delchambre, 1996). It takes into account the main factors affecting the assembly line performances. The physical layout module which is based on a simulation package is executed after the logical layout. Lucertini et al. (Lucertini, 1998) presented a unified framework for designing a given production plant and its corresponding network of material flow.

Agnetis (Agnetis, 1994) presented an application in which two different layouts are analysed: one consisting of a single (long) assembly line, another consisting of three separate lines, carrying out different segments of the assembly process. The aim is to assign tasks to machines and synchronise the different sub-lines in order to optimise the ratio between productivity and cost. A dynamic programming algorithm was developed, tacking into account these constraints and exploiting the special structure of the problem.

Heragu (Heragu, 1994) provides a thorough survey of published papers on GT and CM. He stated also important design factors that cannot be ignored. Kamrani et al. (Kamrani, 1995) reported the latest developments and addressed the main issues in the design and implementation of cellular manufacturing systems. They reviewed a collection of works of many academic and industrial researchers in the field of CM systems. They described various techniques for the design and modelling of cellular manufacturing systems and reported some techniques to analyse and measure the system performance. They finished by presenting some applications of artificial intelligence and computer tools in CM systems. Kirton (Kirton, 1994) presented the real improvement in competitive advantage and profitability that can be achieved through CM. He started with the story of the evolution of manufacturing and then discussed how manufacturing and assembly systems evolved from simple hunter-gatherer to the CM.

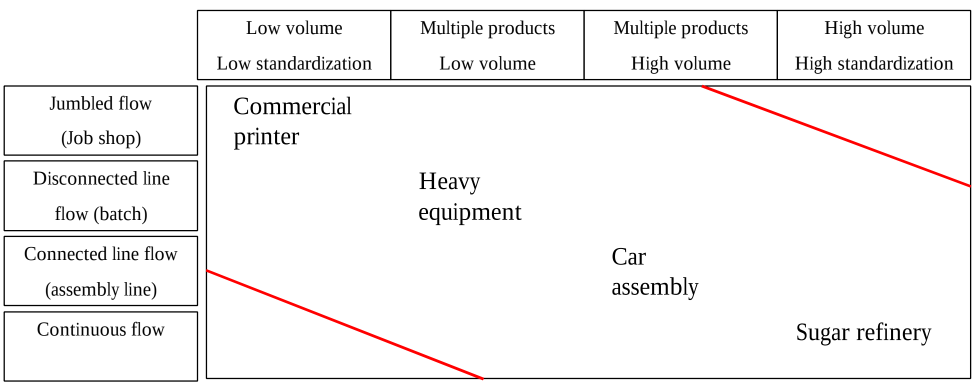


Figure 9.1. Product-process matrix (Hayes, 1979).

Different philosophies of layout are appropriate in different manufacturing environments. Hayes and Wheelwright (Hayes, 1979) consider linking the product and process life cycles using the product-process matrix (Figure 9.1). The matrix is based on four phases of the evolution of the manufacturing process: (1) jumbled flow, (2) disconnected line flow, (3) connected line flow, and (4) continuous flow. The matrix shows that all industries do not necessarily follow the process evolution. Located in the upper left-hand corner of this matrix are companies specialised in *óne of kind* ’jobs with relatively small lots of production. The manufacturing functions in a jumbled flow shop (commercial printer is an example). Farther down the diagonal are firms that require a great deal of flexibility, since they produce a limited line of standardised items. A disconnected line would provide enough flexibility. Manufacturers of heavy equipments fall in this category. The third category down the diagonal includes firms that produce a line of standard products for a large-volume market. Typical examples are producers of home appliances or electronic equipments, and automobile manufacturers. Finally, the lower right-hand portion of the matrix would be appropriate for products involving continuous flow. Chemical processing, oil refining and sugar refining are examples. Such processes are characterised by low unit costs, standardisation of the product, high sales volume, and extreme inflexibility of the production process.

A different approach for designing production facilities would be appropriate in such setting.

Fixed position layouts
Some products are too big to be removed, so that the product remains fixed and the layout is based on the product size and shape. Examples of products requiring fixed position layouts are airplanes, ships and rockets. For such projects, once the basic frame is built, the various required functions will be located in fixed positions around the product.

Product layouts
In product flow layout, machines are organised to conform to the sequence of operations required to produce the product. The product layout is typical of high-volume standardised production. An assembly line (or transfer line) is product layout, because assembly facilities are organised according to the sequence of steps required to produce the item. Product layouts are desirable for flow-type mass production, and provide fastest cycle times.

Process layouts
Process layouts are the most common for small- to medium-volume manufacturers. A process layout groups similar machines having similar functions. A typical process layout would group lathes in one area, drills in one area, and so on. Process layouts are most effective when there is a wide variation in the product mix. Each product has a different routing sequence associated with it. In such an environment it would be difficult to organise the machines to conform with the production flow because flow patterns are highly variable. Process layouts have the advantage of minimising machine idle time.

GT layouts
With increased emphasis on automated factories and flexible manufacturing systems, the GT layouts have received considerable attention in recent years. The GT concept seems best suited for large firms that produce a wide variety of parts in moderate to high volume. A typical firm that would consider this approach might have many different parts, which may be grouped into many parts families. The main difference in comparison with the process layouts architecture is the way the departments are organised. The GT layouts are product family oriented while the process layouts are machines functions oriented.

3. Assembly line design

In order to meet the ever-increasing demand for goods, one of the big innovation in the history of assembly manufacturing was the division of the assembly job. If an assembly task has a long process time or involves too many parts, the work may be broken into a number of smaller tasks. Each task builds a part of the assembly. Factories had been functionally organised–skills and processes were grouped together and managed as a unit. The product or process had to be 'owned' by many different people. The GT created teams that focused on product groups rather than processes–it put all the processes to make a complete component together in one location.

