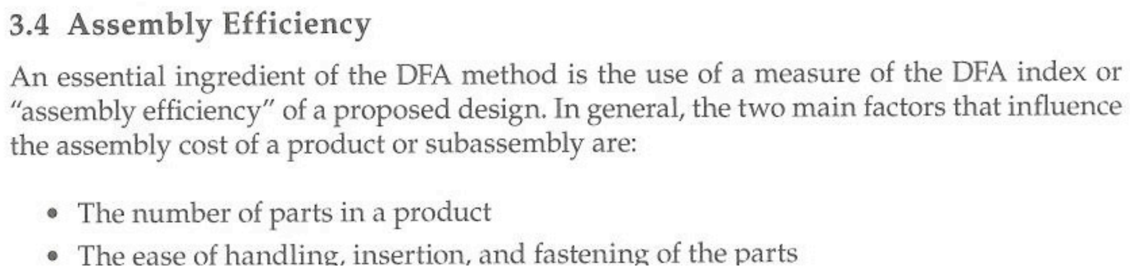
Assembly technology course.

Design for Assembly

Handouts

References:

- Boothroyd, G., P. Dewhurst, et al. (2010). Product Design for Manufacture and Assembly, CRC. [HENCE SIMPLY "**Boothroyd**"]
- Eskilander, S. (2001). Design For Automatic Assembly--A Method for Product Design: DFA2. [HENCE SIMPLY "**Eskilander**"]



3.4 Assembly Efficiency

An essential ingredient of the DFA method is the use of a measure of the DFA index or "assembly efficiency" of a proposed design. In general, the two main factors that influence the assembly cost of a product or subassembly are:

- The number of parts in a product
- The ease of handling, insertion, and fastening of the parts

The DFA index is a figure obtained by dividing the theoretical minimum assembly time by the actual assembly time. The equation for calculating the DFA index E_{ma} is

$$E_{\mathrm{ma}} = \frac{N_{\mathrm{min}} t_{\mathrm{a}}}{t_{\mathrm{ma}}} \tag{3.1}$$

where N_{min} is the theoretical minimum number of parts, t_{a} is the basic assembly time for one part, and t_{ma} is the estimated time to complete the assembly of the product. The basic assembly time is the average time for a part that presents no handling, insertion, or fastening difficulties (about 3 s).

The figure for the theoretical minimum number of parts represents an ideal situation where separate parts are combined into a single part unless, as each part is added to the assembly, one of the following criteria is met:

1. During the normal operating mode of the product, the part moves relative to all other parts already assembled. (Small motions do not qualify when they can be obtained through the use of elastic hinges.)
2. The part must be of a different material, or be isolated from all other parts assembled (for insulation, electrical isolation, vibration damping, etc.).
3. The part must be separate from all other assembled parts; otherwise, the assembly of parts meeting one of the preceding criteria would be prevented.

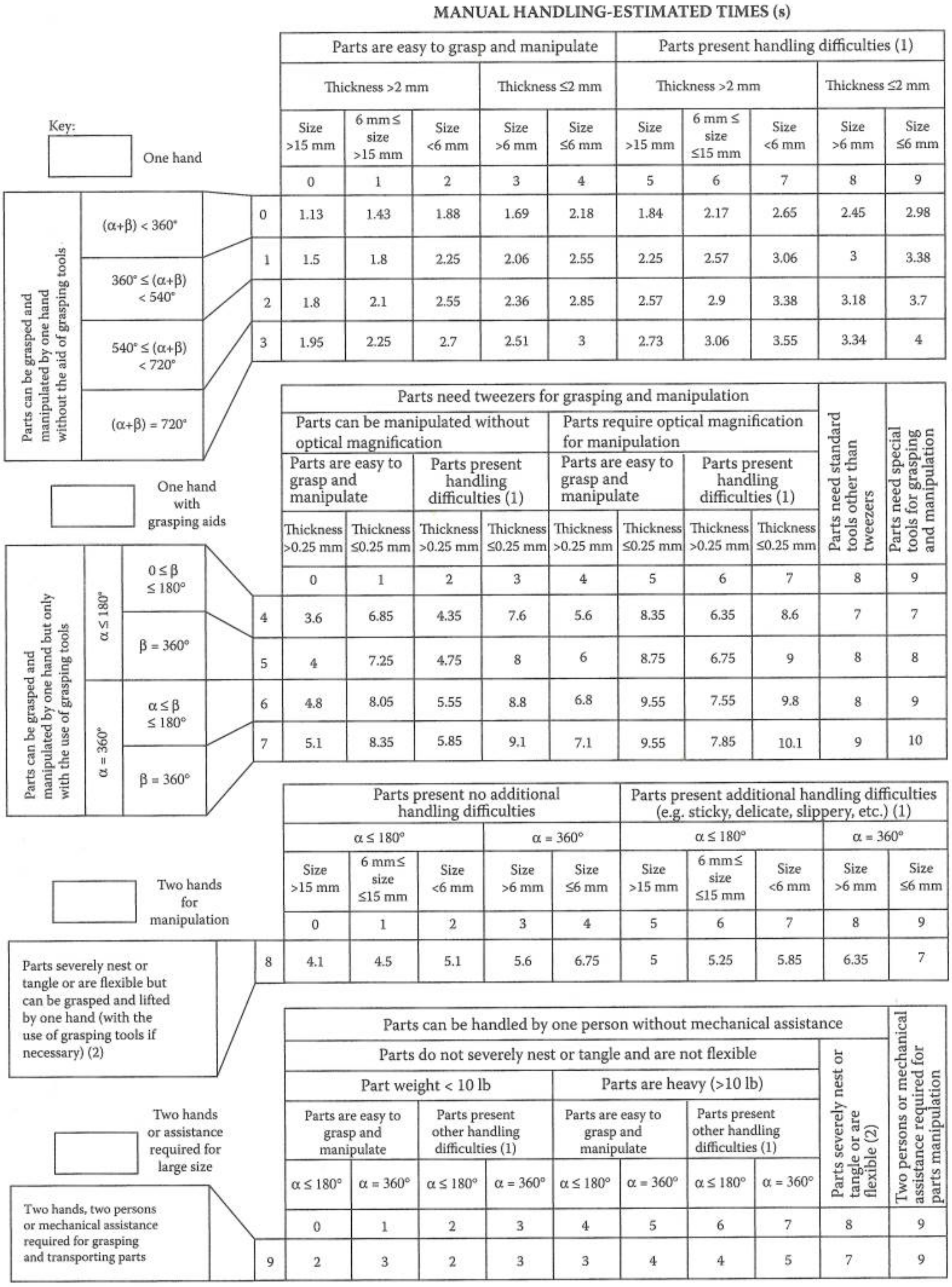
It should be pointed out that these criteria are to be applied without taking into account the general design or service requirements. For example, separate fasteners do not generally meet any of the preceding criteria and should always be considered for elimination. To be more specific, the designer considering the design of an automobile engine may feel that the bolts holding the cylinder head onto the engine block are necessary separate parts. However, they could be eliminated by combining the cylinder head with the block—an approach that has proved practical in certain circumstances.

If applied properly, these criteria require the designer to consider means whereby the product can be simplified, and it is through this process that enormous improvements in assemblability and manufacturing costs are often achieved. However, it is also necessary to be able to quantify the effects of changes in design schemes. For this purpose, the DFA method incorporates a system for estimating the assembly cost which, together with estimates of parts cost, gives the designer the information needed to take appropriate trade-off decisions.

3.5 Classification Systems

The classification system for assembly processes is a systematic arrangement of part features that affect the acquisition, movement, orientation, insertion, and fastening of the part together with some operations that are not associated with specific parts such as turning the assembly over.

The complete classification system, its associated definitions, and the corresponding time standards is presented in tables in Figures 3.15 and 3.16. It can be seen that the classification



MANUAL HANDLING-ESTIMATED TIMES (s)

Key:

One hand

			Parts are easy to grasp and manipulate					Parts present handling difficulties (1)				
			Thickness >2 mm			Thickness ≤2 mm		Thickness >2 mm			Thickness ≤2 mm	
			Size >15 mm	6 mm ≤ size >15 mm	Size <6 mm	Size >6 mm	Size ≤6 mm	Size >15 mm	6 mm ≤ size ≤15 mm	Size <6 mm	Size >6 mm	Size ≤6 mm
			0	1	2	3	4	5	6	7	8	9
Parts can be grasped and manipulated by one hand without the aid of grasping tools	$(\alpha+\beta) < 360°$	0	1.13	1.43	1.88	1.69	2.18	1.84	2.17	2.65	2.45	2.98
	$360° \le (\alpha+\beta) < 540°$	1	1.5	1.8	2.25	2.06	2.55	2.25	2.57	3.06	3	3.38
	$540° \le (\alpha+\beta) < 720°$	2	1.8	2.1	2.55	2.36	2.85	2.57	2.9	3.38	3.18	3.7
	$(\alpha+\beta) = 720°$	3	1.95	2.25	2.7	2.51	3	2.73	3.06	3.55	3.34	4

One hand with grasping aids

				Parts need tweezers for grasping and manipulation								Parts need standard tools other than tweezers	Parts need special tools for grasping and manipulation
				Parts can be manipulated without optical magnification				Parts require optical magnification for manipulation					
				Parts are easy to grasp and manipulate		Parts present handling difficulties (1)		Parts are easy to grasp and manipulate		Parts present handling difficulties (1)			
				Thickness >0.25 mm	Thickness ≤0.25 mm	Thickness >0.25 mm	Thickness ≤0.25 mm	Thickness >0.25 mm	Thickness ≤0.25 mm	Thickness >0.25 mm	Thickness ≤0.25 mm		
				0	1	2	3	4	5	6	7	8	9
Parts can be grasped and manipulated by one hand but only with the use of grasping tools	$\alpha \le 180°$	$0 \le \beta \le 180°$	4	3.6	6.85	4.35	7.6	5.6	8.35	6.35	8.6	7	7
		$\beta = 360°$	5	4	7.25	4.75	8	6	8.75	6.75	9	8	8
	$\alpha = 360°$	$\alpha \le \beta \le 180°$	6	4.8	8.05	5.55	8.8	6.8	9.55	7.55	9.8	8	9
		$\beta = 360°$	7	5.1	8.35	5.85	9.1	7.1	9.55	7.85	10.1	9	10

Two hands for manipulation

		Parts present no additional handling difficulties					Parts present additional handling difficulties (e.g. sticky, delicate, slippery, etc.) (1)				
		$\alpha \le 180°$			$\alpha = 360°$		$\alpha \le 180°$			$\alpha = 360°$	
		Size >15 mm	6 mm ≤ size ≤15 mm	Size <6 mm	Size >6 mm	Size ≤6 mm	Size >15 mm	6 mm ≤ size ≤15 mm	Size <6 mm	Size >6 mm	Size ≤6 mm
		0	1	2	3	4	5	6	7	8	9
Parts severely nest or tangle or are flexible but can be grasped and lifted by one hand (with the use of grasping tools if necessary) (2)	8	4.1	4.5	5.1	5.6	6.75	5	5.25	5.85	6.35	7

Two hands or assistance required for large size

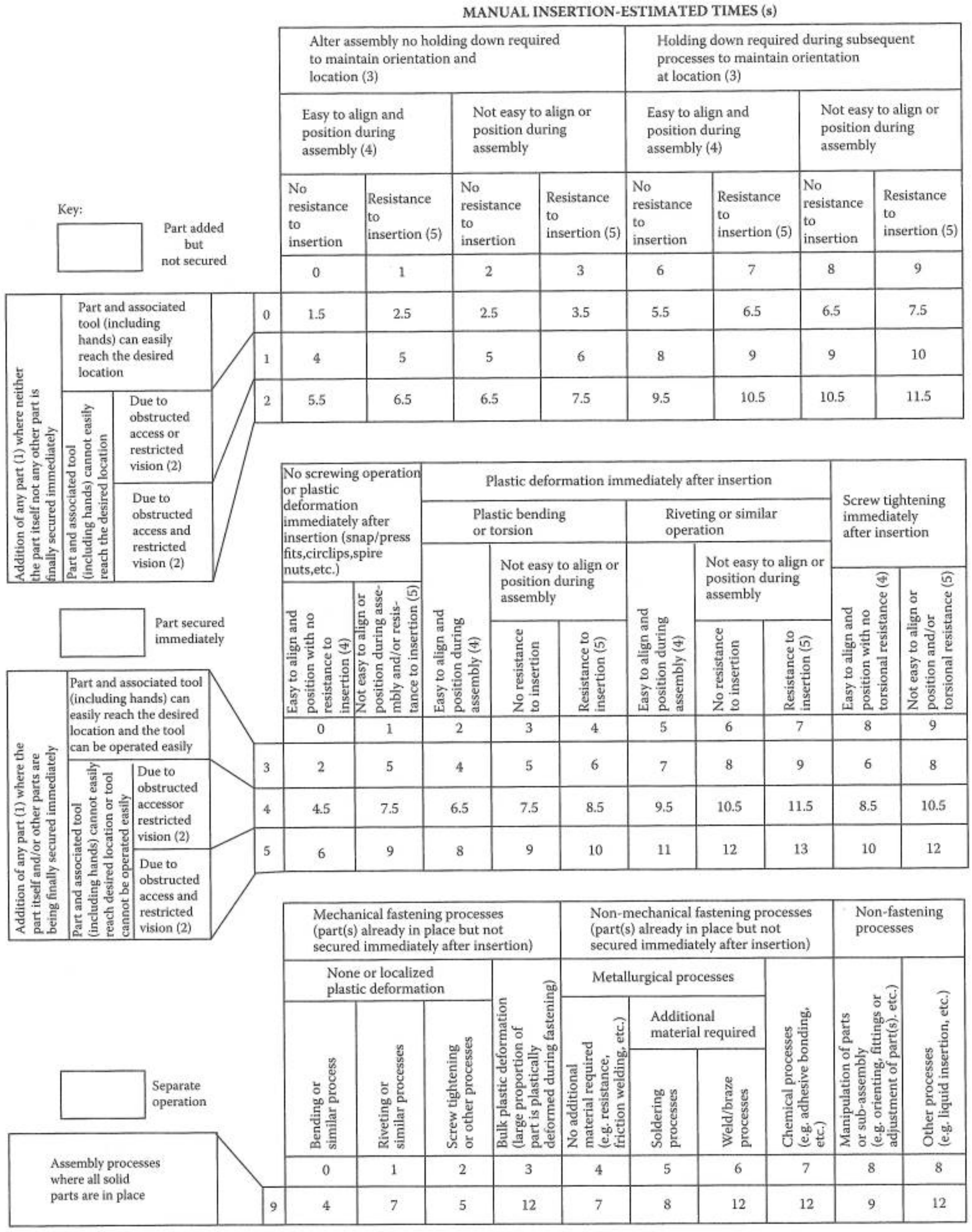
		Parts can be handled by one person without mechanical assistance									Two persons or mechanical assistance required for parts manipulation
		Parts do not severely nest or tangle and are not flexible								Parts severely nest or tangle or are flexible (2)	
		Part weight < 10 lb				Parts are heavy (>10 lb)					
		Parts are easy to grasp and manipulate		Parts present other handling difficulties (1)		Parts are easy to grasp and manipulate		Parts present other handling difficulties (1)			
		$\alpha \le 180°$	$\alpha = 360°$	$\alpha \le 180°$	$\alpha = 360°$	$\alpha \le 180°$	$\alpha = 360°$	$\alpha \le 180°$	$\alpha = 360°$		
		0	1	2	3	4	5	6	7	8	9
Two hands, two persons or mechanical assistance required for grasping and transporting parts	9	2	3	2	3	3	4	4	5	7	9

Notes:

1. Parts can present handling difficulties if they nest or tangle, sick together because of magnetic force or grease coating, and so on, are slippery, or require careful handling. Parts that nest or tangle are those that interlock when in bulk but can be separated by one simple manipulation of a single part; for example, taper cups, closed-end helical springs, circlips, and so on. Parts that are slippery are those that easily slip from fingers or standard grasping tool because of their shape and/or surface condition. Parts that require careful handling are those that are fragile or delicate, have sharp corners or edges, or present other hazards to the operator.
2. Parts that nest or tangle severely are those parts that interlock when in bulk and both hands are needed to apply a separation force or achieve specific orientation of inter-locking parts to achieve separation. Flexible parts are those that substantially deform during manipulation and necessitate the use of two hands. Examples of such parts are large paper or felt gaskets, rubber bands or belts, and so on.

FIGURE 3.15

Original classification system for part features affecting manual handling time. (Copyright 1999 Boothroyd Dewhurst, Inc. With permission.)



