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IMPROVING MAINTAINABILITY OF PRODUCTS THROUGH THE ADOPTION OF A COMPREHENSIVE DESIGN FOR MAINTAINABILITY METHOD

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This paper presents a systematic methodology to enhance the maintenance operation of products and systems. This is accomplished through the adoption of Design for X (DfX) principles as well as the use of MTM predetermined time system. As is well known, maintenance, often a necessary evil, is responsible for equipment downtime. Lack of regular maintenance can result in serious equipment failure with catastrophic consequences. The methodology presented in this paper deals with product design for maintenance. It also addresses the human factors associated with the maintenance operation. The authors have made a conscious effort to incorporate this factor into the methodology, given the labor intensive nature of virtually all maintenance operations. This paper is divided into two parts. The first part presents a brief overview of selected maintenance related concepts, given limited space availability. The second part of the paper presents the aforementioned methodology. A real life case study is also used to demonstrate the practical utility of the methodology.

Significance: This paper presents a design for maintenance methodology. The methodology is supported through use of an actual case study.

Keywords: Design for Maintenance, Methods Time Measurement, Design for X, Human Factors

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1. INTRODUCTION

Maintainability can be defined as 'the degree of facility with which an equipment or system is capable of being retained in, or restored to, serviceable operation. Maintainability is a function of parts accessibility, interval configuration, use and repair environment and the time, tools and training required to effect maintenance (Morgan et al, 1963) .' According to the department of defense, maintainability is 'a characteristic of design and installation which is expressed as the probability that an item will conform to specified conditions within a given period of time when maintenance action is performed in accordance with prescribed procedures and resources (Harring.M and Greenman.L, 1965).' It is well known that individual components of a machine assembly will eventually break down as a result of fatigue and wear (sometimes also as a result of improper use) over time. At the same time, no amount of redundancy built into the machine assembly will be able to account for consistent performance over an extended period of time unless periodic maintenance is performed.

The rapidly evolving complexity of machines has kept pace with evolving technology. Improvements in reliability techniques however, have been unable to keep pace with the growing degree of machine complexity (Crawford and Altman, 1972; Morgan et al, 1963; Oborne, 1981). New problems in equipment downtime have been proliferating, and the concept of maintenance to serve as a tool to reduce downtime has assumed growing importance (Imrhan S, 1991).

Designing equipment for maintenance is the obvious solution to retaining equipment functionality. It has been practiced more as an art than as a science. Its evolution can be greatly attributable to common sense than to means of scientific investigation (Oborne, 1981). Maintenance is perhaps the most expensive of all human-machine systems for the following reasons:

- Given the proliferation of different types of products and systems, there has been an ever increasing need to perform different kinds of maintenance operations.
- The cost of human labor has increased consistently over a period of time. An estimation of the cost of human labor is extremely important since maintenance is probably the only field of operation that relies solely on human capital and human skill.

Some examples from the military aircraft industry are presented as follows to emphasize the expensive nature of maintenance operations:

- Aircraft maintenance costs in the US have been estimated to amount to approximately 35% of life cycle costs of military systems (McDaniel and Askren, 1985).

- The technical complexity of modern aircraft has compounded the problem of quick, cost effective maintenance even more. Adding to the degree of complexity is the wide array of hardware made possible by Computer aided design systems (Adams, 1988).
- In 1970, the US department of defense allocated 25% of its budget to maintenance costs (Smith et al, 1970). This percentage has been growing continuously with increasing level of complexity of components and machine assemblies.

Maintenance friendly machines are important, when it comes to production as well as safety. Also, machines that are difficult to maintain routinely are less likely to receive the required standard of maintenance. (Ferguson *et al*, 1985). For example, Johnson (1988), illustrated that breakdown on some machines was often found to be associated with, or was a direct result of, lack of maintenance or abuse of equipment. It was also demonstrated that poor engineering was less likely to be the causal factor. The following section of this paper will present some elementary concepts related to maintainability.

2. MAINTAINABILITY CONCEPTS

There are two principal methods by which maintenance can be affected.

