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FACILITATING DESIGN FOR ASSEMBLY THROUGH THE ADOPTION OF A COMPREHENSIVE DESIGN METHODOLOGY

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The principal objective of this paper is to present a comprehensive Design for Assembly methodology. This will enable product designers to design for ease of assembly. A product/system that is easy to assemble tends to lend itself to expedited manufacturing cycle times by means of reducing the time required during product assembly. Similarly, the methodology also makes special concessions for incorporating 'green techniques' during the assembly process. This is especially important given the current emphasis being placed upon 'green' design and environment conscious manufacturing.
This paper is divided into two parts: The first part presents a brief overview of some commonly used practices that focus on design for assembly. The second part presents the aforementioned methodology. The methodology is corroborated by means of a real life case study that proves its practical usefulness.

Significance: A novel design for assembly methodology is presented in this paper. The practical utility of the methodology is demonstrated by means of an actual case study.

Keywords: Design for Assembly, Methods Time Measurement, Proactive Design

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1. INTRODUCTION

Design for Assembly, or DFA, may be defined as a process for improving product design for easy and low-cost assembly. This is achieved by means of simultaneous focus on the dual aspects of functionality as well as assemblability. Assembly of a product is a function of design parameters that are both intensive (material properties) and extensive (physical attributes) in nature. Examples of such design parameters include. but are not limited to shape, size, material compatibility, flexibility, thermal conductivity etc. It is easy to see that when individual components are manufactured with ease of assembly in mind, the result is a significant reduction in assembly lead times. This leads to savings in both material and human resources. Designers have grappled with the problem of designing products for assembly since the beginning of the industrial revolution. The importance of designing in order to facilitate assembly is beyond apparent. The case of designing for easy and efficient assembly has been made repeatedly. A product is often the assemblage of various individual components. The spatial alignment between components that are functionally important constitutes a product. In this light, it is important that each component needs to be designed so as to align and mate with its neighbor efficiently. This entails the design and processing of the component in a specific manner with respect to shape, size, tolerances and surface finish. A component that is designed in such a way leads to substantial reduction in assembly related metrics. Examples of such metrics could include assembly time, as well as cost. The practice of DFA is considered to be a recent development, however, many companies have been involved with DFA for a long time. General Electric (GE) published an internal manufacturing producibility handbook in the 1960's. The principal objective of this was to serve as a set of guidelines and manufacturing data for designers. These guidelines included many of the now known principles of DFA. The following section will introduce readers to basic concepts concerning assembly processes.

2. DIFFERENT KINDS OF ASSEMBLY PROCESSES

Within the industrial context, there are three principal methods of carrying out an assembly process. These methods are detailed as follows:

1. *Manual Assembly*: Manual Assembly can be defined as an assembly process in which operations are performed manually with or without the aid of simple tools such as screwdrivers and pliers. One of the distinguishing characteristics of this process is that Cost/unit is constant and the process requires little initial investment. Hand tools are generally used for the purpose of easy assembly. There is usually an upper limit to the production volume and labor costs, including benefits, cases of workers compensation due to fatigue and injury, and overhead for maintaining a clean, healthy environment, are higher.

2. *Automatic Assembly*: Automatic Assembly, also known as fixed automation, uses either synchronous indexing machines and part feeders or non-synchronous machines where parts are handled by a free transfer device. A system using Automatic Assembly is generally built for a single product and the cost/unit decreases with increasing volume of production. This process involves a custom-built machine that assembles one and only one specific product. As production volume increases, the fraction of the capital investment compared to the total manufacturing cost decreases. Indexing tables, parts feeders, and automatic controls typify this inherently rigid assembly method. This is also what is referred to as "Detroit-type" assembly.
3. *Robotic Assembly*: This method of product assembly is the most flexible and can achieve volumes closer to the automatic assembly methods. It is also referred to as Soft Automation. It incorporates the use of robotic assembly systems. Robotic Assembly can take the form of a single robot, or a multi-station robotic assembly cell. All activities are simultaneously controlled and coordinated by a PLC or computer. The one distinguishing feature of this process is high flexibility which tends to offset high capital requirements. Figure 1 depicts the aforementioned processes graphically.