MANUAL INSERTION-ESTIMATED TIMES (s)

Key:

Part added but not secured

			Alter assembly no holding down required to maintain orientation and location (3)				Holding down required during subsequent processes to maintain orientation at location (3)			
			Easy to align and position during assembly (4)		Not easy to align or position during assembly		Easy to align and position during assembly (4)		Not easy to align or position during assembly	
			No resistance to insertion	Resistance to insertion (5)	No resistance to insertion	Resistance to insertion (5)	No resistance to insertion	Resistance to insertion (5)	No resistance to insertion	Resistance to insertion (5)
			0	1	2	3	6	7	8	9
Addition of any part (1) where neither the part itself not any other part is finally secured immediately	Part and associated tool (including hands) can easily reach the desired location	0	1.5	2.5	2.5	3.5	5.5	6.5	6.5	7.5
	Part and associated tool (including hands) cannot easily reach the desired location: Due to obstructed access or restricted vision (2)	1	4	5	5	6	8	9	9	10
	Part and associated tool (including hands) cannot easily reach the desired location: Due to obstructed access and restricted vision (2)	2	5.5	6.5	6.5	7.5	9.5	10.5	10.5	11.5

Part secured immediately

			No screwing operation or plastic deformation immediately after insertion (snap/press fits,circlips,spire nuts,etc.)		Plastic deformation immediately after insertion						Screw tightening immediately after insertion	
					Plastic bending or torsion			Riveting or similar operation				
						Not easy to align or position during assembly			Not easy to align or position during assembly			
			Easy to align and position with no resistance to insertion (4)	Not easy to align or position during assembly and/or resistance to insertion (5)	Easy to align and position during assembly (4)	No resistance to insertion	Resistance to insertion (5)	Easy to align and position during assembly (4)	No resistance to insertion	Resistance to insertion (5)	Easy to align and position with no torsional resistance (4)	Not easy to align or position and/or torsional resistance (5)
			0	1	2	3	4	5	6	7	8	9
Addition of any part (1) where the part itself and/or other parts are being finally secured immediately	Part and associated tool (including hands) can easily reach the desired location and the tool can be operated easily	3	2	5	4	5	6	7	8	9	6	8
	Part and associated tool (including hands) cannot easily reach desired location or tool cannot be operated easily: Due to obstructed accessor restricted vision (2)	4	4.5	7.5	6.5	7.5	8.5	9.5	10.5	11.5	8.5	10.5
	Part and associated tool (including hands) cannot easily reach desired location or tool cannot be operated easily: Due to obstructed access and restricted vision (2)	5	6	9	8	9	10	11	12	13	10	12

Separate operation

		Mechanical fastening processes (part(s) already in place but not secured immediately after insertion)				Non-mechanical fastening processes (part(s) already in place but not secured immediately after insertion)				Non-fastening processes	
		None or localized plastic deformation				Metallurgical processes					
							Additional material required				
		Bending or similar process	Riveting or similar processes	Screw tightening or other processes	Bulk plastic deformation (large proportion of part is plastically deformed during fastening)	No additional material required (e.g. resistance, friction welding, etc.)	Soldering processes	Weld/braze processes	Chemical processes (e.g. adhesive bonding, etc.)	Manipulation of parts or sub-assembly (e.g. orienting, fittings or adjustment of part(s). etc.)	Other processes (e.g. liquid insertion, etc.)
		0	1	2	3	4	5	6	7	8	8
Assembly processes where all solid parts are in place	9	4	7	5	12	7	8	12	12	9	12

Notes:

1. A part is the solid of nonsolid element of an assembly during an assembly process. A subassembly is considered a part if it is added during assembly. However, adhesives, fluxes, fillers, and so on, used for joining parts are not considered to be parts.
2. Obstructed access means that the space available for the assembly operation causes a significant increase in the assembly time. Restricted vision means that the operator has to rely mainly on tactile sensing during the assembly process.
3. Holding down required means that the part is unstable after placement or insertion or during subsequent operations and will require griping, realignment, or holding down before it is finally secured. Holding down refers to an operation that, if necessary, maintains the position and orientation of a part already in place, prior to, or during the next assembly operation. A part is located if it will not require holding down or realignment for subsequent operations and is only partially secured.
4. A part is easy to align and position if the position of the part is established by locating features on the part or on its mating part and insertion is facilitated by well designed chamfers or similar features.
5. The resistance encountered during part insertion can be due to small clearances, jamming or wedging, hang-up conditions, or insertion against a large force. For example, a press fit is an interference fit where a large force is required for assembly. The resistance encountered with self-tapping screws is similarly an example of insertion resistance.

FIGURE 3.16

Original classification system for part features affecting insertion and fastening. (Copyright 1999 Boothroyd Dewhurst, Inc. With permission.)

numbers consist of two digits; the first digit identifies the row and the second digit identifies the column in the table.

The portion of the classification system for manual insertion and fastening processes is concerned with the interaction between mating parts as they are assembled. Manual insertion and fastening consists of a finite variety of basic assembly tasks (peg-in-hole, screw, weld, rivet, press-fit, etc.) that are common to most manufactured products.

It can be seen that for each two-digit code number, an average time is given. Thus, we have a set of time standards that can be used to estimate manual assembly times. These time standards were obtained from numerous experiments, some of which will now be described.

Definitions

For Figure 3.15:

Alpha is the rotational symmetry of a part about an axis perpendicular to its axis of insertion. For parts with one axis of insertion, end-to-end orientation is necessary when alpha equals 360°, otherwise alpha equals 180°.

Beta is the rotational symmetry of a part about its axis of insertion. The magnitude of rotational symmetry is the smallest angle through which the part can be rotated and repeat its orientation. For a cylinder inserted into a circular hole, beta equals zero.

Thickness is the length of the shortest side of the smallest rectangular prism that encloses the part. However, if the part is cylindrical, or has a regular polygonal cross-section with five or more sides, and the diameter is less than the length, then thickness is defined as the radius of the smallest cylinder which can enclose the part.

Size is the length of the longest side of the smallest rectangular prism that can enclose the part.

For Figure 3.16:

Holding down required means that the part will require gripping, realignment, or holding down before it is finally secured.

Easy to align and position means that insertion is facilitated by well-designed chamfers or similar features.

Obstructed access means that the space available for the assembly operation causes a significant increase in the assembly time.

Restricted vision means that the operator has to rely mainly on tactile sensing during the assembly process.

3.6 Effect of Part Symmetry on Handling Time

One of the principal geometrical design features that affects the time required to grasp and orient a part is its symmetry. Assembly operations always involve at least two component parts: the part to be inserted and the part or assembly (receptacle) into which the part is inserted [15]. Orientation involves a proper alignment of the part to be inserted relative to the corresponding receptacle and can always be divided into two distinct operations: (1)

alignment of the axis of the part that corresponds to the axis of insertion, and (2) rotation of the part about this axis.

It is therefore convenient to define two kinds of symmetry for a part:

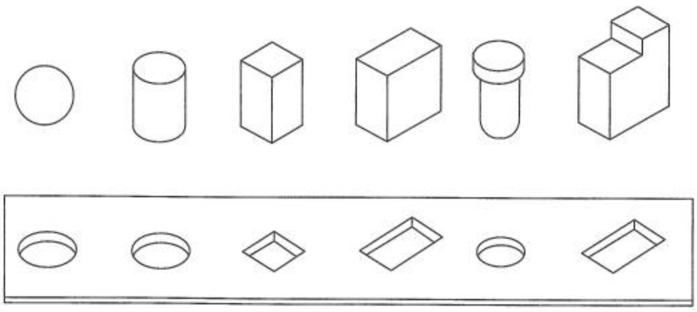
1. *Alpha Symmetry*: Depends on the angle through which a part must be rotated about an axis perpendicular to the axis of insertion to repeat its orientation.
2. *Beta Symmetry*: Depends on the angle through which a part must be rotated about the axis of insertion to repeat its orientation.

For example, a plain square prism that is to be inserted into a square hole would first have to be rotated about an axis perpendicular to the insertion axis. Since, with such a rotation, the prism repeats its orientation every 180°, it can be termed 180° alpha symmetry. The square prism would then have to be rotated about the axis of insertion, and since the orientation of the prism about this axis would repeat every 90°, this implies a 90° beta symmetry. However, if the square prism were to be inserted in a circular hole, it would have 180° alpha symmetry and 0° beta symmetry. Figure 3.17 gives examples of the symmetry of simple-shaped parts.

A variety of predetermined time standard systems are presently used to establish assembly times in the industry. In the development of these systems, several different approaches have been employed to determine relationships between the amount of rotation required to orient a part and the time required to perform that rotation. Two of the most commonly used systems are the methods time measurement (MTM) and work factor (WF) systems.

In the MTM system, the "maximum possible orientation" is employed, which is one-half the beta rotational symmetry of a part mentioned above [16]. The effect of alpha symmetry is not considered in this system. For practical purposes, the MTM system classifies the maximum possible orientation into three groups, namely, (1) symmetric, (2) semisymmetric, and (3) nonsymmetric [3]; again, these terms refer only to the beta symmetry of a part.

In the WF system, the symmetry of a part is classified by the ratio of the number of ways the part can be inserted to the number of ways the part can be grasped preparatory to insertion [17]. In the example of a square prism to be inserted into a square hole, one par-



α	0	180	180	90	360	360
β	0	0	90	180	0	360

FIGURE 3.17
Alpha and beta rotational symmetries for various parts.

ticular end first, it can be inserted in four ways out of the eight ways it could be suitably grasped. Hence, on the average, one-half of the parts grasped would require orientation, and this is defined in the WF system as a situation requiring 50% orientation [17]. Thus, in this system, account is taken of alpha symmetry, and some account is taken of beta symmetry. Unfortunately, these effects are combined in such a way that the classification can only be applied to a limited range of part shapes.

Numerous attempts were made to find a single parameter that would give a satisfactory relation between the symmetry of a part and the time required for orientation. It was found that the simplest and most useful parameter was the sum of the alpha and beta symmetries [5]. This parameter, which would be termed the total angle of symmetry, is therefore given by

$$\text{Total angle of symmetry} = \text{alpha} + \text{beta}. \tag{3.2}$$

The effect of the total angle of symmetry on the time required to handle (grasp, move, orient, and place) a part is shown in Figure 3.18. In addition, the shaded areas indicate the values of the total angle of symmetry that cannot exist. It is evident from these results that the symmetry of a part can be conveniently classified into five groups. However, the first group, which represents a sphere, is not generally of practical interest; therefore, four groups are suggested that are employed in the coding system for part handling (Figure 3.15). A comparison of these experimental results with the MTM and WF orientation parameters show that these parameters do not account properly for the symmetry of a part [5].

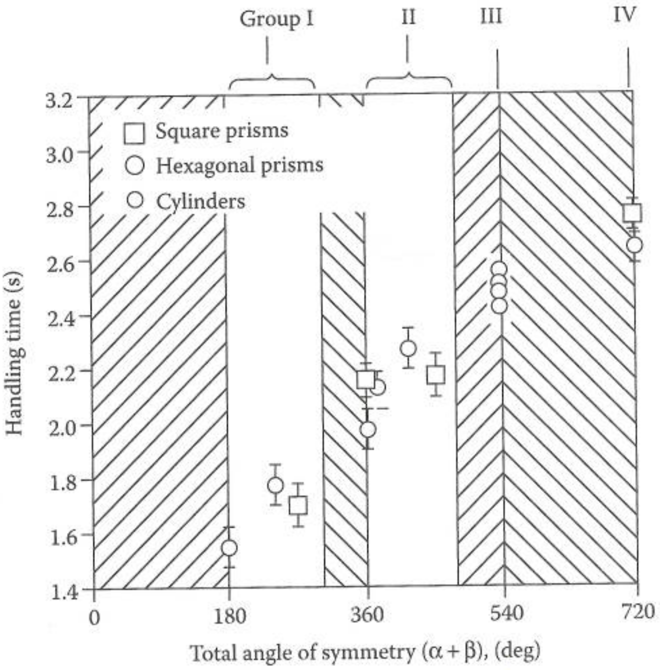


FIGURE 3.18
Effect of symmetry on the time required for part handling. Times are average for two individuals and shaded areas represent nonexistent values of the total angle of symmetry.

3.7 Effect of Part Thickness and Size on Handling Time

Two other major factors that affect the time required for handling during manual assembly are the thickness and size of the part. The thickness and size of a part are defined in a convenient way in the WF system, and these definitions have been adopted for the DFA method. The thickness of a "cylindrical" part is defined as its radius, whereas for noncylindrical parts the thickness is defined as the maximum height of the part with its smallest dimension extending from a flat surface (Figure 3.19). Cylindrical parts are defined as parts having cylindrical or other regular cross-sections with five or more sides. When the diameter of such a part is greater than or equal to its length, the part is treated as noncylindrical. The reason for this distinction between cylindrical and noncylindrical parts when defining thickness is illustrated by the experimental curves shown in Figure 3.19. It can be seen that parts with a "thickness" greater than 2 mm present no grasping or handling problems. However, for long cylindrical parts, this critical value would have occurred at a value of 4 mm had a diameter been used for the "thickness." Intuitively, we see that grasping a long cylinder 4 mm in diameter is equivalent to grasping a rectangular part of 2 mm thickness if each is placed on a flat surface.

The size (also called the major dimension) of a part is defined as the largest nondiagonal dimension of the part's outline when projected on a flat surface. It is normally the length of the part. The effects of part size on handling time are shown in Figure 3.20. Parts can be divided into four size categories as illustrated. Large parts involve little or no variation in handling time with changes in their size; the handling time for medium and small parts displays progressively greater sensitivity with respect to part size. Since the time penalty involved in handling very small parts is large and very sensitive to decreasing part size, tweezers are usually required to manipulate such parts. In general, tweezers can be assumed to be necessary when the size is less than 2 mm.

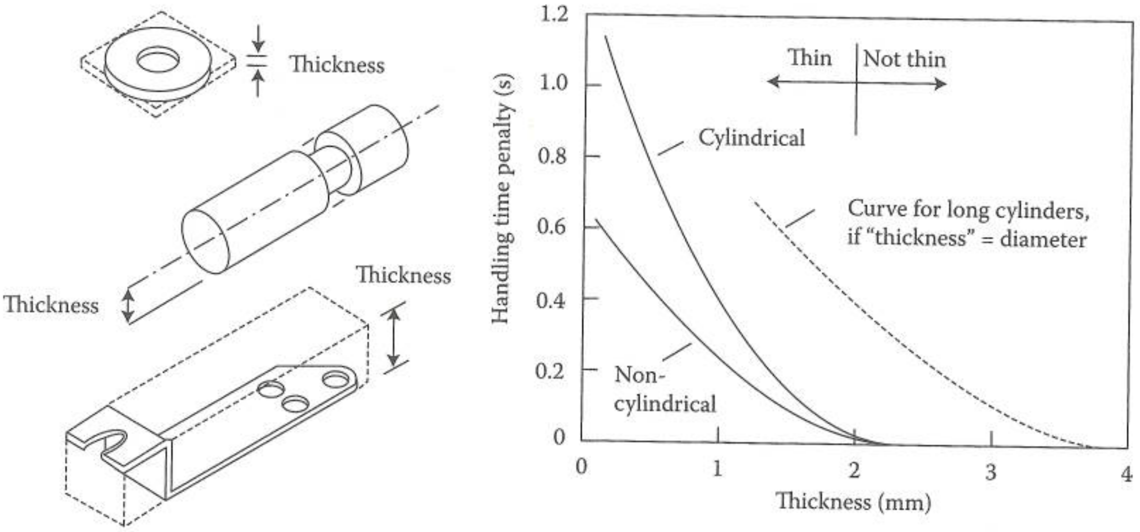


FIGURE 3.19
Effect of part thickness on handling time.

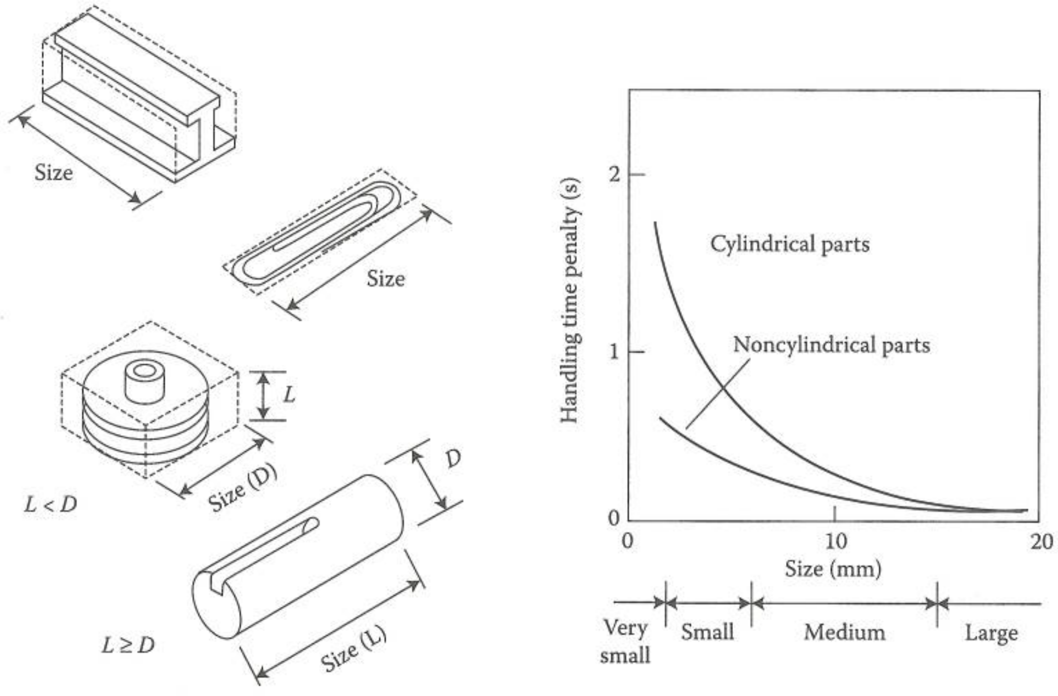


FIGURE 3.20
Effect of part size on handling time.