1. Corrective Maintenance: Every time an equipment/system fails, a repair or restore action must follow in order to restore the operability of the system/equipment in question. This is achieved by adopting the following steps.

- Failure detection leads to non-confirmation. If the failure is not confirmed, the item must be returned to service. This no-fault-found problem leads to a considerable amount of time being wasted at significant cost. It also entails the carrying of unnecessarily large amount of inventory for a large portion of the time.
- If the failure is confirmed, the item is prepared for maintenance action and the failure report is completed.
- Localization and isolation of a failed part in the assembly is the natural next step in performing corrective maintenance.
- The failed part is removed for disposal or repair. If it is disposed, a new part is installed in its place. Examples of repairable parts/connections include broken connections, open circuit board on a PCB or a poor solder.
- The item may be reassembled, realigned and adjusted after repair. It is checked before being put back to use.

The chief disadvantage of this maintenance procedure is the inherent amount of uncertainty associated with it. Equipment downtime and reduced productivity constitutes the other major disadvantage.

2. Predictive Maintenance: Predictive maintenance is also referred to as preventive maintenance. Preventive maintenance is carried out so as to minimize the probability of a failure. It is often referred to as use-based maintenance (Swanson, L. 2001), (Meulen et al, 2008), (Sarja, A. 2002). This type of maintenance is comprised of maintenance activities that are undertaken after a specific amount of time or after a specific amount of equipment use (Gits, C. 1992 and Herbaty, F. 1990), (Monga and Ming, 1998), (Goel et al, 2003), (Hernandez et al, 2002). It relies on the estimated probability of equipment failure in the given interval of time. Preventive maintenance tasks may include equipment lubrication, parts replacement, cleaning and adjustment (e.g.: tightening, slackening, etc). Equipment may also be checked for telltale signs of deterioration during preventive maintenance. In order to be fully effective, predictive maintenance must follow rigid maintenance schedules.

In spite of all the work that has been done in order to develop efficient maintenance schedules, a design methodology to build ease of maintenance into a product at the design stage appears to be lacking. Such a methodology has been developed in this paper and is presented in the next section.

3. DESIGN FOR MAINTENANCE METHODOLOGY

3.1. Maintenance Tasks as a function of Design Variables

The most common and widely used maintenance operations are recorded and described in complete detail. Every maintenance operation is then subdivided into basic elemental tasks. Only a small fraction of all the tasks in the entire maintenance operation are actually responsible for performing effective maintenance. The remaining tasks constitute such actions as reaching for tools, grasping tools and cleaning components prior to maintenance. For example, consider a simple lubrication operation that may be subdivided into the following elemental tasks:

OPERATION: LUBRICATION

1. Isolate the component to be lubricated.
2. Constrain the product in order to avoid displacement during maintenance.
3. Locate the component to be lubricated (Location of component)
3.a. Visual location
3.b. Tactile location
3.c. Visual and tactile location.
4. Access the component to be lubricated (Accessing the component): Tactile Access

4.a. Access with tool and accessories: Difficult maintenance operation, may involve component unfastening, slackening or removal for maintenance (time consuming)
4.b. Access without tool or accessories: Easier maintenance operation. May involve only on-site lubrication (less time consuming).
5. Check the component
5.a. Visual check: Easiest and least time consuming
5.b. Tactile check: Easy and quick
5.c. Check requiring tool: More time consuming than visual and tactile check
5.d. Check requiring precision tool: Complicated and may take the most time.
6. Cleaning for maintenance
6.a. Cleaning around unions and fasteners to facilitate maintenance: least time depending on number of fasteners and unions
6.b. Cleaning small areas on machine
6.c. Cleaning large areas on machine: may be most time consuming depending on amount of cleaning required.
7. Perform maintenance operation
7.a. Lubricate on site: Easiest and least time consuming
7.b. Slacken fasteners and perform lubrication. Refasten component
7.c. Remove fasteners and remove component. Perform lubrication and put the component back in place followed by refastening it.