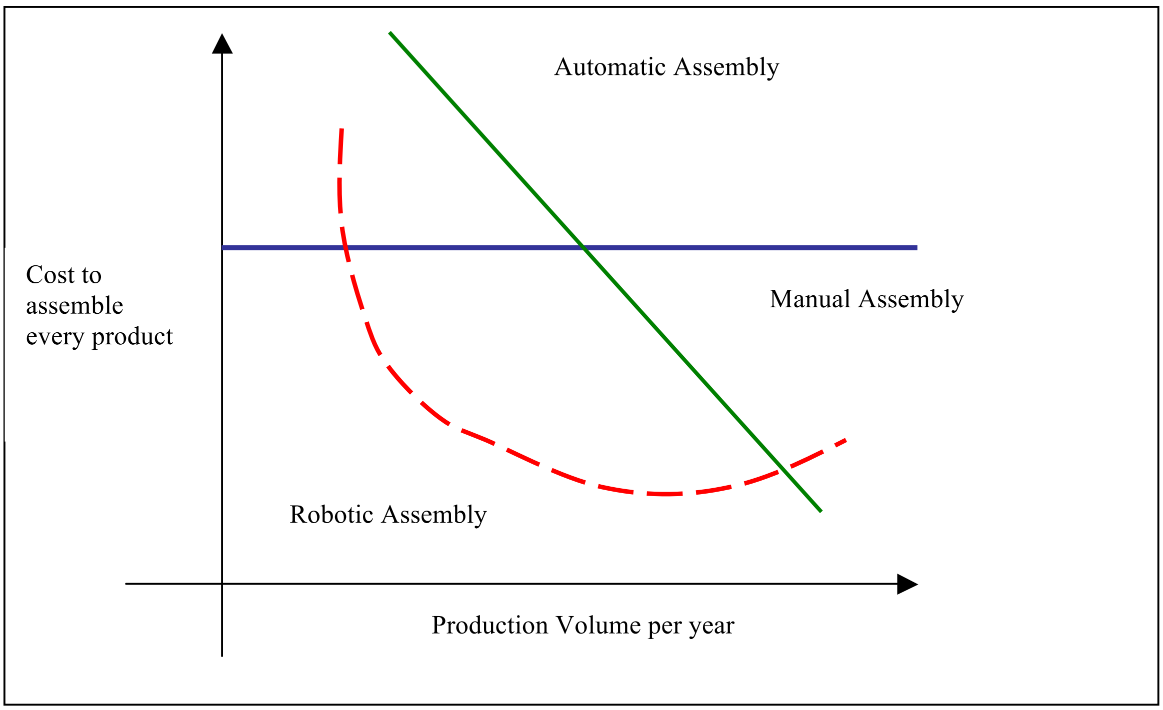

Figure1: Three principal kinds of assembly processes

Figure 1 is a graphical representation of the three kinds of assembly processes differentiated on the basis of level of automation inherent in each of the processes. The relation between assembly cost per product and production volume has been depicted. For instance, in the case of a manual assembly process, the cost to assemble every product is more or less constant and does not change with respect to production volume (assuming uniformity in product architecture and design). In the case of automatic assembly, it is obvious that assembly cost/product is inversely proportional to production volume due to favorable economies of scale. In the case of robotic assembly, however, this method being the most flexible of all assembly processes, the relation is not linear. It is neither directly nor inversely proportional all the time. Depending on production volume, the slope of this relationship could be either negative or positive as is shown in figure 2. The next section of this paper will briefly discuss some of the work that has aimed at trying to facilitate the product assembly process.