3.8 Effect of Weight on Handling Time

Work has been carried out [18] on the effects of weight on the grasping, controlling, and moving of parts. The effect of increasing weight on grasping and controlling is found to be an additive time penalty and the effect on moving is found to be a proportional increase of the basic time. For the effect of weight on a part handled using one hand, the total adjustment t_{pw} to handling time can be represented by the following equation [3]:

$$t_{pw} = 0.0125W + 0.011Wt_h \tag{3.3}$$

where W (lb) is the weight of the part and t_h (s) is the basic time for handling a "light" part when no orientation is needed and when it is to be moved by a short distance. An average value for t_h is 1.13, and therefore the total time penalty due to weight would be approximately $0.025W$.

If we assume that the maximum weight of a part to be handled using one hand is around 10–20 lb, the maximum penalty for weight is 0.25–0.5 s and is a fairly small correction. It should be noted, however, that Equation 3.3 does not take into account the fact that larger parts are usually moved greater distances, resulting in more significant time penalties. These factors are discussed later.

3.9 Parts Requiring Two Hands for Manipulation

A part may require two hands for manipulation when:

- The part is heavy.
- Very precise or careful handling is required.
- The part is large or flexible.
- The part does not possess holding features, thus making one-hand grasp difficult.

Under these circumstances, a penalty is applied, because the second hand could be engaged in another operation—perhaps grasping another part. Experience shows that a penalty factor of 1.5 should be applied in these cases.

3.10 Effects of Combinations of Factors

In the previous sections, various factors that affect manual handling times have been considered. However, it is important to realize that the penalties associated with each individual factor are not necessarily additive. For example, if a part requires additional time to move it from A to B, it can probably be oriented during the move. Therefore, it may be wrong to add the extra time for part size and an extra time for orientation to the basic handling time. The following gives some examples of results obtained when multiple factors are present.

5

Design for High-Speed Automatic Assembly and Robot Assembly

5.1 Introduction

Although design for assembly is an important consideration for manually assembled products and can reap enormous benefits, it is vital when a product is to be assembled automatically. The simple example shown in Figure 5.1 illustrates this. The slightly asymmetrical threaded stud would not present significant problems in manual handling and insertion, whereas for automatic handling an expensive vision system would be needed to recognize its orientation. If the part were made symmetrical, automatic handling would be simple. For economic automatic assembly therefore, careful consideration of product structure and component part design is essential. In fact, it can be said that one of the advantages of introducing automation in the assembly of a product is that it forces a reconsideration of its design—thus offering not only the benefits of automation, but also those of improved product design. Not surprisingly, the savings resulting from product redesign often outweigh those resulting from automation.

The example of the part in Figure 5.1 illustrates a further point. The principal problems in applying automation usually involve the automatic handling of the parts rather than their insertion into the assembly. To quote an individual experienced in the subject of automatic assembly "if a part can be handled automatically, then it can usually be assembled automatically." This means that, when we consider design for automation, we would be paying close attention to the design of the parts for ease of automatic feeding and orienting.

In considering manual assembly we were concerned with prediction of the time taken to accomplish the various tasks such as grasp, orient, insert, and fasten. From knowledge

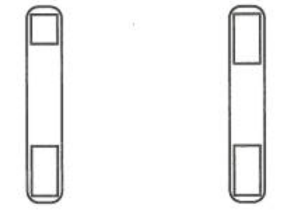


FIGURE 5.1
Design change to simplify automatic feeding and orienting.

of the assembly worker's labor rate we could then estimate the cost of assembly. In automatic assembly, the time taken to complete an assembly does not control the assembly cost. Rather, it is the rate at which the assembly machine or system cycles, because, if everything works properly, a complete assembly is produced at the end of each cycle. Then, if the total rate (cost per unit time) for the machine or system and all the operators is known, the assembly cost can be calculated after allowances are made for down-time. Thus, we shall be mainly concerned with the cost of all the equipment, the number of operators and technicians, and the assembly rate at which the system is designed to operate. However, so that we can identify problems associated with particular parts, we shall need to apportion the cost of product assembly between the individual parts and, for each part, and we shall need to know the cost of feeding and orienting and the cost of automatic insertion.

In the following discussion, we first look at product design for high-speed automatic assembly using special-purpose equipment and then we consider product design for robot assembly (i.e., using general-purpose equipment).

5.2 Design of Parts for High-Speed Feeding and Orienting

The cost of feeding and orienting parts depend on the cost of the equipment required and on the time interval between delivery of successive parts. The time between the delivery of parts is the reciprocal of the delivery rate and is nominally equal to the cycle time of the machine or system. If we denote the required delivery or feed rate F_r (parts/min), then the cost of feeding each part C_f is given by

$$C_f = \left(\frac{60}{F_r}\right) R_f \text{ cents} \tag{5.1}$$

where R_f is the cost (cents/s) of using the feeding equipment.

Using a simple payback method for estimation of the feeding equipment rate R_f, this is given by

$$R_f = \frac{C_F E_o}{(5760 P_b S_n)} \text{ cents/s} \tag{5.2}$$

where C_F is the feeder cost ($), E_o is the equipment factory overhead ratio, P_b is the payback period in months, and S_n is the number of shifts worked per day. The constant 5760 is the number of available seconds in one shift working for one month divided by 100 to convert dollars to cents.

For example, if we assume that a standard vibratory bowl feeder costs $5000 after installation and debugging, that the payback period is 30 months with 2 shifts working, and that the factory equipment overheads are 100% ($E_o = 2$), we get

$$\begin{aligned} R_f &= \frac{5000 \times 2}{(5760 \times 30 \times 2)} \\ &= 0.03 \text{ cent/s} \end{aligned}$$

In other words, it would cost 0.03 cents to use the equipment for 1 s. Supposing that we take this figure as the rate for a "standard" feeder and we assign a relative cost factor C_r to any feeder under consideration, then Equation 5.1 becomes

$$C_f = 0.03\left(\frac{60}{F_r}\right)C_r \tag{5.3}$$

Thus, we see that the feeding cost per part is inversely proportional to the required feed rate and proportional to the feeder cost.

To describe these results in simple terms, we can say that for otherwise identical conditions it would cost twice as much to feed each part to a machine with a 6 s cycle compared with the cost for a machine with a 3 s cycle. This illustrates why it is difficult to justify feeding equipment for assembly systems with long cycle times.

For the second result, we can simply state that for otherwise constant condition, it would cost twice as much to feed a part using a feeder costing \$10,000 compared with a feeder costing \$5000.

If the feeding cost for a particular feeder is plotted against the required feed rate F_r on logarithmic scales, a linear relationship results, as shown in Figure 5.2. It appears that the faster the parts are required, the lower the feeding cost. This is true only as long as there is no limit on the speed at which a feeder can operate. Of course, there is always an upper limit to the feed rate obtainable from a particular feeder. We shall denote this maximum feed rate by F_m and consider the factors that affect its magnitude. However, before doing so, let us look at its effect through an example.

Suppose that the maximum feed rate from our feeder is 10 parts/min. Then if parts are required at a rate of 5 parts/min, the feeder can simply be operated more slowly involving an increased feeding cost as given by Equation 5.3 and illustrated in Figure 5.2. Suppose that parts are required at a rate of 20 parts/min. In this case two feeders could be used, each delivering parts at a rate of 10 parts/min. However, the feeding cost per part using two feeders to give twice the maximum feed rate would be the same as one feeder delivering parts at its maximum feed rate. In other words, if the required feed rate is greater than the maximum feed rate obtainable from one feeder, the feeding cost becomes constant and equal to the cost of feeding when the feeder is operating at its maximum rate. This is

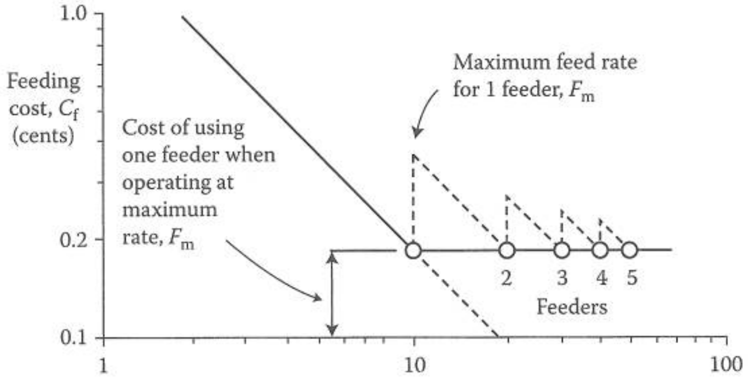


FIGURE 5.2
Effect of required feed rate on feeding cost.

shown in Figure 5.2 by the horizontal line. If multiple feeders are used for increased feed rates, then the line will be saw-toothed as shown. However, in practice, the line can be smoothed by spending more on feeders to improve their performance when necessary.

From this discussion, we can say that Equation 5.3 holds true only when the required feed rate F_r is less than the maximum feed rate F_m, and when this is not the case the feeding cost is given by

$$C_r = 0.03\left(\frac{60}{F_m}\right)C_r \tag{5.4}$$

Now the maximum feed rate F_m is given by

$$F_m = 1500\frac{E}{l}\text{ parts/min} \tag{5.5}$$

where E is the orienting efficiency for the part and l (mm) is its overall dimension in the direction of feeding and where it is assumed that the feed speed is 25 mm/s.

To illustrate the meaning of the orienting efficiency E, we can consider the feeding of dies (cubes with faces numbered 1–6). Suppose that if no orientation is needed, the dies can be delivered at a rate of 1 per second from a vibratory bowl feeder. However, if only those dies with the 6 side uppermost were of interest, a vision system could be employed to detect all other orientations and a solenoid-operated pusher could be used to reject them. In this case, the delivery rate would fall to an average of 1 die every 6 s or a feed rate of 1/6 per second. The factor 1/6 is defined as the orienting efficiency E and it can be seen that the maximum feed rate is proportional to the orienting efficiency (Equation 5.5).

Now let us suppose our dies were doubled in size and that the feed speed or conveying velocity on the feeder track were unaffected. It would then take twice as long to deliver each die. In other words, the maximum feed rate is inversely proportional to the length of the part in the feeding direction (Equation 5.5).

Equation 5.4 shows that when $F_r > F_m$, the feeding cost per part is inversely proportional to F_m. It follows that under these circumstances, the cost of feeding is inversely proportional to the orienting efficiency and proportional to the length of the part in the feeding direction.

This latter relationship illustrates why automatic feeding and orienting methods are only applicable to "small" parts. In practice, this means that parts larger than about 8 in. in their major dimension cannot usually be fed economically.

When considering the design of a part and its feeding cost, the designer would know the required feed rate and the dimensions of the part. Thus, F_r and l would be known. The remaining two parameters that affect feeding cost, namely, the orienting efficiency E and the relative feeder cost C_r, would depend on the part symmetry and the types of features that define its orientation. A classification system for part symmetry and features has been developed [1] and for each part classification the average magnitudes of E and C_r have been determined [2]. This classification system and data are presented in Figures 5.3 through 5.5. Figure 5.3 shows how parts are categorized into basic types, either rotational or nonrotational. For rotational parts, their cylindrical envelopes are classified as discs, short cylinders, or long cylinders. For nonrotational parts, the subcategories are flat, long, or cubic depending on the dimensions of the sides of the rectangular envelope.

Figure 5.3 gives the first digit of a three-digit shape code. Figure 5.4 shows how the second and third digits are determined for rotational parts (first digit 0, 1, or 2) and gives

Rotational	Discs	L/D < 0.8	0
	Short cylinders	0.8 ≤ L/D ≤ 1.5	1
	Long cylinders	L/D > 1.5	2
Nonrotational	Flat	A/B ≤ 3 A/C > 4	6
	Long	A/B > 3,	7
	Cubic	A/B ≤ 3 A/C ≤ 4	8

Notes:

1. A part whose basic shape is a cylinder or regular prism whose cross section is a regular polygon of five or more sides is called a rotational part. In addition, triangular or square parts that repeat their orientation when rotated about their principal axis through angles of 120° or 90°, respectively, are rotational parts.
2. L is the length and D is the diameter of the smallest cylinder that can completely enclose the part.
3. A is the length of the longest side, C is the length of the shortest side and B is the length of the intermediate side of the smallest rectangular prism that can completely enclose the part.

FIGURE 5.3
First digit of geometrical classification of parts for automatic handling. (From Boothroyd, G and Dewhurst, P. *Product Design for Assembly Handbook*, Boothroyd Dewhurst Inc., Wakefield, RI, 1986. With permission.)

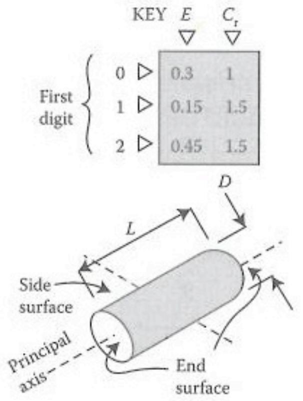
the corresponding values of the orienting efficiency E and the relative feeder cost C_r. Similarly, Figure 5.5 shows how the second and third digits are determined for nonrotational parts (first digit 6, 7, or 8). The geometrical classification system was originally devised by Boothroyd and Ho [1] as a means of cataloging solutions to feeding problems.

5.3 Example

Suppose that the part shown in Figure 5.6 is to be delivered to an automatic assembly station working at a 5 s cycle. We now use the classification system and database to determine the feeding cost and assume that the cost of delivering simple parts at 1 per second using our "standard" feeder is 0.03 cents per part.

First, we must determine the classification code for our part. Figure 5.6 shows that the rectangular envelope for the part has the dimensions $A = 30$ mm, $B = 20$ mm, and $C = 15$ mm.

Thus, $A/B = 1.5$ and $A/C = 2$. Referring to Figure 5.3, since A/B is less than 3 and A/C is less than 4, the part is categorized as cubic nonrotational and is assigned a first digit of 8. Turning to Figure 5.5, which provides a selection of data for nonrotational parts, we first determine that our example part has no rotational symmetry about any of its axes. Also, we must decide whether the part's orientation can be determined by one main feature. Looking at the silhouette of the part in the X direction, we see a step or projection in the basic rectangular shape and we realize that this feature alone can always be used to



				AUTOMATIC HANDLING-DATA FOR ROTATIONAL PARTS (first digit 0, 1 or 2)							
				Part is symmetrical about its principal axis (BETA symmetric) (see note 2)	Part is not BETA symmetric (code the main feature or features requiring orientation about the principal axis)						
					BETA asymmetric projections, steps, or chamfers (can be seen in silhouette)			BETA asymmetric grooves or flats (can be seen in silhouette)			Slightly asymmetric or small features less than D/10 and L/10 or holes or recesses which cannot be seen in outer shape of silhouette
					On side surface only	On end surface(s) only	On both side and end surface(s)	Through groove or flat can be seen in end view	Through groove can be seen in side view		
									On end surface	On side surface	
				0	2	3	4	5	6	7	8
Part is ALPHA symmetric (see note 1)			0	0.7 1 0.7 1 0.9 1	0.3 1 0.15 1 0.45 1	0.5 1 0.2 1 0.9 2	0.3 1 0.15 1 0.45 1	0.35 1 0.2 1 0.9 1	0.2 1 0.2 1 0.9 2	0.5 1 0.2 1 0.9 2	MANUAL HANDLING REQUIRED
Part is not ALPHA symmetric (code the main feature or features requiring end-to-end orientation) (see note 1)	Part can be fed in a slot supported by large end or protruding flange		1	0.4 1 0.3 1 0.9 1	0.2 1 0.1 1 0.45 1	0.25 1 0.1 1 0.9 2	0.2 1 0.1 1 0.45 1	0.2 1 0.1 1 0.9 1	0.1 1 0.1 1 0.9 2	0.25 1 0.1 1 0.9 1	
	BETA symmetric steps or chamfers on external surfaces (see note 3)		2	0.4 1 0.3 1 0.75 1	0.15 1 0.1 1.5 0.37 1.5	0.25 1 0.1 1.5 0.25 3	0.15 1 0.1 1.5 0.37 2.5	0.35 1 0.2 1.5 0.5 1	0.1 1 0.05 1.5 0.5 3	0.25 1 0.1 1.5 0.5 2	
	BETA symmetric groves holes or recesses (see note 3)	On both side and end surface(s)	3	0.5 1 0.2 1 0.85 1	0.15 1 0.1 1.5 0.48 1.5	0.25 1 0.1 1.5 0.25 2	0.15 1 0.1 1.5 0.43 1.5	0.2 1 0.1 1.5 0.5 1	0.1 3 0.05 1.5 0.5 2	0.25 1 0.1 1.5 0.5 2	
		On side surface only	4	0.5 1 0.1 1 0.85 1	0.15 1 0.1 1.5 0.43 1.5	0.25 1 0.1 1.5 0.25 2	0.15 1 0.1 1.5 0.13 1.5	0.2 1 0.1 1.5 0.5 1	0.1 1 0.05 1.5 0.5 2	0.25 1 0.1 1.5 0.5 2	
		On end surface(s) only	5	0.5 1 0.2 1 0.6 1	0.15 1 0.1 1.5 0.27 1.5	0.25 1 0.1 1.5 0.25 2	0.15 1 0.1 1.5 0.27 1.5	0.2 1 0.1 1.5 0.15 1	0.1 1 0.05 1.5 0.45 2	0.25 1 0.1 1.5 0.45 2	
	BETA symmetric hidden features with no corresponding exposed features (see note 4)		6	0.6 1	0.27 1.5	0.25 2	0.27 1.5	0.45 1	0.45 2	0.45 2	
	BETA asymmetric features on side or end surface(s)		7		0.27 2	0.25 1 0.1 1.5 0.25 3	0.1 1 0.05 1.5 0.27 2	0.1 3	0.1 1 0.05 1.5 0.5 3	0.25 1 0.1 1.5 0.5 3	
	Slightly asymmetric or small features amount of asymmetry or feature size less than D/10 and L/10		8	MANUAL HANDLING REQUIRED							

Notes:

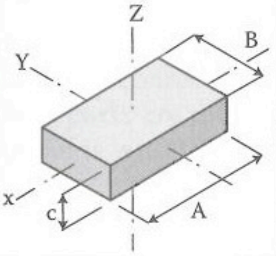
1. A rotational part is alpha symmetric if it does not require orienting end-to-end. If a part can only be inserted into the assembly in one direction then it is referred to as "not alpha symmetric."
2. A beta-symmetric part has rotational symmetry and therefore does not require orienting about its principal axis.
3. A beta-symmetric step, chamfer or groove is a concentric reduction or increase in diameter; its cross section can be circular or any regular polygon. Less significant features should be ignored.
4. Parts in this category have an alpha-symmetric external shape, but the internal surface (composed perhaps of cavities, counterbores, grooves, etc.) requires that the part be oriented end to end.