It is clear from the above sequence of operations that the maintenance operation is not limited solely to maintenance. An entire gamut of tasks needs to be performed in order to achieve effective maintenance. Each of the above tasks can be further expanded in order to accommodate practical issues related to maintenance. For example, tasks 3 and 4 can be expanded to take into account postural requirements and ergonomic issues such as bending, stretching, stooping, visual fatigue, etc. while performing maintenance. Similarly as far as the maintenance operation itself is concerned, task 7.c. which involves lifting of a component can be further expanded to include component's physical and chemical properties. Examples of physical properties include weight of the component, physical dimensions of the component, shape of the component, nature of surface finish on the component, etc. The relationship between each factor that affects the maintenance operation is presented in figure 1.

The figure depicts the different variables that directly affect each step of the process. For instance, maintenance may be performed onsite or may require removal of the component in question. In case the component needs to be removed, one or more fasteners may have to be removed using ordinary tools or special tools. Other related factors such as necessity for exertion of normal or abnormal force can also be explained along similar lines. It is clear that each of the variables affecting task accomplishment is a direct function of design variables. For instance, non-standard fasteners may require specialized tools to affect slackening and unfastening as well as refastening (for restoration). Physical features of a component such as weight, shape and size also dictate the need for extra force. This is clearly not maintenance friendly since it entails extra labor requirement every time a maintenance operation on the component is to be performed. Similarly, lifting and carrying elements are a function of component design variables such as component shape, size, weight and composition.

Most industrial equipment that involve moving parts or components that exhibit relative motion in all planes (vertical, horizontal, and rotational) are subject to wear with the passage of time. Friction is inherent in all pairs of mating surfaces and is directly responsible for surface degradation. Once surface breakdown exceeds a certain threshold value, it interferes with equipment performance.

The design for maintenance methodology developed in this paper is based on the concept that each maintenance operation is a function of design variables as explained in the preceding paragraphs. Since maintenance is largely a manual operation, it can be performed with varying degrees of ease or difficulty. For instance, a maintenance operation involving lifting a large piece of equipment is difficult and time consuming. The proposed methodology seeks to break down each maintenance operation into basic elemental tasks and assign numeric scores to those tasks so as to be objective in terms of design evaluation. Numeric scores assigned to each task are based on the MTM (Methods Time Measurement) system. Thus a low score implies less time spent in performing a task which is likely to be directly attributable to design simplicity, which forms the aim of the methodology. The next section describes how a numeric index to design for maintenance is developed.