3. A BRIEF EVALUATION OF SOME DFA METHODOLOGIES

There have been numerous efforts made by various researchers to enhance the design process by facilitating design for Assembly. (Leaney, P.G and Wittenberg, ; 1992); (Suzuki, T; Ohashi, T; Asano, M; Arai, T, 2003); (Leclerc, S and

Subbarayan, G, 1996); (Li et al; 1992); (Hsu et al; 1993); (Kim et al; 1995) . However only a few of these efforts have been truly seminal in value as well as contribution and are discussed in brief in the following paragraphs:

3.1. Hitachi Assembly Evaluation Method

The Hitachi Assembly evaluation method facilitates design improvements by means of adopting the following approach (Miyakawa, S and Ohashi, T; 1986): Identifying weaknesses in the design at the earliest stage in the design process by using an assemblability evaluation score (E) and an assembly cost ratio (K). The general procedure of design evaluation is presented stepwise as follows:

- The universe of Assembly operations is categorized into twenty (20) elemental assembly tasks. Each task is assigned a symbol indicating the task content. Each task relates specifically to insertion and fastening processes and not to parts handling.
- Each of the elemental tasks is subject to a penalty score reflects the degree of difficulty of the task. The penalty scores are obtained from analysis of shop floor data and are constantly revised to reflect changes in technology and methods. Factors which influence elemental tasks are extracted as coefficients and the penalty scores are modified accordingly.
- Attaching (contacting) conditions appropriate for each part are expressed using further AEM symbols.
- The total of the various penalty scores for an individual component are then modified by the contacting coefficients (as described above) and subtracted from the best possible score (100) to give the assemblability evaluation score for the part.
- The total score for the product is defined as the sum of the assemblability scores for individual tasks divided by the total number of tasks.

3.2. The Boothroyd-Dewhurst Method

This DFA method proposed by Boothroyd and Dewhurst (Boothroyd, G; 1980); (Boothroyd, G; 1982) seeks to reduce the total number of parts in an assembly by means of trying to reduce the amount of manual handling time as well as insertion time. It is based on two principles:

- The application of criteria to each part to determine if it should be separate from all other parts.
- The estimation of the handling and assembly costs for each part using the appropriate assembly process.

The process follows the following steps:

1. Select an assembly method for each part
2. Analyze the parts for the given assembly methods
3. Refine the design in response to shortcomings identified by the analysis
4. Refer back to step 2 until the analysis yields a satisfactory design

This method can be quite time consuming owing to the amount of intricate detail involved in the analysis procedure.

3.3 The Lucas DFA Evaluation Method

The Lucas DFA method was developed in the early 1980''s by the Lucas Corp. in the United Kingdom. The Lucas method is based on a "point scale" which gives a relative measure of the difficulty associated with assembly. The following is a hierarchical decision making system followed by the Lucas method.

1. Product Design Specification
2. Product Analysis
3. Functional analysis (this is the first Lucas analysis). Loop back to step 2 if the analysis yields problems
4. Feeding analysis (this is the second Lucas analysis)
5. Fitting analysis (this is the third Lucas analysis)
6. Assessment
7. Possibly return to step 2 if the analyses identify problems

4. A DESIGN FOR ASSEMBLY METHODOLOGY BASED ON TIME STANDARDS

An improved assembly methodology has been designed by the authors. It takes into consideration numerous factors such as weight, size and shape of components being disassembled, frequency of assembly tasks and requirement of manpower, postural requirements, material handling requirements and need for component preparation.

The most common and widely used assembly operations are recorded and described in detail. Every assembly operation is then subdivided into basic elemental tasks. Only a fraction of all the tasks in the entire assembly operation are actually responsible for performing assembly. An MTM based index for assembly is presented in table 1. The simplest assembly task of inserting an easily grasped object without the exertion of much force by hand by a trained worker under average conditions has been considered as the basic assembly task. A score of 73 TMU's was assigned to this task which corresponded to time duration of approximately 2 seconds.

Table 1: Evaluation system to analyze assembly processes numerically.

