Reduction of Acquisition Time Through New Design for Assembly Heuristics

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EDRC 24-1*2-94

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ABSTRACT

Rearranging component positions and orientations inside products can reduce the acquisition times associated with handling distance and component orientation. Modeling the acquisition process with an information-based Design for Assembly methodology identifies and quantifies acquisition difficulty for manual and automatic processes. Heuristics based on evaluations of acquisition difficulty guide the relocation and orientation of components inside the product to reduce assembly time. Since acquisition time averages one third of the total assembly time, significant improvements are shown to be feasible.

1. INTRODUCTION

Assembly tasks occupy approximately 50 percent of total product production time [Owen 1985] and labor costs are between twenty and thirty percent of total product costs [Whitney/Nevins 1989] [Owen 1985]. Reduction of assembly times will consequently have potentially significant effects in reducing assembly costs.

Given that a large fraction of product assembly time is taken in acquisition of the components being assembled [Sturges 1989a], a reduction in acquisition difficulty will lead to a significant reduction in assembly time, with a commensurate rise in efficiency. This type of analysis targets high-volume operations where even a saving of pennies per assembly translates to significant returns in reduced production costs. Less quantifiable benefits may also accrue due to decreased error rates.

Our previous work in the reduction of assembly time examined the optimization of component bin layouts at a manual assembly workstation [Hunt/Sturges 1993}. This paper will present the application of the interactions between workstation design factors and the product itself.

1.1 Assembly Workspaces

The design of easy-to-assemble products has become a priority for manufacturers in recent years. The Design for Assembly (DfA) discipline that has grown from these concerns has as its primary goals the reduction of assembly time and errors. Design guidelines which reduce time and errors have advanced the field of product design [Boothroyd/Dewhurst 1983] [Sturges 1989a]. In particular, work cell layout has been examined to reduce assembly time and difficulty [Whitney/Nevins 1989] [Jayarman 1985]. Ergonomic and DfA methods have been applied to optimize the presentation of component bins for maximum efficiency [Drezner/Nof 1984] [Yunis/Cavalier 1990].

DfA heuristics examine the process of assembly by classifying it into separate motions. These motions, such as peg-in-hole insertions and screw actions, are treated in current DfA methodology. However, DfA methods do not make specific recommendations on the placement of components in the product being assembled, nor do these methods examine the effects of rotating preoriented objects from their presented position.

1.2 Sources of Workstation Assembly Difficulty

Overall assembly time is known to depend on several factors which describe task elements during acquisition of the parts (free motions and grasping) and part insertion (fine motions and fitting). On average, acquisition accounts for about one third of the total time [Sturges 1989a], and this time is affected by the location and orientation of the components internal to the product.

The most significant factors relevant to assembly difficulty are recognition, orientation, weight, and handling distance. Evaluations of assembly difficulty based on measures of both effectors and tasks have been developed which are independent of assembly sequence [Sturges 1989b]. A model of assembly difficulty and actual elapsed time due to these factors is the Index of Difficulty (ID) based on Fitt's Law [Fitts 1954]. An ID is defined as the base-two log of the range divided by the resolution, and has the units of bits. For example, the ID arising from handling distance is found by taking the distance to be traveled and dividing by the needed accuracy, as shown in Figure 1. The time needed to perform a task is found to be linearly proportional to the ID over a wide range of tasks and effector types, although the constant of proportionality varies with the effector. For example, the manual assembler performance constant for handling distance varies between 90 and 110 msec per bit [Fitts 1954].

Recognition ID is defined as the time it takes the assembler (human or robotic) to recognize the orientation of the component [Kilani/Sturges 1992]. The recognition ID is calculated by taking the base-2 log of the largest dimension of the object divided by the size in the same direction of the feature being recognized. For example, the head of a screw could be recognized by the slot head, where the range would be the diameter of the head and the resolution would be the width of the slot. Preorientation of components removes the necessity for recognition-IKhwaja/Radhakrishnan 1990].

Orientation ID represents the time necessary to actually rotate the component to the proper orientation for assembly. Preorientation of components can remove the necessity for orientation as well as for recognition penalties, and thus result in significant time savings. Orientation difficulty can be calculated from orientation entropy [Sanderson 1984]: if the resolution of each rotation axis is held to 7.5 bits, or 2 degrees out of 360, predicted task times correlate well with empirical data [Boothroyd/Dewhurst 1983]. Axes of symmetry reduce the rotation necessary to correctly orient the part for assembly, thus reducing orientation times. Similar guidelines for automatic preorientation and feeding of small components to an assembly effector have also been developed based on empirical studies [Boothroyd/Dewhurst 1981].

Weight ID is observed for components with a mass greater than about ten percent of the effector mass, and it increases with both the mass and the distance traversed [Wong/Sturges 1992]. This observation contrasts with earlier empirical results which only take the part weight into account [Boothroyd/Dewhurst 1983] and considers only human assemblers [Sturges, et al. 1986].

This paper assumes that the actions of orientation and traversing the distance from the bin to the point of assembly are concurrent if a preoriented component is being rotated. Motions involving randomly-oriented components, however, require that the assembler first recognize the current orientation before the component can be correctly oriented. Thus the orientation and recognition times are not presumed to be concurrent with the traversal of the workspace for randomly-oriented components, and should be added in as a penalty.