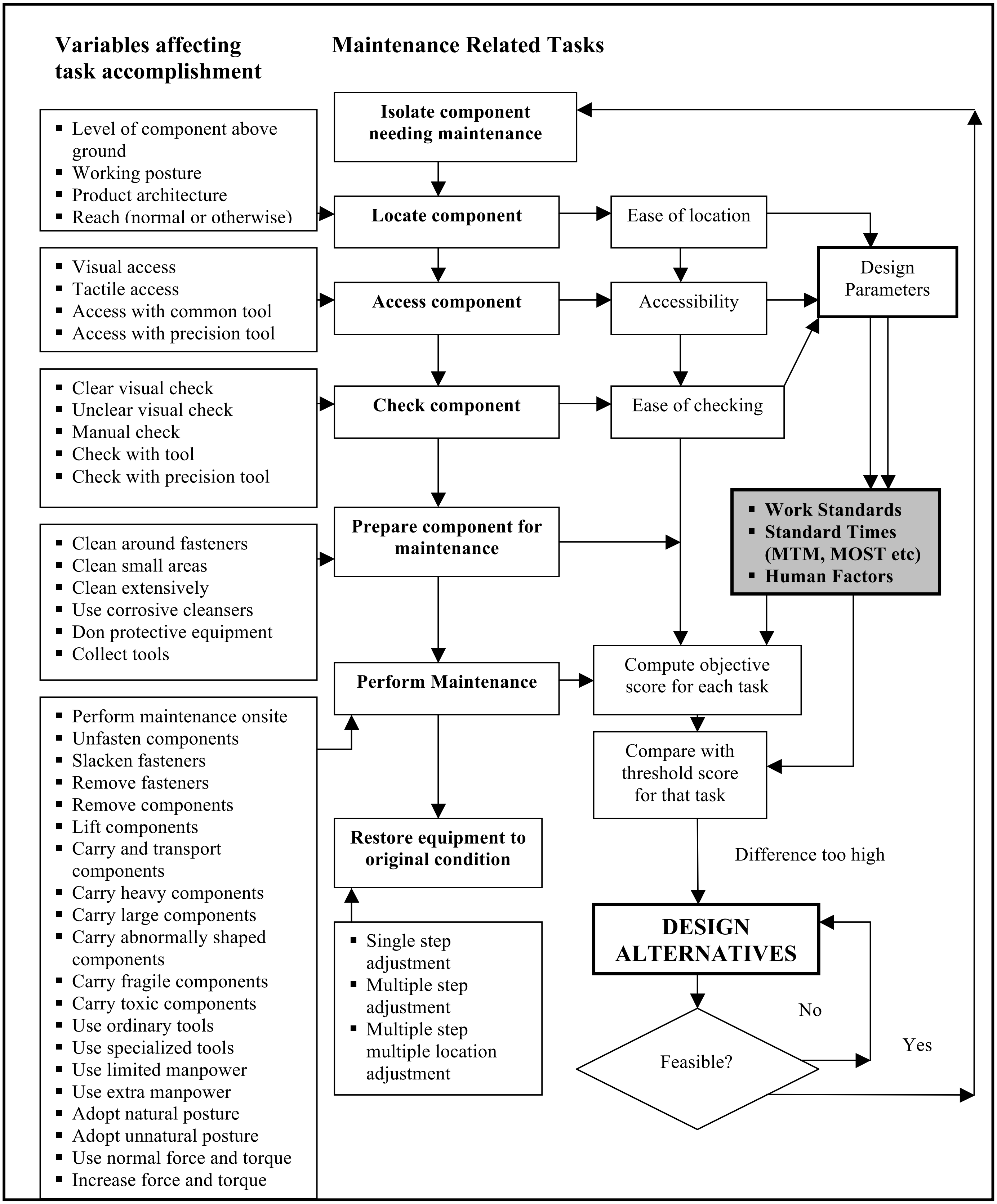

Figure 1: The maintenance procedure and how each factor affects it

3.2. Development of a Numeric Index for Disassembly/Assembly and Maintenance

Most maintenance operations are comprised of three major tasks: disassembly, maintenance and (re) assembly. Disassembly may be partial or total. It is done to facilitate access to the component being maintained. Products that can do away with the need to disassemble prior to maintenance are often the easiest to maintain. The simplest disassembly task of removing 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 disassembly task. A score of 73 TMU (Time measurement Units) was assigned to this task corresponding to time duration of 2 seconds. An explanation of how this value was arrived at follows in table 1.

Table 1: Numeric score calculation for a simple maintenance task to disassemble a component

Operation No	Operation Description	TMU (Time measurement Unit) associated with operation)
1	Reach for object (hand empty): Accessibility	10
2	Grasp object without much accuracy or visual attention	12
3	Remove object by pulling it with exertion of minimal amount of force	5
4	Put away object: Move hand loaded: material handling	48
5	Release object	
	Total TMU	73

An abridged version of a time based numeric index for disassembly has been presented in table 2. Each numeric score presented in the following tables corresponds to 1/10th of 1 TMU

Table 2: Example of a numeric time based index for disassembly

Design attribute	Design Feature	Design parameters	Score	Interpretation
Disassembly force	Straight line motion without exertion of pressure	Push/pull operations with hand	0.5	Little effort required
			1	Moderate effort required
			3	Large amount of effort required
	Straight line and twisting motion without pressure	Twisting and push/pull operations with 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	2.5	Little effort required
			3	Moderate effort required
			5	Large amount of effort required

3.3. Design for Maintenance: Addressing the Human Factors requirement

Maintenance workers, in most cases need to adopt a particular posture and expend a requisite amount of energy in order to accomplish a particular maintenance task. The simplest and easiest task to perform is one which can be performed at desk level while the worker is sitting down. This entails the least expenditure of energy (in terms of posture requirements) and is the most natural working position. There are several other postures such as bending squatting etc which are most uncomfortable. An effective design methodology needs to take into account the different postures adopted by workers when performing maintenance tasks. Allowances for various maintenance operations developed on the MTM system are presented in table 3.