Design attribute	Design Feature	Design parameters	Score	Interpretation
Assembly force	Straight line motion without exertion of pressure	Push operations by hand	0.5	Little effort required
			1	Moderate effort required
			2	Large amount of effort required
	Straight line and twisting motion without pressure	Twisting and Push operations by hand	1	Little effort required
			2	Moderate effort required
			4	Large amount of effort required
	Straight line motion with exertion of pressure	Inter-surface friction and /or wedging	2	Little effort required
			2.5	Moderate effort required
			4	Large amount of effort required
	Straight line and twisting motions with exertion of pressure	Inter-surface friction and /or wedging	2.5	Little effort required
			3	Moderate effort required
			5	Large amount of effort required
	Twisting motions with pressure exertion	Material Stiffness	2.5	Little effort required
			4	Moderate effort required
			6	Large amount of effort required
Material Handling	Component/fastener Size	Component dimensions (Very large or very small)	2	Easily grasped
			3.5	Moderately difficult to grasp
			4	Difficult to grasp
		Magnitude of weight	2	Light (<7.5 lb)
			2.5	Moderately heavy (<17.5 lb)
			3	Very heavy (<27.5 lb)
	Component/fastener Symmetry	Symmetric components are easy to handle	0.8	Light and Symmetric
			1.2	Light and semi symmetric
			1.4	Light and asymmetric
			2	Moderately heavy, symmetric
			2.2	Moderately heavy, semi symmetric
			2.4	Moderately heavy, asymmetric
			4.4	Heavy and symmetric
			4.6	Heavy and semi symmetric
			5	Heavy and asymmetric
Requirement of tools for Assembly	Exertion of force		1	No tools required
			2	Common tools required
			3	Specialized tools required
	Exertion of torque		1	No tools required
			2	Common tools required
			3	Specialized tools required
Accessibility of joints/grooves	Dimensions	Length, Breadth, Depth, radius, angle made with surface	1	Shallow and broad fastener recesses, large and readily visible slot/ recess in case of snap fits
			1.6	Deep and narrow fastener recesses, obscure slot/recess in case of snap fits
			2	Very deep and very narrow fastener recesses, slot for prying open snap fits difficult to locate
	Location	On plane surface	1	Groove Location allows easy access.
		On angular surface	1.6	Groove Location is difficult to access. Some manipulation required.
		In a slot	2	Groove location very difficult to access.
		On Vertical Surface	1.5	Some manipulation required against gravity
		On Horizontal Surface	1	Groove location allows easy access

Table 2: Multipliers for Unnatural postures while accomplishing the Assembly Process

Motions Allowances	Multiplier
Normal Motions	0%
Limited Motions	5%
Awkward Motions	5%
Motions with confined limbs	10%
Motions with confined body	10%
Motions Allowances	
Normal Motions	0%

Table 2 depicts multipliers that are to be used when the assembler needs to adopt unnatural postures during the assembly process. The total task time is augmented by a factor as specified in the table above for each unnatural posture during the assembly process.

Figure 2 depicts a methodology to enable design improvement for Product Assembly. The Design for Assembly (DFA) process starts with evaluation of the current design based on the methodology. This is done through a detailed breakdown of the assembly process by means of thorough documentation of each step. For example, the assembly process of a CRT is a conventional computer monitor entails picking up the CRT, aligning it with locator lugs, stabilizing the components and screwing in fasteners such as fastening screws etc. Each step of this process is associated with a certain amount of assembly force, a particular amount of material handling requirement, a specific amount of accessibility associated with location of grooves etc. Each of the aforementioned features is directly related to a specific design attribute of the product.

After the assembly score for the product has been ascertained, the next step is to arrange each assembly step in descending order. For example, if the total assembly score for a CRT assembly is 20 and that for a PCB assembly is 15, then the assembly steps will be arranged as: CRT, PCB and so on. Each major assembly score is comprised of sub actions such as those detailed in table 3 depending on which category they fall under. To present an example of this, sub action could be related to a design feature that elicits the exertion of a large amount of force or it could be related to special material handling requirements due to the size, shape, weight or material of the component being assembled. These sub actions are now arranged in descending order of numeric scores. The next step is the evaluation of each of the design characteristics (as detailed in the preceding discussion) so that design anomalies can be either eliminated or rectified as much as possible. This process should take place without affecting product functionality. Once these design decisions have been made, the cost of manufacturing those components can be taken into consideration in order to optimize the manufacturing process and maximize profit potential. Table 4 of this paper examines how the design for assembly numeric scores, as presented in Table 1, are applied in practice to a consumer product. Table 3 presents the various components that constitute a computer monitor.