As mentioned above, the handling distance ID increases as the logarithm of the distance traveled (Sturges 1989a]. For handling distances greater than "arm's reach" the task time becomes additive: a fixed time can be added for "stand and sit" motions. Predictions of assembly time based on Indices of Difficulty for ail of the above factors have been shown to correspond well with empirical results [Sturges/Wright 1989].

Other factors associated with part acquisition include smallness of the components, whether the component is hot, delicate, etc. These factors are not included in this analysis because they affect assembly time regardless of the positions and orientations of the components in their bins or in the product.

2. REDUCTION OF HANDLING TIME

Assembly acquisition time can be broken down into phases during which different actions occur. Three of these phases are the handling distance phase, the recognition phase, and the prientation phase. Examination of these phases and what they represent in product and process design may yield significant time savings in the factory.

Examples of efficient assembly layouts show components presented in drawers, pallets, or other such holders. Components are not normally allowed to lie free in the assembly area; e.g., screws are placed in small drawers or recesses. Rectangular component bins of varying dimensions are considered in this study, with only right-angle rotations of these bins permitted. While it is possible that non-right angle rotations could lower the handling distance, such freedom would greatly increase the dimensionality of the problem. Examining the effects of moving assembly point positions relative to the bins supplying the components is simplified by modeling an assembly task with discrete points [Drezner/Nof 1984].

2.1 Reduction of Handling Distances

At least three possibilities exist for reducing handling distances. The first is to redesign the assembly workstation. Optimization of component bin placement around the assembly workspace has been examined [Yunis/Cavalier 1990] [Drezner/Nof 1984] [Hunt/Sturges 1993]. Minimizing the clear workspace through knowledge of the product size and ergonomics has also been extensively studied [McCormick/Sanders 1982] [Kvalseth 1983] [Clark/Corlett 1984] [Konz 1983]. these methods, while effective, do not contribute to the product design itself, hence, are not included in this analysis.

A second method of reducing handling distances is to optimally locate the components in the product where the functionality of the product is insensitive to such location. Relocation may involve both planar and spatial layering of components to reduce product size.

A third method is to redesign the components themselves to locate them closer to their source bins. Components that mate with others may have a range of mating options for which the component's function is not impaired. Knowledge of preliminary product and workstation layouts may thus bring valuable information into the detailed component design stage.

2.2 Reduction of Orientation Times

No orientation is required between grasping and use of the component in the assembly if a component has been preoriented for assembly by a bowl feeder or other device. Preorientation has been used to great effect for small components in mechanical assemblies [Boothroyd/Dewhurst 1991], and in the electronics industry [Kwaja/Radhakrishnan 1990]. Preorientation has not been significantly used in manual mechanical assembly, which suggests an area for further investigation.

A significant percentage of total orientation time is due to component asymmetries [Boothroyd/Dewhurst 1983]. Redesigning components to create rotational symmetries reduces the time required to orient the component for assembly when starting from a random orientation.

2.3 Reduction of Recognition Times

Another important criterion in reducing recognition times examines components which are subtly asymmetric. The worker must spend additional time determining which orientation is correct even if the features of the component are easily recognized. Reductions in recognition times are achieved by increasing the feature sizes on the component for easier recognition [Boothroyd/Dewhurst 1981]. As this area of acquisition is riot affected by the design of the workstation, it is outside the scope of this study.

3. REARRANGING COMPONENTS

Traditional Df A techniques recommend reducing the number of components to lower assembly times [Whitney/Nevins 1989], although such reduction may increase the cost of some parts [Barkan/Hinckley 1993]. Reducing the number of components shortens the handling distance by minimizing the number of trips to the component bins. Another method of reducing the handling distance is rearranging the components inside the product. This method applies when the function of the product is not affected by such rearrangement. Components may require certain spatial relations between each other to function properly, and must either not be moved, or be moved in groups. Evaluating the functionality of the rearranged components requires high-level design interpretation, which current DfA methodologies are not able to perform [Reed/Sturges 1993].

3.1 Selecting Candidate Components

Two criteria have been identified that determine if a component is a candidate for movement in the product. The first criterion is the frequency of use of the component, since even small changes in position will be multiplied if the component is used frequently. Frequency of use also applies to groups of dissimilar components that can move together. The second criterion is to preferentially select components that are already close to their source bins.

Figure 2 shows an ideal case of component relocation in an assembly. According to Fitt's Law, the time reduction for this case is given by:

$$\Delta ID = \log_2\left(\frac{D+A-R}{D+A}\right) = \log_2\left(1 - \frac{R}{D+A}\right) \qquad (1)$$

where D is the distance from the assembly point to the edge of the component bin, R is the handling distance reduction, and A is the relevant dimension of the bin. For the ideal case multiply the above change in ID by the frequency. In realistic settings, however, components are not typically used multiple times at the same location.

The right hand side of Equation 1 expresses the ID reduction as a function of the ratio of the distance reduction to the original distance, and gives measure of the ID reduction achieved by the relocation of a component.

The designer should choose relocations that significantly decrease the handling distance ID. A useful criterion for this purpose is the percentage reduction in ID achieved by the movement of a component location. The percent reduction of the ID as a function of the original distance D+A and the distance reduction R is given by:

$$\%\Delta ID = 100 * \frac{\log_2\left(1 - \frac{R}{D+A}\right)}{\log_2\left(\frac{D+A}{3}\right)} \qquad (2)$$

where the units are in millimeters and the parameter 3 mm derives from the transition between free motions and fine motions.