Table 3: Example of human factor allowances to facilitate maintenance

Posture Allowances	Percentage Multipliers
Sitting down	0%
Standing up	2%
Bending down	5%
Lying down	3%
Crouching	5%
Stretching	8%
Squatting	8%

A similar numeric index for assembly as well as maintenance is presented in tables 4 and 5 respectively

Table 4: Example of a numeric index for assembly

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

Table 5: Example of a numeric index for maintenance

Maintenance Task	Design Feature	Score	Interpretation
Cleaning			
• Wiping with cloth • Wiping in crevices • Blow with air/water • Single bath wash • Wash and oil • Drain and wash filter • Multiple Washes	Cleaning on the machine, around fasteners, in crevices, on surfaces etc.	2/Surface 3.5/Crevice 2 5 10/Surface 10 15/Surface	• Minor Cleaning on surface • Minor Cleaning in inaccessible areas • Major Cleaning in inaccessible areas • Cleaning needs washing with solvent • Washing followed by oiling to prevent corrosion • Filter needs to be washed and drained • Requires more than one Wash/Surface

3.2. Development of a methodology to enhance design for maintenance

The index formulated in the preceding section consists of three distinct sections. The first section is comprised of pre-maintenance actions such as slackening, tightening, etc. The design parameters affecting these actions are evaluated. The second section of the index focuses on evaluating design variables directly affecting the actual maintenance processes such as lubrication, fitting, replacement, etc. The third section takes into account all allowances that play a role in all maintenance operations. Maintenance activities include lubrication, cleaning, filling, fitting, replacement, etc. As the definition implies, the former constitute actual reinstatement of equipment to working condition. The latter on the other hand, constitute either preparation of equipment condition in order to facilitate maintenance. Human factor allowances have also been incorporated into the methodology as presented in the preceding section. The method of using the index is illustrated in figure 2.

The methodology begins with evaluation of numeric scores of individual maintenance operations. This includes disassembly, actual maintenance and re-assembly operations. Numeric scores are arrived at by using data presented in tables 1 through 5. The next step consists of arranging individual task totals in descending order of numeric value. The idea behind doing this is to identify the most fallacious task and improve on it. This process can be facilitated by subdividing each individual task into elemental constituents for design evaluation and simplification. This process is continued and design improvements are applied with a view towards feasibility in terms of cost to implement change. The process ends when the last elemental subtask has been evaluated for a design improvement. It should be noted that the term ‘Design for X’ pertains to general design criteria for design for assembly, disassembly, maintenance, cost, quality, etc. These criteria are available in design handbooks and product design literature.