Table 3: Components of a computer monitor

No	**Component Name**	**Component Material**	**Quantity**
1	Back Screw	Copper	4
2	PCB Screws	Copper	2
3	CRT Screws	Copper	4
4	CRT/PCB Assembly	Mixed	1
5	Back Cover	Plastic	1
6	Swivel Base	Plastic	1
7	Pivot	Plastic	1
8	Yoke Assembly	Mixed	1
9	Deflection Wire lead	Mixed	1
10	Retainer Screws	Copper	2
11	Main Wire lead	Copper	1
12	Adjusting knobs	Plastic	4
13	PCB Retainer Screw	Copper	1
14	Retaining lugs	Aluminum	4
15	PCB Assembly	Mixed	1
16	Rear Board	Plastic	1
17	CRT	Mixed	1

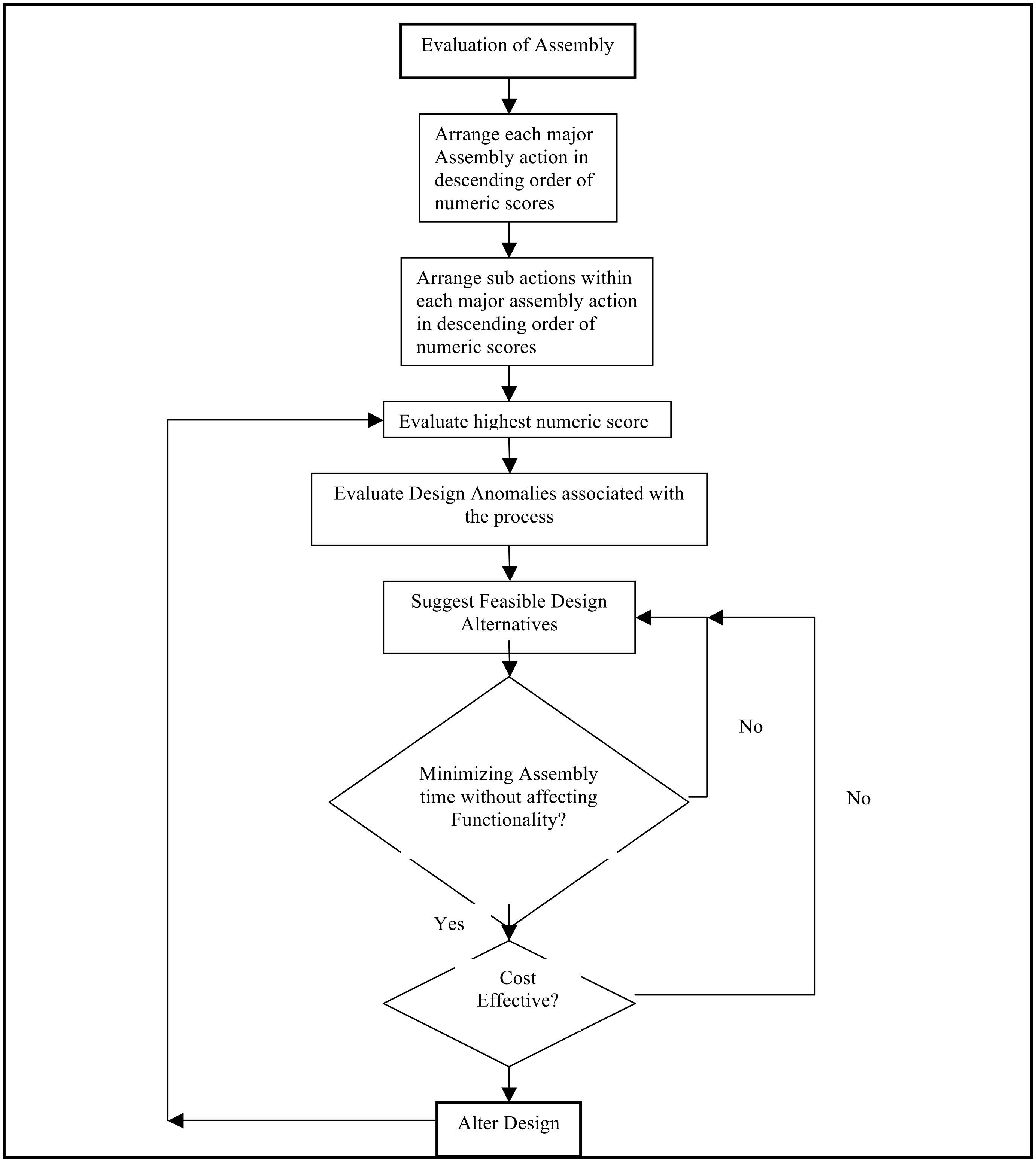

Figure 2: Methodology to enable design improvement for Product Assembly

5. DISCUSSION AND COMPARISON

This section of the paper strives to explain the case study in more detail. It also presents a comparison between our method and other established methods for design for assembly.

Table 4 portrays a detailed breakdown of the assembly process. Task 1 constitutes the first step in the assembly process namely placing the rear board in place to start the assembly process. This is followed by the process of bending the retaining lugs (4 lugs) in sequence in order to assemble the rear board. Since this process can be visually tiring, a 10% visual fatigue allowance has been assigned to it. The total amount of time required to assemble the rear board is approximately 98.92 TMUs. The second step of the assembly operation is the assembly of the PCB. The sequence of operations followed in this step is documented in table 4. The total amount of time taken to accomplish this step is 127.9 TMUs. The third step is fitting the CRT/PCB assembly in place by means of 6 screws in place followed by fitting the yoke assembly and the deflection wire lead in place. The last operation on the assembly process consists of fitting 4 adjustment knobs into place which as is evident from table 4 constitute the easiest of all assembly operations for this particular product. It will be appreciated that this last operation is not visually tiring nor does it require the adoption of any unnatural working postures. The total amount of time taken for the entire assembly operation is 5630 TMU's which translates to about 3.378 minutes. It is obvious from table 4 that bending retaining lugs and fitting screw in place are by far the most time consuming operations and design features corresponding to those actions need to be improved first. Design solutions that are not cost effective will be discarded until a cost effective design solution is obtained. This sequence is demonstrated in figure 2. A similar case study if done using the Boothroyd method would result in highly complicated design features on components. These would render them difficult to manufacture. The handling and insertion time used in the Boothroyd method are not based on data derived from actual experiments with human subjects. As a result their assembly time would not be very useful in actual practice. This argument can be extended to the Lucas method as well.

The following section of this discussion will expatiate on the significance of our methodology by drawing a comparison with the Boothroyd and Dewhurst system, the Lucas system and the Hitachi method.

Significance of the methodology: A comparison between our method of designing for assembly and other established methods (as examined in the third section of this paper) is outlined below.