FIGURE 5.4

Second and third digits of geometrical classification for rotational parts. (From Boothroyd, G. and Dewhurst, P. *Product Design for Assembly Handbook*, Boothroyd Dewhurst Inc., Wakefield, RI, 1986. With permission.)

KEY		*E*	C_r
First digit	6 ▷	0.7	1
	7 ▷	0.45	1.5
	8 ▷	0.3	2

AUTOMATIC HANDLING-DATA FOR NON-ROTATIONAL PARTS (first digit 6, 7 or 8)										
			A ≤ 1.1B or B ≤ 1.1C (Code the main feature or features which distinguish the adjacent surfaces having similar dimensions)							
			Steps or chamfers (2) parallel to-			Through grooves (2) parallel to-			Holes for recesses > 0.1B (cannot be seen in silhouette)	Other including slight asymmetry (3), features too small etc
		A > 1.1B and B > 1.1C	X axis and > 0.1C	Y axis and > 0.1C	Z axis and > 0.1B	X axis and > 0.1C	Y axis and > 0.1C	Z axis and > 0.1B		
		0	1	2	3	4	5	6	7	8
Part has 180° symmetry about all three axes (1)	0	0.8 1 0.9 1 0.6 1	0.8 1 0.9 1 0.5 1	0.2 1 0.5 2 0.15 2	0.5 1 0.5 1.5 0.15 1.5	0.75 1 0.5 1 0.5 1	0.25 1 0.5 1.5 0.15 1	0.5 1.6 0.6 1 0.15 1.5	0.25 2 0.5 1 0.15 2	Manual handling required



			Code the main feature or if orientation is defined by more than one feature, then code the feature that gives the largest third digit							
			Steps or chamfers (2) parallel to-			Through grooves (2) parallel to-			Holes for recesses > 0.1B (cannot be seen in silhouette)	Other including slight asymmetry (3), features too small etc
			X axis and > 0.1C	Y axis and > 0.1C	Z axis and > 0.1B	X axis and > 0.1C	Y axis and > 0.1C	Z axis and > 0.1B		
			0	1	2	3	4	5	6	7
Part has 180° symmetry about one axis only (1)	About X axis	1	0.4 1 0.5 1 0.4 1	0.6 1 0.15 1 0.6 1	0.4 1.5 0.25 2 0.4 2	0.4 1 0.5 1 0.2 1	0.3 1 0.25 1 0.3 1	0.7 1 0.25 1.5 0.15 1	0.4 2 0.25 3 0.1 2	MANUAL HANDING REQUIRED
	About Y axis	2	0.4 1 0.4 1 0.5 1	0.3 1 0.2 1 0.15 1	0.4 1.5 0.25 2 0.5 2	0.5 1 0.4 1 0.2 1	0.3 1 0.25 1 0.15 1	0.4 1 0.25 1 0.15 2	0.4 2 0.25 2 0.15 2	
	About Z axis	3	0.4 1 0.3 1 0.4 1	0.3 1 0.2 1 0.2 1	0.4 1.5 0.25 2 0.4 2	0.4 1 0.3 1 0.2 1	0.3 1 0.25 1 0.15 1	0.1 1.5 0.25 2 0.15 2	0.4 2 0.25 2 0.15 2	
Part has no symmetry (code the main feature(s) that define the orientation) (4)	Orientation defined by one main feature	4	0.25 1 0.25 1 0.15 1	0.15 1 0.1 1.5 0.14 1	0.15 1.5 0.24 2 0.15 1	0.1 1 0.2 1 0.1 1	0.25 1 0.1 1.5 0.05 1	0.1 1.5 0.15 2 0.1 1.5	0.1 2 0.15 3 0.08 2	
	Orientation defined by two main features and one is a step, chamfer or groove	6	0.2 2 0.1 3 0.05 2	0.15 2 0.1 3.5 0.05 2	0.1 2.5 0.1 4 0.05 2.5	0.1 2 0.1 3 0.05 2	0.15 2 0.1 3.5 0.05 2	0.1 2.5 0.1 4 0.05 2.5	0.1 3 0.1 5 0.05 3	
	Other including slight asymmetry (3) etc.	9	MANUAL HANDLING REQUIRED							

Notes:

1. A rotational symmetry of 180° about an axis means that the same orientation of the part will be repeated only once by rotating the part through 180° about that axis.
2. Steps, chamfers, or through grooves are features that can be seen in silhouette.
3. Exposed features are prominent but the asymmetry caused by these features is less than 0.1 of the appropriate envelope dimension. For a part that has 180° rotational symmetry about a certain axis, slight asymmetry implies that the part has almost 90° rotational symmetry about that axis.
4. A part having no rotational symmetry means that the same orientation of the part will not be repeated by rotating the part through any angle less than 360° about any one of the three axes X, Y, or Z.

A main feature is a feature that is chosen to define the orientation of the part. All the features that are chosen to completely define the orientation of the part should be necessary and sufficient for the purpose.

Often, features arise in pairs or groups and the pair or group of features is symmetric about one of the three axes X, Y, or Z. In this case, the pair or group of features should be regarded as one main feature. Using this convention, two main features at most are needed to completely define the orientation of a part.

FIGURE 5.5
Second and third digits of geometrical classification for nonrotational parts. (From Boothroyd, G. and Dewhurst, P. *Product Design for Assembly Handbook*, Boothroyd Dewhurst Inc., Wakefield, RI, 1986. With permission.)

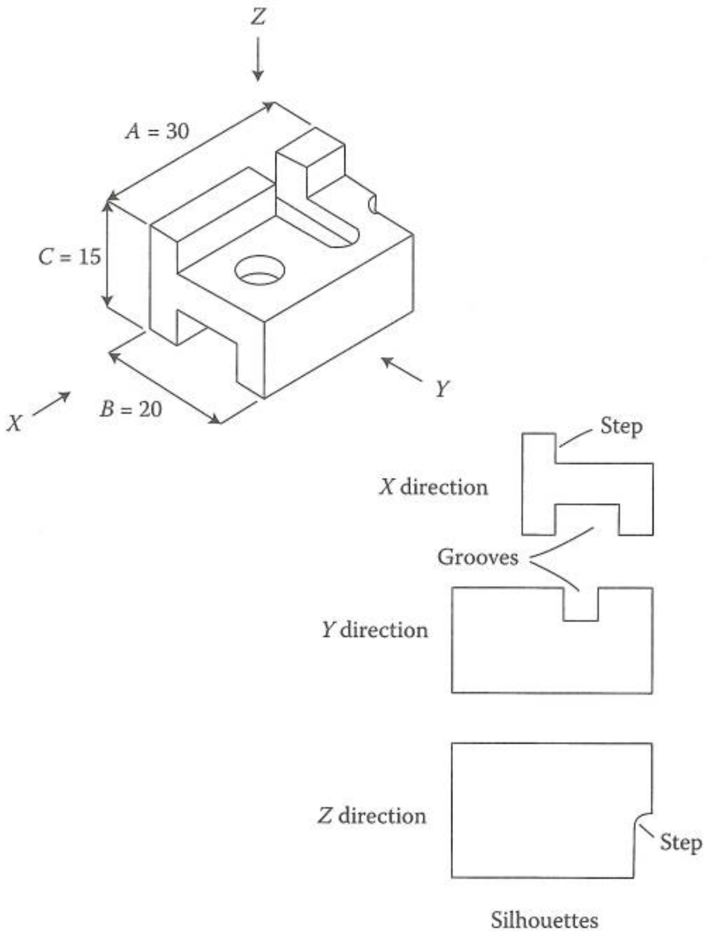


FIGURE 5.6
Sample part.

determine the part's orientation. This means that if the silhouette in the X direction is oriented as shown in Figure 5.6, the part can be in only one orientation and, therefore, the second digit of the classification is 4. However, either the groove apparent in the view in the Y-direction and the step seen in the view in the Z-direction could also be used to determine the part's orientation. The procedure now is to select the feature giving the smallest third classification digit; in this case it is the step seen in the X-direction. Thus, the appropriate column number in Figure 5.5 is 0. The three-digit code is thus 840 and corresponding values of orienting efficiency $E = 0.15$ and relative feeder cost $C_r = 1$.

Using the fact that the longest part dimension l is 30 mm and that the orienting efficiency E is 0.15, Equation 5.5 gives the maximum feed rate obtainable from one feeder; thus

$$
\begin{aligned}
F_m &= 1500 \frac{E}{l} \\
&= 1500 \times \frac{0.15}{30} \\
&= 7.5 \text{ parts/min}
\end{aligned}
$$

Now, from the cycle time of 5 s the required feed rate F_r is 12 parts per min, which is higher than F_m. Therefore, since $F_r > F_m$ we use Equation 5.4 and since $C_r = 1$ we get a feeding cost of

$$\begin{aligned} C_r &= 0.03\left(\frac{60}{F_m}\right)\mathrm{C}_r \\ &= 0.03\left(\frac{60}{7.5}\right)1 \\ &= 0.24 \text{ cents} \end{aligned}$$

5.4 Additional Feeding Difficulties

In addition to the problems of using the part's geometric features to orient it automatically, other part characteristics can make feeding particularly difficult. For example, if the edges of the parts are thin, shingling or overlapping may occur during feeding, which leads to problems with the use of orienting devices on the feeder track (Figure 5.7).

Difficult to feed - parts overlap

Easy to feed

FIGURE 5.7
Parts that shingle or overlap on the feeder track.

Many other features can affect the difficulty of feeding the part automatically and can lead to considerable increases in the cost of developing the automatic feeding device. These features can also be classified as shown in Figure 5.8, where, for each combination of features, an approximate additional relative feeder cost is given that should be taken into account in estimating the cost of automatic feeding.

5.5 High-Speed Automatic Insertion

If a part can be sorted from bulk and delivered to a convenient location correctly oriented, a special-purpose mechanism or workhead can usually be designed that would place it in the assembly. Such workheads can generally be built to operate on a cycle as short as 1 s. Thus, for assembly machines operating on cycles greater than 1 s, the automatic insertion cost C_i is given by

$$C_i = \left(\frac{60}{F_r}\right)R_i \tag{5.6}$$

where F_r is the required assembly rate (or feed rate of parts) and R_i is the cost (cents/s) of using the automatic workhead.

AUTOMATIC HANDLING-ADDITIONAL FEEDER COSTS

Figures to be added to C_r					Parts will not tangle or nest				Tangle or nest but not severely					
					Not light		Light		Not light		Light			
					Not sticky	Sticky	Not sticky	Sticky	Not sticky	Sticky	Not sticky	Sticky	Severely tangle	Severely tangle
					0	1	2	3	4	5	6	7	8	9
Parts are small and non-abrasive	Parts do not tend to overlap during feeding	Not delicate	Non-flexible	0	0	1	2	3	2	3	3	4	MANUAL HANDLING REQUIRED	
			Flexible	1	2	3	4	5	4	5	5	6		
		Delicate	Non-flexible	2	1	2	3	4	3	4	4	5		
			Flexible	3	3	4	5	6	5	6	6	7		
	Parts tend to overlap during feeding	Not delicate	Non-flexible	4	2	3	3	4	4	5	4	5		
			Flexible	5	4	5	5	6	6	7	6	7		
		Delicate	Non-flexible	6	3	4	4	5	5	6	5	6		
			Flexible	7	5	6	6	7	7	8	7	8		

		Very small parts					Large parts				
		Rotational		Non-rotational			Rotational		Non-rotational		
		$L/D \leq 1.5$	$L/D > 1.5$	$A/B \leq 3$ $A/C > 4$	$A/B > 3$	$A/B \leq 3$ $A/C \leq 4$	$L/D \leq 1.5$	$L/D > 1.5$	$A/B \leq 3$ $A/C > 4$	$A/B > 3$	$A/B \leq 3$ $A/C \leq 4$
		0	1	2	3	4	5	6	7	8	9
Parts are very small or large but are nonabrasive	8	2	2	2	2	2	9	9	9	9	9

		Parts will not severely tangle or nest									
		Small parts					Large parts		Very small parts		
		Orientation defined by geometric features			Orientation defined by non-geometric features		Orientation defined by geometric features	Orientation defined by non-geometric features	Orientation defined by geometric features	Orientation defined by non-geometric features	Severely tangle or nest
		Non-flexible		Flexible	Do not overlap	Overlap					
		Do not overlap	Overlap								
		0	1	2	3	4	5	6	7	8	9
Abrasive parts	9	2	4	4			9		4		

Notes:

Flexible: A part is considered flexible if the part cannot maintain its shape under the action of automatic feeding so that orienting devices cannot function satisfactorily.

Delicate: A part is considered delicate if damage may occur during handling, either due to breakage caused by parts falling from orienting sections or tracks onto the hopper base, or due to wear caused by recirculation of parts in the hopper. When wear is the criterion, a part would be considered delicate if it could not recirculate in the hopper for 30 min and maintain the required tolerance.

Sticky: If a force, comparable to the weight of a nontangling or nonnesting part, is required to separate it from bulk, the part is considered sticky.

Light: A part is considered too light to be handled by conventional hopper feeders if the ratio of its weight to the volume of its envelope is less than 1.5 kN/m^3.

FIGURE 5.8

Additional relative feeder costs for a selection of feeding difficulties. (From Boothroyd, G. and Dewhurst, P. *Product Design for Assembly Handbook*, Boothroyd Dewhurst Inc., Wakefield, RI, 1986. With permission.)

Overlap: Parts will tend to overlap in a feeder when an alignment of better than 0.2 mm is required to prevent shingling or overlapping during feeding in single file on a horizontal track.

Large: A part is considered to be too large to be readily handled by conventional hopper feeders when its smallest dimension greater than 50 mm or if its maximum dimension is greater than 150 mm. A part is considered to be too large to be handled by a particular vibratory hopper feeder if L > d/8, where L is the length of the part measured parallel to the feeding direction and d is the feeder or bowl diameter.

Very small: A part is considered to be too small to be readily handled by conventional hopper feeders when its largest dimension is less than 3 mm. A part is considered to be too small to be readily handled by a particular vibratory hopper feeder if its largest dimension is less than the radius of the curved surface joining the hopper wall and the track surface measured in a plane perpendicular to the feeding direction.

Nest: Parts are considered to nest if they interconnect when in bulk, causing orientation problems. No force is required to separate the parts when they are nested.

Severely nest: Parts are considered to severely nest if they interconnect and lock when in bulk and require a force to separate them.

Tangle: Parts are said to tangle if a reorientation is required to separate them when in bulk.

Severely tangle: Parts are said to severely tangle if they require manipulation to specific orientations and a force is required to separate them.

Abrasive: A part is considered to be abrasive if it may cause damage to the surface of the hopper feeding device unless these surfaces are specially treated.

FIGURE 5.8
Continued.

Again, using a simple payback method for estimation of the equipment rate R_i, this is given by

$$R_i = \frac{W_c E_o}{(5760 P_b S_n)} \text{ cents/s} \tag{5.7}$$

where W_c is the workhead cost ($), E_o is the equipment factory overhead ratio, P_b is the payback period in months, and S_n is the number of shifts worked per day.

If we assume that a standard workhead costs $10,000 after installation and debugging, that the payback period is 30 months with two shifts working, and the factory equipment overheads are 100% ($E_o = 2$), we get

$$\begin{aligned} R_i &= \frac{10{,}000 \times 2}{(5760 \times 30 \times 2)} \\ &= 0.06 \text{ cents/s} \end{aligned}$$

In other words, it would cost 0.06 cents to use the equipment for 1 s. If we take this figure as the rate for a "standard" workhead and we assign a relative cost factor W_r to any workhead under consideration, then Equation 5.6 becomes

$$C_i = 0.06\left(\frac{60}{F_r}\right)W_r \tag{5.8}$$

Thus, the insertion cost is inversely proportional to the required assembly rate and proportional to the workhead cost.