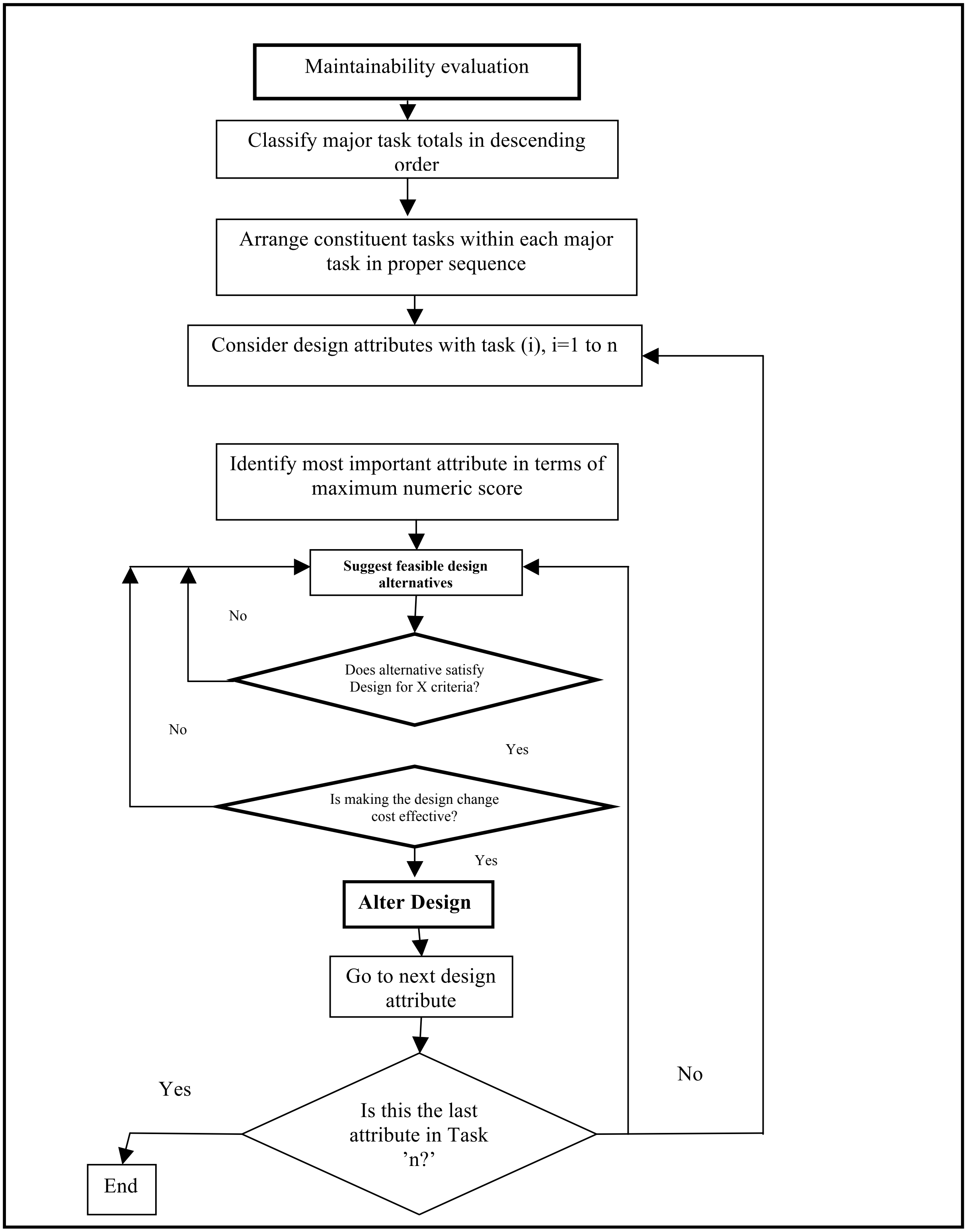

Figure 2: Method of using the index

4. AN ILLUSTRATIVE CASE STUDY

This section presents a case study to illustrate the Lubrication process of a hand held drill rotor. The disassembly and (re)assembly operations are quite simple and straightforward. A list of individual component for the drill is presented in table 6. This list is instrumental when performing the maintenance operation because it involves material handling of specific product components.

Table 6: List of components of a hand-held drill.

No	Component Name	Component Material	Quantity
1	Front/back Screw	Copper	6
2	Middle Screw	Copper	2
3	Bushing	Brass	1
4	Insulating washer	Plastic	1
5	Upper Housing	Plastic	1
6	Lower Housing	Plastic	1
7	Rotor	Mixed	1
8	Wire lead	Copper/Plastic insulation	1

Maintenance operation of drill explained:

The process illustrating the maintenance operation is presented in table 7. Both tables 6 and 7 are used in conjunction since each operation depicted in table 7 consists of handling product components depicted in table 6.