1. Our Design for Assembly Methodology is less complicated and easier to comprehend as compared to Boothroyd and Dewhurst as well as the Lucas technique. It is easier to indentify design anomalies and flaws and thereby corrective action can be implemented quickly. It can be observed that the same level of design comprehension as afforded by the Boothroyd method can be achieved with our methodology but in a fraction of the time. The methodology reduces assembly tasks to the most basic form and therefore any complicated task can be easily built using these elements.
2. It should be noted that the method developed by Boothroyd and Dewhurst deals with manual handling and insertion times exclusively. These times are not derived from experiments conducted on actual people and therefore their applicability is limited. Similarly, the Lucas method is deals with the concept of Design efficiency and uses handling times, the basis of which is not too practical either. On the other hand, our methodology is based on the universally established and followed concept of Methods Time Measurement (MTM). These data are proven in practice on actual people. This imparts a great deal of versatility to our methodology and makes it ergonomically friendly as well.
3. Our Design for Assembly methodology is time based and therefore it is very straight-forward as far as computation of assembly time is concerned. This also makes it very user friendly in terms of computing the cost for assembly operations.
4. Our methodology focuses on identifying and optimizing the product assembly sequence as the outset. This means that elements of proactivity are built in to the methodology and errors of judgment can be minimized.
5. Our methodology is probably the only one that incorporates penalty scores for working postures. This means that the methodology and subsequent design arising from it are ergonomically friendly. This lends itself to not only worker satisfaction but lower assembly costs per assembled product. Neither the Boothroyd nor the Hitachi nor the Lucas method deal with this important concept. The data presented by those methodologies can therefore be applicable more exclusively to automated assembly processes.
6. Our design data can be used for assembly as well as disassembly purposes. It should be noted that the Boothroyd method does not deal with disassembly neither does the Lucas method or the Hitachi method. This makes our methodology far more versatile. This is very important in view of increasing focus on sustainability issues in the contemporary environment.

TASK NO	TASK DESCRIPTION * Assembly of Computer Monitor*	TASK TOTAL	INTER-SURFACE FRICTION	INTER-SURFACE WEDGING	MATERIAL STIFFNESS	COMPONENT SIZE	COMPONENT WEIGHT	COMPONENT SYMMETRY	FORCE EXERTION	TORQUE EXERTION	DIMENSIONS	LOCATION	ACCURACY OF TOOL PLACEMENT	POSTURE ALLOWANCE	MOTIONS ALLOWANCE	MANPOWER ALLOWANCE	VISUAL FATIGUE ALLOWANCE
			ASSEMBLY FORCE			MATERIAL HANDLING			TOOLING		ACCESSIBILITY & POSITIONING			ALLOWANCES			
1	Assemble Rear Board																
1a	Place Rear Board in place	10.92	-	2	-	2	2	1.2	1	-	1	-	1.2	-	-	-	5%
1b	Bend 1st retaining lug	22	-	-	6	3	2	1.4	3	-	1.6	1	2	-	-	-	10%
1c	Bend 2nd retaining lug	22	-	-	6	3	2	1.4	3	-	1.6	1	2	-	-	-	10%
1d	Bend 3rd retaining lug	22	-	-	6	3	2	1.4	3	-	1.6	1	2	-	-	-	10%
1e	Bend 4th retaining lug	22	-	-	6	3	2	1.4	3	-	1.6	1	2	-	-	-	10%
2	Assemble PCB																
2a	Fit PCB in place	11.55	-	2	-	2	2	0.8	1	-	1	1	1.2	-	-	-	5%
2b	Bend 1st retaining lug	24.53	-	-	6	4	2	0.8	3	-	2	2	2.5	-	-	-	10%
2c	Bend 2nd retaining lug	24.53	-	-	6	4	2	0.8	3	-	2	2	2.5	-	-	-	10%
2d	Bend 3rd retaining lug	24.53	-	-	6	4	2	0.8	3	-	2	2	2.5	-	-	-	10%
2e	Bend 4th retaining lug	24.53	-	-	6	4	2	0.8	3	-	2	2	2.5	-	-	-	10%
2f	Fit PCB retaining screw	18.27	5	-	-	4	2	0.8	1	-	1.6	1	2	-	-	-	5%
3	Fit CRT/PCB Assembly																
3a	Screw 1st PCB Screw	15.12	2	-	-	2	2	0.8	-	2	1.6	2	2	-	-	-	5%
3b	Screw 2nd PCB Screw	15.12	2	-	-	2	2	0.8	-	2	1.6	2	2	-	-	-	5%
3c	Screw 1st PCB Screw	15.12	2	-	-	2	2	0.8	-	2	1.6	2	2	-	-	-	5%
3d	Screw 2nd PCB Screw	15.12	2	-	-	2	2	0.8	-	2	1.6	2	2	-	-	-	5%
3e	Screw 3rd PCB Screw	15.12	2	-	-	2	2	0.8	-	2	1.6	2	2	-	-	-	5%
3f	Screw 4th PCB Screw	15.12	2	-	-	2	2	0.8	-	2	1.6	2	2	-	-	-	5%
3g	Fit Yoke Assembly	13.13	-	3	-	2	2	1.4	1	-	1	1	1.6	-	-	-	1%
3h	Fit Deflection Wire lead	13.02	-	3	-	2	2	0.8	1	-	1	1	1.6	-	-	-	1%