GT is a management philosophy that attempts to group products with similar design and/or manufacturing characteristics. CM can be defined as an application of GT and involves grouping machines or processes on the basis of parts or part families they process. The main difference between a traditional job-shop environment and a CM environment is the grouping and layout of machines. In job-shop environment, machines are typically grouped on the basis of their functional similarities. On the other hand, in CM environments, machines or tasks are grouped into cells so that each cell is dedicated to manufacture a specific part family. Typically, machines in each cell are dissimilar in their functions. The concept can be applied to pure manufacturing plants as well as assembly lines. In this book our emphasis is more on assembly systems.

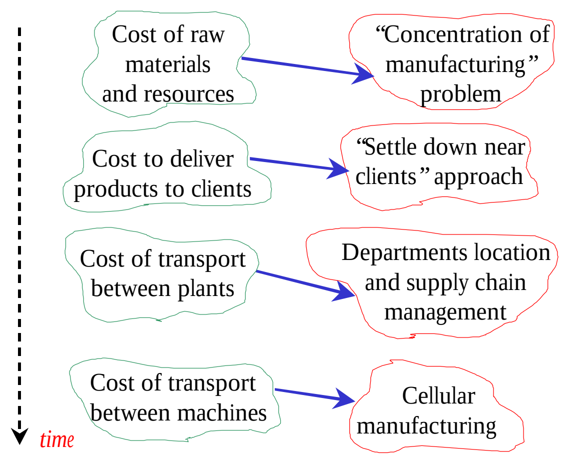


Figure 9.2. Causes and solutions to the evolution of assembly manufacturing.

First factories were rigid and inflexible–it was difficult for them to change production direction (tendency). New ideas emerged based on the theories of scientific management; one of these was GT. The classic idea proposed that machine tools had to be functionally organised in departments, locating all lathes together, all the milling machined together, etc. Such layouts have the advantage that workers and supervisors can specialise in their process. In contrast, they require a large amount of material handling as parts move between departments for various operations. Such technology is not very appropriate to assembly systems.

Instead, GT suggested looking at the components of a product in terms of geometry and grouping the machines together according to component shape. The concepts behind GT were excellent showing the way forward. But on its own, GT was unable to fulfil its promises because it was an island of solutions being applied in a sea of indifference or misunderstanding. Later, CM was able to draw on GT along with other path-finding ideas and help them to realise their full potential. The classical idea '*big is beautiful*' left its place to '*divide to conquer*'.

The central concern of the facility layout is the configuration of manufacturing facilities to facilitate the material flows and the execution of production plans. Today, small focused factories are created as independent operating centres within large facilities. The tendency is due to the application of the theory of management based on the principle that *similar things should be done similarly*.

Manufacturing and assembly has crossed many phases before reaching the current situation. We first observed concentration of manufacturing to tight cost of raw materials and resources. Then, production systems were settled down near cities (customers) to shorten time and costs of transports of goods. Afterwards, came the ere of factories with specialised departments to deal with high costs between plants. Last and perhaps not the last change was the appearance of the GT and the CM concepts is to manage the flow between machines or stations (Figure 9.2).

In plant layout, the location of stations affects the choice of material handling equipment and this choice will also affect the location and layouts of the stations. The determination of the material handling equipments is made by considering what is to be transported, and the point between which the items have to be transported. The stations are determined by considering whether process layout or product layout is to be implemented.

The primary advantage of CM implementation is that a large manufacturing system can be decomposed into smaller subsystems based on similarities in design attributes and manufacturing features of the parts. Thus, the line behaves as if there was a single product type. The decomposition based on similarities of design attributes, manufacturing features, and function leads to improved productivity in various functional areas of an organisation. Design of cellular manufacturing systems (CMS) is a complex exercise with broad implications for an organisation. The main advantages of CMS can be summarised in the following points.

1. The material flow is improved as well as the handling is reduced. Indeed, instead of dividing the facility into process departments it is possible to divide them into product family departments, each department being independently capable of performing almost all the operations required for that product family. Since, the part can be produced entirely in the department, it does not need to travel between totally different departments. This simplifies material flow.
2. The re-design of the assembly line and the pre-production phase is reduced. If a new part must be manufactured, it is placed in a product family that it most *closely resembles* to. Existing process plans and tooling can be slightly modified to suit this part. This reduces the pre-production design phase. This leads to the recovery of existing assembly lines.

3. Because of similarities in the products attributed to each cell, tooling can be standardised. This reduces tooling costs as well as setup times. This can increase the flexibility of the whole assembly system.
4. It increases the throughput, reduces cycle time as well as the work-in-process, and produces a wide variety of other improvements.
5. It enhances the workers' satisfaction since cells increase the amount of information provided to employees. Cells also encourage a culture of teamwork. The cellular configuration requires people to work together to reach their common goals. Cell members must work closely with their internal customers and suppliers to produce products efficiently and effectively.

Advantages of CMS do not mean that they are free of disadvantages. Some are cited below.

1. More equipments are required. Indeed, because each machine group must be self-sufficient, there may be duplication of equipments. This will increase the amount of equipments required for a GT layout over a process layout.
2. The special shape of cells physically separates the people from others in the enterprise. Any physical separation in an enterprise creates an '*us*' and '*them*' mentality among employees. The cell boundaries create a distinction between those in the cell and those in other cells or areas. By the way, this can lead to some bad undesirable behaviours.
3. It can be difficult to determine suitable part families (or tasks to group). Parts may be grouped by size and shape or by manufacturing process requirements. The first approach is easier but not effective for developing layouts.