Referring to figure 2 (method of using the index), the first step in using the methodology is to evaluate maintainability. In order to achieve this, all maintenance operations need to be listed in sequence. This sequence is presented in table 7. Each sequence is further subdivided into individual tasks. For instance, the first step in this process is to gain access to the drill rotor. This is accomplished by opening the hand held drill. The first step in this specific task is to remove the upper housing. This step can be further subdivided into elements such as unscrewing front and back screws followed by unscrewing 2 middle screws and ending with the upper housing being pulled. The numbers in columns corresponding to each element is taken from the numeric scores developed in section 3.2 and presented in tables 1 through 5.

The second step is to gain access to the drill rotor. This is achieved by pulling out the bushing followed by pulling out the insulating washer. Each of the aforementioned steps takes time. This time is a function of design attributes. For instance, non-standard screws used to secure the drill upper housing are likely to take more time and thus are a design flaw that should be rectified. The fatigue allowances as presented in table 3 are also used in appropriate places during study of the maintenance operation. For instance, it is necessary to be visually attentive when locating and unscrewing a small screw from the drill housing. This increases the total amount of disassembly time and so on.

It is clear from table 7 that operations that entail complicated sequence of motions, handling of non-standard components, requires the adoption of unnatural postures etc tend to take more time as well as effort. This is naturally reflected in higher elemental times, which in turn can be pinpointed as specific design anomalies that need rectification.

The first step culminates after the total maintenance time for each element, sub operation ad entire operation has been ascertained. For the sake of our example, this time is 2940 TMUs which translates to about 1.764 minutes. In order to improve the design, tasks that require the most amount of time should be tackled first and vice versa in order to simplify the design. A design simplification is likely to result in lowering elemental times and therefore achieving the operation more efficiently and at lower cost.

The second step (as presented in figure 2) consists of arranging each major task total in descending order. For the sake of our example, this would be task: 'Reassemble drill' since it has the highest numeric value as presented in table 7. Constituent tasks within each major task are then arranged in descending order as well.

The third step (as presented in figure 2) consists of suggesting feasible design solutions to simplify component design. A simplification in design will likely be evident in lowered task totals after the design change has been implemented. The greatest obstacle to feasibility is cost. If design change can be accomplished at a minimal cost, it will be implemented. If this is not possible, the methodology keeps looking for better design solutions. The loop of design changes ends when the last sub-task has been analyzed.

It should be noted that this particular operation required only partial disassembly constrained by obtaining access to the drill rotor. If complete disassembly was required, this would have taken more time, 2.044 minutes to be precise as is explained in the text box following table 7. Thus, the design for maintenance methodology takes into consideration different aspects of disassembly, actual maintenance and assembly operations.

Table 7: Maintenance (Lubrication) operation of a drill rotor

TASK NO	TASK DESCRIPTION *Lubrication of Drill rotor*	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
			(DIS)ASSEMBLY FORCE			MATERIAL HANDLING			TOOLING		ACCESSIBILITY & POSITIONING			ALLOWANCES			
1	Remove Upper Housing																
1a	Unscrew 1st of 6 front/back screws	15.65	2.5	-	-	2	2	0.8	-	2	1.6	2	2	-	-	-	5%
1b	Unscrew 2nd of 6 front/back screws	15.65	2.5	-	-	2	2	0.8	-	2	1.6	2	2	-	-	-	5%
1c	Unscrew 3rd of 6 front/back screws	15.65	2.5	-	-	2	2	0.8	-	2	1.6	2	2	-	-	-	5%
1d	Unscrew 4th of 6 front/back screws	15.65	2.5	-	-	2	2	0.8	-	2	1.6	2	2	-	-	-	5%
1e	Unscrew 5th of 6 front/back screws	15.65	2.5	-	-	2	2	0.8	-	2	1.6	2	2	-	-	-	5%
1f	Unscrew 6th of 6 front/back screws	15.65	2.5	-	-	2	2	0.8	-	2	1.6	2	2	-	-	-	5%
1g	Unscrew 1st of 2 middle screws	15.65	2.5	-	-	2	2	0.8	-	2	1.6	2	2	-	-	-	5%
1h	Unscrew 2nd of 2 middle screws	15.65	2.5	-	-	2	2	0.8	-	2	1.6	2	2	-	-	-	5%
1i	Pull out upper housing	8.7	-	1	-	3.5	2	1.4	1	-	1	1.6	1.6	-	-	-	1%
2	Access Drill Rotor																
2a	Pull out bushing	10.5	1	-	-	2	2	0.8	1	-	1	1	1.2	-	-	-	5%
2b	Pull out insulating washer	10.5	1	-	-	2	2	0.8	1	-	1	1	1.2	-	-	-	5%
3	Lubricate Rotor and Clean Housing																
3a	Lubrication: 2/Location*2locations	4.2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	5%
3b	Clean Upper housing: 2	2.02	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1%