When considering the design of a part, the designer knows the required assembly rate F_r. For the presentation of relative workhead costs, a classification system for automatic insertion similar to that for manual insertion was devised [2] and is shown in Figure 5.9. It can be seen that this classification system is similar to that of manual insertion of parts except that the first digit is determined by the insertion direction rather than whether obstructed access or restricted vision occurs.

AUTOMATIC INSERTION - RELATIVE WORKHEAD COST, W_c

Key:

☐ Part added but not secured

▨ Part secured immediately

▨ Separate operation

				After assembly no holding down required to maintain orientation and location (5)				Holding down required during subsequent process(es) to maintain orientation and location (5)			
				Easy to align and position (6)		Not easy to align or position (no features provided for the purpose)		Easy to align and position (6)		Not easy to align or position (no features provided for the purpose)	
				No resistance to insertion	Resistance to insertion (7)	No resistance to insertion	Resistance to insertion (7)	No resistance to insertion	Resistance to insertion (7)	No resistance to insertion	Resistance to insertion (7)
				0	1	2	3	6	7	8	9
No final securing is taking place (2)	Straight line insertion	From vertically above	0	1	1.5	1.5	2.3	1.3	2	2	3
			1	1.2	1.6	1.6	2.5	1.6	2.1	2.1	3.3
		Not from vertically above (3)									
	Insertion not straight line motion (4)		2	2	3	3	4.6	2.7	4	4	6.1

				No screwing operation or plastic deformation immediately after insertion (snap of press fits, etc.)		Plastic deformation immediately after insertion							Screwing immediately after insertion	
						Plastic bending			Rivetting of similar plastic deformation					
							Not easy to align or position (no features provided for the purpose)			Not easy to align or position (no features provided for the purpose)				
				Easy to align and position (6) no resistance to insertion	Not easy to align or position and/or resistance to insertion	Easy to align and position (6)	No resistance to insertion	Resistance to insertion (7)	Easy to align and position (6)	No resistance to insertion	Resistance to insertion (7)	Easy to align and position (6) no resistance to screwing	Not easy to align or position and/or resistance to screwing (7)
				0	1	2	3	4	5	6	7	8	9
Addition of any part (1) where final securing is taking place	Straight line insertion	From vertically above	3	1.2	1.9	1.6	2.4	3.6	0.9	1.4	2.1	0.8	1.8
		Not from vertically above (3)	4	1.3	2.1	2.1	3.2	4.8	1	1.5	2.3	1.3	2
	Insertion not straight line motion (4)		5	2.4	3.8	3.2	4.8	7.2	1.8	2.8	4.2	3.6	3.6

		Mechanical fastening processes (parts already in place)				Non-mechanical fastening processes (parts already in place)				Non- fastening processes	
		None or localized plastic deformation				Metallurgical processes					
							Additional material required				
		Bending or similar processes	Rivetting or similar processes	Screwing or other processes	Snap fit, snap clip, press fit, etc.	No additional of material (friction or resistance welding, etc.)	Soldering processes	Welding or brazing	Chemical processes (adhesive bonding etc.)	Manipulation of parts or sub-assenbly (orienting, fitting, adjustment etc.)	Other processes (liquid insertion etc.)
		0	1	2	3	4	5	6	7	8	9
Assembly process where all solid parts in place or non-solids added or parts are manipulated	9	1.6	0.9	0.8	1.6	1.2	1.1	1.1	0.8	1.5	

FIGURE 5.9
Relative workhead costs W_r for a selection of automatic insertion situations. (From Boothroyd, G. and Dewhurst, P. *Product Design for Assembly Handbook*, Boothroyd Dewhurst Inc., Wakefield, RI, 1986. With permission.)

Notes:

1. A part is a solid or nonsolid element of an assembly added during an assembly process. A subassembly is considered a part if it is added to an assembly. However, adhesive, fluxes, fillers, and so on, used for joining parts are not considered to be parts.
2. Part addition involves part placing or insertion processes only. Part may be a fastener that is not securing any other part or parts immediately.
3. Placing or insertion of the part into the assembly necessitates access motions from a direction other than vertically above (e.g., from the side or from below, etc.).
4. Part cannot be placed or inserted by a simple single-axis straight-line motion, for example, part access may be obstructed requiring a change in the direction of motion during insertion.
5. Part is unstable after placement or insertion or during subsequent operations an will require gripping realignment or holding down until it is finally secured. *Holding down* refers to an operation that, if necessary, maintains the position and orientation of a part already in place, prior to or during the next assembly operation or during transfer of the assembly to the next workstation. A part is *located* if it will not require holding down or realignment for subsequent operations, and it is only partially secured.
6. A part is easy to align and position if the position of the part is established by locating features on the part, or on its mating part, and insertion is facilitated by well-designed chamfers or similar features.
7. The resistance encountered during part insertion can be due to small clearances, jamming or wedging, hang-up conditions, or insertion against a large force. For exmaple, a press fit is an interferences fit where a large force is required for assembly. The resistance encountered with self-tapping screws is similarly an example of insertion resistance.

FIGURE 5.9
Continued.

5.6 Example

If the part shown in Figure 5.6 is inserted horizontally into the assembly in the direction of the arrow Y and it is not easy to align and position and not secured on insertion, then the appropriate classification is row 1, column 2 in Figure 5.9. The automatic insertion code is thus 12, giving a relative workhead cost of 1.6.

For a cycle time of 5 s, the assembly rate F_r is 12 parts/min and Equation 5.8 gives an insertion cost of

$$\begin{aligned} C_i &= 0.06\left(\frac{60}{F_r}\right)W_r \\ &= 0.06\left(\frac{60}{12}\right)1.6 \\ &= 0.48 \text{ cents} \end{aligned}$$

Thus, the total handling and insertion cost C_t for this part is

$$\begin{aligned} C_t &= C_f + C_i \\ &= 0.24 + 0.48 \\ &= 0.72 \text{ cents} \end{aligned}$$

Appendix: The DFA2 method

This section details the DFA2 method. All references to this appendix are available in section 9.

A short introduction:
DFA2 consists of two parts, product level and part level, Fig 48. It is suggested that the method is first used to analyse (or design) a product at product level, thereafter each part at part level. Each section in the method corresponds to an evaluation criterion and its design rules. The evaluation results are noted on data sheets (available in section A.3 and forward). Since the method, in this shape, is of a general nature, the levels of each evaluation criterion may not fit every company or every manufacturing process. The most important advantage with DFA2 is the structured working approach rather than establishing exactly correct levels for the evaluation criterion.

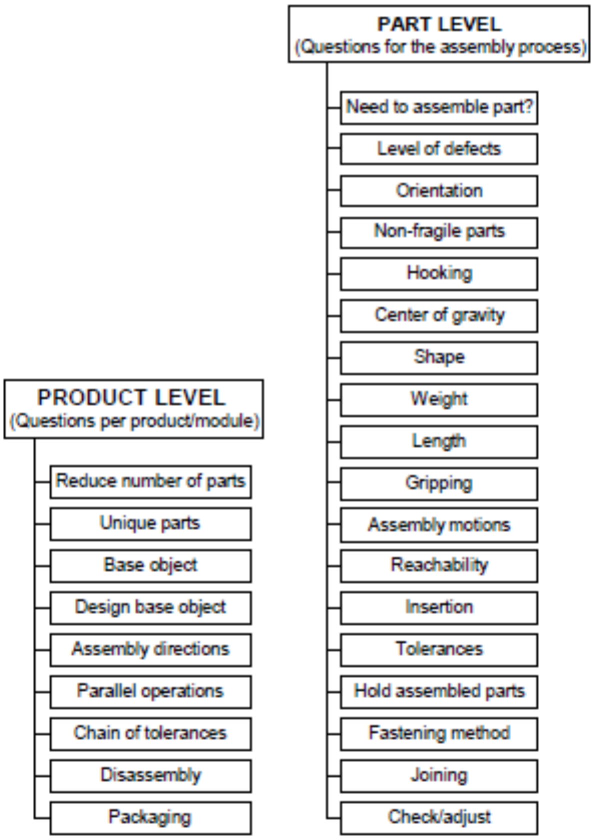


Fig 48: Overview of DFA2.

A.1 Section 1, Product level

The first section of DFA2 deals with questions or design rules for the entire object, module or product, see Fig 49.

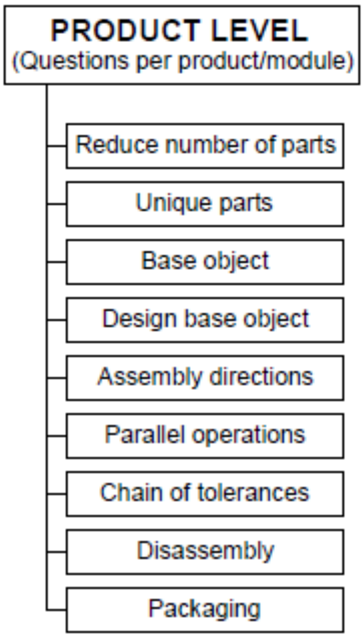


Fig 49: Overview of structure in section 1 of DFA2.

The main goal is to design a product that is as simple (non-complex) as possible, which, in turn, means that the simplest possible assembly process can be used.

By modularising a product, standard modules can be combined to a final product. Modularisation enables opportunity for controlling the number of product variants and to create a modular production system. Identical modules, parts and components might be used in more than one product family. Different product families may result in having the same base material or operations sequence, which can be used when designing a new product or production system (Hallgren *et al*, 1992).

For example, the car industry works with ”platforms” as a way of rendering product families more alike. All the common modules in a number of car variants herewith represent a platform. The platform in a Volvo and a Mitsubishi are the same, i.e. they have several common modules. By working in this manner, products are forced into a kind of standardisation. This standardisation can also facilitate manufacturing, since fewer variants need to be produced and any new product does not have to cause a new or completely rebuilt manufacturing system (Andreasen and Ahm 1986).

A.1.1 Reducing the number of parts

It is very important to reduce the number of parts (both number of variants and total number of parts) in a product (e.g. by standardisation of parts) without changing its functionality (Boothroyd, 1992; Engerstam, 1973; Holbrook *et al*, 1989; Larsson, 1986; Legrain Forsberg, 1988; Norlin, 1970; Pontén *et al*, 1986; Sackett *et al*, 1988). By using integrating production methods (e.g. casting, injection moulding or similar) the number of parts can be reduced, thus facilitating assembly (Andreasen *et al*, 1983; Boothroyd, 1992; Pontén *et al*, 1986).

Reducing the number of fastening elements can be achieved by integration of fastening elements in other parts, e.g. snap fits. Any fastening method should involve few, simple movements to facilitate automatic assembly (Pettersson, 1977). If an extra part is needed, the assembly direction and assembly process should be identical to other parts (Andreasen and Ahm 1986). If the product does not contain any fastening methods like screwing, the possibilities for disassembly, service and maintenance must be evaluated and considered (Norlin, 1970; Sackett *et al*, 1988).

An economic evaluation has to decide whether the cost for developing a special tool for producing an integrated part is higher than the profit of reducing the number of parts (Ulrich *et al*, 1993).

Evaluation support:

Reduce number of parts within each module. Too many parts contribute to large work content within the module.	
Number of parts ≤ 20	9 points
20 < Number of parts ≤30	3 points
Number of parts > 30	1 point

See Fig 50 for a graphical representation of the evaluation criterion.

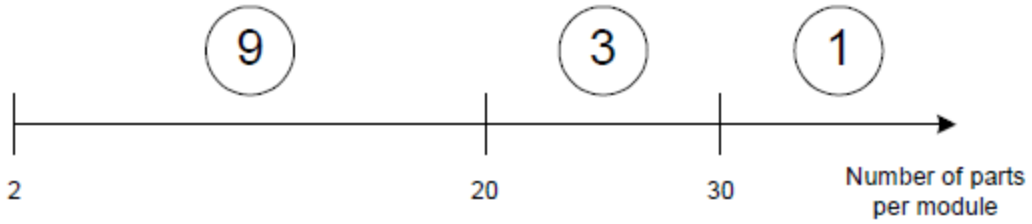


Fig 50: Graphical representation of evaluation criterion for "reducing number of parts".

A.1.2 Unique parts

The strive for using standard parts instead of using only unique parts throughout the whole product family has become common. There are several advantages with using standard parts; i.e. purchases of scale, fewer parts to administrate, and existing equipment can handle all parts etc. However, it is not possible to make an entire product from one type of part, thus it is important to balance the advantages and disadvantages between increasing and reducing number of parts.

Assume that a module among other parts contains five screws. A common approach would be to use the same sort of screw five times instead of five different screws. This could reduce the need for different feeders, grippers and so on.

If no standard parts or already existing parts can be reused, then the approach is to design the new part or component for replacing existing parts or components in different variants of the product (Larsson, 1986). This can lead to several variants being assembled in the same automatic assembly system with no need for new grippers, new fixtures or new feeders.

Evaluation support:

Proportion of unique parts is the ratio $\frac{\text{Number of unique parts in the object}}{\text{Total number of parts in the object}}$ Use only one type of part where it is possible.	
Proportion of unique parts < 40 %	9 points
40 % ≤ Proportion of unique parts ≤ 70 %	3 points
Proportion of unique parts >70 %	1 point

See Fig 51 for a graphical representation of the evaluation criterion.

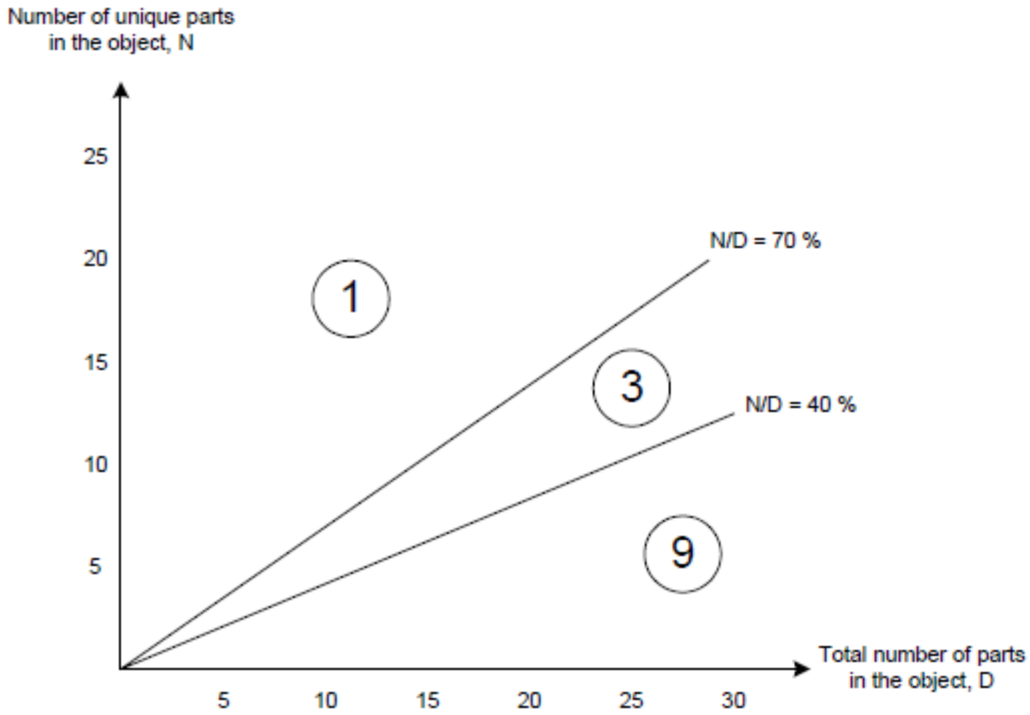


Fig 51: Graphical representation of evaluation criterion "unique parts".

A.1.3 Base object

When assembling automatically it is important to have a base object, i.e. a first part that can be used as a base for the rest of the assembly. The base object can thereby work as a fixture for the rest of the assembly operations and no separate assembly fixtures are needed (Andreasen *et al*, 1983). The base object should have as many assembly surfaces as possible in common with the rest of the components (Andreasen *et al*, 1983).

See, in particular, the section ”design base object”, for design rules on how to design the base object.

Evaluation support:

Base object is a first part that the rest of the assembly can proceed from. All assembly operations are performed on the base object, which leads to simple fixtures and few assembly directions.	
With base object.	9 points
Without base object.	1 point

A.1.4 Design base object

The base object should ideally be designed such that it may be fixed, gripped and transported without loosing its orientation (Andreasen 1988; Boothroyd, 1992; Eriksson, 1983; Pettersson, 1977; Pontén et al, 1986).

Radii and chamfers should be designed such that the base object be easily placed in its fixture. The base object should also be designed to ensure a steady placing in the fixture, see Fig 52. Holes and pegs for guiding the insertion should be conical (Norlin, 1970). A simple contour is ideal, since it facilitates fixturing (Larsson, 1986). The tolerances for the parts should be decided with regards to the base object. If any measure is larger than the tolerance, the assembly system will probably stop (Norlin, 1970).

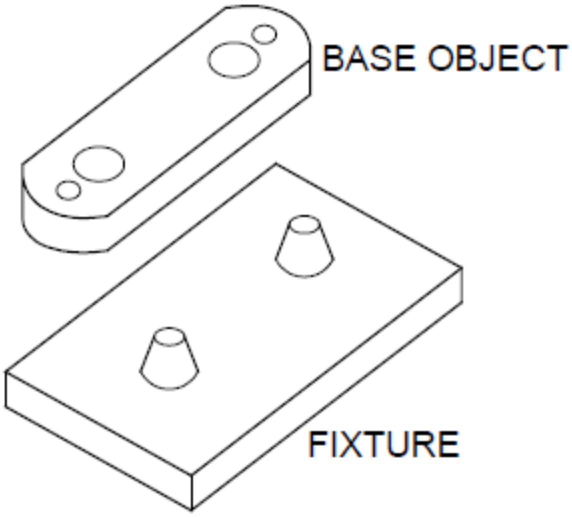


Fig 52: Features, which enables simpler fixturing.