For assembly operations, a slightly different vocabulary is used; the word cell, for example, has a different meaning from that used in manufacturing workshops. In assembly line, a sub-line (a group of stations) called *workcenter* is the equivalent of a *cell* (cellular manufacturing).

An assembly line may be subdivided into a number of logical and physical components. From an analytical point of view, it is convenient to subdivide a line into a number of components[1], and to deal with each of them separately. In the same time, these components must be designed in the most integrated manner as possible. The limit is to have all these components interacted simultaneously. However, as it is difficult to deal with many difficult tasks at the same time, generally the work is clustered and divided to a number of levels. The question is *how to cluster these tasks?*

Logical layout techniques or line balancing for manual assembly line and resource planning approaches for hybrid assembly line are generally suited to a unique linear assembly line, with possibly parallel stations. The main idea behind our design of assembly line philosophy is that, for complex products, the assembly system must be decomposed into subsystems which are easier to manage than the entire one. The line is decomposed into several linked sub-lines (called workcenters in the remainder

[1] A component can represent a line, a sub-line or a cell.

of this chapter), with their own cycle time, reliability, and station requirements. Each sub-line is attributed to one or many sub-assemblies. The routing of a product from one workcenter to another is fixed, as we work according to a line flow topology. The main topology of the line is not necessarily a linear one. With a classical line balancing techniques, a way to tackle the line balancing problem would be to balance each workcenter separately. But in real conditions, some operations allocated to a given workcenter could be affected to another one, linked to the former.

The design problem of organising an assembly process into workcenters (a set of linked stations) along a production plant is the well known facility layout problem. The position of each workcenter is important, since it determines the costs of transportation and storage. Most research on ALD considers the PL problem outright after the line balancing (LL). By separating the two problems, sub-optimal solutions are often obtained. Better solutions can be found by using the premises of the PL to accomplish the balancing or the resource planning. The obtained clustering can serve as input data of a more detailed PL. The main questions to consider are: *"which tasks should be grouped on the same workcenter ?"*, and *"how can we link the different workcenters to achieve a well-balanced set of stations ?"*

4. Integrated approach

A series of attempts have been made in the field of assembly to give assembly workshops a general structure, identical to that of machining systems. Assembly line still retain a linear structure, principally for reasons related to supply, high robustness, ease of management. The drawbacks may be poor fault tolerance and routing flexibility (Agnetis, 1994).

Because facilities are strategic elements of any enterprise, companies cannot afford to build new structures or revamp old ones without careful planning. Space is one of the most valuable resources. Well-designed and well-planned workplaces make organisations more competitive. Planning and designing high performance work-spaces are key elements in business. The main task of our line layout *integrated method* (Figure 9.3) is to cluster twice the tasks (two levels).

1) Workcenter clustering: Partition a set of tasks performing alike activities together. This leads to a number of workcenters.
2) Station clustering: Assign tasks to stations. This leads to a number of stations in each workcenter.

The problem consists in assigning tasks relative to one (or a set of) sub-assemblies to workcenters. This phase let us construct the different departments. This assignment has to take into account precedence, transportation, and synchronisation of the sub-assemblies in order to find the best value of ratio between clustering and transportation index. The second phase permits to design a workcenter dealing with objectives like workload balancing, cost, reliability, imbalance between variants, etc.

The problem is composed by three inter-dependant sub-problems: workcenter clustering, station clustering and workcenter synchronisation.

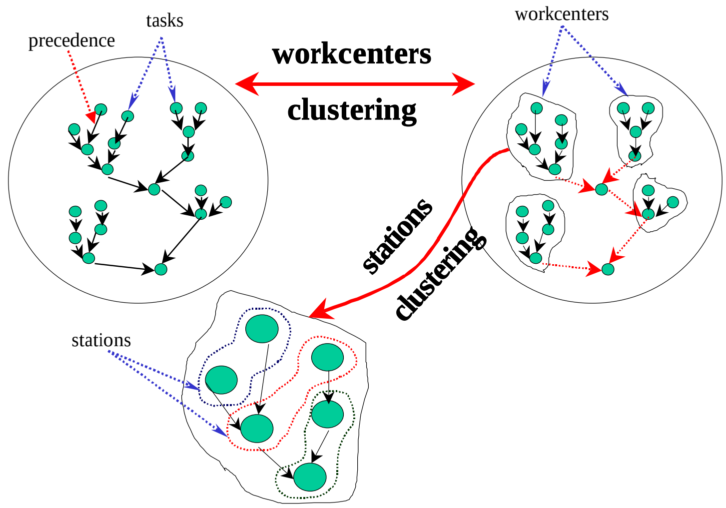


Figure 9.3. Integrated approach of the line layout.

In this book, the accent is put on the design (balancing) of the stations and the *logical placement* of workcenters. The obtained clustering can serve as the input data of a more detailed PL module. Clustering the line in many connected sub-assembly lines strongly facilitates the design or the redesign of an assembly line. Uncoupling the LL problem and the PL one makes the assembly line design less inefficient. So the feedback from the balancing on the facility layout is of a great importance.

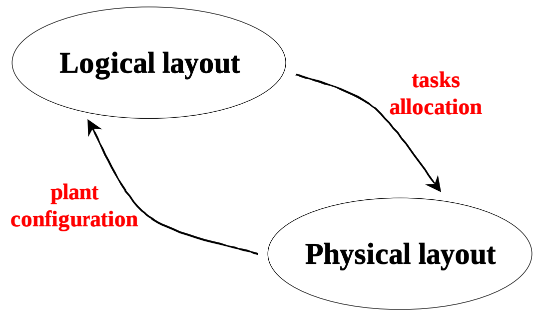


Figure 9.4. Logical and physical layout interaction.