4	(Re) Assemble Drill																
4a	Re-install washer	10.5	1	-	-	2	2	0.8	1	-	1	1	1.2	-	-	-	5%
4b	Re-install bushing	10.5	1	-	-	2	2	0.8	1	-	1	1	1.2	-	-	-	5%
4c	Refit upper housing	8.7	-	1	-	3.5	2	1.4	1	-	1	1.6	1.6	-	-	-	1%
4d	Screw 1^{st} middle screw	15.65	2.5	-	-	2	2	0.8	-	2	1.6	2	2	-	-	-	5%
4e	Screw 2^{nd} middle screw	15.65	2.5	-	-	2	2	0.8	-	2	1.6	2	2	-	-	-	5%
4f	Screw 1^{st} front/back screw	15.65	2.5	-	-	2	2	0.8	-	2	1.6	2	2	-	-	-	5%
4g	Screw 2^{nd} front/back screw	15.65	2.5	-	-	2	2	0.8	-	2	1.6	2	2	-	-	-	5%
4h	Screw 3^{rd} front/back screw	15.65	2.5	-	-	2	2	0.8	-	2	1.6	2	2	-	-	-	5%
4i	Screw 4^{th} front/back screw	15.65	2.5	-	-	2	2	0.8	-	2	1.6	2	2	-	-	-	5%
4j	Screw 5^{th} front/back screw	15.65	2.5	-	-	2	2	0.8	-	2	1.6	2	2	-	-	-	5%
4k	Screw 6^{th} front/back screw	15.65	2.5	-	-	2	2	0.8	-	2	1.6	2	2	-	-	-	5%
		294	Total time for maintenance Operation: 2940 TMU’s = 1.764 minutes.														

Total maintenance time: 1.764 minutes
Task # 1 for Maintenance Analysis: Unscrewing/Screwing back of various screws of Upper housing
Most feasible cost effective design solution: Use toggle type snap fits for upper housing in place of screws to reduce maintenance time.

Total Disassembly time for complete 100% disassembly: 2.044 minutes (Maintenance requires almost complete disassembly of drill)
Task # 1 for Disassembly Analysis: Disassembly of rotor-bushing sub assembly
Most important design anomaly for disassembly: Force required wedging out subassembly of rotor and bushings

Task # 1 for Assembly Analysis: Inserting trigger Assembly. Total Assembly time: 1.30 minutes

Conclusion: Most amount of time is spent in **accessing** the maintenance area. Too many fasteners hamper disassembly and assembly

5. CONCLUSION

This paper presented a comprehensive methodology to facilitate maintenance operations through the incorporation of Design for X techniques. It also illustrated how human factors can be effectively incorporated in order to aid in design modifications for a process that is largely labor intensive. The most significant advantage of this methodology is the fact that it is time based. As a result, two distinct product designs can be readily compared with each other in terms of the ease that they offer when it comes to ease of maintenance. Also, cost of maintenance can be readily ascertained if total time for maintenance is known. Finally, the methodology presented in this paper seeks to fill a void that has existed in maintenance related research.

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BIOGRAPHICAL SKETCH

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