4	Fit Main Wire lead																
4a	Fit main wire lead	17.77	-	3	-	4	2.5	2.2	1	-	1.6	1	2	-	-	-	1%
4b	Fix First Retainer Screw	15.65	2	-	-	2	2	0.8	-	2	1.6	2	2	-	-	-	5%
4c	Fix 2nd Retainer Screw	15.65	2	-	-	2	2	0.8	-	2	1.6	2	2	-	-	-	5%
5	Assemble Back Cover																
5a	Remove Back Cover	15.44	-	3	-	3.5	2	1.2	-	1	1	1	2	-	-	-	5%
5b	Screw first of four back screws	15.12	2	-	-	2	2	0.8	-	2	1.6	2	2	-	-	-	5%
5c	Screw 2nd of four back screws	15.12	2	-	-	2	2	0.8	-	2	1.6	2	2	-	-	-	5%
5d	Screw 3rd of four back screws	15.12	2	-	-	2	2	0.8	-	2	1.6	2	2	-	-	-	5%
5e	Screw 4th of four back screws	15.12	2	-	-	2	2	0.8	-	2	1.6	2	2	-	-	-	5%
6	Assemble Swivel Pivot																
6a	Fit Swivel Pivot	18.16	-	-	4	3.5	2	1.2	2	-	1.6	1	2	-	-	-	5%
6b	Fit Swivel Support	10.92	-	2	-	2	2	1.2	1	-	1	-	1.2	-	-	-	5%
7	Assemble Swivel Base																
7a	Fit Swivel Base	10.50	-	2	-	2	2	1.2	1	-	1	1	1.2	-	-	-	1%
7b	Rotate Swivel base about pivot	13.54	-	4	-	2	2	1.2	1	-	1	1	1.2	-	-	-	1%
8	Assemble adjusting knobs																
8a	Fit 1st of 4 adjusting knobs	10.5	-	1.5	-	2	2	0.8	1	-	1	1	1.2	-	-	-	-
8b	Fit 2nd of 4 adjusting knobs	10.5	-	1.5	-	2	2	0.8	1	-	1	1	1.2	-	-	-	-
8c	Fit 3rd of 4 adjusting knobs	10.5	-	1.5	-	2	2	0.8	1	-	1	1	1.2	-	-	-	-
8d	Fit 4th of 4 adjusting knobs	10.5	-	1.5	-	2	2	0.8	1	-	1	1	1.2	-	-	-	-
		563	**Total Score for Assembly Operation**														
	Total Time for Assembly Operation: 5630 TMU's = 3.378 minutes																

Table 4: Assembly operation of a computer monitor.

It is clear from table 4 that the total amount of time taken to assemble a typical computer monitor is about 3.378 minutes. Also fixing screws and bending lugs are two of the most time consuming tasks that need to be addressed from the design perspective. Simplifying these tasks by means of achieving improvements in product design can cut assembly time as well as related costs.

5. CONCLUSION

This paper presented a design for Assembly methodology based on time standards. It also examined a few noteworthy design for assembly methodologies that were investigated and developed by other researchers. The salient feature of the DfA methodology presented in this paper is that it is very simple to use, easy to understand and highly effective as far as its practical utility value is concerned. It can also be extended in its use and utilized as part of a larger design for maintenance methodology.

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BIOGRAPHICAL SKETCH

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