A base object should be designed with a stable centre of gravity considering (Engerstam, 1973):

- Centre of gravity as low as possible.
- Support points as far apart as possible from one another.
- Possible holes for guiding the insertion and/or strapping elements.

Furthermore, the base object should not exhibit a larger number of composition points than what may be simultaneously assembled. The motions required should, ideally, be vertical or horizontal and no flipping or turning the base object should occur during assembly (Andreasen *et al*, 1983). Turning the assembly requires extra equipment. Furthermore, the fixture becomes more complicated since it has to be adjusted to new surfaces for location. There is also a risk that already assembled parts can lose orientation if the assembly is turned (Norlin, 1970).

Evaluation support:

Design base object for easy fixturing.	
The base object is designed in a way that no further fixture, besides for the base object itself, is needed for the rest of the assembly. The base object does not need repositioning during assembly. One assembly direction.	9 points
Assembling the module requires multiple fixtures that each has only one fixed position. The base object has to be reoriented or transferred between fixtures during assembly.	3 points
Assembling the module requires one or multiple fixtures that have several movable positions. The base object must be transferred between and/or repositioned in the fixtures during assembly.	1 point

A.1.5 Assembly directions

The product should be structured to ensure that all assembly operations occur from one direction, preferably from above (also called hamburger assembly, pyramid assembly or sandwich assembly). This assembly direction is preferable since it is easier to assemble parts from this direction and it is also possible to use gravity when inserting and fastening (Engerstam, 1973; Norlin, 1970; Pettersson, 1977).

Evaluation support:

Assembly directions, totally in the whole product/module	
One assembly direction into a fixed base object.	9 points
Two assembly directions into a fixed base object (alternatively one assembly direction in a movable base object with two different fixed positions).	3 points
Three or more assembly directions into a fixed base object (alternatively assembly in a movable base object with several different fixed positions).	1 point

A.1.6 Parallel operations

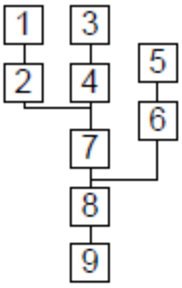
If components can be assembled in parallel, the total lead-time in the assembly shop can be reduced drastically compared to ordinary sequential assembly. A change in any component will result in a significantly limited change in the assembly system if it is being assembled in parallel (Erixon *et al*, 1994).

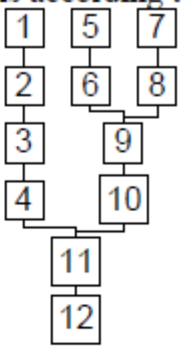
A parallel assembly process and a standardised set of parts may ensure that all the variants of the product can be produced in the final assembly. This can result in simplified logistics, less work in progress, less storage, less buffers and so on (Andreasen and Ahm 1986; Erixon et al, 1994).

A sub-module or component should not be designed as an emergency solution for an assembly problem. There should be a straight assembly sequence that does not require sub-assemblies, but gives the possibility to assemble in parallel, which in turn can shorten the lead-time.

Evaluation support:

Parallel operations according to the following example:





The assembly sequence to the left has $\frac{7}{9}$ parallel operations;

the sequence to the right has $\frac{10}{12}$ parallel operations.

> 50 % parallel operations	9 points
0 % < parallel operations ≤ 50 %	3 points
No parallel operations.	1 point

See Fig 53 for a graphical representation of the evaluation criterion.

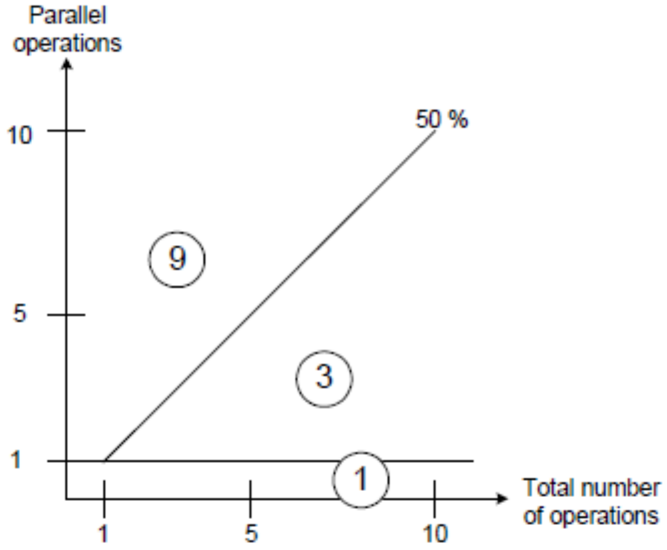


Fig 53: Graphical representation of evaluation criterion for "parallel operations".

A.1.7 Chain of tolerances

When assigning tolerances to a part there is a need for taking into consideration, for example, orientation and insertion of the part. Automatic assembly systems have fixed measures for grippers, fixtures etc., which means that all tolerances must be accordingly adjusted. If any measure is outside these tolerances the assembly system will probably stop (Norlin, 1970). Avoid chains of tolerances; see Fig 54, since it means that a sum of multiple tolerances, which leads to a large risk for having assembly difficulties (Engerstam, 1973; Larsson, 1986).

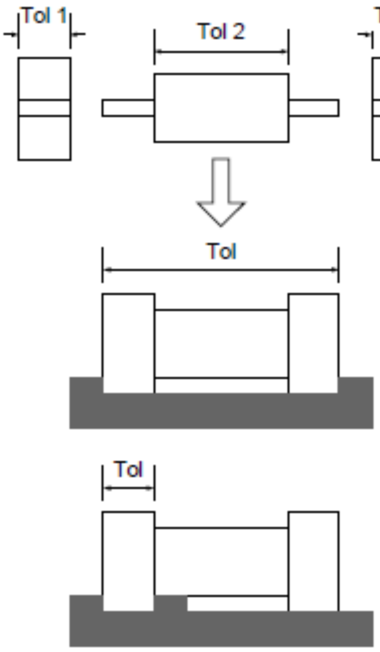


Fig 54: Avoid chains of tolerances.

Evaluation support:

Chains of tolerances should be minimised to have a more reliable assembly process.	
No chains of tolerances significant for the assembly process. Only the tolerance of each individual part is significant.	9 points
There are chains of two tolerances significant for the assembly process in the module.	3 points
There are chains of three or more tolerances significant for the assembly process in the module.	1 point

A.1.8 Disassembly

Few parts and simple fastening methods result in easier, and thereby cheaper, disassembly (Wittenberg, 1992). Snap fits can be disadvantageous for disassembly if they are not designed to simplify disassembly, service and maintenance. Standardisation of fastening elements is important since e.g. fewer types of screws requires fewer types of tools, which simplifies disassembly and service.

Liquids that are hazardous for health or pollution should be avoided (Wittenberg, 1992). Any hazardous substances in a product lead to difficulties in disassembly and re-use of the product.

Valuable parts must be designed to be easily removed (Wittenberg, 1992). These parts can then easily be recycled or re-used in another product.

A large range of materials in a product might cause problems. Use preferably only a few different types of material, which simplifies sorting (e.g. standardisation of plastics) (Wittenberg, 1992).

If a product is easy to disassemble, it will also be easy to adjust (Engerstam, 1973). A product that is easy to disassemble will also be prepared for service. Consider, in this tool, disassembly as ”reversed assembly” for each part and operation according to the same criterion as for normal assembly. This approach entails that for disassembly this tool can be used for all questions at object level and for ”fastening method”, ”joining” and ”fit in” under part level.

Luttropp (1997) divides products into five families:

1 Hamburger design, e.g. mobile phone or toy car. The product has at least two halves that can be separated and then sorted. The joining between the different halves is critical.
2 Shell design, e.g. flashlight, ammunition or electrical toothbrush. The product has a closed shell structure that has to be destroyed before parts can be sorted. Hamburger designs that are glued or welded together are included in this group.
3 Rod design, e.g. screws, pliers or screwdrivers. The product is mostly made of one or several pieces of the same homogenous material and can be sorted immediately.
4 Twin design, e.g. water tap, jewellery, or car wheel. The product has more than one important sorting object on the first sorting level and the loadcase for this first level should be designed with great care. The product is first separated and then sorted.
5 Dressed design, e.g. toaster, computer or car. The product has a carrier on which nearly all parts are mounted and has to be separated before sorting. There is often a lot of empty space inside the product and when designers try to make the product smaller it can often be transformed into a hamburger design.

No evaluation criterions for disassembly were found directly applicable or industrially verified.

A.1.9 Packaging

The product should ideally be packed for transportation to customer in a way that requires a minimum of material and space. If there is a base object, the fixture used during assembly can probably provide suggestions for how to pack the product in a reliable way.

If the customer is going to use the product as a component in his assembly (e.g. products delivered by sub-contractors) process it might be of importance to make sure that the product does not lose orientation during transport. One must ensure that there are surfaces both for packing and un-packing.

No evaluation criterions for packing were found directly applicable or industrially verified.

A.2 Section 2, part level

Section 2 of DFA2 deals with questions and design rules for each part in the product. The questions are as detailed in Fig 55.

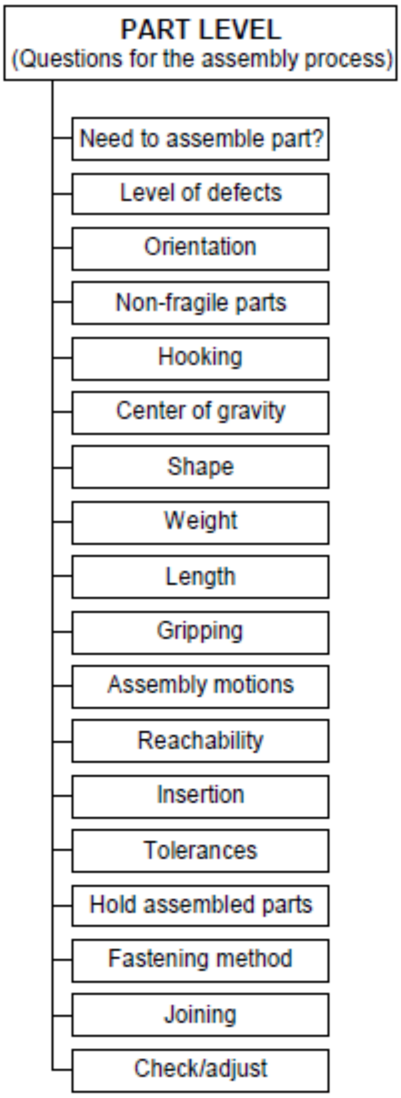


Fig 55: Overview of the structure in section 2 of DFA2.

All the questions are general for any part. The main goal is to design a product that is as simple (non-complex) as possible, but still fulfils the intended functional requirements. This may enable the implementation of the simplest possible assembly process.

NOTE! Time estimations are based on the use of an ideal manual assembly time of three seconds per part (Boothroyd and Dewhurst, 1987). All estimated times in DFA2 are added to these three seconds.

A.2.1 Need to assemble part?

The basic principle is to avoid assembly if possible (Eversheim *et al*, 1982). The aim is to try to integrate parts and thus minimise the number of parts in the product.

According to the Boothroyd & Dewhurst (B&D) method there are three questions for validating the existence of each part in a product (Boothroyd, 1992):

1. Does the part move, relative to other already assembled parts during normal use of the finished product?
2. Does the part have to be of other material than already assembled parts, or isolated from them?
3. Does the part has to be separate from already assembled parts because assembly or disassembly otherwise is impossible?

If any of these questions are answered with a ”yes”, there is an indication that the part needs assembling. If all three questions are answered with ”no” the part has no reason to exist and should be integrated with others or eliminated (Boothroyd, 1992). The first part in an assembly should be a base object and must by definition exist. Thereby, the base object is the target of comparison for part number two regarding question number one and two.

Reasons for parts to be separate might include simplified service and maintenance. There might also be restrictions in the assembly process that does not allow integration of parts (Holbrook *et al*, 1989). It is a good advice to consider benefits and disadvantages in eliminating assembly or increasing variants of parts.

Lin and Hsu, (1995) suggests another approach for part-count reduction as shown in Fig 56. The difference to the approach suggested by Boothroyd (1992) is that Lin and Hsu also include the functionality of the part. This means that each part has to support a function in the product to avoid being eliminated or integrated.

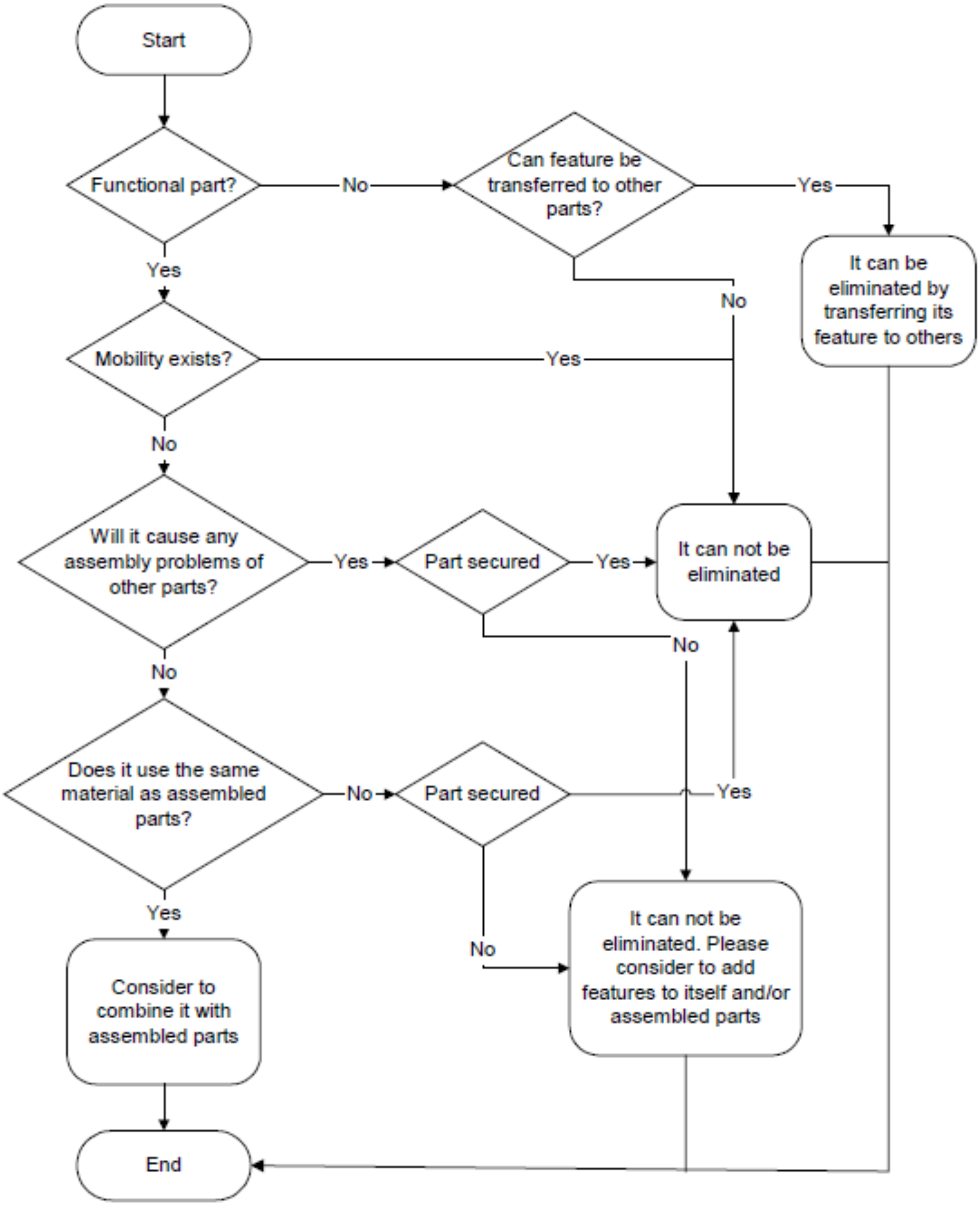


Fig 56: Graphical representation of design rules for eliminating parts (Lin and Hsu, 1995).

Evaluation support:

Need to assemble parts? The questions described above have to be answered for evaluation. A part that does not perform a relative motion has to be of another material or must be separated in order for assembly/disassembly reasons to be eliminated or integrated.	
The part has reasons for being separate (at least one ”yes” to the three questions)	9 points
The part should be eliminated/integrated (all three questions answered with ”no”) but the part is still a separate part in the product.	1 point

A.2.2 Level of defects

Bought standard parts must be reliable enough to eliminate unscheduled stops in an automatic assembly system because of problems in feeders, gripping- or fitting operations. The level of acceptance should be decided by an evaluation of the price of parts with higher quality and costs due to unscheduled stops in the assembly system, (Pettersson, 1977). Parts and components that are produced within the company must also have the same low level of defects.