The proposed method is an iterative and interactive procedure whose philosophy is illustrated in Figure 9.4. The results of the balancing module permit to know the distribution of tasks and resources along the assembly line, and the physical layout module thereafter determines the space requirements taking into account congestion and material storage, handling systems and so on. The whole methodology can be described as follows.

1) Set the desired workcenters, and for each of them:

- assign tasks into workcenters, dealing with precedence graph (see workcenter clustering);
- set the desired number of stations;
- set the desired cycle time;

2) Set the desired links between workcenters.
3) Balance the whole plant (set of workcenters).
4) Position workcenters and stations.
5) Evaluate the efficiency of the corresponding plant layout using a simulation package. Check the congestion of the plant, analyse the flow of the products, the material handling problems, storage area requirements, etc.
6) If no satisfying solution is obtained, exchange the tasks (without violating precedence constraints) and change the links between workcenters.

The overall architecture of the logical layout module is illustrated in Figure 9.5.

The main aim is to balance a set of workcenters using the different links between them. The clustering (local optimisation) is then followed by a global design phase. For each workcenter, it permits to assign tasks to the different stations.

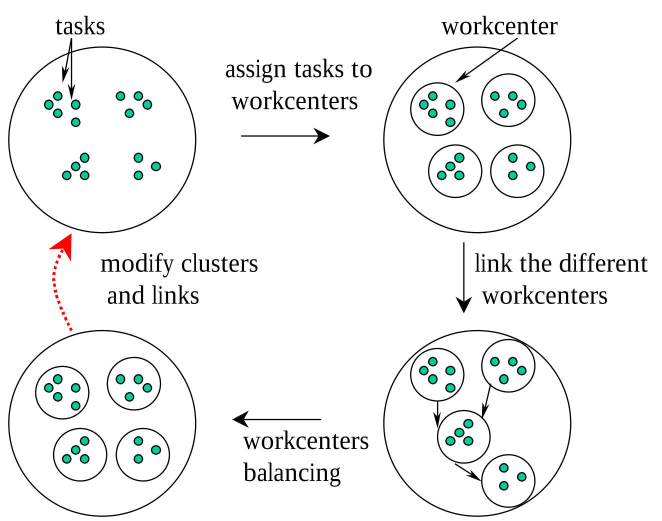


Figure 9.5. Overall architecture of the line layout module.

4.1. Development of the interactive method

Starting from the philosophy of '*divide to conquer*', the CM introduced the grouping of tasks into cells or stations. Processes and people are thereby assigned to cells responsible for manufacturing or assembly of parts or products. The principal goal of the interactive method is to divide the whole manufacturing facility into small manageable groups of workcenters (cells), each cell being dedicated to a specified set of part or sub-assemblies types.

The vast majority of existing layouts are either process or product type. Firms producing a wide variety of parts may choose several layouts for different product line, or may choose some hybrid approaches. Product variation and annual volume are the primary determining factors making the appropriate choice. We believe that the CM concept will play a great role in plant layout and process design in the future.

In the following we will concentrate on the different architectures of assembly line as well as on the flow of materials and products through the assembly facility. Various strategies for organising physical resources are described and some techniques to help designers to interact with the system are presented. Simple indexes to evaluate the performance of these configurations are discussed. The human-computer interactivity can improve efficiency and save considerable effort and resources in facility location and allocation. The main question is how to manage this interaction[2]. In line layout, the problem is how to choose from the available locations those in where to install the facilities and then how to assign tasks to each facility to minimise the overall cost of the system.

4.2.1. Workcenter clustering

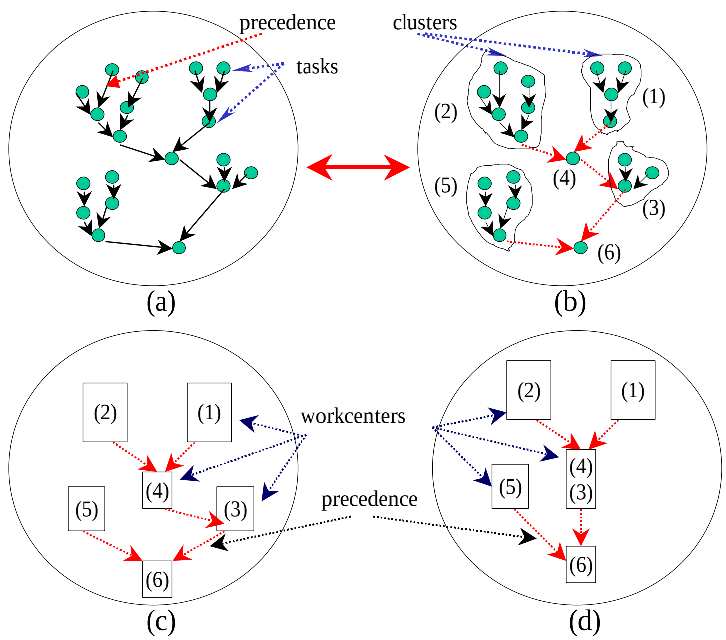


Figure 9.6. Workcenter clustering phase.

[2] It makes no sense to ask the computer to find a solution for something which is obvious–for example the tasks that the human can do better. It is also a wasting time to solve problems for which the computer needs a lot of data to find simple solutions while the human can find them without any difficulty.

The aim of this phase is to cluster tasks among workcenters. In Figure 9.6 the left top (a) represents the precedence graph of product. The right top of the same figure (b) represents one possible clustering, and at the bottom (c) and (d) represent two possible configurations (sets of workcenters) of the proposed clustering. In (c) each cluster is assigned to its own workcenter, while in (d) the clusters (3) and (4) are assigned to one workcenter. The only hard constraint that must be satisfied is the precedence constraints between clusters. The precedence graph between clusters decides on the position of workcenters, in contrast that one between workcenters defines the flow of products between them. As we can observe on (c) and (d), the precedence between the different clusters is preserved. The criteria and constraints influence the choice of a given graph clustering rather than another are described in the following.