Typical dimensions of products assembled at a manual assembly station range from 50 mm to 1000 mm. For example, selecting the possible range of the distance reduction R ranging from 1 mm to 25 mm, and the original distance D+A ranging from 50 mm to 500 mm, and using Equation 2, we find the percent reductions in the Handling Distance ID as a function of R and D+A, shown in Figure 3. The percent reductions are largest when R is large and D+A is small, which is consistent with the logarithmic nature of the handling distance ID, and confirms the second criterion that components that are already close to their source bins should be preferentially selected.

3.2 Evaluating Rearrangement

To intelligently rearrange the components the engineer needs to know where component bins are located in the workspace. A preliminary design of the workstation must be available to supply this data. Ideally, the product and assembly process workstation designs would occur concurrently. More realistically there would be an iteration between the layout of the components inside the product and the component bins in the assembly workstation.

This type of analysis can also feed back important information to the design of the components themselves. For example, components which use fasteners for assembly into the product generally have some flexibility in the location of the fasteners. The engineer can take the relative positions of the fastener bins and the installed component into account when specifying the locations of the fasteners.

Components obviously cannot be moved into interference with each other, nor can they be moved so that they extend beyond the product boundary. Since the product is likely to be relatively densely populated to minimize the handling distance IDs due to size, moves of more than 25 mm are not expected. This fact is also reflected in Figure 3.

4. ROTATIONS OF PREORIENTED COMPONENTS

The time penalty for orienting components is high compared with incremental handling distances. At a manual assembly station, a right-angle rotation takes approximately one second [Boothroyd/Dewhurst 1983]. If a component is preoriented there are two possibilities for introducing unnecessary orientation penalties. The first is a preoriented component bin being rotated in an attempt to reduce the handling distance. The second is the variation of component orientations in the product if the components in the bins all have the same orientation.

4.1 Bin Rotation

If a rectangular bin has an aspect ratio substantially larger than one and has its long axis oriented towards the assembly point, as bin 1 is shown in Figure 4, it is possible that the decrease in handling distance could offset the time penalty required to return the component to the original orientation. The orientation of the component will be known, so recognition of the current orientation is unnecessary and the rotation of the component can be considered to be concurrent with the traversal of the handling distance. A criterion combining handling distance IDs and rotation time penalties may be formulated to show whether or not such a rotation would be advantageous:

$$\mathrm{Klogj(Hp)} - \mathrm{MAX}[\mathrm{Klo}_{g2}(\mathrm{S}\underset{3}{\pm}\mathrm{a}),\mathrm{T}_{rot}] > 0 \qquad (3)$$

In this equation, L and S are the larger and smaller half-sides of the bin (in mm), respectively, K is the effector-specific constant relative ID to time (in sec/bit), D is the distance from the edge of the bin nearer the assembly point to the assembly point, and Trot is the time necessary, in seconds, to rotate the component through 90 degrees back to the proper orientation.

For example, if we choose a rotation time of 1 second to correctly orient the component [Boothroyd/Dewhurst 1983], a K of 0.1 seconds/bit [Fitts 1954], and a best-case D of zero, Equation 3 reduces to:

$$\log_2\left(\frac{L}{3}\right) - \mathrm{MAX}\left[\log_2\left(\frac{S}{3}\right), 10\right] > 0 \qquad (4)$$

Recognizing that the first term in the MAX function must exceed 10 to be selected, we find S $\geq$ 3072 mm, which is an unrealistic dimension for a manual workstation. If the S is not larger than 3 meters, then the criterion calls for L to be larger than 3 meters. Therefore, at a manual workstation the rotation of a preoriented bin will never reduce the handling distance sufficiently to offset the rotation time penalty. For robotic effectors the results of this analysis may be different, since 3 meters is possible, although unlikely.

The above analysis ignores the effects of rotation of one bin on the surrounding bins. Consider the complete situation shown in Figure 4. While the rotation of bin 1 will never yield an improvement, the effects of bringing bin 2 in closer may sufficiently compensate for the time penalty to make this worthwhile.

The criterion that considers another bin in the rotation of a preoriented component is

$$F_1\left[\log_2\left(\frac{D+2L}{3}\right) - \frac{T_{rot}}{K}\right] + F_2\log_2\left(\frac{D+2L+A}{D+2S+A}\right) > 0 \qquad (5)$$

with S, L, K, D, and Trot as defined above, A as the half-side length of the other bin, and Fi and *Fz* being the frequency of components from bins 1 and 2, respectively. If we assume some best-case values for S and A, the 5 degrees of freedom of Equation 5 can be transformed into a function of the aspect ratio, the frequency ratio, and the distance from the assembly point, D.

For example, S and A are set to 25 mm to approximate the smaller dimension of a typical fastener storage drawer. Trot is known to be about 1 second. Creating the variables G and B to represent the ratio of Fi to F2 and the aspect ratio of bin 1 (L to S), respectively, and substituting into Equation 5 results in:

$$\left[\log_2\left(\frac{D+25B}{3}\right) - 10\right] + G\log_2\left(\frac{D+50B+25}{D+75}\right) > 0 \qquad (6)$$

Figure 5 shows the "break-even" curves for three different values of D, with an aspect ratio range of one to five on the X-axis, and a frequency ratio of one to eight on the Y-axis.

Even with a small D and a high aspect ratio, the frequency ratio required to make the rotation of bin 1 advantageous is large. With a D of 25 mm and an aspect ratio of 4 the required frequency ratio is 3.5, at 50 mm the minimum ratio is 3.9, and at 100 mm it becomes 4.4. Not only is this unlikely to occur in a realistic assembly, but if the arrangement of component bins has been optimized, the higher frequency bin is likely to have been placed closer to the clear workspace, rendering the analysis moot.