Acceptable level of defects regarding, e.g. the quality of screws, ought to be at a rate below 0,1 % (less than one defect per 1000 parts) for being suitable for automatic assembly (Langmoen, Ramsli, 1983).

Evaluation support:

Level of defects of parts that are to be assembled. Geometric defects that might cause unscheduled stops in an automatic assembly system should be avoided, or parts with functional defects.	
$P < 0{,}1\ \%$	9 points
$0{,}1\ \% \leq P \leq 1{,}5\ \%$	3 points
$P > 1{,}5\ \%$	1 point

See Fig 57 for a graphical representation of the evaluation criterion.

Fig 57: Graphical representation of the evaluation criterion "level of defects".

A.2.3 Orientation

The need for orientation should be minimised (Eversheim *et al*, 1982). When orientation is needed, the parts should be designed for as easy an orientation as possible to ensure high reliability in e.g. feeders. There are several ways of designing for ease of orientation, e.g. using the shape or the centre of gravity of the part (Pontén *et al*, 1986).

One way of eliminating the need for orientation is to have parts delivered oriented. The supplier has the part exactly orientated during the manufacturing process and it is both expensive and time consuming to re-orient a part. If the supplier instead of throwing the part in bulk, places the part in a fixture, a magazine or something similar the orientation can be maintained into the assembly process. For example, the electronics industry used the technique of having parts on tape, i.e. oriented in small boxes in a plastic film with a lid.

Evaluation support:

Orientation. If a part could be delivered oriented, cost and uncertainty in the process would be eliminated.	
No need for re-orientation of the part	9 points
Part is partly orientated, but needs final orientation	3 points
Part orientation needs to be re-created.	1 points

A.2.4 Non-fragile parts

The feeding of parts is often regarded as a problem area. Some say that when the feeders are working, then the whole assembly system is working. Many of these problems are due to the fact that very few parts are designed for automatic feeding. There are many benefits to be gained in designing for easy feeding, identification and for placing in magazines (Ahlbom *et al*, 1982; Arnström *et al*, 1984; Gröndahl *et al*, 1983; Pontén *et al*, 1986; Boothroyd *et al*, 1979).

Feeding should be as simple as possible. The most preferable approach is to include the part fabrication process in the assembly system (e.g. producing springs only when they are needed for assembly) in order to maintain the orientation of the part (Rooks, 1987).

Ideally, one should design the product with as few fasteners as possible, and let variants of the same part have uniform contact surfaces that are used in the assembly process. This can reduce the need for several feeding and assembly units (Larsson, 1986).

Vibratory feeders are widely used as feeding solution, but they require non-fragile parts with centre of gravity and shapes that can be used for such feeding. Too small tolerances can cause the feeders to stop and thereby the rest of the system (Norlin, 1970). Surface tolerances for parts, which an assembly system does not have to consider, should be avoided when possible (Andreasen *et al*, 1983). High friction for a part can be a drawback since e.g. gliding driven by gravity will be difficult (Engerstam, 1973).

Evaluation support:

Feeding often requires **non-fragile parts**	
Part is not fragile	9 points
Part can be scratched, which is not acceptable.	3 points
Parts can not fall without deforming	1 point

A.2.5 Hooking

Parts should be provided with properties that makes it impossible for the parts to nest, tangle or hook into similar parts when storing them in bulk (Boothroyd, 1992; Eversheim *et al*, 1982), see Fig 58. One way of accomplishing this is to avoid projecting shapes and parts with holes, or making the holes very small (Engerstam, 1973; Mohan, 1987).

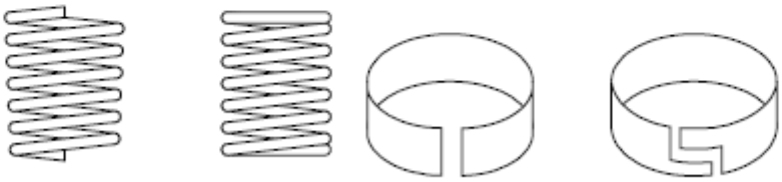


Fig 58: Simple changes may eliminate the risk of parts hooking into each other (Norlin, 1970).

The materials in the part can also have negative effects and it is, for example, a good idea to avoid materials with residual magnetism, sticky materials and so on (Engerstam, 1973).

One effective way to avoid this is to copy the electronics industry, where parts are often fed in tape or ribbons, see Fig 59. This facilitates feeding enormously (Andreasen *et al*, 1983).

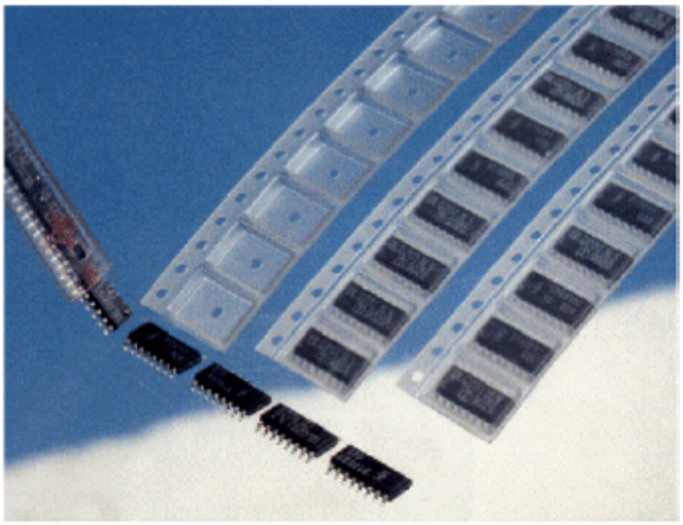


Fig 59: Parts delivered on tape will simplify feeding and orientation.

Evaluation support:

State during feeding, hooking: There should be no risk of parts hooking into each other for example in a bulk vibration feeder.		**Man. ref. time**
Parts cannot hook to each other and tangle up.	9 points	0 s
Parts can hook to each other and tangle up.	1 point	0,7 s

A.2.6 Centre of gravity

The following aspects should be considered regarding the centre of gravity in a part:

- The centre of gravity should give the part a very stable state of rest (Engerstam, 1973)
- The centre of gravity should be very eccentrically or in another special position (Engerstam, 1973).

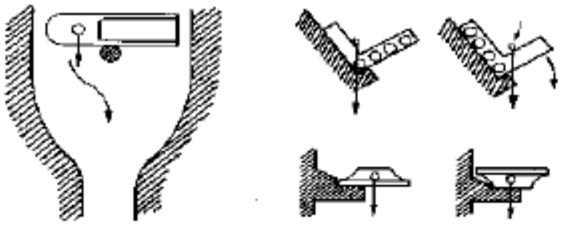


Fig 60: Examples of how centre of gravity can be used for feeding.

Using centre of gravity in feeders is one of the most common ways of separating parts from each other. This is the reason why the assembly process can be significantly simplified if the centre of gravity is placed in a way similar to that illustrated in Fig 60.

Evaluation support:

Centre of gravity for the part should be positioned for use in feeding. Drop the part repeatedly on a table to determine its state of rest. Simple orientation often means reliable and cost effective feeding.	
Part has a stable state of rest and orients itself with correct side upwards.	9 points
Part has a stable state of rest, but orients itself with wrong side upwards.	3 points
Part has an unstable state of rest and orients itself with different sides upwards.	1 point

A.2.7 Shape

To facilitate orientation the following aspects regarding part shape should be considered:

- Shapes that can be used as means for orientation should be placed in the outer contours and preferably well visible (Engerstam, 1973; Eversheim *et al*, 1982).
- Include obstacles for rotation in the contour (Engerstam, 1973).
- Surfaces on the part, e.g. a metal sheet with a bent edge on one side to ensure that the part can be hung (Andreasen *et al*, 1983).
- In cases when parts are going to be identified with a vision system, there is sometimes a need to have surfaces with clear contrasts (Hallgren *et al*, 1992; Pontén *et al*, 1986).

- Symmetrical parts (Andreasen 1988; Pettersson, 1977; Pontén *et al*, 1986), or very asymmetrical (Pontén *et al*, 1986). If a part cannot be symmetrical (which is preferred) it is sometimes better to make it more asymmetrical (Andreasen *et al*, 1983; Boothroyd, 1992; Engerstam, 1973; Holbrook *et al*, 1989; Mohan, 1987; Norlin, 1970; Pontén *et al*, 1986).

The part should have as few vital orientations as possible to simplify orientation. Fig 61 shows an example of how a hole influences the number of vital orientations of a part. To the left, the part has to be oriented not only with one of the sides, but also with one of the edges to find the hole. The next part has the hole in the centre of one side and the probability for orientating the part correctly is 1/6. The two parts to the right are very easy to orient, and the probability for orientating the part correctly is one (Norlin, 1970).

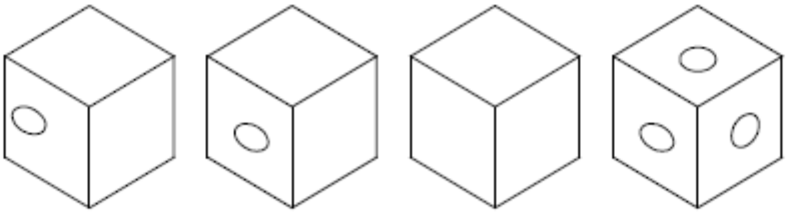


Fig 61: Example of parts with different number of vital orientations (Norlin, 1970).

Smaller asymmetries in a part should not be bigger than 0,1 D (Diameter) or 0,1 L (Length) to simplify orientation in a feeder.

Symmetries can be divided into two classes, α-symmetry and β-symmetry (Boothroyd and Dewhurst, 1987), see Fig 62. The α-symmetry refers to how many degrees the part has to be rotated around one of its ends to regain the same geometrical properties it had in the first position. The β-symmetry refers to how many degrees the part has to be rotated around its axis of insertion to regain the same geometrical properties it had in its first position.

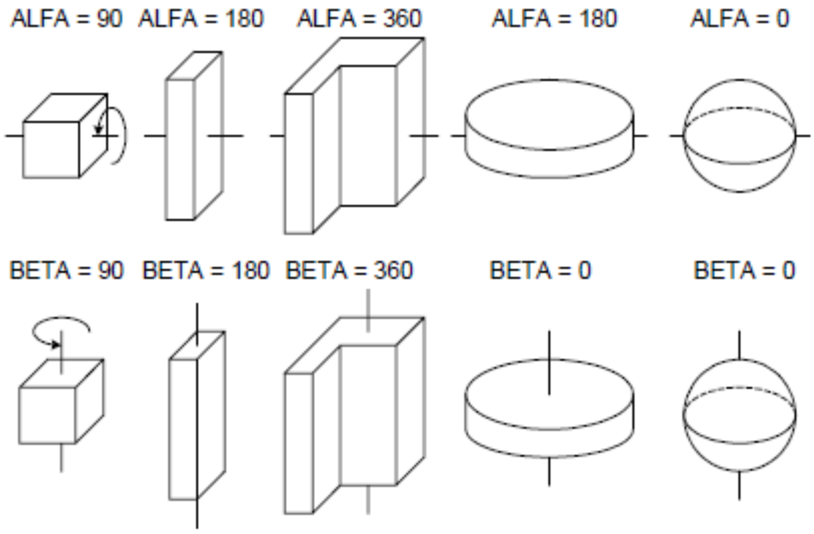


Fig 62: Alfa and beta symmetries for different parts.

Evaluation support:

Shape of a part is the sum of α- and β-symmetry. Symmetrical parts decrease the need for unique orientation.		**Man. ref. time**
$\alpha + \beta < 360$	9 points	0 s
$360 \leq \alpha + \beta < 540$	3 points	0,6 s
$540 \leq \alpha + \beta \leq 720$	1 point	0,9 s

See Fig 63 for a graphical representation of the evaluation criterion.

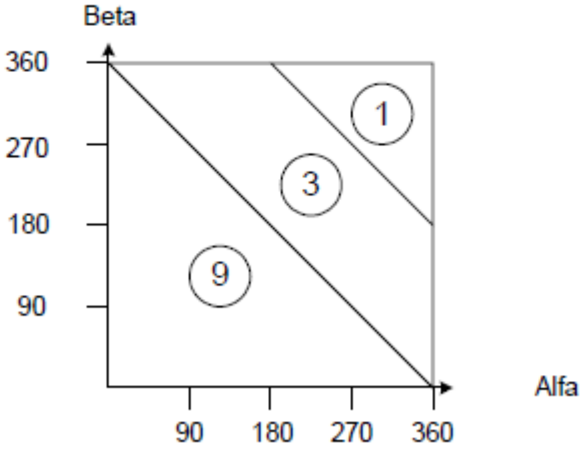


Fig 63: Graphical representation of the evaluation criterion "shape".

A.2.8 Weight

Minimise the weight of the product, since it allows simpler and less expensive assembly equipment (Sackett *et al*, 1988). Since the relation between high precision, fast movements, weight of the part and the price of the assembly equipment are very coupled, it can be wise to avoid heavy parts if possible. Heavy parts mean larger and stiffer equipment and can also mean risk for impact stress, (Engerstam, 1973). Low weight of parts can also mean lower handling- and fitting times, (Holbrook et al, 1989). However, with too low a weight there might be problems with adhesion forces.

Evaluation support:

Weight, of the part. This affects the choice of equipment.		**Man. ref. time**
$0{,}1\ g \le G \le 2\ kg$	9 points	0 s
$0{,}01\ g \le G < 0{,}1\ g$ or $2\ kg < G \le 6\ kg$	3 points	1,5 s
$G < 0{,}01\ g$ or $G > 6\ kg$	1 point	3 s

See Fig 64 for a graphical representation of the evaluation criterion.

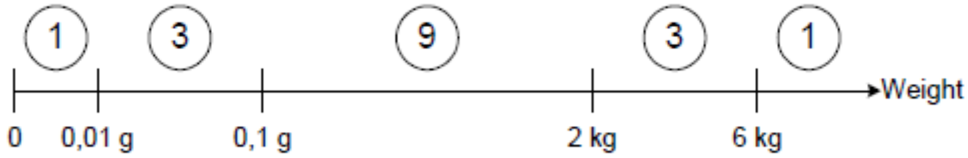


Fig 64: Graphical representation of the evaluation criterion "weight".

A.2.9 Length

The length of a part affects the design of e.g. feeders, grippers, fixtures etc. An assembly cell must also be adjusted to the size of parts going that are to be assembled, whereas long parts might require extra or special equipment.

Evaluation support:

Length. The length of a part is the longest side of an enclosing prism. This affects the choice of equipment.		**Man. ref. time**
$5\ mm \le L \le 50\ mm$	9 points	0 s
$2\ mm \le L < 5\ mm$ or $50\ mm < L \le 200\ mm$	3 points	0,7 s
$L < 2\ mm$ or $L > 200\ mm$	1 point	1,2 s

See Fig 65 for a graphical representation of the evaluation criterion.

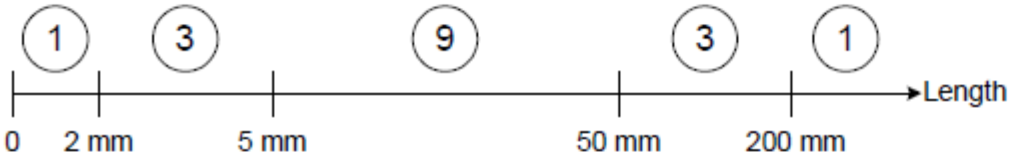


Fig 65: Graphical representation of the evaluation criterion "length".

A.2.10 Gripping

As a general rule, all parts must be easy to grip in automatic assembly since a gripper is less flexible and usually requires more space than the human hand (Hallgren *et al*, 1992; Norlin, 1970). If a part can be assembled with thumb and index finger it can be easy to grip with a mechanical gripper. To resemble the conditions for a robot trying to grip a part, imagine a human assembling with one arm behind the back, blindfolded and the free arm for gripping the part is equipped with a boxing glove.

Grippers are usually relatively expensive since they are often specially made for picking one specific part. If many parts can be gripped with the same gripper it will be economically beneficial. Special surfaces for gripping parts are not always needed, but sometimes necessary in order to avoid multiple grippers (Eversheim *et al*, 1982). The surface for gripping should be possible to use as final positioning of the part when it is gripped. Use different surfaces for gripping and positioning parts in feeders (Hallgren *et al*, 1992).

The outer and inner contours of parts should, ideally, be gripper friendly with defined gripping surfaces. The ability to grip a part increases if the part is symmetrical. Small parts are more difficult to grip than larger parts (Larsson, 1986). Compact, non-slippery and parts with constant shape are easy to grip (Boothroyd, 1992; Holbrook *et al*, 1989; Norlin, 1970).

Round parts should ideally be designed with the centre line to be gripped coaxial to the gripper or the centre line of the robot (Andreasen and Ahm 1986). The centre of gravity for the part should be as close to the gripping position as possible (Larsson, 1986). Use surfaces for gripping that ensure that the part always is positioned the same way (Hallgren *et al*, 1992).

Screws with a long cylindrical body (length > 1,5 diameter) or long cylindrical head are easier to align compared to screws with a short body or head, since it facilitates the fitting process (Pettersson, 1977).

Equally large parts to be assembled should ideally be designed in one sequence, in order to lower the number of gripper changes, which saves time and money (Pontén *et al*, 1986). Changing a gripper does not add any value to the product.