- One of the first information provided to designers is the desired throughput of the given product, this leads to the desired *cycle time* of the line. The desired cycle time can help to estimate the *number of workcenters* needed to assemble the product.
- Generally, designers never start from scratch to design an assembly line. One of the most important constraint is the space of the plant and the space of each sub-plant, each workcenter, and so on. Thus, the *number of stations* of each workcenter is more-or-less known in advance.
- Since the line must operate according to a line flow topology, only clusters satisfying the *precedence constraints* between tasks are valid.
- When analysing the precedence graph of a given cluster, one can have an idea about the production stage of the given product. Thus, designers have an idea on the *stability* states of a given product (or sub-assembly). This information let us to decide if the product at a given stage can or not be transferred from one workcenter to another. It is possible that the product at the end of cluster (2) in Figure 9.6 is unstable and this clustering is less acceptable in comparison with the cluster composed of clusters (2) and (4).
- The *work level* as well as the *work position* of tasks–in the case of bulky products–can help to decide about the way to cluster tasks.
- Each time we have a well defined *sub-assembly*, one should dedicate it a cluster.
- Given a set of tasks executed on all the variants of a given product family, if these tasks have *similar features*, they may belong to the same cluster.
- Generally, the higher the number of variants of a given family, the more the imbalance between the variants is high and the more one have to make less clusters. Making a high number of clusters can lead to high imbalance between variants along the assembly line.
- Depending on the *type of production* (batch[3] or mixed-production[4]), the clustering may not be the same. Indeed, the aim is to equalise the workload of stations in the case of batch production, while in the case of mixed production the aim is to balance the workload on average. The type of production may also change the clustering, since the transfer system may be affected by the choice.

[3] In batch production a given amount of products of the same variant are produced over a certain period.

[4] A mixed-production assembly line is a line capable of producing simultaneously and continuously a variety of different product models (called variants).

On the other hand the main parameters that influence the workcenter clustering can be summarised as follows:

- The importance of human is often disregarded while evaluating the AL performance, factors such as job motivation and training are critical to product quality and line efficiency. Operations complexity and reliability must be taken into account in design and operation of AL. In order to deal with human behaviour a close interaction between designers and workers can define useful clusters satisfying workers desires and enhancing job quality.
- One of the basic information to the clustering phase is how far geographically the different workcenters are. Indeed, the transfer system depends on the *distance* between workcenters.
- Components *storage* space is one of the hard constraints in AL designs. Until now little importance has been given to this problem. Since each assembly task is linked to a given component, it is quite easier to detect if the storage space needed for a given set of tasks exceeds the storage space of a given workcenter.
- The *feeding* system of the different components can help to decide about the grouping or not of a set of tasks. In the case of the '*kiting*' philosophy the feeding has only minor influence on the choice of the clustering.
- The plant layout, its obstacles (walls, paths), the specific stations (quality control cells, and painting stations, etc.) may introduce constraints on the position of workcenters and their links.
- The number of *operators* permit to define the number of workcenters.
- The *transfer systems* between workcenters and their cost and complexity are an interesting factors. Indeed, it makes no sense to introduce a transfer system between two workcenters, each one containing only one task. Techniques like 'cell formation' as well as flow matrix can help to decide about the acceptance or not of a proposed clustering.

It is important to note that the results of this phase constitute a *local* optimisation of the line layout problem. Indeed, this clustering permits us to narrow the search space, whereas the results of the logical layout module constitute a *global* optimisation. Of course, the main goal is the global line layout design.

4.2.2. Kinds of workcenter links

The routing of a product from one workcenter to another is fixed, as we work according to a line flow topology. But the main topology of the line is not necessarily a linear one. Some workcenters may serve to assemble a subassembly which is injected as a whole in the main line. Some stations, like packaging may be used for several products in the same facility, and so are at the confluence of two or more assembly line. Different lines or workcenters are thus linked, yielding several line *topologies*.

Figure 9.7 illustrates our words. Four workcenters are linked to a main line according to a 'fishbone' topology, and the main line separates into two other ones at its end.

The different links–if they exist–represent just a *logical* link between workcenters, as example in (Figure 9.7), the workcenter (4) is linked to the station (5) of the main workcenter. This means that the transfer system have to put the product leaving workcenter (4) on station (5) of the main workcenter.

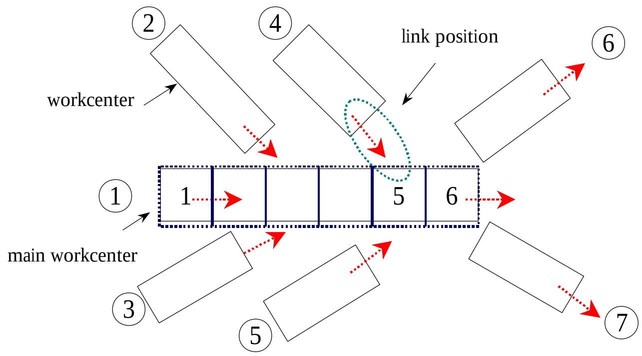


Figure 9.7. Example of plant topology.

There is two general kinds of links, namely links with operations exchange and links without operations exchange. The possible links between workcenters are described in the following.

4.2.2.1. Link without operation exchange

A simple link is when two workcenters are linked logically *without any exchange* of tasks. Such links only help to decide about the flow among workcenters. There are three possible configurations (Figure 9.8). The arrows represent just the flow of the product inside the workcenter.