While this analysis ignores the effects of rotation on additional neighboring bins, we may conclude that rotations of preoriented component bins are never advantageous. This heuristic has been born out by not having observed rotations in over 200 component layout optimization tests of 25 different 15-bin layout problems where the rotational freedoms have not been set [Hunt/Sturges 1993].

4.2 Component **Rotation** In **the Product**

To minimize acquisition time, preoriented components should not have varied orientations in the product If a component is preoriented in its bin, any rotation from that orientation will require some time to accomplish. As shown above, a right-angle rotation of a component incurs a large time penalty. Components that are of different orientations in the product than in the bin will require rotations to correctly orient them for assembly, incurring unnecessary time penalties.

Combining the reduction of handling distance by rotating component bins with aligning all components with the presentation yields a third useful heuristic for component rearrangement, viz.: If the function of the components is orientation-insensitive, for example IC chips on a circuit card, and the component bin can be rotated to bring it closer to the product, the components in the product can be rotated as well to decrease the handling distance without incurring an orientation penalty.

5. EXAMPLES

Four examples are presented which outline the potential for lowering handling distance and rotation IDs. The first three refer to Figure 6, which shows a circuit card that is attached to the assembly base by four screws. On the right of the figure are. the storage bins for both the screws and the circuit card. Table 1 outlines the handling distance IDs for each of the four screws and the circuit card itself using the dimensions from Figure 6. The total handling distance ID is

27.5 bits. Points 1 through 4 refer to screw assembly points, while point 5 refers to the location of the center of the circuit card.

Table One: Baseline Handling Distance **IDs for Examples** 1-3

Paint Number	Handling Distance (mmY	ID (bits)
1	158.9	5.7
2	91.9	4.9
3	176.8	5.9
4	120.2	5.3
5	144.0	5.6
	Total ID:	27.4

5.1 Example One

The first example treats the screws and circuit card as a group of components. The card is moved 20 mm to the right towards the component bins. Recalculation of the handling distance IDs are shown in Table 2.

Table Two: Handling Distance **IDs for** Example **One**

Point Number	IDrbitsV		Percent Reduction
1	5.5		3.3%
2	4.6		6.4%
3	5.7		2.5%
4	5.2		3.1%
5	5.4		3.6%
Total ID:	26.4	Net Reduction:	3.7%

A net reduction of the handling distance ID was 1.0 bits was obtained by choosing the screws and card as a unit. This example highlights the importance of selecting groupings of components, not only high frequency components of one type.

5.2 Example Two

This example redesigns the circuit card with process-specific knowledge to allow the screws to be moved closer to their bins. Each screw is moved 10 mm to the right towards the source bin. Unlike the first exampie, the position of the circuit card is not altered from its original position. The redesign's effects on the handling distance IDs are shown below in Table 3.

Table Three: Handling Distance IDs for Example Two

Point Number	ID(bits)	Percent Reduction
1	5.6	1.6%
2	4.8	2.7%
3	5.8	1.2%
4	5.2	1.6%
5	5.6	0.0%
Total ID:	27.1	Net Reduction: 1.4%

A reduction in the handling distance ID of 0.3 bits was achieved by redesigning the circuit card. Due to the smaller distance changes this reduction is not as significant as in Example 1. However, it shows the possibility of including DfA feedback from factors that affect workstation design, not only into the layout of the product, but into the design of the product components themselves.

To more accurately present the effect of a design change on the handling distance ID, the ID from the immobile circuit card should be removed from consideration. The ID from the base case with the card removed is 21.8 bits. Subtracting the circuit card ID from the total ID in Table 3, a new ID for the four screw points is calculated to be 21.5. This represents a change of 0.3 bits, or 1.7 percent. This is smaller than the change in example 2, and highlights the importance of reducing the distances as much as possible.

5.3 Example Three

This example combines the effects of examples one and two. The card and screws are treated as a unit and moved to the right by 20 mm. The circuit card has also been redesigned to allow an additional 10 mm movement to the right by each screw.

Table Four: Handling Distance IDs for Example Three

Point Number	ID(bits)	Percent Reduction
1	5.4	5.1%
2	**4.4**	10.0%
3	5.7	3.9%
4	5.1	1.2%
5	5.4	4.6%
Total ID:	26.0	Net Reduction: 5.3%

A 1.4 bit reduction in the handling distance ID for these components was achieved by redesigning the circuit card and moving the component group. This represents a significant reduction in the handling distance ID for this grouping of components, and shows that a well-chosen redesign of a component coupled with a rearrangement of the product layout can achieve meaningful reductions of the assembly time.

Example 4

This example examines the effects of having one out of six IC chips on a circuit card are rotated from the preoriented presentation, as shown in Figure 7. In this example no components are rearranged to lower the handling distances. Table 5 shows the handling distance and orientation times before and after the redesign.

The orientation ID of Chip 6 dominates because the chip is not far enough away to complete the rotation during the traversal to the assembly point. The handling distance ID becomes dominant once the orientation ID is removed by aligning chip 6 with its preorientation. An ID reduction of 4.0 bits was achieved by realigning chip 6 with the other chips. For the set of 6 chips, this represents an 11.1 percent reduction. Considering chip 6 on its own, the percent reduction in ID was 44.0 percent.