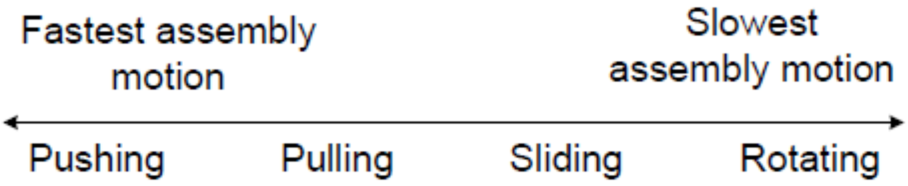
Evaluation support:

Gripping is simplified if there are defined surfaces with determined geometry for use. Soft parts, e.g. plastics and rubber, are difficult to grip with a mechanical gripper since the parts can deform from the forces in the gripper.		**Man. ref. time**
Part has surfaces for gripping and can be gripped with the same gripper as the previous part.	9 points	0 s
Part has surfaces for gripping, but requires a new, unique gripper that could not be used for the previous part. Part has surfaces for gripping and can use the same gripper as used earlier, but not for the previous part.	3 points	0 s
Part has no surfaces for gripping or is flexible.	1 point	1 s

A.2.11 Assembly motions

All parts should be possible to assemble with one hand (Larsson, 1986). Manual assembly with one hand resembles automatic assembly.

One should strive for simple assembly motions when choosing fastening method (Engerstam, 1973; Legrain Forsberg, 1988; Pettersson, 1977). In Fig 66 different assembly motions are compared regarding their relative assembly speed. Fastening elements, or parts that are assembled using a combination of these motions, should be avoided. Pushing a part in place is preferable.



Evaluation support:

Assembly motions (during insertion) will be faster, the simpler they are.		**Man. ref. time**
Assembly motion consists of a pressing motion with one part being assembled to already assembled parts.	9 points	0 s
Assembly motion consists of further motions than pressing motion with one part.	3 points	0,5 s
Assembly motion is an operation with multiple movable parts that simultaneously are assembled to already assembled parts with other motions than pressing motion.	1 point	0,8 s

A.2.12 Reachability

There must be space for grippers and assembly tools around the part to reach for insertion and any special operations (Larsson, 1986; Pontén *et al*, 1986). Degrees of freedom in movements and assembly area should also be considered (Andreasen and Ahm 1986). Obstacles for insertion are to be avoided since they only cause complex movements or tools, which take time and can be difficult to programme.

Obstacles for special equipment, such as screwdrivers, must be avoided. It is also preferable that multiple screwdrivers can work in parallel to shorten the assembly time (Romnäs, 1972). Furthermore, it is vital to ensure that the space for further assembly is not limited (Boothroyd, 1992) see Fig 67.

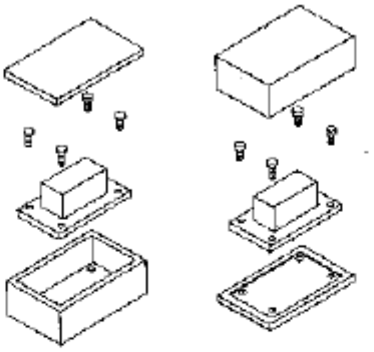


Fig 67: Simplify reachability for following operations.

Evaluation support:

Reachability for assembly operation should not be limited. All parts should be inserted in the same direction.		**Man. ref. time**
No restrictions or problems for reaching when fitting the part.	9 points	0 s
Reachability is limited. Other assembly direction than previous part.	3 points	4,5 s
Reachability is limited and requires special tools or grippers to perform the assembly operation. Other assembly direction than previous part.	1 point	7 s

A.2.13 Insertion

No parts, fixtures or anything else must act as an obstacle to the insertion of a part during the assembly process. The consequences of an obstacle are that the assembly system will be forced to perform more complex movements, which prolongs the assembly time and the programming time. The sandwich assembly principle (all parts are assembled on top of the previous) is desirable if there is a base object to start assembling from. Simple assembly motions and no obstacles while inserting parts can reduce assembly time.

The insertion of several parts at the same time should be avoided. If several parts have to be inserted simultaneously, they should have guiding surfaces to facilitate the assembly process (Andreasen *et al*, 1983; Boothroyd, 1992; Pontén *et al*, 1986). Parts that are symmetrical around their insertion axes are preferable, since this eliminates the need of a unique orientation for insertion (Boothroyd, 1992).

A peg-in-hole insertion operation is no problem for a human assembly worker, since we can use our senses. An automatic assembly unit has to be programmed to have these abilities, which takes time. The easiest way is to simplify the product to have a less complex insertion process. This can be done by the use of chamfers for parts that are to be inserted (Andreasen and Ahm 1986; Holbrook *et al*, 1989; Norlin, 1970), or by using guiding surfaces (Andreasen *et al*, 1983; Boothroyd, 1992), see Fig 68. It is sometimes wise to leave a small gap to compensate for tolerances that are not ideally derived (Holbrook *et al*, 1989; Pontén *et al*, 1986). Friction should be minimised between assembled parts, since high friction might require more sophisticated and expensive assembly equipment (Boothroyd, 1992; Larsson, 1986).

The following design aspects for screws can increase the availability for an automatic assembly system:

- Chamfered holes can prevent the first threads from being smashed.
- Holes with cylindrical openings are easier to fit into if the cylindrical section of the screw is fitted before the threads start working (Pettersson, 1977).
- Avoid assembling short screws in tight holes (Pettersson, 1977).

The design of a screw is especially important if the screw is short. A longer screw is simpler to align by the assembly equipment (Arnström *et al*, 1982). Screws with conical (half-dog point) or rounded ends, as well as pins (full-dog point), are easier to fit into (Norlin, 1970). A conical or chamfered end on a screw makes it easier to fit in and reduces the risk for damaging the threads (Pettersson, 1977). A pin reduces the risk for fitting the screw oblique, but can cause problems at the bottom of holes (Arnström *et al*, 1982). A Philips driver can help align a screw (Pettersson, 1977).

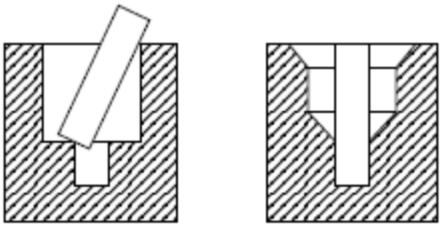


Fig 68: Chamfers may simplify insertion.

Evaluation support:

Insertion is simplified if there are chamfers or other guiding surfaces, e.g. an edge that can be used as a mechanical guide for the fitting operation, in the part.		**Man. ref. time**
Chamfers exist to simplify the insertion operation.	9 points	0 s
No chamfers, but other guiding surfaces simplifies the insertion operation.	3 points	0,2 s
No chamfers or other guiding surfaces.	1 point	0,5 s

A.2.14 Tolerances

High tolerances for parts should, where possible, be avoided since they entail higher manufacturing costs (Andreasen and Ahm 1986). For e.g. a fitting operation, the tolerance decides what equipment is needed.

Evaluation support:

Tolerances for insertion operations, for example the distance between a peg and a hole during insertion or whenever there is manipulation of parts relative to each other. Too small tolerances increases the risk of failure during insertion and the system could stop.		**Man. ref. time**
Tolerance > 0,5 mm	9 points	0 s
0,1 mm ≤ Tolerance ≤ 0,5 mm	3 points	0,2 s
Tolerance < 0,1 mm	1 point	0,4 s

See Fig 69 for a graphical representation of the evaluation criterion.

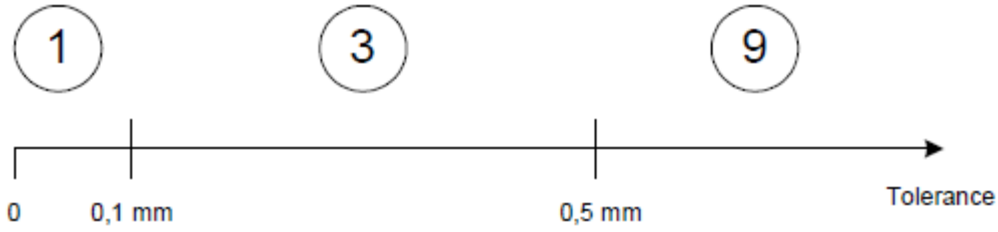


Fig 69: Graphical representation of the evaluation criterion "tolerance".

A.2.15 Holding assembled parts

When the part is assembled in its place it should maintain its position without any external assistance (Boothroyd, 1992; Engerstam, 1973; Larsson, 1986), see Fig 70. This is especially important since extra equipment for holding parts requires space, increases costs and reduces the reliability of the system. The need for holding down parts may be minimised by using e.g. snap fits, secure placing of the centre of gravity, support, etc.

Using temporary support or holders in assembly can be very expensive. Therefore, design parts to be stable during assembly and can stand up without support (Holbrook *et al*, 1989). Parts should only have one stable state of rest

(Eversheim *et al*, 1982). If parts are not stable, the following operations will be less reliable.

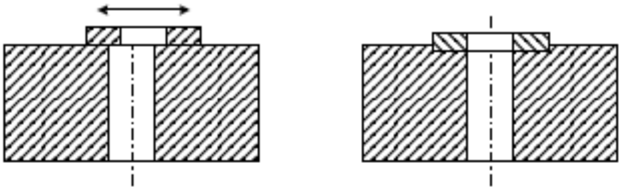


Fig 70: Parts should be able to keep orientation and position after being assembled.

Evaluation support:

Holding assembled parts is necessary if parts cannot keep orientation and position after assembly. Parts that are secured immediately, i.e. does not lose orientation or position if the assembly is turned up side down, ensures a more reliable assembly process.		**Man. ref. time**
Part is secured immediately at insertion.	9 points	0,s
Part keeps orientation and position, but is not secured.	3 points	0 s
Part must be held after insertion to keep orientation and position.	1 point	4 s

A.2.16 Fastening method

The numbers of fastening elements in a product usually determine the assembly time and should thereby be minimised. Number of fasteners can be minimised by integration of fastening elements in other parts (e.g. snap fits). It can also be accomplished by means of standardisation of fasteners. A product could contain fewer types of screw dimensions, screw types or different types of fasteners (Andreasen and Ahm 1986; Boothroyd, 1992; Engerstam, 1973; Holbrook *et al*, 1989; Larsson, 1986; Legrain Forsberg, 1988; Norlin, 1970; Pettersson, 1977; Pontén *et al*, 1986).

Assembling fasteners should entail few and simple motions to facilitate automatic assembly (Pettersson, 1977). If an extra fastener is needed, its assembly direction and assembly process should be identical to other fasteners (Andreasen and Ahm 1986). Snap fits can be designed for disassembly and service see Fig 71.

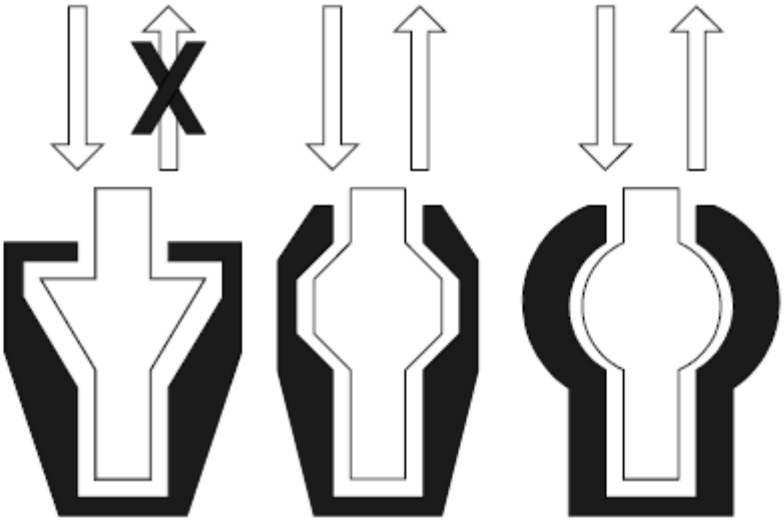


Fig 71: Examples of designing snap fits. The examples in the middle and to the right are suitable for disassembly and service.

The most preferable solution should be evaluated from the cost for developing a special tool, manufacturing integrated parts or eliminating parts (Ulrich *et al*, 1993).

Evaluation support:

Fastening method. How is the analysed part itself fastened?		**Man. ref. time**
No fastening method at all (the part is placed on or in an already assembled part), or only snap fits.	9 points	0 s
Screwing- or pressing operations.	3 points	3 s
Adhesive fastening methods, welding, soldering, riveting	1 point	8 s

A.2.17 Joining

Snap fits should be used where possible (Holbrook *et al*, 1989). The use of snap fits eliminates feeding of fastening elements and renders the joining of parts simple and fast. The benefits of using snap fits must be compared to potential problems in disassembly and orientating the part.

A part should be designed for easy and quick fitting, joining and securing (Larsson, 1986). This would simplify automation of the assembly process since many operations are simplified, the need for holding assembled parts is reduced and no separate tools such as screwdrivers are needed.

All joining, e.g. screwing, should be from the same direction, preferably from above. Gravity helps in the fitting and joining process of e.g. screws (Pettersson, 1977).

Evaluation support:

Joining: Extra equipment or tools (e.g. press tools or screwdrivers) should not be needed to fit the part into place.		**Man. ref. time**
No extra equipment is needed.	9 points	0 s
Extra equipment or tools are needed to fit the part in place and the extra operation is performed in assembly direction.	3 points	2 s
Extra equipment or tools are needed to fit the part in place and the extra operation is not performed in assembly direction.	1 point	3 s

A.2.18 Check/adjust

The product should be designed to have surfaces and points of reference from which the assembly starts (Norlin, 1970). Points of reference should be used throughout the whole production and also be points for positioning during fabrication.

Existing holes, edges, surfaces or shapes can be chosen for reference points (Pontén *et al*, 1986). Avoid placing reference points in parts that are likely to be changed. If there is a huge risk for redesign, in which the reference points will be moved, the whole process might be affected. Points of reference should be placed as far apart as possible (Larsson, 1986). Since points of reference are used for defining coordinate systems when programming the system they should be as far apart as possible to reduce sensitivity.

Points of reference and support for parts should, if possible, be in the same line (Larsson, 1986). Points of reference should be accessible as control points after assembly (Larsson, 1986). This can ensure easier and more reliable error detection and possibility to adjust.

A rule of thumb is to avoid any design that requires adjustments during assembly (Boothroyd, 1992). Adjustment operations are difficult and expensive to automate. In cases where adjustment cannot be avoided, design the product to have the adjustments performed as a separate operation after the automatic assembly. Parts should be designed to ensure clear controls with as simple sensors as possible (Pontén *et al*, 1986).

Designing parts that eliminate the risk of assembling the wrong way is called ”poka yoke” in Japanese (Holbrook *et al*, 1989; Larsson, 1986). It should be impossible to assemble the product in a wrong way. If parts still are assembled the wrong way it should be very visible in a finished product and the product should be refused for packaging. By designing products that are impossible to assemble the wrong way the need for checking and adjustments will be minimised, if not eliminated.

Evaluation support:

Check/adjust is not needed if the product is designed according to ”poka yoke”, i.e. it is impossible to assemble the part in more than one way. Every extra operation for checking or adjusting is extra work and a symptom of a design that is not quite satisfactory.		**Man. ref. time**
Unnecessary to check if part is in place.	9 points	0 s
Necessary to check if part is in place or assembled correctly.	3 points	1 s
Necessary to adjust or re-orient part.	1 point	2 s

A.3 Data sheet for product level

	PRODUCT LEVEL							
	Reduce number of parts	Unique parts	Base object	Design base object	Assembly directions	Parallel operations	Chain of tolerances	**SUM**
Objekt/Produkt/Modul								

Assembly index, A, is calculated through: $\frac{\text{Total sum}}{\text{Maximum points}}$ $A = \frac{\qquad}{63} = \quad \%$

A.4 Data sheet for part level

	Part level																			
List of all parts	Number of identical parts	Need to assemble part?	Level of defects	Orientation	Fragile parts	Hooking	Centre of gravity	Shape	Weight	Length	Gripping	Assembly motions	Reachability	Insertion	Tolerances	Holding assembled parts	Fastening method	Joining	Check/adjust	**SUM**
																			TOTAL SUM:	

Assembly index, A, is calculated through: $\frac{\text{Total sum}}{\text{Maximum points * number of parts}}$

$A = \frac{\qquad}{162 *} = \quad \%$

A.5 Data sheet for cost analysis

Part/module/product	

Supposed manu-facturing volumes	
Number of parts in the product	
Materials cost	
Development costs	
Item cost	
Variant cost	
Cassation	
Guarantee costs	
Other	

Part level, within system borders (focusing on the part alone during analysis).	Description						
	Is the activity needed? (*)						
	Machine time [S]						
	Labour time [S]						
	Setup time [S]						
	Tools [SEK]						
	Manufacturing equipment[SEK]						
	Comment						
System level, outside system border (the observer is standing outside the system during analysis).	Capacity [units/time]						
	Flexibility [units]						
	Maintenance [SEK]						
	Floorspace [M2]						
	Comment						

*** Is the activity needed?**

1. Does the activity add **customer value** to the final product?

2. Is the activity needed to fulfil an external **requirement** (authorities, rules and regulations etc)?

3. Is the activity absolutely necessary to **manufacture** the product?

If all three questions are answered with "no", then there is no need for the activity. If one or more questions are answered with "yes", then the activity is needed.