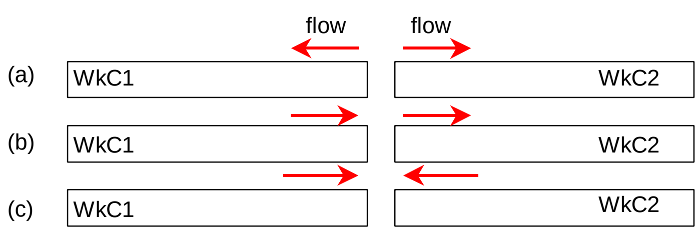


Figure 9.8. Possible links between workcenters.

(a) Physically the two workcenters may be put in parallel, this means that the two sub-assemblies start a the first station of each workcenter, nothing else.
(b) Means that the last station of workcenter WkC1 is linked to the first station of workcenter WkC2. Once WkC1 finishes its work on the product, it transfers it to WkC2.

(c) Means that the last station of workcenter WkC1 is linked to the last station of workcenter WkC2. In this case there are two possibilities.

(1) WkC1 finishes its work on the product and transfers it to WkC2, or once WkC2 finishes its work on the product and transfers it to WkC1,
(2) Suppose the existence of another workcenter WkC3 connecting the two workcenters. Thus, the sub-assemblies assembled on workcenters WkC1 and WkC2 are transferred into WkC3. The two sub-assemblies may be then assembled together on WkC3.

4.2.2.2. Sharing Station

The second kind of links corresponds to a set of workcenters *sharing* physically one station (see Figure 9.9). The product passing through the different workcenters has to visit the shared station. This kind of station can be found in the following situations.

a) In the contact point of many parallel workcenters. Suppose there exist a set of tasks done by a robot. Knowing that the cost of a robot is generally high, it is more beneficial to share it to execute the same task relative to the different workcenter. For two 'paced' workcenters, the process time of the shared station may not exceed the half of the cycle time.
b) In the contact point of workcenters relative to different variants–the contact point belongs to a main workcenter. Each workcenter assembles a sub-assembly relative to a variant, and the main workcenter integrates the different sub-assemblies to the main product.

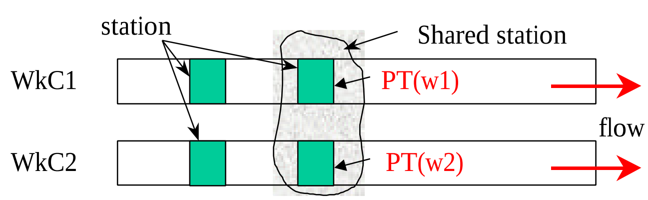


Figure 9.9. Workcenters sharing station.

The hard condition to share an operator between many stations is that:

$$\sum_{w=1..NbLinks} PT(w) <= Minimum(CycleTime) \qquad (1)$$

where:

PT(w) : the process time of the shared station on the product passing through workcenter w,

NbLinks : the number of workcenters sharing this station,
Minimum(CycleTime) : the cycle time corresponding to the fastest workcenter.

Each cycle time the shared station has to work on the products relative to the different workcenters. This means that on each period equal to the cycle time this station has to do its job on each of the *NbLinks* products. Suppose that the process time of the given station relative to each workcenter is equal to the minimum cycle time, then the process time of the station must be less than or equal to the corresponding cycle time. By the way, the *sum* of the process time corresponding to the different workcenters must be less or equal the minimum cycle time. The *upper bound* is then *Minimum(CycleTime)*. Thus, the theoretical maximum process time of the shared station must verify the inequality (1). This upper bound is relative to the synchronised model–the station begins always with the product passing through the fast workcenter (corresponding to the minimum cycle time). Many other combinations (synchronisation) are possible, especially in the case of multi-product assembly line. A deeper investigation may be done to explore all these possibilities. The flow direction corresponding to the different workcenters can be the same as well as in the opposite direction–this last correspond to the U-shaped assembly line (Scholl, 1999).

4.2.2.3. Link with operator move

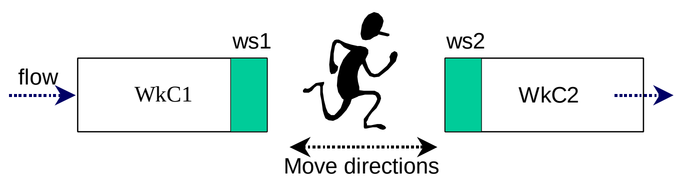


Figure 9.10. Workcenter link with operator move.

The third kind of link corresponds to the case where two physical stations of two different workcenters belong to the same logical station (Figure 9.10). Logically, there is only one station but physically one part of the job is done on WkC1 and the rest of the job is done on WkC2. One operator (machine, or robot) is used to work on station ws1 and to transport the product from WkC1 to WkC2 (station ws2), this later continues assembling the product. This can be the case if a heavy equipment Eqp1 is installed on ws1 and another Eqp2 is installed on ws2, and the product has to go successively from WkC1 to WkC2. The main condition to do such allotment is that the process time on the two stations must verify the following inequality:

$$PT(ws1) + PT(ws2) + 2 * Mvt < Minimum(CycleTime) \qquad (2)$$

where:

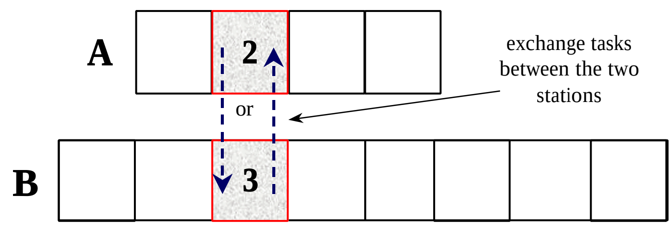
PT(w) : the process time of the station w,
Mvt : the duration of the movement between the two workcenters,

Minimum(CycleTime) : the cycle time corresponding to the fast workcenter.