Table Five: Handling Distance and Orientation Times for Example 4

	Handling Distance ID (bits)		Orientation ID (bits)	
Child Number	Before	After	Before	After
1	5.2	5.2	0.0	0.0
2	5.2	5.2	0.0	0.0
3	5.4	5.4	0.0	0.0
4	5.4	5.4	0.0	0.0
5	5.3	5.3	0.0	0.0
6	10.0	5.6	10.0	0.0
Totals:	36.1	32.1	10.0	0.0

6. CONCLUSIONS

The handling distance and orientation requirements of a product can significantly affect the assembly time. Two new DfA heuristics are derived from the knowledge of what affects assembly time at a workstation:

Heuristic One

Components whose locations can be moved should be moved towards their source bins. The components must have partial functional independence from spatial constraints. The largest improvements will be found with components that are already close to their source bins, and with component groups whose aggregate frequency of use is high.

Heuristic Two

The orientation in the product should be aligned with the preorientation if a component is preoriented in a bin. If the component bin can be rotated to reduce the handling distance and the component orientations in the product can likewise be rotated to maintain alignment with the preorientation then do so.

Examples two and three above demonstrate a new information flow from downstream assembly issues into product design. From preliminary design plans, an optimized workstation can be obtained. Knowledge of the component bin layout around the product can guide designers to locate fasteners and other components closer to their source bins, thus reducing the handling distance acquisition times.

7. DISCUSSION *

When eligible components are identified for movement to reduce handling distance IDs, or reorientation to remove orientation times, the question arises as to how to use the information. A design advisor could be developed that examines CAD models of the design in its early stages and identifies components that could take advantage of the heuristics developed in this paper.

However, suggestions that do not take functional requirements and design specifications into account must be evaluated by the cognizant human designer. Evaluating these performance-ignorant suggestions can waste valuable engineering time. The designer may come to mistrust the advisory system if the ratio of bad to good suggestions is high.

A link between a performance-ignorant design advisor and a functional representation of the product which contains specification knowledge has been demonstrated [Reed/Sturges 1992]. A reasoning system used performance data to filter suggestions which violated engineering specifications from being presentated to the engineer. Such a reasoning system could examine the suggestions made by an advisor and dramatically reduce the ratio of bad to good redesign suggestions.

Further refinements of handling distance acquisition theory will require taking non-linear position and directional biases into account when examining which components would most profitably be moved. For example, Dolan [1991] mapped the impedance of the human arm in a horizontal plane. Using the gradients of such a map to compute an effective handling distance could affect the placement of the components by adding directional preferences in conformance with a valid two dimensional extension of Fitt's Law. It also remains to include the effects of other ID's that relate to air drag, delicate parts, use of tools, and part flexibility. The Design for Assembly theory used here is not limited to human assemblers. Given the ID/time relations for robotic effectors, the present formulations could be extended to synthesize DfA heuristics based on the characteristics of an assembly machine [Sturges 1989b].

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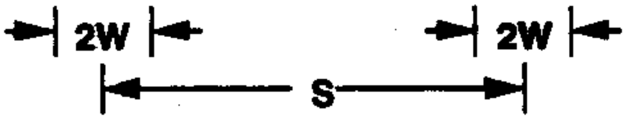

Figure 1: Schematic of Fitt's Tapping Task:
Subject Makes A Jot Between Each Set
Of Bars Alternately At Maximum Speed
And Minimum Error. The ID for this task
is log2 (S/W),bits.