Note, that the same product passes through the two workcenters–the operator (or robot) transfers the product from the first workcenter to the second. Thus, the flow of the two workcenters must be the same, otherwise there is no need for such configuration.

4.2.2.4. Link with operations exchange

Finally, the most interesting kind of links between workcenters, is that one where tasks are exchanged between workcenters (on operator by each workcenter). This exchange can help to balance the workload of two adjacent workcenters if the *surplus of process time* on one station is transferred to its neighbour. Note that the exchange of tasks is done in only one direction and not in both. The surplus of process time on the *over-loaded* workcenter is transferred into the other. Otherwise, the product has to be transferred two times between the two workcenters–remains to find its usefulness. Figure 9.11 represents two linked workcenters. They are able to exchange tasks between the link stations which are the *second* station of workcenter *A* and *third* station of workcenter *B.*



(LWS (2, A), LWS (3, B))

Figure 9.11. Workcenter links with tasks exchange.

Note that the links are not mandatory; a workcenter may be isolated from the remainder of the line.

4.2. Global search phase

The input data of this module is illustrated on Figure 9.12. The workcenter data helps to balance locally a given workcenter (using only the tasks belonging to this workcenter). The link data, if it exists, globally balances the whole plant.
The balancing of the line is done thanks to the EPAL heuristic which was introduced in Chapter 6. In order to take advantage of the links between stations, another heuristic has been developed. The 'link node' is the set of stations by which a set of workcenters are linked. For instance suppose that the link (end(WkC1), end(WkC2)) has been set, which means that the end of WkC1 is linked to the end of WkC2. The link node will be the last station of each workcenter.

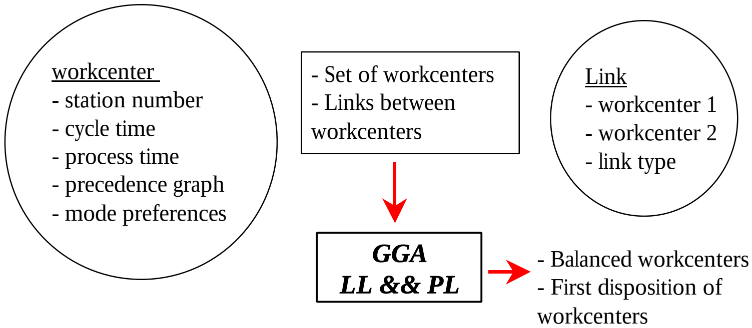


Figure 9.12. Input data of the problem.

The two stations in the link node are chosen (Figure 9.13) and all possible exchanges between them (which do not violate precedence constraints and cycle time) are executed. These kind of moves permit to balance two adjacent workcenters by exchanging tasks between them.

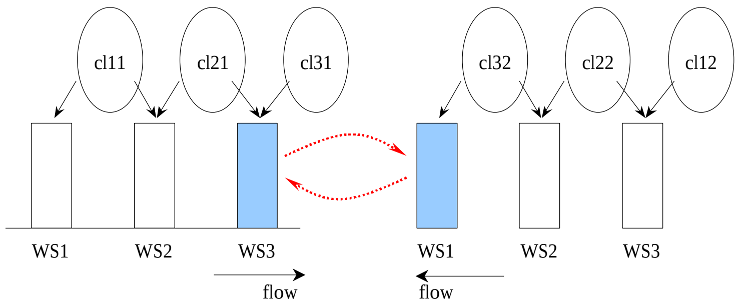


Figure 9.13. Linked wheels heuristic.

The objective is to equalise station durations, under a fixed number of station constraints. We settled for the following cost function:

$$\text{minimise } f_{EP} = \sum_{j=1..W} \left(\sum_{i=1..N_j} (fill_i - cycletime_j)^2 \right)$$

In other words, for each workcenter it minimises the square of the difference between the workload of stations and the desired cycle time.

where W is the number of workcenters, N_j the number of stations of each workcenter, $fill_i$ the sum of working times on station i, and $cycletime_j$ the ideal cycle time of workcenter j, defined as follows:

$$cycletime_j = \frac{\sum_{j=1..nbop_j} time_i}{N_j}$$

The cycle time of each workcenter is the sum of the process time of its tasks divided by the number of stations.

5. Application

The case study is adapted from a problem proposed in the line balancing benchmark suite of (Scholl, 1999). The benchmark considers 29 tasks with precedence constraints and operating times illustrated at Figure 9.14. Table 9.1 summarises the process time and the precedence constraints of each operation as well as their preferable workcenter. We decide to create two workcenters, with the link (end(WkC_A), begin(WkC_B)).

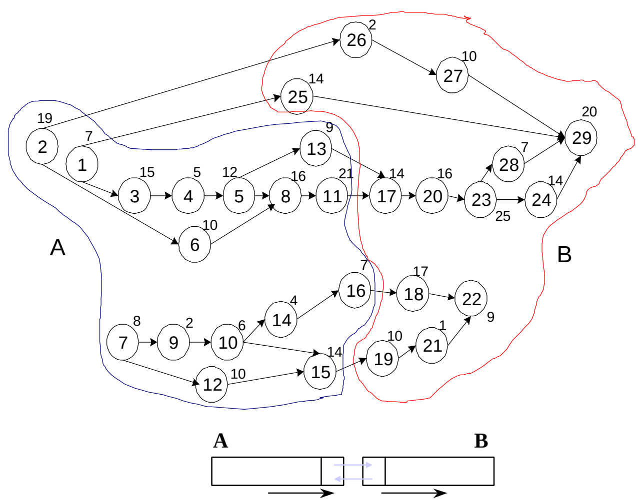


Figure 9.14. Precedence graph of the problem.