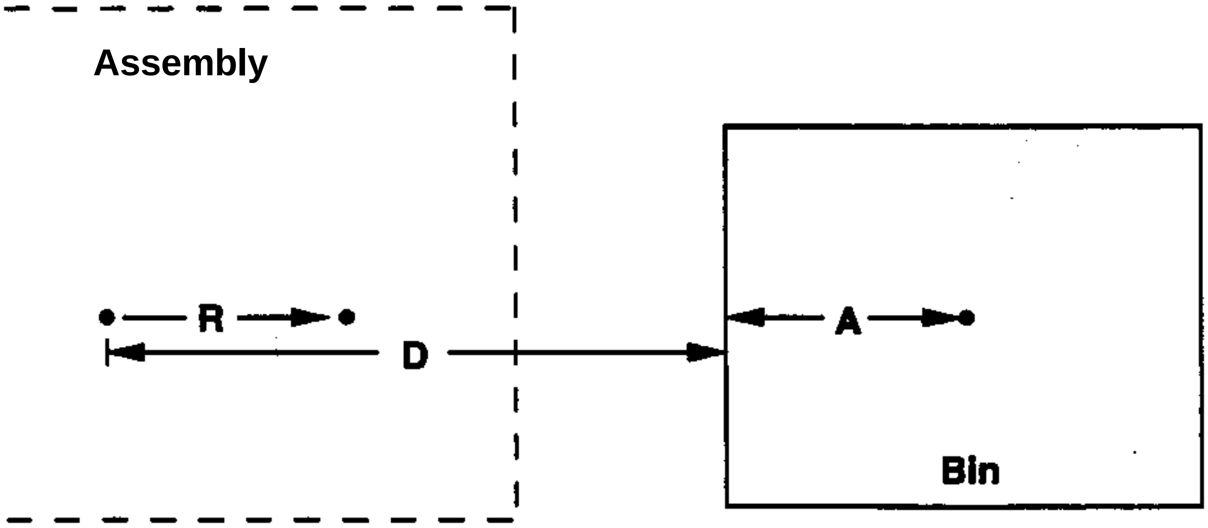

Figure 2: Ideal Relocation of a Component in an Assembly

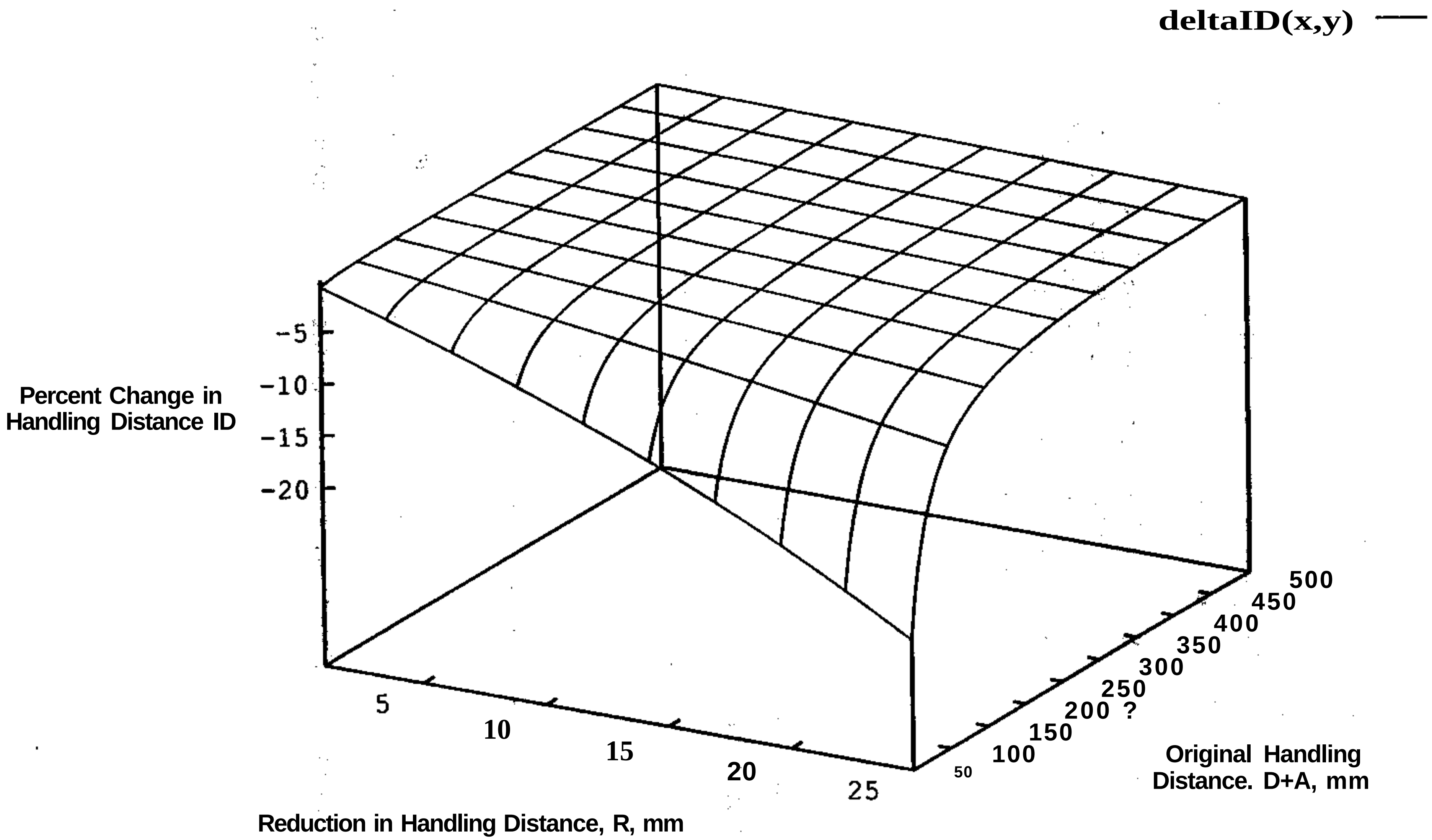

Figure 3: Percent Changes of the Handling Distance ID as a Function of the Original Handling Distance and the Distance Reduction.

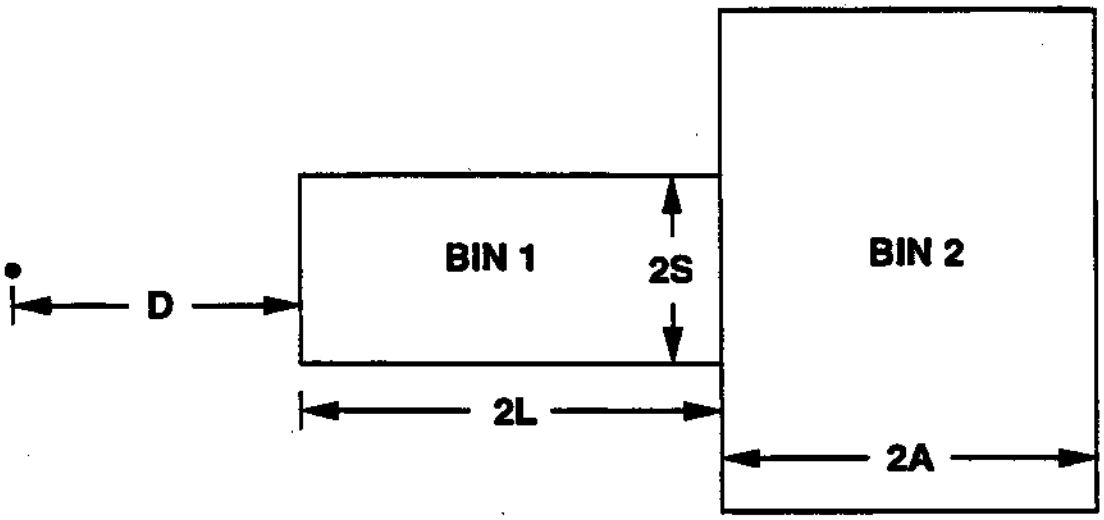

Figure 4: Bin Arrangement for Study of Rotations vs Handling Distance

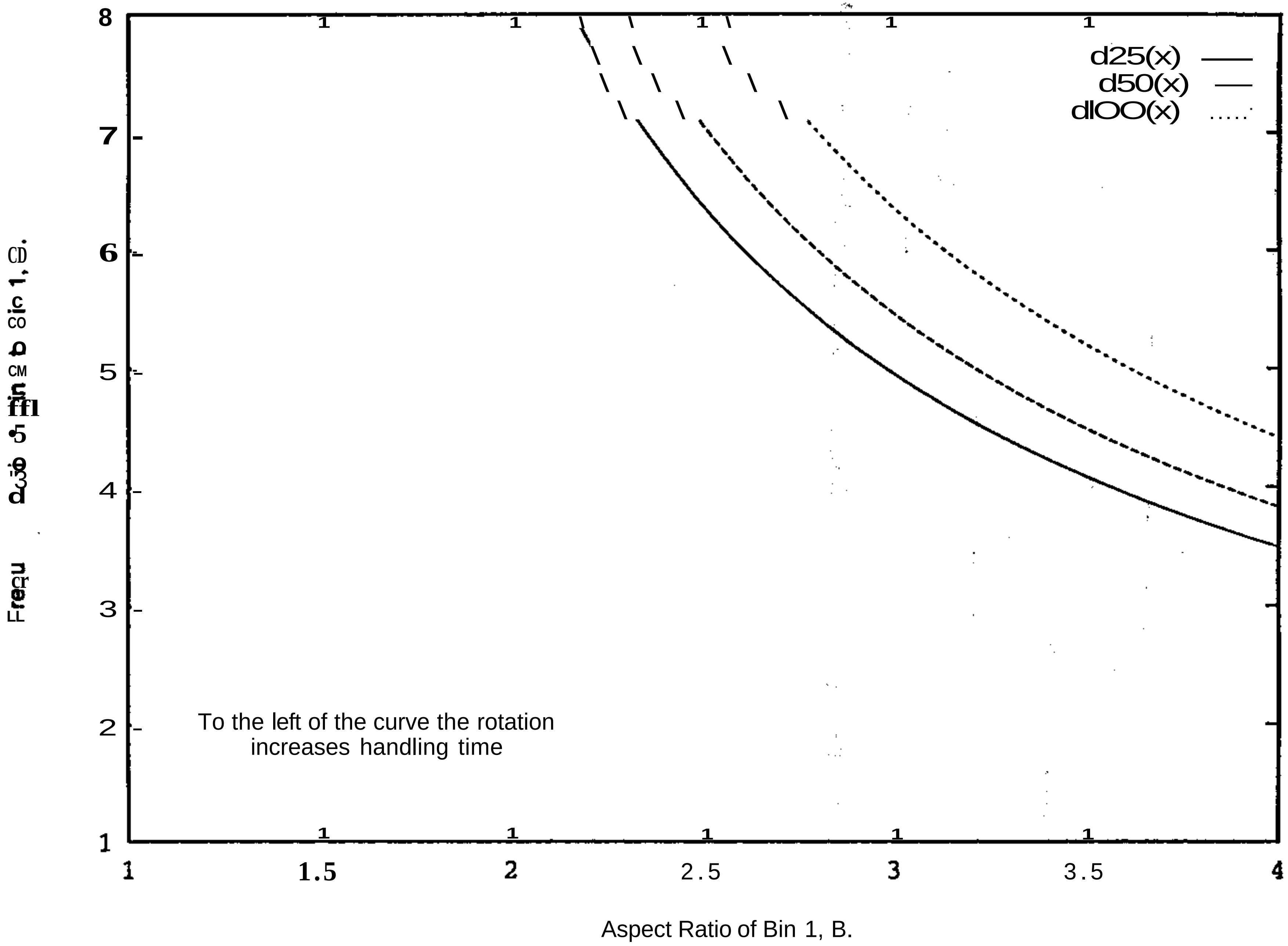

Figure 5: Curves Showing if a flotation of Bin 1 (Figure 4) is Advantageous.