Op	WkC	Duration	Preds	Op	WkC	Duration	Preds
1	A	7		**16**	A	7	8, 14
2	A	19		**17**	B	14	11, 13
3	A	15	1	**18**	B	17	16
4	A	5	3	**19**	B	10	15
5	A	12	4	**20**	B	16	17
6	A	10	2	**21**	B	1	19
7	A	8		**22**	B	9	18, 21
8	A	16	5, 6	**23**	B	25	20, 22
9	A	2	7	**24**	B	14	23
10	A	6	9	**25**	B	14	1, 7
11	A	21	8	**26**	B	2	2
12	A	10	7	**27**	B	10	26
13	A	9	5	**28**	B	7	23
14	A	4	10	**29**	B	20	24, 25, 27, 28
15	A	14	10, 12				

Table 9.1. Workcenter, duration and precedence constraints of each task.

We first balance the two workcenters without using any link. Table 9.2 presents a set of solutions for a given number of stations without cycle time restriction, according to an equal piles strategy. NbS_X denotes the desired number of stations, while WkC_X represents the process time of stations for workcenter X. Finally, Link represents the station by which the two workcenters are connected.

By adding the link between the two workcenters, the whole line may be well balanced. Table 9.3 shows the composition of the different stations in the case the two workcenters are connected (at the left side) and not connected (at the right side). Note, that the operation exchange between workcenters is only allowed at the connection station node. Operations from workcenter A mixed with some of workcenter B were written in *bold font* in the tables.

(NbS_A, NbS_B)	Link	WkC_A	WkC_B
(3, 3)		61, 60, 58	49, 48, 48
(3, 3)	(3, 1)	56, 54, 52	54, 55, 53
(4, 3)		39, 46, 45, 49	49, 48, 48
(4, 3)	(4, 1)	47, 46, 47, 42	46, 48, 48
(4, 4)		43, 47, 45, 44	27, 38, 39, 41
(4, 4)	(4, 1)	41, 43, 41, 43	38, 38, 39, 41
(5, 3)		35, 37, 36, 37, 34	49, 48, 48
(5, 3)	(5, 1)	38, 44, 42, 41, 37	40, 41, 41
(5, 4)		35, 37, 36, 37, 34	27, 38, 39, 41
(5, 4)	(5, 1)	37, 35, 36, 36, 31	33, 36, 39, 41
(6, 3)		30, 34, 30, 30, 30, 25	49, 48, 48
(6, 3)	(6, 1)	35, 37, 36, 37, 34, 37	28, 39, 41

Table 9.2. Results of the algorithm, with and without link between workcenters.

Table 9.2 shows that using the link between the two workcenters improve the balancing. Indeed, the two workcenters are linked by an 'operations exchange link' (see section 4.2.2.4.). Table 9.3 presents the results corresponding to the case the desired number of stations of WkC_A and WkC_B are equal to 3. If the two workcenters are disconnected the cycle time of each one is equal to the process time of its corresponding tasks divided by its desired number of stations. Thus, is set to 60 units for WkC_A and to 49 units for WkC_B. In contrast, if they are connected the cycle time is then set to the process time of all the tasks divided by its sum of the desired number of stations, is set in this case to 54 units.

WkC	PT	Ops (without link)	PT	Ops (with link)
A	61	0, 2, 6, 8, 1, 5	56	0, 6, 1, 11, 5, 8
A	60	9, 11, 13, 3, 14, 4, 12	54	9, 2, 3, 4, 7
A	58	7, 10, 16, 15	52	13, 15, 14, **17**, **18**
B	49	17, 20, 21, 18, 25, 26	54	**12**, **10**, 20, 21, **16**
B	48	19, 22, 27	55	22, 19, 23
B	48	23, 24, 28	53	25, 24, 28, 26, 27

Table 9.3. Process time and list of tasks of each station with (NbS_A=3, NbS_B=3).

Table 9.4 shows that the balancing obtained using the link between the two workcenters (connected by the fourth station of WkC_A and the first station of WkC_B) is better than the first one. The results show that the links allow to smooth the workload of the different stations along the two workcenters. Indeed, the maximum difference is not more than 6 (48-42) in the second case (with link) while it is equal to 10 (49-39) in the first case (without link).

WkC	PT	Ops (without link)	PT	Ops (with link)
A	39	0,2,3,4	47	0, 2, 3, 6, 4
A	46	1,12,6,5	46	8, 9, 11, 12, 1
A	45	7,8,11,9,13,15	47	5, 7, 10
A	49	10,16,14	42	13, 16, 15, **17**
B	49	17,18,20,21,25,26	46	18, 20, 21, 25, 26, **14**
B	48	19,22,27	48	19, 22, 27
B	48	23,24,28	48	23, 24, 28

Table 9.4. Process time and list of tasks of each station with (NbS_A=4, NbS_B=3).

Appendix 5 presents solutions obtained in the case of (NbS_A, NbS_B) ={(4, 4), (5, 3), (5, 4), (6, 3)}.

6. Summary and further works

The balancing of assembly line is most of the time uncoupled from the facility layout problem. This yields sub-optimal line layouts. We proposed in this chapter an iterative procedure partially treating the two problems simultaneously. We first split tasks between the desired workcenters. We then balance the given workcenters. The designer will select a best architecture having the well balanced workcenters, and the manageable transportation network needed to satisfy the material flow requirements.

A new heuristic has been developed to tackle the problem: the 'linked wheels' heuristic. Further research would be to develop an integrated method to tackle the physical layout of assembly line problem. The influence of the workcenters clustering method will be analysed and tested on industrial cases. The next step is to provide a designer with some tools to manage the workcenter clustering.

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