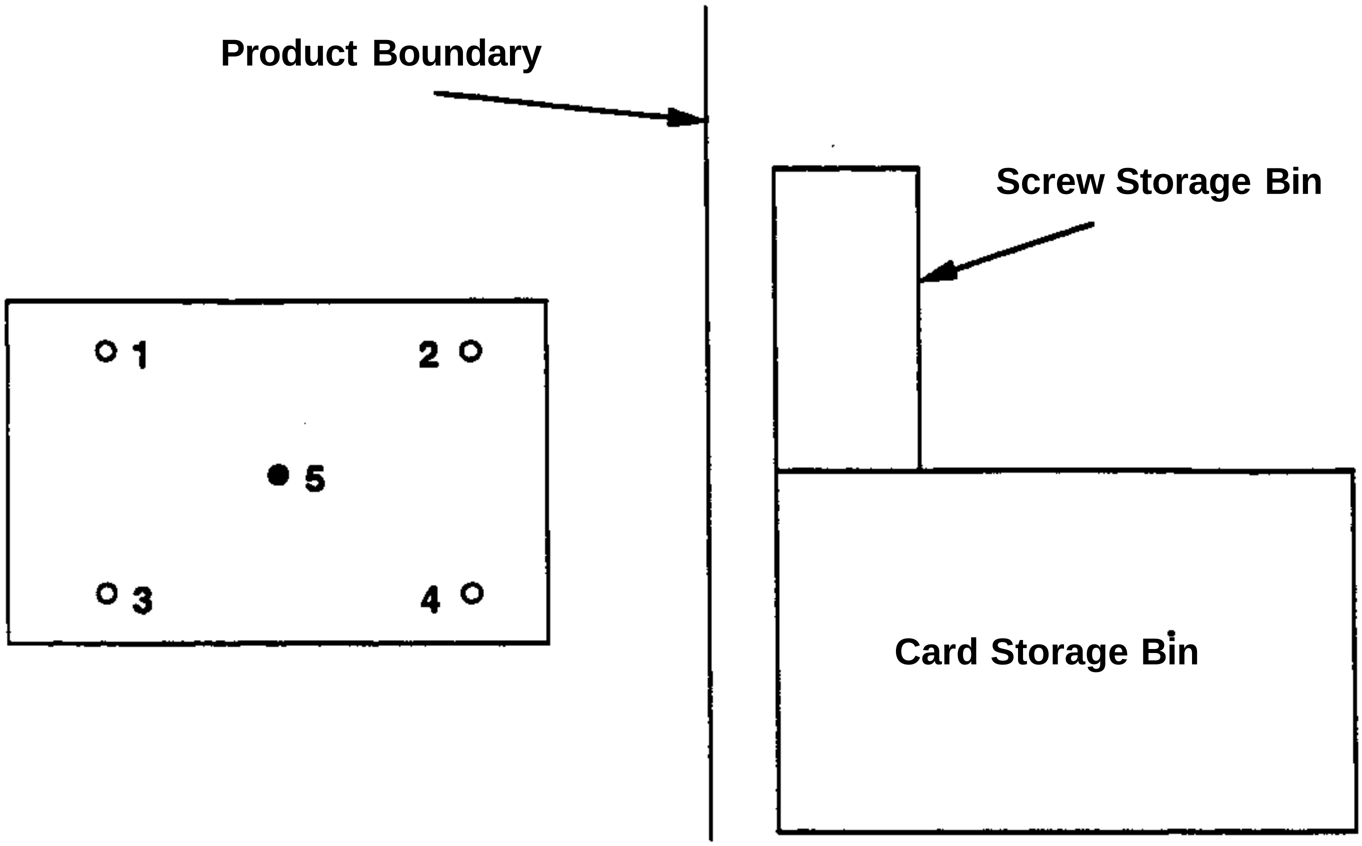

Figure 6: Set-up For Examples 1 through 3

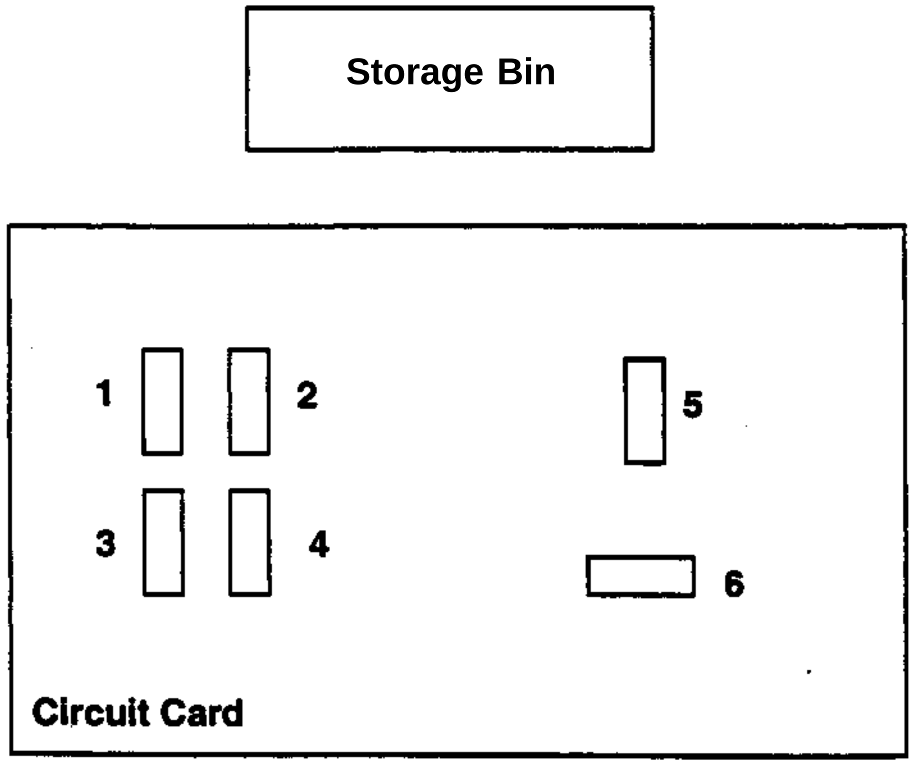

Figure 7: Chip Layout for Example 4